



CMD 25-H9.14-Ref1

Date: 2025-11-20

**Reference Package from the
Saskatchewan Environmental
Society and the Nuclear
Transparency Project**

**Dossier de référence de la
Saskatchewan Environmental
Society et du Projet de
transparence nucléaire**

In the matter of

À l'égard de

Denison Mines Corporation

Licence Application to Prepare Site and
Construct for Denison Mines' Wheeler
River Mine and Mill Project

Denison Mines Corporation

Demande de permis pour la préparation de
l'emplacement et la construction du projet
de mine et d'usine de concentration
d'uranium Wheeler River de Denison Mines

Commission Public Hearing

Audience publique de la Commission

December 2025

Décembre 2025



Saskatchewan
Environmental
Society



nuclear
transparency
project

November 19, 2025

The documents provided in this reference package are some of those cited in **COMMENTS TO THE CANADIAN NUCLEAR SAFETY COMMISSION REGARDING WHEELER RIVER PROJECT PROPOSAL OF DENISON MINES CORP. AND THE REVIEW BY CNSC STAFF**, which was submitted to the CNSC by the Saskatchewan Environmental Society and the Nuclear Transparency Project on October 24, 2025.

REFERENCE PACKAGE CONTENTS

1.3-12
Borch, T., Roche, N., & Johnson, T. E. (2012). Determination of contaminant levels and remediation efficacy in groundwater at a former in situ recovery uranium mine. *Journal of Environmental Monitoring*, 14(7), 1814-1823. <https://doi.org/10.1039/C2EM30077J>
2.13-23
Caro, T. M., & O'Doherty, G. (1999). On the use of surrogate species in conservation biology. *Conservation Biology*, 13(4), 805–814. <https://doi.org/10.1046/j.1523-1739.1999.98338.x>
3.24-25
Chen, Z., Zou, Q., Gao, S., Zhan, J., Chen, C., Ran, Q., & Sun, X. (2023). Long-term evolution of overlying rock fractures in mined-out areas and its effect on gas flow conductivity [p. 1–2]. *Fuel*, 353, 129213. <https://doi.org/10.1016/j.fuel.2023.129213>
4.26
Ekert, V., & Mužák, J. (2010). Mining and remediation at the Straz pod Ralskem uranium deposit [Abstract]. *GeoScience Engineering, Volume LVI*, No. 3 – Special Issue. <https://gse.vsb.cz/2010/LVI-2010-3-01-06.pdf>
5.27-37
Government of South Australia. (n.d.). *Beverley uranium mine incident summary report*. <https://www.energymining.sa.gov.au/industry/minerals-and-mining/mining/major-projects-and-mining-activities/major-operating-and-approved-mines/beverley-and-beverley-north-mines/beverley-uranium-mine-incident-summary-report>
6.38-71
Hall, S. (2009). Groundwater restoration at uranium in-situ recovery mines, south Texas coastal plain. U.S. Geological Survey Open-File Report 2009–1143. <https://pubs.usgs.gov/of/2009/1143/pdf/OF09-1143.pdf>

7.	.....	72-137
Joint Federal-Provincial Panel on Uranium Mining Developments in Northern Saskatchewan. (1993). Uranium mining developments in northern Saskatchewan: Dominique-Janine extension, McClean Lake project, and Midwest joint venture. <i>Government of Canada</i> .		
8.	.....	138-143
Kopecky, P., & Slezak, J. (2002). Uranium mining in the North Bohemia, Straz, Czech Republic and geological evaluation prior to remediation. (<i>Number no. 10/P, pp. p. 380–385</i>).		
9.	.....	144-172
Li, G., & Yao, J. (2024). A review of in situ leaching (ISL) for uranium mining. <i>Mining</i> , 4(1), 120-148. https://doi.org/10.3390/mining4010009		
10.	.....	173-193
Newsome, L., Morris, K., & Lloyd, J. R. (2014). The biogeochemistry and bioremediation of uranium and other priority radionuclides. <i>Chemical Geology</i> , 363, 164-184. https://doi.org/10.1016/j.chemgeo.2013.10.034		
11.	.....	194-205
Ruiz, O., Thomson, B., Cerrato, J. M., & Rodriguez-Freire, L. (2019). Groundwater restoration following in-situ recovery (ISR) mining of uranium. <i>Applied Geochemistry</i> , 109, 104418. https://doi.org/10.1016/j.apgeochem.2019.104418		
12.	.....	206-228
Schlissel, D., & Wamsted, D. (2024). Small modular reactors: Still too expensive, too slow and too risky. <i>IEEFA</i> . https://ieefa.org/resources/small-modular-reactors-still-too-expensive-too-slow-and-too-risky		
13.	.....	229-236
WISE Uranium Project. (n.d.). Impacts of uranium in-situ leaching. https://www.wise-uranium.org/uisl.html		
14.	.....	237-291
WISE Uranium Project. (n.d.). Issues at operating uranium mines and mills - USA. https://www.wise-uranium.org/umopusa.html#CROWB		

Cite this: *J. Environ. Monit.*, 2012, **14**, 1814

www.rsc.org/jem

PAPER

Determination of contaminant levels and remediation efficacy in groundwater at a former *in situ* recovery uranium mine†‡

Thomas Borch,^{*a} Nicholas Roche^b and Thomas E. Johnson^{*b}

Received 28th January 2012, Accepted 10th May 2012

DOI: 10.1039/c2em30077j

There has been increasing interest in uranium mining in the United States *via in situ* recovery techniques. One of the main environmental concerns with *in situ* uranium mining is the potential for spreading groundwater contamination. There is a dearth of detailed analysis and information regarding the outcome of *in situ* uranium mine remediation to ascertain the environmental impacts. Regulatory measurements performed at a Wyoming *in situ* uranium mine were collected and analysed to ascertain the efficacy of remediation and potential long term environmental impact. Based on the measurements, groundwater sweeping followed by reverse osmosis (RO) treatment proved to be a highly efficient method of remediation. However, injection of a reductant in the form of H₂S after groundwater sweeping and RO did not further reduce the aqueous concentration of U, Mn, or Fe. Low concentrations of target species at monitoring wells outside the mined area appear to indicate that in the long term, natural attenuation is likely to play a major role at reductively immobilizing residual (after remediation) concentrations of U(VI) thus preventing it from moving outside the mined area. Our analysis indicates the need for additional monitoring wells and sampling in conjunction with long term monitoring to better understand the impacts of the different remediation techniques.

Introduction

Background

Uranium is used to produce approximately 20% of all electricity consumed in the United States.¹ Domestic mining of uranium is based primarily on utilizing the most economic methods to extract the primarily low grade ore (<0.1%) that is common in the US.^{1,2} The bulk of US uranium reserves available for economic extraction at \$50 per pound (275 million tons) is *via In Situ Recovery*

(ISR) (145 million tons), making ISR the most economical method for the majority of uranium deposits in the US.¹ Currently, there are six operational ISR mines (2010), with an additional six either partially licensed or licensed, and another four in standby or development.¹ There are no other currently active uranium mines in the US. Complete remediation has been accomplished at only a few facilities, although restoration of specific mine units of the various operational mines is ongoing.³

Several former ISR mine sites have been remediated, and significant amounts of data on ISRs collected for regulatory purposes, but to date, no complete scientific evaluation of the data, restoration process or the efficacy of the restoration process has been performed.^{4–8}

ISR process

Uranium in the environment is found as two major species of differing oxidation states: U(VI), which is soluble and mobile, and

^aDepartment of Soil and Crop Sciences, Colorado State University, Fort Collins, Colorado 80523-1170, USA. E-mail: borch@colostate.edu; Fax: +1 970 491 0562; Tel: +1 970 491 6235

^bDepartment of Environmental and Radiological Health Sciences, Colorado State University, Fort Collins, Colorado 80523-1618, USA. E-mail: tj@colostate.edu; Fax: +1 970 491 0623; Tel: +1 970 4910563

† Published as part of a special issue dedicated to Emerging Investigators.

‡ Electronic supplementary information (ESI) available: A detailed map of mine unit A layout. See DOI: 10.1039/c2em30077j

Environmental impact

This project evaluated the remediation efficacy at a former *in situ* recovery uranium mine based on a statistical analysis of data publicly available to help determine the potential long term environmental impact. A combination of groundwater sweeping and reverse osmosis proved to be an efficient remediation approach. The relatively low concentrations of key species such as U observed at monitoring wells outside the mined area indicate that natural attenuation likely plays an important role in controlling the mobility of redox sensitive contaminants.

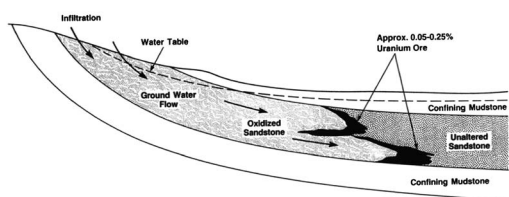


Fig. 1 Creation of uranium roll front by precipitation (adapted from U.S. Nuclear Regulatory Commission 2007).⁶

$U(IV)$, which is sparingly soluble and usually precipitates as $UO_2(s)$ (uraninite).⁹ In areas with naturally high uranium concentrations, dissolved oxygen in groundwater will oxidize uranium to its $U(VI)$ species. As the groundwater continues down a hydrological gradient into a reducing environment, the oxygen content becomes depleted and the uranium will become reduced to its $U(IV)$ species and precipitates.⁶ The precipitation process eventually creates a roll front of uranium bearing sands, as seen in Fig. 1.

If a potential site is deemed geologically feasible for ISR uranium mining, then the uranium is recovered from the roll front through the use of wells. ISR is geologically feasible when a permeable ore body is within a confined aquifer, and located such that groundwater away from the ore body cannot be contaminated. Wells are typically drilled in square patterns, with a production well in the middle of the square (see Fig. 2).

Oxygen (O_2), or other oxidizing agents such as H_2O_2 , and a carbon alkaline (generally CO_2) are added to the water that is pumped into the injection wells (Fig. 3), and the water then flows towards the production well due to the positive net flux of water being pumped out. The oxygen in the water oxidizes the $U(IV)$ into its soluble $U(VI)$ form.¹¹ The addition of CO_2 buffers the pH of the water and promotes the formation of highly stable uranyl {or $U(VI)$ } (hydroxy)carbonate ions, further enhancing the $U(VI)$ solubility. The uranium bearing water is then pumped back to the surface, where the uranium is extracted through an ion exchange process. The water is then reoxygenated before being pumped back into the injection wells.

The main environmental concern from ISR mining is the transport of contaminated water into a regional aquifer, whose water may be consumed by livestock or humans. Another concern is the possible diffusion or leaching of contaminants

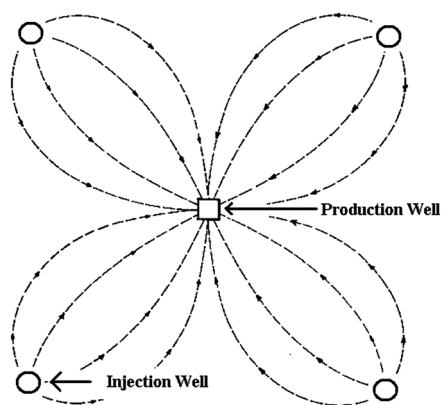


Fig. 2 Typical well pattern (with permission from PRI, 2000).¹⁰ The four wells which make up the points on the square are the injection wells and the inner well is the production well.

through the soil and subsequent uptake by plants, which can then enter the human food chain by consumption of either the plants or animals which have eaten the plants. The third risk of ISR mining is the potential for a spill or accident (e.g. release of contaminated water).⁶

Post-mining: remediation

Mining companies, as part of their license contract, must remediate the mine site back to preexisting conditions, or as close as reasonably possible based on regulatory guidance. This entails ensuring that the groundwater contaminant concentration levels reach agreed upon standards. There are several methods used by the mining companies in order to remediate the groundwater. These methods include groundwater sweep, reverse osmosis, chemical reductant, bioremediation, and natural attenuation.

Groundwater sweep remediation is accomplished by continually pumping water from the production well, with no water pumped into injection wells. The groundwater which is pumped up through the production well is then disposed of through various methods.¹² Regional groundwater then restores the aquifer through the hydrological gradient created by pumping the high concentration water from the production well and the regional water replacing it. Reverse osmosis remediation is where contaminated water is pumped to the surface treated through reverse osmosis then re-injected into the aquifer. Injecting a chemical reductant, such as H_2S , to restrain further oxidation reactions within the roll front and cause contaminants to precipitate back onto their surrounding environment is another method of remediation.¹² Bioremediation consists of using naturally occurring bacterial species such as *Geobacter* to reduce contaminants to their insoluble form through natural metabolic pathways. Electron donors such as ethanol are injected into the wells, increasing proliferation of naturally occurring bacteria, and resulting in re-precipitation of contaminants.^{13,14} For example, bacteria reduce $Fe(III)$ to $Fe(II)$ which can reduce $U(VI)$ (soluble) to $U(IV)$ (insoluble) and bacteria can also directly reduce $U(VI)$ to $U(IV)$, resulting in $U(IV)$ precipitation.^{15,16} There are three main natural attenuation processes: adsorption, dispersion, and precipitation. Adsorption occurs when a solid material comes into contact with the groundwater. The solid material will attract the ions in the groundwater, and the ions will adsorb onto the surrounding material. Dispersion occurs when a fluid flows through a porous medium. It arises due to the different flow paths and flow velocities established by the pore diameters and the pore configurations in the host rock. The contaminants in the groundwater will disperse and mix with the uncontaminated groundwater, thus diluting the concentrations over a period of time. Precipitation is caused by the reduction of sulfate to sulfide due to reducing conditions that were not disturbed by mining. As the groundwater reverts to its original flow direction, towards the reduced side of the roll front, certain minerals, such as pyrite and uraninite, will precipitate out of the groundwater into the surroundings as they encounter the reducing environment.¹⁷

Post-mining: determination of remediation efficacy and goals

There is limited information available on how best to monitor efficiency and efficacy, and how long to monitor *in situ* uranium

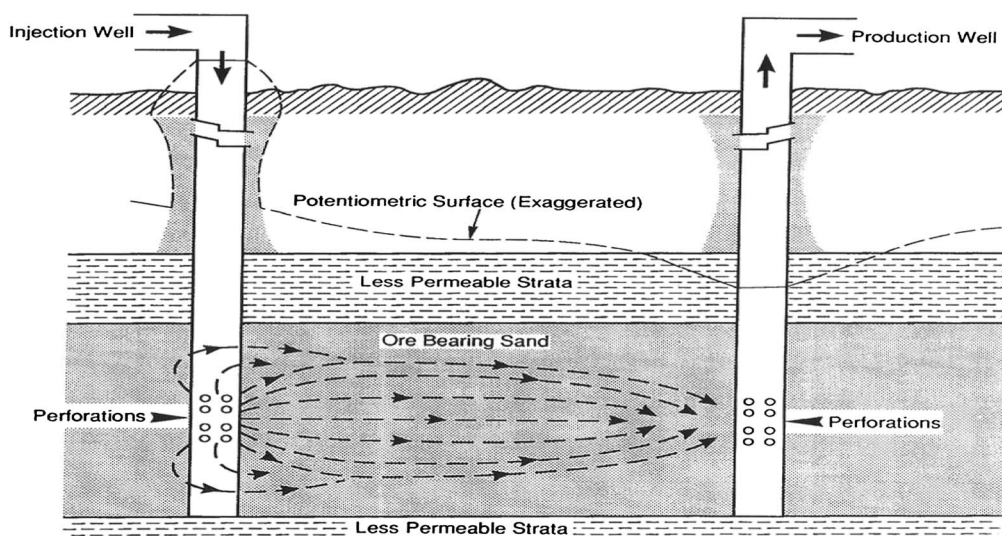


Fig. 3 Process of ISR uranium mining (adapted from U.S. Nuclear Regulatory Commission 2007).⁶

mines during and post-remediation. Furthermore, the specific fate of the remediated species has not been well documented.¹⁸

Thus, the objectives of this paper are to (1) evaluate the efficacy of groundwater sweep remediation in combination with reverse osmosis (RO) and H₂S (chemical reductant) treatment and (2) determine the time needed for site stabilization and immobilization of target contaminants.

Methods

Site general information

The Smith Ranch Highland Uranium Project (HUP) is an *in situ* uranium mine site currently operated by Cameco Corporation (previously operated by Power Resources, Inc.), located in central Converse County, Wyoming, in the southern portion of the Powder River Basin. Cameco Corporation has several mine units currently in operation at the HUP. The mine unit of interest in this study is mine unit A, or the A-Wellfield (see detailed map in ESI†).

Mine specifications

The Highland Sand Group, containing uranium roll fronts, are a part of the lower Wasatch Formation of early Tertiary age, and regionally forms a single aquifer and consists of fluvial sandstones of the Fort Union Formation. The Wasatch Formation is nearly flat in this vicinity, with a regional dip of <0.5 degrees to the east and north. Mine unit A “was installed in a lens of sand surrounding an isolated uranium roll-front which had infiltrated downwards from the sand.”¹⁹ The sand was discontinuous; however the western boundary was well defined (near well M-8). There is shale separating the two sand aquifers, with a less than 0.6 m (2 feet) thick elongated northeast to southwest trending zone and the two aquifers are interconnected. Monitoring during and after mining was conducted such that the trending zone was partially enclosing the aquatard (see ESI† for a detailed map). The average depth of mine unit A, 161.5 m (530 feet), is deeper than the typical aquifers used for domestic and livestock supply in the surrounding area. The gradient in the regional groundwater is approximately 0.6 degrees in the north-westerly

direction,¹⁹ and the average natural flow rate of the groundwater is estimated to be 1.7 m (5.6 feet) per year generally eastward, with local southerly or northerly components.¹⁰ Groundwater flow was established prior to mining activities based on groundwater recharge and discharge areas and analysis of water level data. When in operation, the A-Wellfield was composed of 31 production patterns divided into three sections: A-1, A-2, and A-3. The A-Wellfield also had 14 monitoring wells in a ring surrounding the wellfield. The monitoring ring and monitoring wells above and below the aquifer were used to detect excursions.

Source of data

Data were obtained from publicly available Nuclear Regulatory Commission (NRC) and Wyoming Department of Environmental Quality (WYDEQ) reports concerning Cameco’s Smith Ranch Highland Uranium Project. Uranium was mined in the A-Wellfield from January 1988 until July 1991.¹⁰ Restoration of groundwater in the A-Wellfield was conducted from July 1991 to October 1998, using the groundwater sweep, reverse osmosis, and chemical reductant remediation methods. The groundwater sweep was utilized from July 1991 until June 1994 (utilizing 13 million gallons), followed by the reverse osmosis method from June 1994 until November 1997. Hydrogen sulphide (H₂S) gas was selected as the reductant to be used for phase 3 of groundwater restoration, and this method was started in May 1998 and continued until October 1998. The stabilization period was from February 1999 until October 1999, and the successful restoration of mine unit A was satisfactorily demonstrated to the Wyoming Department of Environmental Quality (WYDEQ). The mine unit has been inactive since declared remediated in 1999. Monitoring is still being conducted at selected wells as part of the long term monitoring plan.

The study locations were selected based on the detailed information available for wells MP-4, I-21, LTM-4, M-3, and M-4. Since this study was not sponsored, funded or authorized by Cameco (current mine operators and owners of the data), only publicly available information submitted as a part of the regulatory process was available. During restoration, regulatory reporting of detailed well by well chemistry is not required, and,

for regulatory purposes, is unnecessary. Some well by well detail is available for the six month period following the declaration of completion of restoration, in order to establish wellfield “stability” per WYDEQ regulation. The dataset used for analysis is unique, as the WYDEQ identified these wells as being those with the highest concentrations of constituents, and of most interest to follow long term post-restoration completion. Detailed chemistry for the entire mine unit may exist, but, if so, it is proprietary to Cameco since it is not necessary to make regulatory decisions, and not readily available for scientific analysis.

Remediation efficacy parameters chosen for mine unit A

Concentration levels from 2005 to 2010 were only available for six parameters: naturally occurring uranium (U-nat), radium-226 (Ra-226), chlorine (Cl), alkalinity (Alk), pH, and manganese (Mn). Data on these six variables were obtained from five wells in the A-Wellfield: I-21, MP-4, LTM-4, M-3, and M-4 (see Fig. 4). Well I-21, which was previously an injection well, and well MP-4, which was previously a (monitored) production well, are located within the grid of injection and production wells. Wells M-3 and M-4 are monitoring wells located roughly 300 feet from the A-Wellfield. Well LTM-4, which is between the grid and the monitoring wells, was drilled as part of the long term monitoring project, and is roughly 50 feet to the east of well I-21, in the flare from the production zone. These wells were chosen by Cameco Corporation and the WYDEQ for the long term monitoring of contaminants over time as groundwater flowed. Well MP-4 had the highest concentration of three elements of concern (U, Ra and Se) and MP-4 along with the associated downstream wells were selected for long term monitoring by Cameco and WYDEQ.

Statistical analysis of long term monitoring data

Statistical analysis was performed using Statistical Analysis Software (SAS V. 9.0, Cary, NC). First, the data were tested for

significant changes in concentrations of each parameter in each well using regressions of the natural logarithm of concentration on elapsed days since January 1st, 2005. The null hypothesis of no change in the slope of the regression line was tested using the *T*-test at the 99% confidence level.

The second method used analysis of covariance (ANCOVA) to test for significant differences in the regression slopes among wells for a particular parameter. The ANCOVA analyses of differences in slopes among wells were performed separately for the two monitoring wells (M-3 and M-4) and the three wells in or near the field (I-21, MP-4, and LTM-4). The null hypothesis of equal slopes among wells for a parameter was tested using the SAS function proc glm. Significance was determined at the 95% confidence level, using the Type III sum of squares error method for the interaction between wells and days. If a significant interaction term occurred, indicating that variables could be dependent upon each other, the slopes for the various wells were compared using linear contrasts to determine which wells differed.

The third method tested for differences in means between the wells, and utilized the permutation analysis from SAS. Similar to the Monte Carlo method, the permutation analysis randomly reassigned the 50 data points to five bins, representing the five wells. SAS then analyzed the differences between specified combinations of means. These combinations included the following: the mean of the production zone wells (I-21 and MP-4) was compared to well LTM-4; the mean of the production zone wells was compared to the mean of the monitoring wells (M-3 and M-4); and well LTM-4 was compared to the mean of the monitoring wells. The comparisons were repeated 20 000 times to produce statistically significant values, and a distribution of differences between means was produced. The actual difference between specified means was then compared to the distribution to determine if the difference between means is improbably larger or smaller than that which would be expected. Thus, the null hypothesis that the pattern in the data was no different from that which would be expected if the observations were assigned randomly to the different bins was tested against the constructed distribution. If a result was determined to be significant, then a large positive difference in means or a large negative difference in means existed. As the analysis was two-tailed, an improbability level, which is analogous to a significance level, of $p < 0.005$ was used.

Results

Groundwater quality

The groundwater quality pre-mining was designated as Wyoming Class of Use 5 (commercial-mineral) due to the elevated concentrations of dissolved radium. The water was found to be unsuitable for domestic, irrigation, or livestock purposes. The concentrations of contaminants were generally elevated at the end of restoration, with uranium, arsenic, iron, manganese, and selenium having levels increased by at least a factor of five from their baseline concentration levels.¹⁰ The concentration levels at the various stages of mining are shown in Table 1. Data in Table 1 also indicate that the use of H₂S after groundwater sweeping and RO did not further improve the water quality.

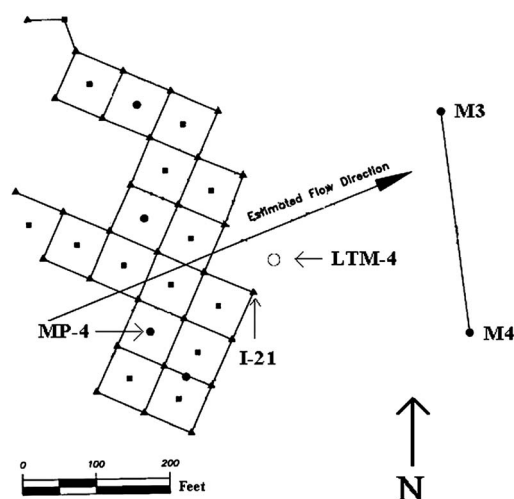


Fig. 4 Well locations of MP-4, I-21, LTM-4, M-3, and M-4 in the A-Wellfield. MP-4 indicates monitored production well 4, I-21 indicates injection well 21, LTM-4 indicates long term monitoring well 4, M-3 and M-4 indicate monitoring wells 3 and 4. See ESI† for a detailed map (adapted from PRI, 2000).¹⁰

Although the concentration levels post-restoration were higher than baseline concentration, the water “Class of Use” standards established by the WYDEQ deemed to have been met. Also, 30 of 35 parameters had concentrations post-restoration below limits for any Class of Use (see Table 2).

Covariance analysis

Covariance analysis was performed to ascertain differences in concentration over time. The covariance analysis results yielded statistically significant differences in slopes among the inside wells (I-21, MP-4, and LTM-4) for natural uranium, chlorine, and manganese. For natural uranium, I-21 was decreasing, MP-4

was increasing, possibly indicating oxidation of U, and LTM-4 was showing no change over time. For chlorine, wells I-21 and LTM-4 were decreasing while well MP-4 was showing no change over time. For manganese, well LTM-4 was increasing (possibly indicating a reducing environment) while wells I-21 and MP-4 were showing no change over time. There was no consistent pattern as to which wells would be increasing or decreasing for a given parameter.

Regression analysis

Statistically significant ($p < 0.01$) regression slopes were observed for natural uranium, chlorine, and manganese (see Table 3). No

Table 1 Average water quality at wells MP-1 through MP-5 in the A-Wellfield for various stages of operations ($n = 5$).¹⁰ All values in mg L⁻¹, except for pH in standard units and Ra in pCi L⁻¹. The pH value was measured in the laboratory and was affected by the unavoidable degassing of the water during sampling. The actual values in the aquifer are believed to have been closer to pH 6.0. The range of values is in parenthesis. Complete information on values for other wells is not available. See ESI† for a detailed map of mine unit A and well locations

	Baseline Aug. 1987	Post-mining July 1991	Pre-H ₂ S May 1998	Post-restoration Feb. 1999	% of baseline post-restoration	EPA primary standards for drinking water
Ca	44.1 (43.8–44.4)	313.4 (296.0–343.0)	68.6 (35.2–117.0)	73.4 (64–83.0)	166	—
Mg	9 (8.6–10.2)	59.5 (53.5–63.6)	12.4 (6.1–21.6)	13.5 (7.8–16.2)	150	—
Na	55 (52.5–55.6)	80.8 (77.9–83.8)	37.4 (32.4–51.6)	42.2 (35.1–57.0)	77	—
K	8 (6.1–12.1)	13.4 (13.1–14.1)	4.7 (3.0–6.8)	4.4 (3.3–5.9)	55	—
CO ₃	0	0	0	0	—	—
HCO ₃	215 (207.0–223.0)	720.2 (690.0–810.0)	242.21 (122.0–401.0)	256.6 (211.0–314.0)	119	—
SO ₄	91 (89.4–94.5)	380.6 (364.0–413.0)	83.9 (61.6–108.0)	127.2 (94.0–159.0)	140	250
Cl	4.7 (4.2–5.1)	212.6 (188.0–239.0)	14.4 (4.0–34.9)	18 (15.0–20.0)	383	250
NH ₄	0.1 (0.11–0.15)	0.7 (0.08–1.97)	0.2 (0.06–0.46)	0.29 (0.12–0.54)	290	0.5
NO ₂	0	0.1 (0.1–0.1)	0.1 (0.1–0.1)	0.1 (0.1–0.1)	—	1
NO ₃	0	0.2 (0.10–0.41)	0.1 (0.10–0.10)	0.1 (0.10–0.10)	—	10
F	0.2 (0.10–0.17)	0.2 (0.13–0.29)	0.14 (0.11–0.20)	0.15 (0.11–0.18)	75	4
SiO ₂	16 (15.40–16.50)	20.5 (17.40–22.10)	12.6 (9.50–16.50)	11.9 (7.20–15.70)	74	—
TDS	330 (312–352)	1507 (1420–1593)	342 (227–532)	410 (366–443)	124	500
Cond.	525 (506–562)	2390 (2346–2468)	579 (396–901)	647 (582–697)	123	—
Alk.	177 (170–183)	591 (566–664)	199 (100–329)	211 (173–258)	119	—
pH	8 (7.65–8.28)	6.78 (6.54–7.20)	7.25 (6.71–7.73)	7.31 (7.09–7.53)	91	6.5–8.5
Al	0.1 (0.1–0.1)	0.1 (0.1–0.1)	0.1 (0.1–0.1)	0.1 (0.1–0.1)	100	—
As	0.001 (0.001–0.002)	0.001 (0.001–0.002)	0.01 (0.001–0.049)	0.03 (0.001–0.092)	3000	0.05
Ba	0.1 (0.1–0.1)	0.1 (0.1–0.1)	0.1 (0.1–0.1)	0.1 (0.1–0.1)	100	2
B	0.1 (0.1–0.1)	0.1 (0.1–0.14)	0.1 (0.1–0.1)	0.1 (0.1–0.1)	100	0.75
Cd	0.01 (0.01–0.01)	0.03 (0.01–0.1)	0.005 (0.005–0.005)	0.005 (0.005–0.005)	5	0.005
Cr	0.05 (0.05–0.05)	0.05 (0.05–0.05)	0.05 (0.05–0.05)	0.05 (0.05–0.05)	100	0.1
Cu	0.01 (0.01–0.02)	0.02 (0.01–0.04)	0.03 (0.01–0.10)	0.01 (0.01–0.01)	100	1
Fe	0.05 (0.05–0.05)	0.05 (0.05–0.05)	1.32 (0.05–3.55)	1.3 (0.44–2.20)	2600	0.3
Pb	0.05 (0.05–0.05)	0.05 (0.05–0.05)	0.05 (0.05–0.05)	0.05 (0.05–0.05)	100	0.015
Mn	0.03 (0.01–0.03)	0.66 (0.07–1.08)	0.41 (0.14–0.54)	0.49 (0.30–0.80)	1633	0.05
Hg	0.001 (0.001–0.001)	0.001 (0.001–0.001)	0.001 (0.001–0.001)	0.001 (0.001–0.001)	100	0.002
Mo	0.1 (0.1–0.1)	0.1 (0.1–0.1)	0.1 (0.1–0.1)	0.1 (0.1–0.1)	100	—
Ni	0.05 (0.05–0.05)	0.08 (0.05–0.14)	0.05 (0.05–0.05)	0.05 (0.05–0.05)	100	—
Se	0.001 (0.001–0.004)	0.99 (0.313–1.590)	0.16 (0.001–0.504)	0.07 (0.001–0.343)	7000	0.05
V	0.1 (0.1–0.1)	0.19 (0.1–0.29)	0.1 (0.1–0.1)	0.1 (0.1–0.1)	100	—
Zn	0.01 (0.01–0.02)	0.04 (0.01–0.12)	0.01 (0.01–0.01)	0.01 (0.01–0.01)	100	5
U	0.05 (0.02–0.07)	40.19 (24.40–62.50)	3 (0.08–9.86)	3.53 (0.17–8.35)	7060	0.03
Ra	675 (67–916)	3286 (1974–5984)	1056 (284–3030)	1153 (293–3220)	171	5

Table 2 Average water quality post-restoration for wells MP-1 through MP-5 (see Table 1 for details). *Note:* in general, Wyoming classifications of water quality are as follows: Class 1 – outstanding quality water, Class 2 – fisheries and drinking water, Class 3 – aquatic life other than fish, and Class 4 – agriculture, industry, recreation and wildlife

At or below baseline	Above baseline, but below limits for any Class of Use	Above baseline and above limits for Classes 1–3
Na, K, CO ₃ , NO ₂ , NO ₃ , F, SiO ₂ , Al, Ba, B, Cd, Cr, Cu, Pb, Hg, Mo, Ni, Zn, V	NH ₄ , Ca, Mg, HCO ₃ , Cl, TDS, conductivity, Alk., pH, SO ₄ , As	U, Fe, Mn, Se, Ra

Table 3 Analysis of regression lines. The six instances of significant regression slopes. Significance level at 99%. Note that negative slope indicates that the parameter has decreased in concentration over the five years post-remediation. Positive slope indicates that the parameter has increased in concentration over the five years post-remediation. All other parameters did not change, based on the value of $p = 0.05$

Parameter	Well (type)	Slope (% per year)
Natural uranium	I-21 (injection)	−30.0
Natural uranium	MP-4 (production)	4.4
Chlorine	I-21 (injection)	−3.0
Chlorine	LTM-4 (long-term monitoring)	−5.0
Manganese	LTM-4 (long-term monitoring)	7.5
Manganese	M-4 (monitoring)	−7.2

significant trends of either increasing or decreasing values with time were observed for radium, alkalinity, or pH. No statistically significant trends of increasing values with time were observed for either of the two monitoring wells. Slopes were expressed as percent change per year, and most slopes indicated rates of change per year of less than 10% except for natural uranium in injection well I-21, where concentrations were declining at a rate of 30% per year. There were no significant differences in slopes between the monitoring wells except for the decrease in levels of manganese in well M-4.

Analysis of differences between means

The average mean of the inside wells (MP-4 and I-21) was significantly higher than the average mean of the monitoring wells for all parameters except pH. The mean of well LTM-4 either was equal to the average mean of the inside or monitoring wells or was less than the inside wells but greater than the monitoring wells (see Table 4).

The graphs of the two main parameters of interest, U-nat and Ra-226, are shown in Fig. 5 and 6. Due to the large difference in concentration levels among the wells, the ordinate is on a logarithmic scale. We were unfortunately not able to obtain data covering the immediate time period after remediation (*i.e.*, February 1999 to January 2005). However, Table 1 clearly shows that the post-restoration analysis of U and Ra in MP-1–5 conducted in 1999 resulted in concentrations very similar to the

Table 4 Analysis of differences between means. Significance level at 0.005. Inside wells: wells in the mineralized region, I-21 and MP-4. Monitoring wells: M-3 and M-4

Parameter	Differences in means
Alkalinity (mg L^{-1})	Inside wells (394) > LTM-4 (327) > monitoring wells (185)
pH	Monitoring wells (7.7) = LTM-4 (7.7) > inside wells (7.1)
U-nat (mg L^{-1})	Inside wells (8.35) > LTM-4 (0.016) = monitoring wells (0.016)
Ra-226 (pCi L^{-1})	Inside wells (2096) > LTM-4 (27.0) > monitoring wells (7.6)
Chlorine (mg L^{-1})	Inside wells (18) = LTM-4 (20.8) > monitoring wells (3.4)
Manganese (mg L^{-1})	Inside wells (0.48) > LTM-4 (0.087) > monitoring wells (0.032)

concentrations observed at MP-4 nearly six years later (Fig. 5 and 6), indicating that the concentration of these species likely had already stabilized.

Discussion

Covariance and regression analysis

Statistical analysis was performed to ascertain which parameters had significant changes over time and then the importance of each.

Parameter changes prior to 2005

Since the water between I-21 and LTM-4 is replaced in about nine years (based on a flow rate of 1.7 m per year and a distance of 15 meters), it is reasonable to assume that U has been removed primarily due to natural attenuation, since the H_2S treatment did not result in any significant change in U concentration (Table 1). It should be mentioned that the high bicarbonate concentrations (avg. 4 mmol L^{-1}) will promote the formation of U(VI) -carbonate complexes and likely prevent the reduction of U(VI) by H_2S due to the lower redox potential of these U(VI) species.^{20,21} The As concentration is approximately 3 times higher after the H_2S treatment, indicating that not all As precipitated as sulfide bearing mineral phases, but As might also have been released due to reductive dissolution of Fe(III) oxides and secondary Fe mineral formation.²² The H_2S treatment also did not influence the aqueous Fe concentration indicating that sulphide-bearing Fe minerals such as pyrite did not form. There are at least three additional reasons for why H_2S may have had little effect. First, the injection well (I-21) is located far enough away from the MP wells, that there was insufficient mixing, and reactions were limited. Secondly, it is possible that soluble Fe(II) was initially precipitated out as FeS_x ; however, the sample indicating the presence of aqueous Fe was collected several months after the H_2S injection. Thus, it is likely that biologically induced reductive Fe dissolution allowed the Fe(II) to re-enter the water after the pool of sulfide had been exhausted. Thirdly, there are indications (Table 1) that averaging data to ascertain the efficacy of H_2S injection is not an optimal technique. Baseline data for MP-4 might have been misleading, since overall averages were used to determine the efficacy, and MP-4 seemed to trend higher, possibly skewing results. Again, additional samples and more frequent sampling would provide a more clear understanding of the response of the environment to the addition of H_2S and the apparent lack of impact.

Parameters with no significant changes from 2005–2010

The temporal behaviour of concentration levels among the wells is similar for the parameters of alkalinity, pH, and radium.

Radium can be immobilized by adsorption to Fe oxides or precipitation with sulphates or co-precipitation with Ba bearing minerals. There are also no significant changes in the slopes of the regression lines for these parameters. If the levels for the three parameters are consistent over time among wells due to the behaviour of the parameters, then it is reasonable that the levels should also remain constant at a particular well. These results would imply that the flux of these parameters is stable across all

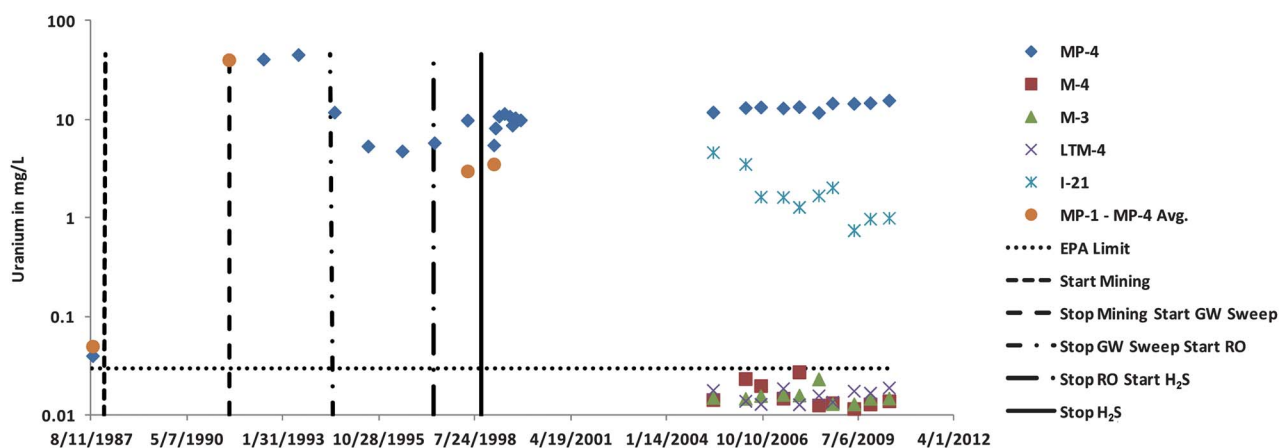


Fig. 5 Concentration (mg L^{-1} ; log scale) vs. time (y) of sampling for U-nat. MP-4 = monitored production well, I-21 = injection well, LTM-4 = long term monitoring well, M-3 and M-4 = monitoring wells ("outside mined area"). EPA limit = EPA primary standards for drinking water.

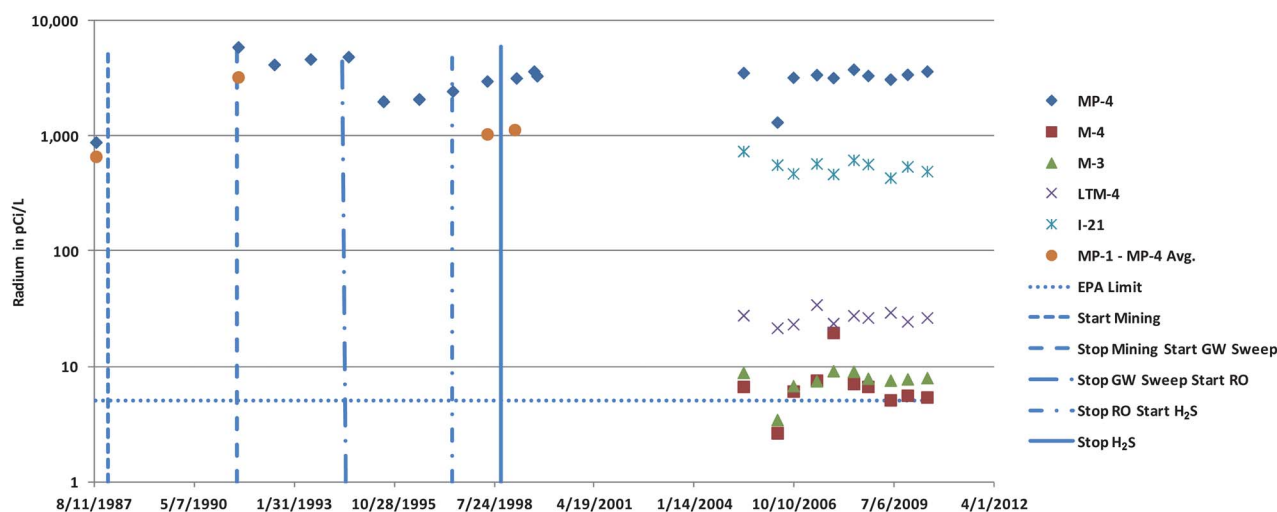


Fig. 6 Concentration (pCi L^{-1} ; log scale) vs. time (y) of sampling for Ra-226. MP-4 = monitored production well, I-21 = injection well, LTM-4 = long term monitoring well, M-3 and M-4 = monitoring wells ("outside mined area"). EPA limit = EPA primary standards for drinking water.

five wells. The implication is that the restoration was successful for these parameters.

Parameters with significant changes from 2005–2010

There was a difference in the temporal behaviour of the concentration levels among the inside wells for the parameters of uranium, manganese, and chlorine. From the regression analysis for natural uranium, it can be seen that the slope of concentration levels over time at well I-21 declines, the slope of well MP-4 slightly increases, and the slope of well LTM-4 remains constant. This indicates that the levels are not in equilibrium, and could be due to changing conditions or a net flux of contaminants into the area.

Uranium is sensitive to reduction–oxidation (redox) conditions, and these conditions will vary depending on the location of the well. This could possibly explain the differences in the temporal behaviour among the wells for uranium as well I-21 was used as an injection site during the chemical reductant phase of

remediation. Therefore, the concentration levels of uranium could be decreasing due to that area still being in a predominantly reducing environment (as indicated by Table 3). Well MP-4 is situated in the middle of the production zone, and a slight oxidizing environment in that zone could still exist, leading to the increase over time. Another explanation is that the net flux for the uranium concentration is positive for MP-4 and negative for I-21. The trend at I-21 could be due to more uranium being attenuated by natural processes or leaving with groundwater than the influx of uranium. It is very difficult to speculate or model the most likely natural attenuation processes controlling the fate and transport of U at this site due to the general lack of hydrological and biogeochemical data. In addition, numerous studies have discussed the many potential natural attenuation mechanisms but only few studies have attempted to model natural attenuation kinetics.^{23–25} The higher Mn concentration inside the mined area indicates continued reducing conditions, even after restoration has been completed (Table 4). Additionally, the high Fe concentration indicates that reduction may still

be taking place. Because of these various alternate possible explanations and data from only three wells, there are insufficient data to determine the cause of the trends in the regression lines.

Monitoring wells

There were no changes in the slopes of the regression lines, except the slight decrease (7.2% per year) in the slope of M-4 for manganese. There were also no significant temporal differences between wells M-3 and M-4 for any of the parameters, implying that the groundwater chemistry and redox environment are stable at that point on the monitoring ring, and have not been affected by the mining operations.

Stability at the monitoring ring indicates that there is a strong potential for natural attenuation, since the conditions were originally reduced or reducing (low redox potential) and redox measurements conducted post-restoration showed clear evidence for Fe reducing conditions (Table 5). The concentration levels are also similar to baseline levels at wells MP-1 through MP-5 (Table 6).

Interestingly, well LTM-4 is located approximately 16.1 m (53 feet) down gradient of the flare zone of well I-21 where uranium concentration levels are declining at a rate of 30% per year. The groundwater will have had time to migrate from the production zone into the area of well LTM-4 at the estimated migration rate of 1.7 m per year (5.6 ft per year) in the 10 years which have elapsed. Thus the water at LTM-4 has probably only been replaced one time since the end of remediation. However, no statistical changes occurred in the concentration levels of uranium for LTM-4, where the mean levels are statistically similar to those of M-3 and M-4; yet, the levels of manganese at well LTM-4 are increasing by 7.2% per year. Manganese generally exists in three oxidation states (+2, +3, and +4). Mn(II) is generally soluble, but precipitates out of solution as Mn(IV) (hydr)oxides when oxidized.¹⁶ Uranium behaves opposite in that it is generally soluble in its oxygenated species of U(VI), but generally much less soluble when reduced to its U(IV) species. Since well I-21 was used as an injection well during the reductant phase of remediation (the last phase to be completed), it is possible that the reducing environment has migrated to well LTM-4, and the altered redox conditions are causing the decrease in uranium levels and the increase in manganese levels. Further, the Cl concentration at LTM-4 compared to M-3 and M-4 (Table 4) provides some evidence that water from the mine unit has indeed reached LTM-4, but other less soluble minerals are being naturally attenuated. It would be interesting to add

Table 6 Comparison of baseline water quality values with monitoring wells

Parameter	Average baseline values for MP-1 through MP-5	Average values for M-3 and M-4 post-remediation	LTM-4 post-remediation
Cl (mg L ⁻¹)	4.7	3.4	20.8
ALK (mg L ⁻¹)	177	185	327
pH (mol L ⁻¹)	8.0	7.9	7.7
Mn (mg L ⁻¹)	0.030	0.032	0.087
U nat (mg L ⁻¹)	0.050	0.016	0.016
Ra-226 (pCi L ⁻¹)	675	7.6	27.0

future data from LTM-4 to affirm trends and provide information on natural attenuation.

Conclusion

No long term studies of the fate of a restored *in situ* uranium mine could be located in the literature, and it is believed that this is the first documented attempt to examine long term conditions post-mining.

Based on the measurements, groundwater sweeping followed by reverse osmosis (RO) treatment proved to be a highly efficient method of remediation. Injection of a reductant in the form of H₂S after groundwater sweeping and RO did not further reduce the aqueous concentration of U, Mn, or Fe. The efficacy of H₂S injection and impact on constituent concentration require further study to ascertain why it was ineffective. However, the formation of U(VI)–carbonate complexes is the most likely reason for the lack of U(VI) reduction by H₂S.²¹

The subsurface of Mine Unit A was strongly reduced before mining was initiated. It is likely that sulfate reducing conditions were initially present. However, pockets of O₂ may exist within the subsurface where H₂S did not permeate and fully restore the redox potential to baseline conditions. The lack of permeation of a reductant may explain why certain wells still seem to be situated in an oxic or Fe(III) rich zone resulting in high or above baseline concentrations of U(VI).²⁶ Since Fe(III) is still present, adsorption sites are most likely still available for Ra, so long term concentration of Ra may decrease. Sulfate is also present at fairly high concentrations; thus sulfate reduction is likely to control the redox potential in zones with no O₂ or low Mn(IV), Fe(III), and NO₃ concentrations within the sub-surface environment. However, the fairly high concentration of sulfate (*i.e.*, avg. 127 mg L⁻¹) did not seem to cause precipitation of the high Ra radioactivity during the observed period. In addition, since Fe

Table 5 Wells analyzed for pH, temperature, dissolved oxygen, Eh, pe, Fe(II) and Fe total post-restoration. M7, M16, M10A, and M12 are A-Wellfield ring wells and MP3 and MP4 are A-Wellfield ore zone wells

Well	Date	Field pH	Field temp. (°C)	Field diss. O ₂ (mg L ⁻¹)	Field Eh (mV)	Field pe	Field Fe(II) (mg L ⁻¹)	Field Fe-tot. (mg L ⁻¹)
M7	10/30/00	7.9	14.6	7	242	4.1	0.1	0.2
M16	10/30/00	7.8	14.1	1	121	2.0	1.0	2.0
M10A	12/01/00	7.6	14.2	2	221	3.7	0.3	0.4
M12	12/01/00	7.7	14.9	1	102	1.7	0.4	0.4
MP3	12/01/00	6.3	15.2	0	164	2.8	1.0	2.0
MP4	12/01/00	6.2	14.7	1	276	4.7	0.4	0.4

reducing conditions were confirmed at multiple wells shortly after the restoration had ended (Table 5) it is likely that Fe(III) is outcompeting sulfate as an electron acceptor.

U, Cd, Pb, and Ra were above EPA standards for drinking water before mining, while U, Fe, Mn, Se, and especially Ra were above baseline and EPA drinking water standards after remediation.

The very low concentrations of target species (U and Ra) at the two monitoring wells indicate that natural attenuation is likely to play a major role at immobilizing residual (after remediation) concentrations of U(VI) species, thus preventing them from moving outside the mined area.

There is a potential for natural attenuation in this system, since the conditions were originally reduced (low redox potential), especially if sulfate reducing conditions can be re-established. Undisturbed soil outside the mining area is also conducive to precipitation, complexation and immobilization of uranium due to the existing reducing conditions.

Many factors that were not measured in this paper need to be addressed in future studies. Additional measurements of redox potential and redox speciation of U, Fe, and Mn would help improve our understanding and prediction of the remediation efficacy at this site. The influence of hydrological, chemical and microbial changes on the constituent concentrations in the remediated mine unit has not been documented or measured. The residence time, flow rate relative to original replacement of water, needs to be accurately measured over a span of time. More wells and information across the mined area, and between the monitoring wells and the mined area, are needed for a better understanding of remediation efficacy at future sites.

Acknowledgements

The authors have no economic interests associated with Cameco. This study was not funded, approved or authorized by Cameco. All opinions expressed are solely those of the authors. All data were obtained from public sources. Detailed map of mine unit A and Fig. 2 and 4 are copyright Cameco Resources (formally PRI). A-Wellfield Ground Water Quality Stabilization Report, Highland Uranium Project. Submitted to Wyoming Department of Environmental Quality, permit to Mine no. 603-A2. Published with permission of Cameco Resources, granted 18JAN2012, by John Schmuck, Senior Permitting Manager.

References

- 1 Energy Information Agency, Washington DC, <http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb0802a> accessed 30 November 2011.
- 2 J. Thomas Nash, *Volcanogenic Uranium Deposits—Geology, Geochemical Processes, and Criteria for Resource Assessment*, U.S. Geological Survey Open-File Report 2010–1001, 2010.
- 3 S. M. Hall, *Groundwater Restoration at Uranium In-Situ Recovery Mines, South Texas Coastal Plain, in abstracts with programs, Global Uranium Symposium U2009, CMA, DREGS, CRMC Health Physics Society, Society of Economic Geologists, Society of Mining Engineers*, Wyoming Mining Association Joint Meeting, Keystone, CO, May 9–13, 2009.
- 4 G. Catchpole, R. Garling and M. Neuman, *Groundwater Restoration at Wyoming Uranium Solution Mining Sites Part I*, The Mining Claim, June, 1984.
- 5 G. Catchpole, R. Garling and Mike Neuman, *Groundwater Restoration at Wyoming Uranium Solution Mining Sites Part II*, The Mining Claim, July, 1984.
- 6 J. A. Davis and G. P. Curtis, NUREG/CR-6870, *Consideration of Geochemical Issues in Groundwater Restoration at Uranium in-situ Leach Mining Facilities*, U.S. Geological Survey, Menlo Park, CA 94025, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, Washington, DC 20555–0001, 2007.
- 7 W. J. Deutsch, R. J. Serne, N. E. Bell and W. J. Martin, NUREG/CR-3136, PNL-4604, *Aquifer Restoration at in-situ Leach Uranium Mines: Evidence for Natural Restoration Processes*, Pacific Northwest laboratory, Richland, WA 99352, Division of Health, siting and Waste Management, Office of Nuclear regulatory Research, U.S. Nuclear regulatory Commission, Washington, D.C. 20555, 1983.
- 8 W. J. Deutsch, W. J. Martin, L. E. Eary and R. J. Seme, NUREG/CR-3709, PNL-5319, *Methods of Minimizing Ground-Water Contamination from in situ Leach Uranium Mining*, Pacific Northwest laboratory, Richland, WA 99352, Division of Radiation programs and Earth Sciences, Office of Nuclear regulatory Research, U.S. Nuclear regulatory Commission, Washington, D.C. 20555 Final Report, March 1985.
- 9 Y. A. Gorby and D. R. Lovley, Enzymatic uranium precipitation, *Environ. Sci. Technol.*, 1992, **26**, 205–207.
- 10 Power Resources, Inc. (PRI). 2000. A-Wellfield ground water quality stabilization report, Highland uranium project. Submitted to Wyoming Department of Environmental Quality. Permit to Mine No. 603-A2.
- 11 G. Taylor, V. Farrington, P. Woods, R. Ring & R. Molloy, *Review of environmental impacts of the Acid in-situ Leach uranium mining process*, CSIRO Land and Water Client Report, 2004.
- 12 International Atomic Energy Agency (IAEA), *Environmental Remediation of Uranium Production Facilities*, OECD Nuclear Energy Agency, Danvers, MA, 2002.
- 13 R. T. Anderson, H. A. Vrionis, I. Ortiz-Bernad, C. T. Resch, P. E. Long, R. Dayvault, K. Karp, S. Marutzky, D. R. Metzler, A. Peacock, D. C. White, M. Lowe and D. R. Lovley, Stimulating the in situ activity of geobacter species to remove uranium from the groundwater of a uranium-contaminated aquifer, *Appl. Environ. Microbiol.*, 2003, **69**(10), 5884–5891.
- 14 V. Sivaswamy, M. I. Boyanov, B. M. Peyton, S. Viamajala, R. Gerlach, W. A. Apel, R. K. Sani, A. Dohnalkova, K. M. Kemner and T. Borch, Multiple mechanisms of uranium immobilization by *Cellulomonas* sp. strain es6, *Biotechnol. Bioeng.*, 2011, **108**, 264–276.
- 15 W. M. Wu, J. Carley, T. Gentry, M. A. Ginder-Vogel, M. Fienen, T. Mehlhorn, H. Yan, S. Carroll, M. N. Pace, J. Nyman, J. Luo, M. E. Gentile, M. W. Fields, R. F. Hickey, B. Gu, D. Watson, O. A. Cirpka, J. Zhou, S. Fendorf, P. K. Kitanidis, P. M. Jardine and C. S. Criddle, Pilot-scale in situ bioremediation of uranium in a highly contaminated aquifer. 2. reduction of u(VI) and geochemical control of u(VI) bioavailability, *Environ. Sci. Technol.*, 2006, **40**, 3986–3995.
- 16 T. Borch, R. Kretzschmar, A. Kappler, P. V. Cappellen, M. Ginder-Vogel, A. Voegelin and K. Campbell, Biogeochemical redox processes and their impact on contaminant dynamics, *Environ. Sci. Technol.*, 2010, **44**, 15–23.
- 17 B. E. Rittmann and the Committee on Intrinsic Remediation, *Natural Attenuation for Groundwater Remediation*, National Academy Press, Washington, DC, 2000.
- 18 Environmental Protection Agency, Science Advisory Board, 2012, *Considerations Related to Post Closure Monitoring of Uranium in-situ Leach/in-situ Recovery (ISL/ISR) Sites*, Draft Report, January 17, 2012.
- 19 T. Olsen, *Environmental Assessment for the Highland Uranium Project*, Docket No. 40–8857, SUA-1511. U.S. Nuclear regulatory Commission uranium recovery field Office region IV. Prepared for the Everest minerals Corporation, Highland uranium project, 1987.
- 20 J. R. Bargar, R. Reitmeyer and J. A. Davis, Spectroscopic confirmation of uranium(VI)-carbonate adsorption complexes on hematite, *Environ. Sci. Technol.*, 1999, **33**, 2481–2484.
- 21 H. Beyenal, R. K. Sani, B. M. Peyton, A. Dohnalkova, J. E. Amonette and Z. Lewandowski, Uranium immobilization by sulfate-reducing biofilms, *Environ. Sci. Technol.*, 2004, **38**, 2067–2074.

- 22 B. D. Kocar, T. Borch and S. Fendorf, Arsenic repartitioning during biogenic sulfidization and transformation of ferrihydrite, *Geochim. Cosmochim. Acta*, 2010, **74**, 980–994.
- 23 G. E. Hammond and P. C. Lichtner, Field-scale model for the natural attenuation of uranium at the hanford 300 area using high-performance computing, *Water Resour. Res.*, 2010, **46**, W09527, DOI: 10.1029/2009WR008819.
- 24 R. Ma, C. Zheng, H. Prommer, J. Greskowiak, C. Liu, J. Zachara and M. Rockhold, A field-scale reactive transport model for U(vi) migration influenced by coupled multirate mass transfer and surface complexation reactions, *Water Resour. Res.*, 2010, **46**, W05509, DOI: 10.1029/2009wr008168.
- 25 O. Nitzsche and B. Merkel, Reactive transport modeling of uranium 238 and radium 226 in groundwater of the Konigstein uranium mine, Germany, *Hydrogeol. J.*, 1999, **7**, 423–430.
- 26 M. Ginder-Vogel, B. Stewart and S. Fendorf, Kinetic and mechanistic constraints on the oxidation of biogenic uraninite by ferrihydrite, *Environ. Sci. Technol.*, 2010, **44**, 163–169.

On the Use of Surrogate Species in Conservation Biology

Author(s): T. M. Caro and Gillian O'Doherty

Source: *Conservation Biology*, Aug., 1999, Vol. 13, No. 4 (Aug., 1999), pp. 805-814

Published by: Wiley for Society for Conservation Biology

Stable URL: <https://www.jstor.org/stable/2641695>

REFERENCES

Linked references are available on JSTOR for this article:

https://www.jstor.org/stable/2641695?seq=1&cid=pdf-reference#references_tab_contents

You may need to log in to JSTOR to access the linked references.

JSTOR is a not-for-profit service that helps scholars, researchers, and students discover, use, and build upon a wide range of content in a trusted digital archive. We use information technology and tools to increase productivity and facilitate new forms of scholarship. For more information about JSTOR, please contact support@jstor.org.

Your use of the JSTOR archive indicates your acceptance of the Terms & Conditions of Use, available at <https://about.jstor.org/terms>



Wiley and are collaborating with JSTOR to digitize, preserve and extend access to *Conservation Biology*

JSTOR

On the Use of Surrogate Species in Conservation Biology

T. M. CARO* AND GILLIAN O'DOHERTY†

*Department of Wildlife, Fish, and Conservation Biology and Center for Population Biology, University of California, Davis, CA 95616, U.S.A., email tmcaro@ucdavis.edu

†Section of Evolution and Ecology, University of California, Davis, CA 95616, U.S.A.

Abstract: *Conservation biologists have used surrogate species as a shortcut to monitor or solve conservation problems. Indicator species have been used to assess the magnitude of anthropogenic disturbance, to monitor population trends in other species, and to locate areas of high regional biodiversity. Umbrella species have been used to delineate the type of habitat or size of area for protection, and flagship species have been employed to attract public attention. Unfortunately, there has been considerable confusion over these terms, and several have been applied loosely and interchangeably. We attempt to provide some clarification and guidelines for the application of these different terms. For each type of surrogate, we briefly describe the way it has been used in conservation biology and then examine the criteria that managers and researchers use in selecting appropriate surrogate species. By juxtaposing these concepts, it becomes clear that both the goals and selection criteria of different surrogate classes differ substantially, indicating that they should not be conflated. This can be facilitated by first outlining the goals of a conservation study, explicitly stating the criteria involved in selecting a surrogate species, identifying a species according to these criteria, and then performing a pilot study to check whether the choice of species was appropriate before addressing the conservation problem itself. Surrogate species need to be used with greater care if they are to remain useful in conservation biology.*

Uso de Especies Sustituatas en la Conservación Biológica

Resumen: *Biólogos de la conservación han utilizado especies sucedáneas como atajos para monitorear o resolver problemas de conservación. Las especies indicadoras han sido utilizadas para evaluar la magnitud de la perturbación antropogénica, para monitorear tendencias poblacionales en otras especies y para localizar áreas de alta biodiversidad regional. Las especies sombrilla han sido utilizadas para delinear el tipo de hábitat o tamaño de área para protección y las especies bandera han sido empleadas para atraer la atención del público. Desafortunadamente, ha habido una considerable confusión sobre estos términos y muchos han sido aplicados de un amañera vaga e intercambiable. Intentamos proveer algunas aclaraciones y lineamientos para la aplicación de estos diferentes términos. Para cada tipo de sustituto describimos brevemente la forma en que ha sido usado en la conservación biológica y posteriormente examinamos los criterios que los manejadores e investigadores usan en la selección de las especies sustitutas apropiadas. Al juxtaponer estos conceptos, se hace claro que tanto las metas como los criterios de selección de diferentes clases de sustitutos difieren substancialmente indicando que estos no deberán ser confundidos. Esto puede ser facilitado primero al subrayar las metas de un estudio de conservación, estableciendo explícitamente los criterios involucrados en la selección de la especie sustituta, identificando a las especies utilizando este criterio y posteriormente llevando a cabo un estudio piloto para checar si la especie seleccionada es la apropiada antes de proceder a abordar el problema de conservación en sí. Las especies sucedáneas necesitan ser utilizadas con mayor cuidado si queremos que sigan siendo útiles para la biología de conservación.*

Paper submitted July 6, 1998; revised manuscript accepted November 26, 1998.

Introduction

Conservation biologists often use one or a small number of species as surrogates to help them tackle conservation problems (Thomas 1972; Cairns et al. 1979; Panwar 1984; Wilcox 1984; Jarvinen 1985; Bibby et al. 1992). Surrogate species are employed to indicate the extent of various types of anthropogenic influence (e.g., Burdick et al. 1989; Stolte & Mangis 1992) or to track population changes of other species; these types of surrogate are by far the best worked examples (D. H. McKenzie et al. 1992). Surrogate species are also used proactively to locate areas of high biodiversity (Ricketts et al. 1999) or to act as “umbrellas” for the requirements of sympatric species (Berger 1997); they thus can help in locating and designing reserves. Finally, surrogate species may be used as flagships in a sociopolitical context for attracting public attention and funding for a larger environmental issue (Dietz et al. 1994). In contrast, a keystone species is an ecological concept that is used to describe a species whose impact on the community or ecosystem is disproportionately large relative to its abundance (Mills et al. 1993; Power et al. 1996). Keystone species are not used as a shortcut to describe patterns and processes in conservation biology and have never been successfully used as surrogate species, although they may be relevant in choosing them (Simberloff 1998).

Conservation biologists employ surrogate species in three main ways. (1) Managers may use a species as a surrogate knowing in advance that it is a sensitive indicator of a particular conservation problem. (2) Managers may use or advocate the use of a species without having determined whether it does act as a proper surrogate for the task at hand. Consequently, the attributes of the species do not always serve the research or conservation goal very well. (3) In more-academic exercises, conservation biologists investigate the ability of a surrogate species to fit a particular research goal. This approach explores the surrogate's suitability rather than examines a particular conservation problem. Unfortunately, in each approach, it is easy to find examples where conservation goals have been poorly defined, where the terms *indicator species*, *umbrella species*, and *flagship species* were applied loosely, and where authors have even substituted different surrogate terms for one another (e.g., U.S. Department of the Interior 1980). For instance, indicators of environmental quality and indicators of population changes in other species have often been conflated, and the terms umbrella species and flagship species have been used interchangeably in promoting the role of a single species in protecting a community. Despite these acknowledged problems with study design and terminology, the use of surrogate species continues to increase in conservation biology.

We attempt to provide guidelines for future workers by drawing attention to different uses of surrogate spe-

cies and systematically examining the criteria that researchers and managers have used in choosing surrogate species successfully. We have drawn on strong studies with clear goals, in which selections of surrogate species have been made with care. For convenience, we have divided criteria used to select surrogates into attributes of measurement, life-history traits, ecological characteristics, attributes of rarity, and sensitivity to environmental change. We conclude by making recommendations for using surrogate terms more appropriately. We do not try to provide a definitive guide to surrogate species or to assess their efficacy from a practical standpoint; instead we attempt to show how they can be used successfully.

Indicator Species

Landres et al. (1988) defined “an indicator species [as] an organism whose characteristics (e.g., presence or absence, population density, dispersion, reproductive success) are used as an index of attributes too difficult, inconvenient, or expensive to measure for other species or environmental conditions of interest.” There is a historical dichotomy between indicator species that pinpoint areas of high biodiversity—here termed biodiversity indicators—and those that measure environmental changes (Pearson 1995). Following Landres (Landres et al. 1988; Landres 1992), one can further divide the latter into those that assess changes in habitat (health indicators) and those that serve as a yardstick for changes in populations of other species (population indicators), although in practice these may sometimes be difficult to separate. Indicator species are also used to assess the effects of agricultural practices on habitats. For example, oribatid mite populations have been used to examine the effects of soil disturbance (Franchini & Rockett 1996), and attempts have been made to use populations of some bird species to measure the effects of cattle grazing (Bock & Webb 1984). We do not discuss these types of indicators further, nor have we included environmental variables that might be indices of species richness.

Health Indicator Species

In theory, environmental monitoring might best be achieved by sampling air, water, or soil directly, but, in practice, detection of intermittent pollution sources depends on the time and place of sampling and can be logistically problematic in remote areas. Instead, sublethal hazardous chemicals accumulated within selected tissues of certain species can provide a measure of pollution at a given site over a known time period (e.g., Karlsson et al. 1994). Furthermore, the diversity or abundance of species—often invertebrates—can be used to measure the accumulated concentration of certain pollutants at a

location (e.g., Sarkka 1996). For years, indicator species of this type have been used by environmental toxicologists to assess the effects of pollutants on organisms or on ecosystem processes (e.g., Ott 1978; Cairns et al. 1979; Levin et al. 1989) and to assess environmental conditions such as temperature and pH (Zonnevald 1988). Patton (1987) provides a good definition of a health indicator species: "In biology an indicator is an organism so ultimately associated with particular environmental conditions that its presence indicates the existence of those conditions."

Indicators of environmental health are also used to assess the effects of chemicals on a subsample of organisms in the environment (Karr 1991; Kremen 1992). For example, in describing the "most sensitive species" concept, Cairns (1986) suggested that if standards were set "for toxic materials and other stressors in natural systems, presumably all other species and all other activities at higher levels of biological organization could be protected." Used in this way, health indicators have some of the hallmarks of umbrella species.

More recently, attention has turned to forms of anthropogenic disturbance other than pollution, particularly direct exploitation and extractive use, such as deforestation, fishing (McClenahan et al. 1996), and hunting (Bodmer et al. 1997). For instance, the Spotted Owl (*Strix occidentalis*), specifically its population size and reproductive rate, has been used as a management indicator species (MIS) of the effect of old-growth logging on small mammals and on lower trophic levels in the Pacific Northwest (Dawson et al. 1986). A MIS is defined by the U.S. Forest Service (1984) as any species, groups of species, or species habitat elements selected to focus management attention for the purpose of resource production, population recovery, or maintenance of population viability or ecosystem diversity.

Indicators of environmental health may be successful as a single species or a guild of species (Cook 1976; but see Cairns 1983). In either case, it is important that biologists know a substantial amount about their natural history, particularly the ecological factors affecting their population growth rates, because changes in their population need to be related to specific environmental factors (Pearson & Cassola 1992; but see Kremen 1992). Be-

cause indicators of environmental health are often chosen to reduce the costs of monitoring, they need to be observed, counted, or collected relatively easily (Temple & Wiens 1989; Noss 1990; Pearson & Cassola 1992). For example, it may be helpful if they have accessible breeding sites where they can be monitored (Miller & Davis 1993; Table 1).

Small species are most successful as indicators of environmental health because they are more sensitive to environmental disturbance than are larger species (Siemann et al. 1996). Moreover, small species often have relatively short generation times, an attribute that makes them more sensitive to the effects of pollution or habitat disturbance because juvenile life stages will more often be subjected to environmental insult (Blus et al. 1974). Also, species with high rates of reproduction and the potential for rapid population growth rates may show a quicker response to environmental stresses than slow reproducers, and these are often small species. Species with high metabolic rates—again smaller species—are likely to incorporate environmental pollutants more rapidly than those with low metabolic rates (Walker 1983; Table 2).

If a species is mobile, it will be subjected to different parts or aspects of a polluted environment and will thus provide information on a wider area than if it were restricted to a single site. Amphibians have for this reason been advocated as health indicators (Vitt et al. 1990; Lips 1998). On the other hand, a small home range allows researchers to pinpoint the location of pollution or disturbance with greater accuracy. Whereas indicators of environmental quality might usually be resident species because they are subject to sustained environmental stress, migratory species also can be effective, as in the case of Brown Pelicans (*Pelecanus occidentalis*), which indicated levels of DDT (Anderson et al. 1975). Because species at the end of the food chain accumulate toxic materials rapidly, health indicators may come from particular trophic levels, such as bottom feeders or predators (e.g., Gilman et al. 1979; Mix et al. 1979; Table 3).

Indicators of environmental health are easier to monitor if they have large populations. If they have a wide geographic range, moreover, they can provide an authoritative documentation of habitat disturbance or pop-

Table 1. Measurement attributes of surrogate species.

Type of surrogate	Represents other species	Single or guild of species	Well-known biology	Easily sampled or observed	Accessible breeding site
Health indicator	not necessarily	single or guild	yes	yes	probably
Population indicator	yes	single	yes	yes	possibly
Biodiversity indicator	yes	guild	yes	yes	no
Umbrella species	yes	single*	yes	yes	no
Flagship species	usually	single	not necessarily	no	no

*Usually single.

Table 2. Life-history traits of surrogate species.

Type of surrogate	Body size	Generation time	Metabolic rate
Health indicator	small	short	high
Population indicator	irrelevant	short	irrelevant
Biodiversity indicator	irrelevant	irrelevant	irrelevant
Umbrella species	large	long	irrelevant
Flagship species	large	long	irrelevant

ulation trends because their survival and reproduction in one place may be extrapolated across a large geographic area (Pearson 1995). If health indicators are restricted to certain habitats, they will provide specific information about environmental change in that habitat (Table 4).

In general, effective health indicator species need to be acutely sensitive to human disturbance in order to provide an early warning of anthropogenically induced environmental change (Munn 1988; Cairns 1986; Frost et al. 1992). Raptors, for example, are poor indicators of environmental change in Baja California because they rapidly adapt to human-altered habitats (Rodriguez-Estrella et al. 1998). A low level of individual variability in response to environmental change is also important because a subsample of the population will reflect the overall response of the population with some certainty (Frost et al. 1992; Table 5).

Population Indicator Species

Some species have been used as indicators of population trends in other species, such as prey, that may be subject to human disturbance or environmental variation. For example, juvenile mortality in Cape Gannets (*Morus capensis*) has been used as a measure of temperature-dependent changes in the distribution of oceanic fish because young gannets cannot dive deeply enough to find fish in cool waters (Oatley et al. 1992). Surrogates are also used as indicators of the suitability of the habitat for other members of their guild (Verner 1984; Block et al. 1986). Nevertheless, there are considerable difficulties in extrapolating between guild members because the factors that influence their respective populations may differ and are often unknown, because they may show only partial overlap in niche or habitat, and because

there are practical difficulties in identifying the time course over which changes in the population size of one species reflect those in another (Landres 1983; Verner 1984; Szaro 1986; Temple & Wiens 1989; Swanson 1998).

Indicators of population trends in other organisms are usually a single species and may be most successful if the principal factors affecting their population size are well understood (Landres 1983). They need to be monitored relatively easily at least during one stage of their life cycle (Temple & Wiens 1989; Noss 1990; Pearson & Cassola 1992; Table 1).

For a species to be a sensitive indicator of population trends in other species, it should have a rapid rate of reproduction, because changes in population size are difficult to discern in species with long generation times (Table 2).

Population indicators will be most effective if they are resident species and if they occupy particular feeding niches. For example, the best indicator of a prey population may be its specific predator (Elton & Nicholson 1942). Keystone species might be particularly effective in discerning population changes in other species. For example, because the flying fox (*Pteropus samoensis*) pollinates many plants on islands in the South Pacific (Cox et al. 1991), its numbers might indicate plant population viability. On the other hand, the abundance of a keystone species does not necessarily reflect population trends in members of the same guild (Table 3).

Population indicators are easier to monitor if they have large populations themselves. If they have a wide geographic range, their function can be extrapolated across a large geographic area (Pearson 1995). Habitat specificity has relevance for population indicators only if they are being used to monitor population trends in other species based on mutual habitat requirements (Table 4).

A good population indicator must be sensitive to human disturbance in order to provide an early warning of anthropogenically induced environmental change (Cairns 1986; Munn 1988; Frost et al. 1992), and its growth rate should mirror those of other species reacting to anthropogenic disturbance (but see Landres et al. 1988). A low level of individual variability in response to environmental change will reflect the population's overall response (Table 5).

Table 3. Ecological characteristics of surrogate species.

Type of surrogate	Home range size	Resident or migratory	Particular trophic level	Keystone species
Health indicator	medium	resident	yes	not necessarily
Population indicator	irrelevant	resident	possibly	possibly
Biodiversity indicator	irrelevant	either	no	irrelevant
Umbrella species	large	migratory	no	possibly
Flagship species	irrelevant	either	no	not necessarily

Table 4. Attributes of commonness and rarity in surrogate species.

Type of surrogate	Large population size	Wide geographic range	Habitat specialist
Health indicator	probably	yes	probably
Population indicator	probably	yes	not necessarily
Biodiversity indicator	irrelevant	yes	yes
Umbrella species	possibly	probably	yes
Flagship species	no	no and yes	not necessarily

Biodiversity Indicator Species

Areas of high biological diversity are increasingly identified by means of indicator taxa (Humphries et al. 1995; Kerr 1997). Thus, instead of attempting to measure the total number of species or families in an area, conservation biologists use the number of species (or other taxa) in a well-known taxonomic group as a surrogate for the number of species (or other taxa) in sympatric, poorly known taxonomic groups (Beccaloni & Gaston 1994; Dobson et al. 1997). For example, tiger beetle (Coleoptera: Cincindelidae) diversity predicts bird and butterfly diversity at very large scales (Pearson & Cassola 1992; Pearson & Carroll 1998). By this method, large regions of high diversity may be identified and then targeted for protection (N. L. McKenzie et al. 1989; Ryti 1992; Prendergast et al. 1993).

In addition, the number of higher taxonomic groups in a region is used as a surrogate for the number of local species of the same clade, given that a relationship between these different taxonomic levels can be established elsewhere (Gaston 1996). The idea here is that the number of families or genera can be documented more rapidly than the number of species within those families or genera. Positive relationships have been found between higher and lower taxa in many groups (Williams & Gaston 1994; but see Prance 1994).

One or a small number of species may be used to pinpoint the location of biological productivity. For example, Schafer (1989) attempted to compute the future productivity of pine plantations from associations of different types of native vegetation at a site.

Good biodiversity indicators necessarily involve the use of several species to estimate the relative number of species in one area compared to another (Gaston 1996). The group should represent diversity within or across taxonomic boundaries within a region (Pearson & Cas-

sola 1992). The extent to which individuals can be identified to the species, generic, or family level will affect the taxonomic level at which analysis can be carried out (Wilcox 1984; Williams & Gaston 1994). Obviously, biodiversity indicators need to be readily surveyed or censused in the field (Wilcox 1984; Table 1).

Biodiversity indicators will be useful only if they have a reasonably wide geographic range (Wilcox 1984). Within this geographic area, they should have high habitat fidelity because their absence (in the face of habitat disturbance) may be a sensitive indicator of the absence of other species (Panzer et al. 1995; Table 4).

Umbrella Species

Where the conservation goal is to protect a habitat or community of species, an umbrella species may be employed as a surrogate to delineate the size of area or type of habitat over which protection should occur. As Wilcox (1984) wrote, "to provide a 'protective umbrella' select a 'target species' such that its minimum area requirement is at least as comprehensive as the rest of the community." Effective protection of a viable population in this area is assumed to protect populations of other sympatric members of the same guild (Berger 1997), biota at lower trophic levels (Launer & Murphy 1994), or appreciable parts of the ecosystem (Foose 1993). Recently, Lambeck (1997) advocated the use of a suite of "focal species," or several umbrella species, each of which is used to define spatial and compositional attributes that must be present in a landscape. Umbrella species differ from biodiversity indicators in that they are used to specify the size and type of habitat to be protected rather than its location (Berger 1997). The use of umbrella species in conservation biology is less devel-

Table 5. Sensitivity to environmental change in surrogate species.

Type of surrogate	Sensitive to human disturbance	Low variability in response	Long persistence time
Health indicator	yes	yes	irrelevant
Population indicator	yes	yes	irrelevant
Biodiversity indicator	irrelevant	irrelevant	irrelevant
Umbrella species	not necessarily	irrelevant	yes
Flagship species	yes	irrelevant	not necessarily

oped than that of indicator species, and we know of no study in which a strong, empirically based argument can be made to support the efficacy of an umbrella species in protecting other species. Nonetheless, many conservation plans implicitly base their conservation philosophy on this concept.

Umbrella species are usually single species (but see Lambeck 1997). It is necessary to know the area and habitat requirements of a species to determine whether it will be an effective umbrella. For example, Berger (1997) determined that the home ranges of black rhinoceros (*Diceros bicornis*) in the Kaokoveld region of Namibia did not change seasonally as did those of other herbivores, making it a poor candidate as an umbrella species despite its large home range (Table 1).

Good umbrella species are likely to be large (Wilcox 1984) because of the allometric relationship between body size and home range size (Gittleman 1986; Brown 1995). Such large species reproduce slowly, but this is not a criterion of an umbrella species (Table 2).

A principal requirement of an umbrella species is that its range is large compared to sympatric species, so that a viable population can encompass the habitat requirements of other similar species (Berger 1997). Thus, migratory species may be particularly effective. For example, the annual range of migratory wildebeest (*Connochaetes taurinus*) was used to delineate the boundaries of the Serengeti and Ngorongoro protected areas in Tanzania (Grzimek & Grzimek 1959). If an umbrella species is a keystone species, the integrity of its population partially guarantees the integrity of other species (Table 3).

Monitoring an umbrella species will be facilitated if its population size is large. An umbrella species will be more useful if it has a large geographic range because the protection it affords other species in one area may be used for similar purposes elsewhere. An umbrella species with specific habitat requirements may be especially beneficial because, other things being equal, it will need a larger area to encompass sufficient fruiting trees or nest sites and thus will overlap the ranges of more species and more individuals within each species (Table 4).

Umbrella species are employed in designing reserves, sometimes in an area little affected by people, so they do not necessarily have to be sensitive to anthropogenic disturbance. Nonetheless, umbrella species that are sensitive to disturbance will be the best suited for pinpointing suitable habitat for other less sensitive species. Umbrella species are only useful if they do not become locally extinct (Table 5).

Flagship Species

Flagship species are used to attract the attention of the public (Western 1987). For example, as Johnsingh & Joshua (1994) wrote, "by focusing on one [flagship] spe-

cies and its conservation needs, large areas of habitat can be managed not only for the species in question but for other less charismatic taxa." Flagship species can garner sympathy for nature at a global level, as in the case of the giant panda (*Ailuropoda melanoleuca*), the emblem for the World Wide Fund for Nature, or at a national level. Indeed, most countries have a national bird or mammal. Flagship species are also an important public relations tool in setting aside areas for protection (e.g., the Cockscomb Jaguar Reserve in Belize [Rabinowitz 1986]). Some flagships are also umbrella species, although flagships need only be popular, not ecologically significant. An umbrella species lacking charisma need not be a flagship species.

Effective flagship species are often restricted to a particular ecosystem, such as Neotropical rainforest, and often are de facto representatives of species in the same community. But global flagships, such as the Arabian oryx (*Oryx leucoryx*) that are used to represent environmental organizations may become relatively divorced from ecological considerations. Flagships are single species by definition (Table 1).

Flagship species are usually large, for example the tiger (*Panthera tigris*) (Dinerstein et al. 1997), mountain tapir (*Tapirus pinchaque*) (Downer 1996), and elephant (*Elephas maximus*) (Johnsingh & Joshua 1994). Nonetheless, the golden lion tamarin (*Leontopithecus rosalia*), a small (<1 kg) primate, has been used as an education tool to great effect in Brazil (Kleiman et al. 1986; Table 2).

Successful flagship species are sometimes chosen on the basis of their dwindling population size or endangered status (Dietz et al. 1994). Flagship species may be most effective if they are endemic to one country (Kleiman & Mallinson 1998), although conversely they may also be effective if they are known to many people in a range of nations (Table 4).

Flagship species are frequently chosen post hoc, after a species has suffered from exploitation or habitat destruction; consequently, they may be species that are sensitive to disturbance (Table 5). In sum, there are few strict criteria in choosing flagships, which is one of the main points differentiating them from other surrogate classes.

Conclusions

We constructed tables 1–5 to demonstrate how different classes of surrogates fit different profiles within a fixed set of criteria. They show that, (a) researchers and managers use common features in choosing different classes of surrogate, but that (b) each surrogate has a different selection profile.

(a) Surrogate species usually act as representatives of other species in the community (Table 1). They may be

individual species or, less commonly, a collection of species, usually a guild. (The use of a guild is problematic in that only one species need be tolerant of a perturbation and respond positively for guild abundance to be maintained, even though others respond negatively). For most classes of surrogate, it is helpful if species are well known at either an ecological or a taxonomic level (Pearson & Cassola 1992; but see Kremen 1992). The best surrogate species are those that can be easily monitored, as for example if they have accessible breeding sites.

Body size considerations are often relevant in choosing good surrogates (Table 2). On one hand, small size makes an organism more sensitive to environmental disturbance, whereas on the other, large size is associated with large range size or charisma. Small size is correlated with short generation time, which is a helpful characteristic for health indicators and population indicators, and is also correlated with high metabolic rate, an important attribute for indicators of ecosystem health.

A large area requirement is important in choosing some surrogate species because it enables an organism to experience a greater range of environments or to cover a more representative area (Table 3). Some surrogates occupy particular trophic levels. It has been suggested that certain indicator species should be keystone species (Simberloff 1998). Loss of a keystone species or a reduction in its numbers will have ramifications for the abundance and interactions of other organisms (Gilbert 1980; Noss 1990), but there are many examples of effective surrogate species that are not keystone species.

Some types of surrogate are easier to monitor if they have large populations; they may be of greater use if they have a wide geographic range or specific habitat requirements (Table 4). Most surrogate species need to be sensitive to human disturbance (Table 5).

(b) The second point to emerge is that each class of surrogate has a different selection profile. Our review shows that there is not a single criterion among the 18 we examined for which there is complete agreement across the five classes of surrogates (Tables 1–5). This alone indicates that it is foolhardy to use terms interchangeably because underlying assumptions about them differ so much.

In general, species or guilds that are useful as surrogates for one conservation goal will be unsuitable for another. For example, the Common Loon (*Gavia immer*) has been used by managers as both an indicator of habitat quality and of population changes in other species, but it does neither job well (Strong 1990). Its variable responses to environmental factors and its migratory nature make it a weak indicator of habitat quality, and its slow rate of reproduction makes it insensitive to population changes in smaller bird species. Nevertheless, it may be suitable as a flagship for lacustrine habitats (Esbensen 1990).

Occasionally, however, certain species may be useful for more than one task. For example, the Spotted Owl is a good umbrella species for old-growth forest and animals found within that forest (Franklin 1993), it has acted as a flagship for attracting public attention to logging practices in the Pacific Northwest (Chase 1995) and, more equivocally, it may indicate population trends in other species (Murphy & Noon 1992). More often, however, the opposite is the case, with one species filling multiple roles for which it is unsuited and is a poor surrogate.

Recommendations

As conservation biologists continue to use surrogate species in solving conservation problems, they should define their objectives more clearly. First, we advocate the advance formulation of goals and subgoals before a research study or management plan is carried out. If a number of goals are involved, a single surrogate species is unlikely to satisfy them all (Lambeck 1997). Second, we advocate that criteria on which surrogates are being chosen be specified explicitly and that the species selected meet as many of the criteria (in Tables 1–5) as possible, or represent a reasonable compromise between criteria. The literature currently abounds with cases of surrogate species being implicitly chosen on the basis of charisma, historical precedent, or the ease with which they can be managed (Mealy & Horn 1981; Sidle & Surging 1986), rather than according to objective criteria. Third, we recommend preliminary study of the efficacy of proposed surrogates before the main study is initiated. Choosing a flagship species may be an exception to this rule but demands some knowledge of local or national attitudes (Kellert 1986). If a pilot study reveals the usefulness of the surrogate as a tool for monitoring or delineating an area or for raising money, the main conservation project can proceed.

Careful formulation of research goals, use of appropriate criteria, and judicious choice of surrogate species will eventually overcome the legitimate concerns of using indicator, umbrella, and flagship species as shortcuts in effecting management strategies (Landres 1992; Simberloff 1998). This should enable us to choose surrogates with greater clarity and to employ them more usefully in solving urgent conservation problems.

Acknowledgments

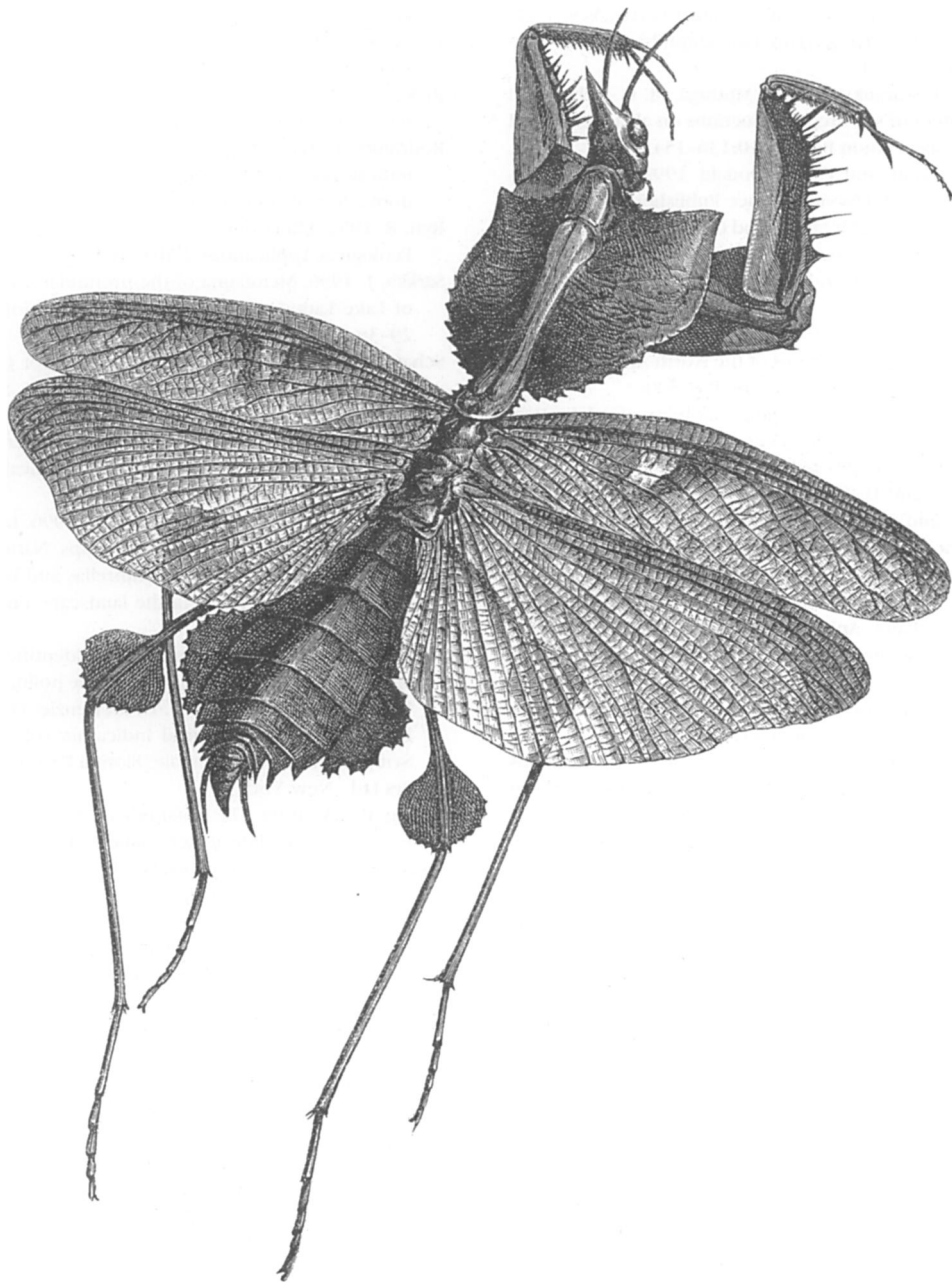
We thank R. Blair, P. Brussard, E. Fleishman, P. Gros, P. Landres, M. Schwartz, and four anonymous reviewers for insightful comments.

Literature Cited

- Anderson, D. W., J. R. Jehl, R. W. Risebrough, L. A. Woods Jr., L. R. DeWeese, and W. G. Edgecomb. 1975. Brown Pelicans: improved reproduction off the southern California coast. *Science* **190**:806–808.
- Beccaloni, G. W., and K. J. Gaston. 1994. Predicting the species richness of Neotropical forest butterflies: Ithomiinae (*Lepidoptera: Nymphalidae*) as indicators. *Biological Conservation* **71**:77–85.
- Berger, J. 1997. Population constraints associated with the use of black rhinos as an umbrella species for desert herbivores. *Conservation Biology* **11**:69–78.
- Bibby, C. J., N. J. Collar, M. J. Crosey, M. F. Heath, C. Imboden, T. H. Johnson, A. J. Long, A. J. Stattersfield, and S. J. Thirgood. 1992. Putting biodiversity on the map: priority areas for global conservation. International Council for Bird Preservation, Cambridge, United Kingdom.
- Block, W. M., L. A. Brennan, and R. J. Guterrez. 1986. The use of guilds and guild indicator species for assessing habitat suitability. Pages 109–113 in J. Verner, M. L. Morrison, and C. J. Ralph, editors. *Wildlife 2000: modeling habitat relationship of terrestrial vertebrates*. University of Wisconsin Press, Madison.
- Blus, L. J., B. S. Neely Jr., A. A. Belisle, and R. M. Prouty. 1974. Organochloride residues in Brown Pelican eggs: relation to reproductive success. *Environmental Pollution* **7**:81–91.
- Bock, C. E., and B. Webb. 1984. Birds as grazing indicator species in southeastern Arizona. *Journal of Wildlife Management* **48**:1045–1049.
- Bodmer, R. E., J. E. Eisenberg, and K. H. Redford. 1997. Hunting and the likelihood of extinction of Amazonian mammals. *Conservation Biology* **11**:460–466.
- Brown, J. 1995. *Macroecology*. University of Chicago Press, Chicago.
- Burdick, D. M., D. Cushman, R. Hamilton, and J. G. Gosselink. 1989. Faunal changes and bottomland hardwood forest loss in the Tensas watershed, Louisiana. *Conservation Biology* **3**:282–289.
- Cairns, J. 1983. Are single species toxicity tests alone adequate for estimating environmental hazard? *Hydrobiologia* **100**:47–57.
- Cairns, J., G. P. Patil, and W. E. Waters. 1979. Environmental biomonitoring, assessment, prediction, and management: certain case studies and related quantitative issues. International Cooperative Publishing House, Fairland, Maryland.
- Cairns, J., Jr. 1986. The myth of the most sensitive species. *BioScience* **36**:670–672.
- Chase, A. 1995. In a dark wood: the fight over forests and the rising tyranny of ecology. Houghton Mifflin, New York.
- Cook, S. E. K. 1976. Quest for an index of community structure sensitive to water pollution. *Environmental Pollution* **11**:269–288.
- Cox, P. A., T. Elmqvist, E. D. Pierson, and W. E. Rainey. 1991. Flying foxes as strong interactors in the south Pacific island ecosystems: a conservation hypothesis. *Conservation Biology* **5**:448–454.
- Dawson, W. R., J. D. Ligon, J. R. Murphy, J. P. Myers, D. Simberloff, and J. Verner. 1986. Report of the scientific advisory panel on the Spotted Owl. *The Condor* **89**:205–229.
- Dietz, J. M., A. L. Dietz, and E. Y. Nagagata. 1994. The effective use of flagship species for conservation of biodiversity: the example of lion tamarins in Brazil. Pages 32–49 in P. J. S. Olney, G. M. Mace, and A. T. C. Feistner, editors. *Creative conservation: interactive management of wild and captive animals*. Chapman and Hall, London.
- Dinerstein, E., E. Wikramayake, J. Robinson, V. Karanth, A. Rabonowitz, D. Olson, T. Mathew, P. Hedao, M. Connor, G. Hemley, and D. Bolze. 1997. A framework for identifying high priority areas and actions for the conservation of tigers in the wild. World Wildlife Fund, Washington, D.C.
- Dobson, A. P., J. P. Rodriguez, W. M. Roberts, and D. S. Wilcove. 1997. Geographic distribution of endangered species in the United States. *Science* **275**:550–553.
- Downer, G. C. 1996. The mountain tapir, endangered “flagship” species of the high Andes. *Oryx* **30**:45–58.
- Elton, C., and M. Nicholson. 1942. The 10 year cycle in numbers of the lynx in Canada. *Journal of American Ecology* **11**:215–244.
- Esbensen, B. J. 1990. Great northern diver: the loon. Little Brown, Boston.
- Foose, T. J. 1993. Global management of rhinos. Pages 32–47 in O. A. Ryder, editor. *Rhinoceros biology and conservation*. San Diego Zoological Society, San Diego.
- Franchini, P., and C. L. Rockett. 1996. Oribatid mites as “indicator” species for estimating the environmental impact of conventional and conservation tillage practices. *Pedobiologia* **40**:217–225.
- Franklin, J. F. 1993. Preserving biodiversity: species, ecosystems, or landscapes. *Ecological Applications* **3**:202–205.
- Frost, T. M., S. R. Carpenter, and T. K. Kratz. 1992. Choosing ecological indicators: effect of taxonomic aggression on sensitivity to stress and natural variability. Pages 215–228 in D. H. McKenzie, D. E. Hyatt, and V. J. McDonald, editors. *Ecological indicators*. Volumes 1 and 2. Elsevier Science Publishers, New York.
- Gaston, K. J. 1996. Species richness: measure and measurement. Pages 77–113 in K. J. Gaston, editor. *Biodiversity: a biology of numbers and difference*. Blackwell Science, Oxford, United Kingdom.
- Gilbert, L. E. 1980. Food web organization and the conservation of Neotropical diversity. Pages 11–34 in M. E. Soulé and B. A. Wilcox, editors. *Conservation biology: an evolutionary-ecological perspective*. Sinauer Associates, Sunderland, Massachusetts.
- Gilman, A. P., D. P. Peakall, D. J. Hallett, G. A. Fox, and R. J. Norstrom. 1979. Herring Gulls (*Larus argentatus*) as monitors of contamination in the Great Lakes. Pages 280–289 in S. W. Nielsen, G. Migaki, and D. G. Scarpelli, chairs. *Animals as monitors of environmental pollutants*. National Academy of Sciences, Washington, D.C.
- Gittleman, J. L. 1986. Carnivore life history patterns: allometric, phylogenetic and ecological associations. *American Naturalist* **127**:744–771.
- Grzimek, B., and M. Grzimek. 1959. *Serengeti shall not die*. Ullstein, A. G., Berlin, Germany.
- Humphries, C. J., P. H. Williams, and R. I. Vane-Wright. 1995. Measuring biodiversity value for conservation. *Annual Review of Ecology and Systematics* **26**:93–111.
- Jarvinen, O. 1985. Conservation indices in land use planning: dim prospects for a panacea. *Ornis Fennica* **62**:101–106.
- Johnsingh, A. J. T., and J. Joshua. 1994. Conserving Rajaji and Corbett National Parks: the elephant as a flagship species. *Oryx* **28**:135–140.
- Karlsson, G. P., G. Sellden, L. Skarby, and H. Pleijel. 1994. Clover as an indicator plant for phytotoxic ozone concentrations: visible injury in relation to species, leaf age and exposure dynamics. *Agriculture Ecosystems and Environment* **59**:55–62.
- Karr, J. R. 1991. Biological integrity: a long-neglected aspect of water resource management. *Ecological Applications* **4**:244–250.
- Kellert, S. R. 1986. Social and perceptual factors in the preservation of animal species. Pages 50–73 in B. G. Norton, editor. *The preservation of species: the value of biological diversity*. Princeton University Press, Princeton, New Jersey.
- Kerr, J. T. 1997. Species richness, endemism, and the choice of areas for conservation. *Conservation Biology* **11**:1094–1100.
- Kleiman, D. G., and J. J. C. Mallinson. 1998. Recovery and management committees for lion tamarins: partnerships in conservation planning and implementation. *Conservation Biology* **12**:27–38.
- Kleiman, D. G., B. B. Beck, J. M. Dietz, L. A. Dietz, J. D. Ballou, and A. F. Coimbra-Filho. 1986. Conservation program for the golden lion tamarin: captive research and management, ecological studies, educational strategies and reintroduction. Pages 959–979 in E. Benirschke, editor. *Primates: the road to self-sustaining populations*. Springer-Verlag, New York.
- Kremen, C. 1992. Assessing the indicator properties of species assemblages for natural areas monitoring. *Ecological Applications* **2**:203–217.
- Lambeck, R. J. 1997. Focal species: a multi-species umbrella for nature conservation. *Conservation Biology* **11**:849–857.
- Landres, P. B. 1983. Use of the guild concept in environmental impact assessment. *Environmental Management* **7**:393–398.

- Landres, P. B. 1992. Ecological indicators: panacea or liability? Pages 1295-1318 in D. H. McKenzie, D. E. Hyatt, and V. J. McDonald, editors. Ecological indicators. Volumes 1 and 2. Elsevier Science Publishers, New York.
- Landres, P. B., J. Verner, and J. W. Thomas. 1988. Ecological uses of vertebrate indicator species: a critique. *Conservation Biology* 2: 316-327.
- Launer, A. E., and D. D. Murphy. 1994. Umbrella species and the conservation of habitat fragments: a case of a threatened butterfly and a vanishing grassland ecosystem. *Biological Conservation* 69: 145-153.
- Levin, S. A., M. A. Harwell, J. R. Kelly, and K. D. Kimball. 1989. Ecotoxicology problems and approaches. Pages 3-8 in S. A. Levin, editor. Ecotoxicology: problems and approaches. Springer Verlag, New York.
- Lips, K. R. 1998. Decline of a tropical montane amphibian fauna. *Conservation Biology* 12:106-117.
- McClenahan, T. R., A. T. Kamukuru, N. A. Muthiga, M. G. Yebio, and D. Obura. 1996. Effect of sea urchin reductions on algae, coral and fish populations. *Conservation Biology* 10:136-154.
- McKenzie, D. H., D. E. Hyatt, and V. J. McDonald. 1992. Ecological indicators. Volumes 1 and 2. Elsevier Science Publishers, New York.
- McKenzie, N. L., L. Belbin, C. R. Margules, and G. J. Keighery. 1989. Selecting representative reserve systems in remote areas: a case study in the Nullarbor region, Australia. *Biological Conservation* 50: 239-261.
- Mealy, S. P., and J. R. Horn. 1981. Integrating wildlife habitat objectives into the forest plan. Transactions of the North American Wildlife and National Resources Conference 46:488-500.
- Miller, G. D., and L. S. Davis. 1993. Foraging flexibility of Adelie Penguins *Pygoscelis adeline*: consequences for an indicator species. *Biological Conservation* 63:223-230.
- Mills, L. S., M. E. Soulé, and D. F. Doak. 1993. The keystone-species concept in ecology and conservation. *BioScience* 43:219-224.
- Mix, M. C., S. R. Trenholm, and K. I. King. 1979. Benzo[a]pyrene body burdens and the prevalence of proliferative disorders in mussels (*Mytilus edulis*) in Oregon. Pages 52-64 in S. W. Nielsen, G. Migaki, and D. G. Scarpelli, chairs. Animals as monitors of environmental pollutants. National Academy of Sciences, Washington, D.C.
- Munn, R. E. 1988. The design of integrated monitoring systems to provide early indications of environmental/ecological changes. *Environmental Monitoring and Assessment* 11:203-217.
- Murphy, D. D., and B. R. Noon. 1992. Integrating scientific methods and habitat conservation planning: reserve design for Northern Spotted Owls. *Ecological Applications* 2:3-17.
- Noss, R. F. 1990. Indicators for monitoring biodiversity: a hierarchical approach. *Conservation Biology* 4:355-364.
- Oatley, T. B., L. G. Underhill, and G. J. B. Ross. 1992. Recovery rate of juvenile Cape Gannets: a potential indicator of marine conditions. *Colonial Waterbirds* 15:140-143.
- Ott, W. R. 1978. Environmental indices: theory and practice. Ann Arbor Science, Ann Arbor, Michigan.
- Panzer, R., D. Stillwaugh, R. Gnaedinger, and G. Derkovitz. 1995. Prevalence of remnant dependence among the prairie and savanna inhabiting insects of the Chicago region. *Natural Areas Journal* 15: 101-116.
- Panwar, H. S. 1984. What to do when you've succeeded: Project Tiger, ten years later. Pages 183-189 in A. Jeffrey, editor. National parks, conservation and development: the role of protected areas in sustaining society. Smithsonian Institution Press, Washington, D.C.
- Patton, D. R. 1987. Is the use of "management indicator species" feasible? *Western Journal of Applied Forestry* 2:33-34.
- Pearson, D. 1995. Selecting indicator taxa for the quantitative assessment of biodiversity. *Philosophical Transactions of the Royal Society of London B* 345:75-79.
- Pearson, D. L., and S. S. Carroll. 1998. Global patterns of species richness: spatial models for conservation planning using bioindicator and precipitation data. *Conservation Biology* 12:809-821.
- Pearson, D. L., and F. Cassola. 1992. World-wide species richness patterns of tiger beetles (Coleoptera:Cicindelidae): indicator taxon for biodiversity and conservation studies. *Conservation Biology* 6: 376-391.
- Power, M. E., D. Tilman, J. A. Estes, B. A. Menge, W. J. Bond, L. S. Mills, G. Daily, J. C. Castilla, J. Lubchenko, and R. T. Paine. 1996. Challenges in the quest for keystones. *BioScience* 46:609-620.
- Prance, G. T. 1994. A comparison of the efficiency of higher taxa and species numbers in the assessment of biodiversity in the Neotropics. *Philosophical Transactions of the Royal Society of London B* 345:89-99.
- Prendergast, J. R., R. M. Quinn, J. H. Lawton, B. C. Eversham, and D. W. Gibbons. 1993. Rare species, the coincidence of diversity hot-spots and conservation strategies. *Nature* 365:335-337.
- Rabinowitz, A. 1986. Jaguar: one man's struggle to establish the world's first jaguar preserve. Arbor House, New York.
- Ricketts, T. H., E. Dinerstein, D. M. Olson, and C. Loucks. 1999. Who's where in North America. *BioScience* 49:369-381.
- Rodriguez-Estrella, R., J. A. Donazer, and F. Hiraldo. 1998. Raptors as indicators of environmental change in the scrub habitat of Baja California Sur, Mexico. *Conservation Biology* 12:921-925.
- Ryti, R. 1992. Effect of focal taxon on the selection of nature reserves. *Ecological Applications* 2:404-410.
- Sarkka, J. 1996. Meiofauna of the profundal zone of the northern part of Lake Ladoga as an indicator of pollution. *Hydrobiologia* 322: 29-38.
- Schafer, G. N. 1989. Site indicator species for predicting productivity of pine plantations in the southern Cape. *South African Forestry Journal* 148:7-17.
- Sidle, W. B., and L. H. Suring. 1986. Management indicator species for the national forest lands in Alaska. Technical publication R10-TP-2. U.S. Forest Service, Juneau, Alaska.
- Siemann, E., D. Tilman, and J. Haarstad. 1996. Insect species diversity, abundance and body size relationships. *Nature* 380:704-706.
- Simberloff, D. 1998. Flagships, umbrellas and keystones: is single-species management passé in the landscape era? *Biological Conservation* 83:247-257.
- Stolte, K. W., and D. R. Mangis. 1992. Identification and use of plant species as ecological indicators of air pollution stress in Nat'l Park Units. Pages 373-392 in D. H. McKenzie, D. E. Hyatt and V. J. McDonald, editors. Ecological Indicators vols 1 and 2, International Symposium, Fort Lauderdale, Florida USA. Elsevier Science Publishers Ltd., New York.
- Strong, P. I. V. 1990. The suitability of the Common Loon as an indicator species. *Wildlife Society Bulletin* 18:257-261.
- Swanson, B. J. 1998. Autocorrelated rates of change in animal populations and their relationships to precipitation. *Conservation Biology* 12:801-808.
- Szaro, R. C. 1986. Guild management: an evaluation of avian guilds as a predictive tool. *Environmental Management* 10:681-688.
- Temple, S. A., and J. A. Wiens. 1989. Bird populations and environmental changes: can birds be bio-indicators? *American Birds* 43: 260-270.
- Thomas, W. A. 1972. Indicators of environmental quality. Plenum Press, New York.
- U.S. Department of the Interior. 1980. Habitat evaluation procedures. Ecological services manual 102. U.S. Fish and Wildlife Service, Division of Ecological Services, Washington, D.C.
- U.S. Forest Service. 1984. Wildlife, fish and sensitive plant habitat management. Title 2600. Amendment 48. U.S. Forest Service, Washington, D.C.
- Verner, J. 1984. The guild concept applied to management of bird populations. *Environmental Management* 8:1-14.
- Vitt, L. J., J. P. Caldwell, H. M. Wilbur, and D. C. Smith. 1990. Amphibians as harbingers of decay. *BioScience* 40:48.
- Walker, C. H. 1983. Pesticides and birds: mechanisms of selective toxicity. *Agriculture, Ecosystems and Environment* 9:211-226.

- Western, D. 1987. Africa's elephants and rhinos: flagships in crisis. *Trends in Ecology* 2:343-346.
- Wilcox, B. A. 1984. In situ conservation of genetic resources: determinants of minimum area requirements. Pages 639-647 in J. A. McNeely and K. R. Miller, editors. *National parks: conservation and development*. Smithsonian Institution Press, Washington, D.C.
- Williams, P. H., and K. J. Gaston. 1994. Measuring more of biodiversity: can higher-taxon richness predict wholesale species richness? *Biological Conservation* 67:211-217.
- Zonnevald, I. S. 1988. Environmental indication. Pages 491-498 in A. W. Kuchler and I. S. Zonneveld, editors. *Vegetation mapping*. Kluwer Academic Press, Dordrecht, The Netherlands.





Full Length Article

Long-term evolution of overlying rock fractures in mined-out areas and its effect on gas flow conductivity



Zihan Chen^a, Quanle Zou^{a,*}, Shikang Gao^b, Jinfei Zhan^a, Chunmei Chen^a, Qican Ran^a, Xiaoyan Sun^{c,d}

^a State Key Laboratory of Coal Mine Disaster Dynamics and Control, School of Resources and Safety Engineering, Chongqing University, 174, Shapingba Street, Chongqing 400044, China

^b School of Mining, Guizhou University, Huaxi District, Guiyang, Guizhou 550025, China

^c Hancheng Zaozhuang Industrial Co., Shaanxi 715400, China

^d School of Energy and Mining Engineering, China University of Mining and Technology-Beijing, Beijing 100083, China

ARTICLE INFO

Keywords:

Long-term evolution
Abandoned mines
Mined-out areas
Gas flow conductivity
Future development
Gas distribution law

ABSTRACT

Abandoned mines are often closed for long periods, and the overlying rock in mined-out areas is subjected to creep due to constant stress, which affects the overlying rock fracture morphology. The fractures in these rocks have a conductive effect on the gas flow, and previous studies less consider the influence of the long-term evolution process of the fractures on the gas distribution in these areas. Long-term experiments were conducted using a physical similarity experimental model of the mined-out area. To further explain the evolution law of the overlying rock displacement and fracture fields, a method for quantifying the percentage of the fracture field of the overlying rock based on computer image recognition technology is proposed. The results show that the long-term evolution of the overlying rock fractures have the characteristics of transfer and closure, and the change process determines the gas flow trajectory of overlying rock. The long-term evolution of the overlying rock is clarified, which incorporates the three-stage development of the delamination fractures and the stage density increase of the broken fractures. The gas storage capacity of the overlying rock first increases, then decreases, before stabilizing, and the gas diffusion capacity gradually increases. The gas distribution range fluctuates and increases with the evolution of the overlying rock fractures at different times. The time-varying law of the long-term evolution of overlying rock fractures in the mined-out area is explained and theoretical support is provided for clarifying the time-varying law of gas distribution in the overlying rock.

1. Introduction

With the restructuring of the coal industry and technological upgrading of coal mining enterprises, coal mines with small production scales and backward production capacities will gradually close. In recent years, the international community has proposed the goal of “carbon neutrality”, which aims to accelerate coal overcapacity reduction. By 2020, the number of coal mines in China reached 428 [1]. After underground coal resource mining, a mined-out area forms behind the working face. The rock mass moves into the mined-out area, and subsidence and collapse occur [2], promoting the development of overlying rock fractures in the mined-out area. Above the mined-out area, the rock mass will fracture to form blocks of different sizes and form the caving zone, fracture zone, and bending subsidence zone [3,4]. Additionally,

coal seams in coal mines contain large amounts of gas [5,6]. Gas is a clean energy source, and its full utilization can effectively reduce carbon dioxide emissions [7]. Several technologies exist for the extraction and utilization of gases from abandoned mines, including replacing carbon dioxide [8], surface vertical well extraction [9], and networked distribution well extraction [10]. However, challenges remain, such as low gas pressure and inefficient arrangement of gas extraction locations. This is mainly due to the fact that in closed abandoned mines, gas can spread into the overlying rock area of the mined-out area [11], which in turn affects the efficiency of gas extraction. Therefore, clarifying the distribution of the overlying rock gas in mined-out area is beneficial for the further development and utilization of gas resources in abandoned mines.

Abandoned mines are often closed for long periods, and the

* Corresponding author.

E-mail address: quanlezou2011@126.com (Q. Zou).

<https://doi.org/10.1016/j.fuel.2023.129213>

Received 9 March 2023; Received in revised form 19 June 2023; Accepted 10 July 2023

Available online 18 July 2023

0016-2361/© 2023 Elsevier Ltd. All rights reserved.

overlying rock mass in the mined-out area is mainly subjected to constant stress (ground stress), leading to creeping [12]. During long-term creep, tiny fractures within the rock develop, expand and aggregate to form large fractures, which eventually damage the rock [13], that in turn leads to changes in the fracture field morphology of the overlying. Many creep loading studies have been conducted on rock specimen. In a study of rock damage caused by different stress loadings, Li and Yin [14] derived a sandstone constitutive model under creep disturbance loading based on sandstone triaxial creep experiments. The model was used to clarify the effect of disturbance loading on the increase of creep in sandstone. Chu et al. [15] conducted secondary creep experiments on rocks after different creep damage and found that the secondary creep deformation capacity of rocks increased with the degree of initial creep damage. Moreover, the surrounding pressure affected the rock to creep damage process. Niu et al. [16] studied the creep damage process of sandstone under different surrounding pressures. They found that the creep strain of the rock decreases under high surrounding pressure conditions. Feng et al. [17], on the other hand, found an exponential relationship between the surrounding pressure and the rock's creep strain and creep rate. At the same time, the rock is often accompanied by fracture development during destabilization and deformation [18]. Chen and Azzam [19] predicted of the fracture extension process under rock creep conditions based on gray prediction theory. Bacha et al. [20] observed the process of microfracture development in sandstone under long-term creep by applying a constant uniaxial load to sandstone specimens and performing a nondestructive scanning analysis on compressed sandstone specimens. Shi et al. [21] used an acoustic emission technique to monitor the rock creep process and spatially localized the fracture development process under rock creep conditions. Previous studies have explained the fracture development process under rock creep conditions using theoretical analysis, scanning monitoring, and other technical means. In addition, rock fractures as the main gas flow channels, affect the permeability of rock layers. Zhou et al. [22] found that in creep experiments, the permeability of coal decreased, stabilized, and then increased rapidly in the primary creep stable creep, and accelerated creep phases, respectively. However, the overlying rock fractures in mined-out area are often developed by extension between rock layers. The gas diffusion of rock layers depends on the fracture channels between the rock layers [23]. However, it is difficult for rock specimens to reflect the development of fractures between rock layers. In response, researchers have constructed physical similarity models based on coal mine geological data and conducted relevant studies. In the study of the effect of coal seam mining on the overlying rock collapse in the mined-out area, Ran et al. [24] constructed a physical similarity model for inclined coal seams. They investigated the fracture area during the mining of inclined coal seams. Li et al. [25] studied overlying rock collapse in the coal mining process by constructing a physical similarity experimental model of the working face and guided the safe mining of coal seams. Celik and Ozcelik [26] examined the effectiveness of the longwall top coal caving method in thick coal seams based on a physical similarity experimental model. They proposed a new longwall design to reduce coal loss during coal mining. The collapse of overlying rock in the mined-out area promotes the development of fractures in the overlying rock. Li et al. [27] clarified that the key layer in the mined-out area exists to control the development of overlying rock fractures. Furthermore, the fractures are developed in the form of "diagonal stripes" along the working face advancement direction. Guo et al. [28] constructed a physical similarity experimental model of the double-fault mined-out area. They explained the distribution pattern and pressure law of the overlying rock fractures in the mined-out area under the influence of faults. In addition, the overlying rock fracture development has an impact on stress conditions of the rock layers. Ma et al. [29] combined numerical simulation and similar simulation experimental methods to investigate the effect of protection layer mining on the pressure relief of the protected layer in a slowly inclined coal mine. Ye et al. [30] found that, in an inclined coal seam, the collapse of the

overlying rock in the mined-out area increased, and the large dip angle of the coal seam led to an unbalanced stress distribution on both sides of the mined-out area. Liu et al. [31] arranged monitoring points around the perimeter of a similar experimental roadway model and investigated the stress changes in the rock surrounding the roadway caused by coal mining in a close-distance coal seam group. In summary, previous studies have discussed the fracture development law of rock specimens during creep and the mined-out area overlying rock during coal mining. However, it is difficult for rock specimens to reflect the expansion of fracture channels between the rock layers and the characteristics of gas flow conductivity during fracture development under creep. Meanwhile, the previous studies using physically similar experimental model have focused on the overlying rock fractures and pressure changes during coal seam mining and less on the long-term evolution of the overlying rock fractures after the coal seam has been mined.

Therefore, in this study, the Sangbei Coal Mine in Shaanxi Province, China, was used as the geological background. A physical similarity experimental model was established, and long-term experiments were conducted. The morphological evolution and displacement change law of the overlying rocks in the mined-out area during long-term evolution was investigated. A method for extracting the fracture channel percentage using image recognition technology is proposed, and a realize the quantitative analysis of the fracture field of the overlying rocks in the mined-out area at different times is conducted. A numerical simulation was used to study the gas percolation pattern inside sandstone at different times to verify the influence of the fracture development of the overlying rock in the mined-out area on the gas distribution. The results of this study help to explain the evolution law of the fracture field morphology and its gas flow conductivity characteristics at different times in the overlying rocks of abandoned mines. They also provide theoretical support to clarify the gas distribution law of the overlying rocks in mined-out areas.

2. Experimental methods

The Sangbei Coal Mine is located in Hancheng City, Shaanxi Province, China. The mining area of the Sangbei Coal Mine is an integrated area. No.3 coal seam is the main mineable coal seam in the area, with an average thickness of 5.48 m. The lithology directly above coal seam No. 3 comprises mainly mudstone, siltstone and fine sandstone, whereas that directly below comprises mainly mudstone and siltstone, with fine sandstone in the local section. The inclination angle of No. 3 coal seam is 2° to 5° , which can be regarded as a near horizontal. Additionally, the coal mining method adopted by the Sangbei Coal Mine was integrated with mechanized coal mining.

As shown in Fig. 1, a coal mine pressure-relieving mining simulation experiment system, developed by Chongqing University, was adopted in this study to investigate the long-term evolution law of the overlying rock fracture field in the mined-out area. The equipment consisted of a control system, a physical similarity experimental stand, a pressure monitoring system, a loading system, and an image acquisition system. The experimental system simulated a maximum stratigraphic tilt angle of 70° and the maximum stress that could be applied was 0.4 MPa. The simulated experimental equipment was 1316 mm long, 50 mm wide, and 1262 mm in high.

For the physical similarity experimental model the composition of similar simulation materials was selected to simulate the actual geological data of the rock layer of the working face of the Sangbei Coal Mine. In addition, according to the similarity theory, it is determined that the geometric similarity ratio of the physical similarity model was 1:200, the bulk density similarity ratio was 1:1.5, the stress similarity ratio was 1:300, and the model time ratio was 1:14. The simulated material comprised sand as an aggregate, calcium carbonate and gypsum as cementing materials, and mica powder as the layered auxiliary material. The model only considers the overlying rock self-weight. The physical similarity experimental model of each rock layer was obtained

MINING AND REMEDIATION AT THE STRAZ POD RALSKEM URANIUM DEPOSIT

TĚŽBA A SANACE NA URANOVÉM LOŽISKU STRÁŽ POD RALSKEM

Vladimír EKERT¹, Jiří MUŽÁK²

¹Mgr., DIAMO state enterprise, division TÚU
471 27 Stráž pod Ralskem, Czech Republic, tel. (+420) 487 894 258
e-mail: ekert@diamo.cz

²Ing., Ph.D., DIAMO state enterprise, division TÚU
471 27 Stráž pod Ralskem, Czech Republic, tel. (+420) 487 894 324
e-mail: muzak@diamo.cz

Abstract

The presented paper brings brief information about the history of chemical uranium mining in the area of Straz pod Ralskem. It further presents the extent of environmental contamination caused by the operations of in-situ uranium leaching during 32 years. There is more than 370 million m³ of affected ground water, in which almost 5 million contaminating substances are dissolved. In conclusion, descriptions of used and forward-looking surface technologies of contamination removal involving time and financial assessments of the entire remediation process are given. It is envisaged that the remediation will take nearly 25 years and the total costs of its implementation are estimated in the amount of CZK 40 billion.

Abstrakt

Přednáška stručně informuje o historii chemické těžby uranu v oblasti Stráže pod Ralskem. Dále je prezentován současný rozsah kontaminace horninového prostředí zapříčiněné provozováním chemického vyluhování uranu in-situ po dobu 32 let. V podzemí je ovlivněno více než 370 milionů m³ vod, ve kterých je rozpuštěno téměř 5 milionů tun kontaminujících látek. Závěrem jsou charakterizovány používané i do budoucna plánované povrchové technologie pro likvidaci kontaminace s časovým i finančním ohodnocením celého sanačního procesu. Předpokládá se, že sanace bude trvat téměř 25 let a celkové náklady na její realizaci jsou odhadnuty na úrovni 40 miliard Kč.

Key words: uranium mining, ground water, contamination, remediation, Czech Republic

1 HISTORY OF URANIUM MINING

The history of uranium exploitation in the Czech Republic (and in the former Czechoslovakia) dates back 60 years. Over the initial period, from 1946 until the early 1950s, the exploitation was mainly carried out in the reopened mines of the Jachymov mining area. Rapid development of surveying and extracting works was reflected in the large growth of exploitation in other areas of Bohemia and Moravia. This concerned the regions Příbram, Hamr-Straz pod Ralskem and Dolní Rozinka, i.e. southern and western Bohemia. More than 100 000 tons of uranium have been extracted from over 800 trial and production shafts since 1946.

Owing to the diversity of the deposits, the uranium exploitation was carried out with the whole spectrum of mining methods available, which were selected as appropriate for the host rock in the given locality. In general terms, there are two basic methods of uranium extraction applied in the Czech Republic:

- conventional underground mine workings, and
- underground in situ leaching.

The deposits in the area of Hamr - Straz were discovered in the 1960s. In 1963, an aerial geophysical surveying detected high magnetic anomalies into which a borehole, HJ-1 (Hamr na Jezere-1), was drilled. Following the detection of the anomaly at the well HJ-1, other exploration boreholes were drilled in its vicinity and all of them confirmed uranium mineralization. The well HJ-1 located at the Hamr pod Ralskem deposit represented the beginning of an exploration borehole network. Locations of uranium deposits in the area of Hamr - Straz within the Czech Republic are shown in Figure 1.

Beverley uranium mine incident summary report

Beverley mine spill incidents

The reporting procedure addresses incidents involving unplanned release of radioactive process materials, radioactive liquids or radioactive wastes associated with physical and chemical processing of uranium ores.

- More about standard criteria and procedures for reporting uranium incidents
(https://www.energymining.sa.gov.au/industry/minerals-and-mining/mining/regulating-mining-activity/standard-criteria-and-procedures-for-reporting-uranium_incidents)

Incidents reported in 2021

Date of incident: 9 July 2021

Date reported: 9 July 2021

Quantity: 20 litres

Description of incident

The decant filters at the Beverley Processing Plant were found to be blocked. Following several unsuccessful attempts by operational staff to backflush the decant filters, the vent valve was removed and process water passed through the bottom of the tank. Due to the size of the blockage, pressure built up and ammonium diuranate (uranium), combined with process water was ejected from the vent valve hole. As a result, approximately 20 litres of the spray landed outside the concrete bund.

Comments

The company reported no environmental impacts and no health, safety or radiological impacts to employees or members of the public. All contaminated material was collected

and managed in accordance with site procedures.

The root cause of the incident was the plant was overfilled by the operator, and a lack of engineering controls were in place for the manual backflush outlets of the decant filters.

To prevent a recurrence, a number of actions have been implemented, including redesigning backflush systems, revising operational procedures and training programs.

Incidents reported in 2012

Date of incident: 28 February 2012

Date reported: 29 February 2012

Quantity: 30–34 m³

Description of incident

The incident occurred at approximately 12:25 pm on 28 February 2012 in the central wellfield.

The size of the spill was over an unconfined area due to local creek flooding and site inundation. Volume of spill was estimated from a water mass balance (inflow – outflow) and calculated from actual pipe length and diameter.

A blowdown valve (BDV) was damaged on the extraction trunkline. The BDV is used to empty mining solutions from isolated sections of trunklines for maintenance and repairs. The solution can either be sent back to the wellfield or transported to the Water Management ponds on site. After flood waters subsided a risk assessment was undertaken and an action plan was implemented.

Comments

It was difficult to contain the spill due to the extreme weather conditions (over 200 mm rainfall in 48 hrs).

Probable cause was floodwater moving an injection lateral pipeline causing it to come into contact with a blow down valve on the extraction trunkline, shearing the valve stub off. This caused a spill of extraction solution (pregnant liquor) into surface run-off. The immediate corrective action was a plant shut down including shutdown of extraction well pumps to prevent any flows within the well fields.

Water and soil samples have been collected for testing. Radionuclide levels are low due to dilution by fresh water during the extreme rainfall event. The incident did not result in injury to personnel or any environmental harm.

Final investigation report was received 28 June 2012.

Incidents reported in 2011

Date of incident: 19 February 2011

Date reported: 19 February 2011 (with follow up reporting 21 February 2011)

Quantity: 10 to 15 m³

Description of incident

The incident occurred at approximately 3:15 am and due to heavy rainfall was not discovered until 4:00 am. A filter canister failed in E2 Wellhouse causing a spill of between 10 to 15 cubic metres of injection mining solution (7 ppm U) at the Beverley East E2 Wellhouse. The area affected by the spill was 400 m² however the footprint area is somewhat subjective due to the influence of rain prior to and subsequent preventing defined edges to the affected area.

Rainfall recorded at the Beverley Weather Station approximately 5 km northwest of the spill location on the evening prior to the spill was 6.6 mm. Rainfall recorded later in the day following the spill was 12.8 mm.

Comments

The exact cause of the spill is being investigated – there is minor damage to a part of the thread of the filter canister lid however this is not significant. The filter canister involved has been locked out of service and replacement of the filter canister will not occur as the wellfield is nearing the end of its mineable life. When the wellhouse is turned back on, the filter canister in question will remain locked out. The remaining solution has been retrieved from the culvert.

When the area is suitably dry, soil samples will be collected from the area of the spill as well as at two or three points downstream of the spill location. One of these sample locations is a permanent soil sampling location (S16) and is part of annual sediment sampling, hence background analysis is available. S16 is approximately 1.25 km downstream (southeast) of the spill location. A grab sample will be collected from North Mulga Dam, approximately 2 km downstream of the spill location, when safe access is available.

Background analysis of water from this dam is also available for comparison. The incident does not appear to have caused any environmental harm or injury to personal.

Incidents reported in 2007

Date of incident: 20 December 2007

Date reported: 20 December 2007

Quantity: 500 litres

Description of incident

A small split approximately 150 mm long occurred in the underside of an injection pipeline. This allowed some fluid to escape into a bunded corridor around the pipeline. However, it is estimated that 500 litres of solution containing approximately 0.003% uranium went outside the bund. This area was previously disturbed and no live vegetation was adversely affected.

Comments

The pipeline was replaced and the bunded area repaired. Any affected soil was removed. The incident did not cause any environmental harm or injury to personnel.

Date of incident: 30 September 2007

Date reported: 30 September 2007

Quantity: 580 litres

Description of incident

A buried high-density polyethylene (HDPE) pipe that is used to transfer liquid waste from the plant to the approved liquid waste disposal well, was pierced by a steel fence post, which was being put into the ground to prevent vehicle access to an ephemeral watercourse. The disposal pipe is buried where it crosses the ephemeral watercourse. An initial estimate suggests approximately 580 litres of disposal liquid was released. The spill was discovered by an operator, who observed a damp patch of soil around the post.

Comments

The discharge of disposal liquid was stopped and the punctured section of pipe bypassed. The saline disposal liquid contains low levels of dissolved radium and uranium and, any contaminated soil will be assessed to determine appropriate remedial action. The incident did not cause any environmental harm or injury to personnel.

Incidents reported in 2006

Date of incident: 6 August 2006

Date reported: 6 August 2006

Quantity: 1 litre

Description of incident

Two flanges in the southern trunkline were found to be slowly dripping solution onto the ground below. The location of the drip was in an undisturbed environment making it a reportable incident. The injection solution contained some 0.005% uranium and the extraction fluid contained 0.013% uranium.

Comments

The pressure in the trunkline was immediately reduced and the leaking flange bolts tightened. An inspection of all other flanges in the trunkline was also undertaken. The incident did not cause any environmental harm or injury to personnel.

Date of incident: 20 July 2006

Date reported: 20 July 2006

Quantity: not applicable

Description of incident

One of two reverse osmosis units became contaminated when a maintenance technician mistakenly added 4 litres of solution containing 0.4% uranium to the unit instead of hydrochloric acid. Some of the solution made its way into the potable water system.

Comments

The reverse osmosis plant and associated pipe work has been disconnected from the circuit and the unit replaced. A full investigation of the incident was undertaken by the appropriate State government agencies. All staff were notified and restrictions placed on the use of potable water.

Date of incident: 15 July 2006

Date reported: 15 July 2006

Quantity: 2 litres

Description of incident

An operator was disconnecting the discharge line from a sump pump. The residual pressure in the discharge line caused some of the solution to spray outside the concrete bund, making it a reportable incident. The solution containing some particulates of uranium.

Comments

All of the solution and particulate material was recovered and transferred back into the circuit. The incident did not cause any environmental harm or injury to personnel.

Date of incident: 22 April 2006

Date reported: 23 April 2006

Quantity: 14.4 m³

Description of incident

The spill occurred during the filling of a tank. The level alarm failed to operate resulting in the tank overflowing into the sump area below the tank. The liquor, contained approximately 0.5% uranium.

Comments

The liquor was collected in the sump and transferred back into the processing circuit. The incident did not cause any environmental harm or injury to personnel.

Date of incident: 14 February 2006

Date reported: 15 February 2006

Quantity: less than 100 grams

Description of incident

Small droplets of uranium concentrate were dropped from old piping during a changeover of acrylonitrile butadiene styrene (ABS) pipes to high-density polyethylene (HDPE) piping. The droplets were outside the thickener bund in the plant area.

Comments

Area flagged off and the material recovered. The incident did not cause any environmental harm or injury to personnel.

Incidents reported in 2005

Date of incident: 31 October 2005

Date reported: 1 November 2005

Quantity: 27.3 m³

Description of incident

An injection well in the central wellfield was not locked 'out of service' in accordance with standard operating procedure, and as a number of additional wells were brought online, fluid commenced flowing from the pipe connected to the injection well. The night shift operator noticed fluid on the ground during an inspection of the wellfield.

Comments

The spilt fluid was contained within the bunded well field. All residual surface fluid was recovered and the area affected by the spill was flagged off.

Heathgate advise that disciplinary action has been taken in relation to this incident.

Date of incident: 8 August 2005

Date reported: 8 August 2005

Quantity: 13.5 m³

Description of incident

An extraction well started producing sand and consequently was turned off. The sand from the well made its way into the wellhead and fouled the non-return valve in the pipeline. This allowed extraction fluid to flow back down the well casing which filled, and the excess extraction fluid started flowing from the top of the well onto the surrounding ground.

Analysis indicated that the fluid contained approximately 124 ppm uranium.

Comments

The spilt fluid was contained within the bunded well field. Standard clean up measures were implemented, and the excess water around the extraction well was collected returned to the evaporation pond. The company has checked the installation of all other probes and drip trays, reinforcing to all wellfield staff the importance of the correct installation procedures. The incident did not cause any environmental harm or injury to personnel.

Date of incident: 19 May 2005

Date reported: 19 May 2005

Quantity: Small quantity

Description of incident

An alarm in the control room was triggered which indicated a leak between the liners during the commissioning of a new pond. The leak was very small and analysis of the fluid recovered between the primary and secondary containment liners contained traces of uranium.

Comments

The pond was subsequently emptied to enable repairs to the primary high-density polyethylene (HDPE) liner. The incident did not cause any environmental harm or injury to personnel.

Date of incident: 7 March 2005

Date reported: 7 March 2005

Quantity: 76.7 m³

Description of incident

Injection fluid was found flowing from an open 90 mm pipe disconnected from the wellhead of an injection well. The fluid contained only low levels of uranium, approximately 0.019%. All of the fluid was contained by the internal bunds within the wellfield and none of the fluid reached the outer perimeter bund of the wellfield.

Comments

Most of the escaped fluid was recovered and returned to the ponds. Heathgate are reviewing internal standard operating procedures for tag out isolation and will apply engineering solutions to ensure such incidents do not occur in future. Because the spill was contained within the wellfield bunds the incident did not cause any environmental harm or injury to personnel.

Date of incident: 5 February 2005

Date reported: 8 February 2005

Quantity: not applicable

Description of incident

The electronic leak detection system under the primary liner of evaporation pond 5 was triggered during the commissioning of the pond. Subsequent analysis confirmed that a very small amount of disposal fluid had migrated to between the primary and secondary liner of the pond.

Comments

Immediate action was taken to empty that area of the pond to enable a detailed inspection of the liner and to undertake any subsequent repairs. The internal communication processes within Heathgate Resources are being reviewed. The incident did not cause any environmental harm or injury to personnel.

Date of incident: 30 January 2005

Date reported: 30 January 2005

Quantity: not applicable

Description of incident

Leak detection system under the primary liner of evaporation pond 5 was triggered during the commissioning of the pond. Analysis confirmed that pond solution had migrated to between the primary and secondary liner of the pond.

Comments

Immediate action was taken to empty to pond to enable a detailed inspection of the liner and to undertake any subsequent repairs. The incident did not cause any environmental harm or injury to personnel.

Incidents reported in 2004



Energy & Mining

<https://www.energymining.sa.gov.au/industry/minerals-and-mining/mining/major-projects-and-mining-activities/major-operating-and-approved-mines/beverley-and-beverley-north-mines/beverley-uranium-mine-incident-summary-report>

Nov 7, 2025 12:17 pm

Groundwater Restoration at Uranium In-Situ Recovery Mines, South Texas Coastal Plain



Open-File Report 2009–1143

**U.S. Department of the Interior
U.S. Geological Survey**

Groundwater Restoration at Uranium In-Situ Recovery Mines, South Texas Coastal Plain

By Susan Hall

Open-File Report 2009–1143

**U.S. Department of the Interior
U.S. Geological Survey**

U.S. Department of the Interior

KEN SALAZAR, Secretary

U.S. Geological Survey

Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2009

For product and ordering information:

World Wide Web: <http://www.usgs.gov/pubprod>

Telephone: 1-888-ASK-USGS

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment:

World Wide Web: <http://www.usgs.gov>

Telephone: 1-888-ASK-USGS

Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

Although this report is in the public domain, permission must be secured from the individual copyright owners to reproduce any copyrighted materials contained within this report.

Suggested citation:

Hall, Susan, 2009, Groundwater restoration at uranium in-situ recovery mines, south Texas coastal plain: U.S. Geological Survey Open-File Report 2009–1143, 32 p.



Introduction

This talk was presented by U.S. Geological Survey (USGS) geologist Susan Hall on May 11, 2009, at the Uranium 2009 conference in Keystone, Colorado, and on May 12, 2009, as part of an underground injection control track presentation at the Texas Commission on Environmental Quality (TCEQ) Environmental Trade Fair and Conference in Austin, Texas.

Texas has been the location of the greatest number of uranium in-situ recovery (ISR) mines in the United States and was the incubator for the development of alkaline leach technology in this country. For that reason, the author chose to focus on the effectiveness of restoration at ISR mines by examining legacy mines developed in Texas. The best source for accurate information about restoration at Texas ISR mines is housed at the TCEQ offices in Austin. The bulk of this research is an analysis of those records.



USGS Uranium ISR Research

Phase 1: Forensic Chemistry (Nearing Completion)

- Compile historic chemistry of ISR operations throughout the United States
- Characterize groundwater chemistry in past ISR operations
- Compare effectiveness of restoration techniques (monitor ongoing studies)

Phase 2: Long-term Monitoring (Site and Funding Search Underway)

- Resample old well fields to test for long-term aquifer contamination
- Measure capacity of host formations to naturally attenuate ISR well field waters
- Resample around well fields to determine if contamination has moved outside original monitor wells
- Determination of mineralogic transformations through mining and reclamation

Phase 3: Improved Restoration Techniques (Preliminary Testing Initiated)

- Bench scale testing to try to develop more effective geochemical techniques for groundwater restoration in ISR mines
- Pilot studies implementing new techniques



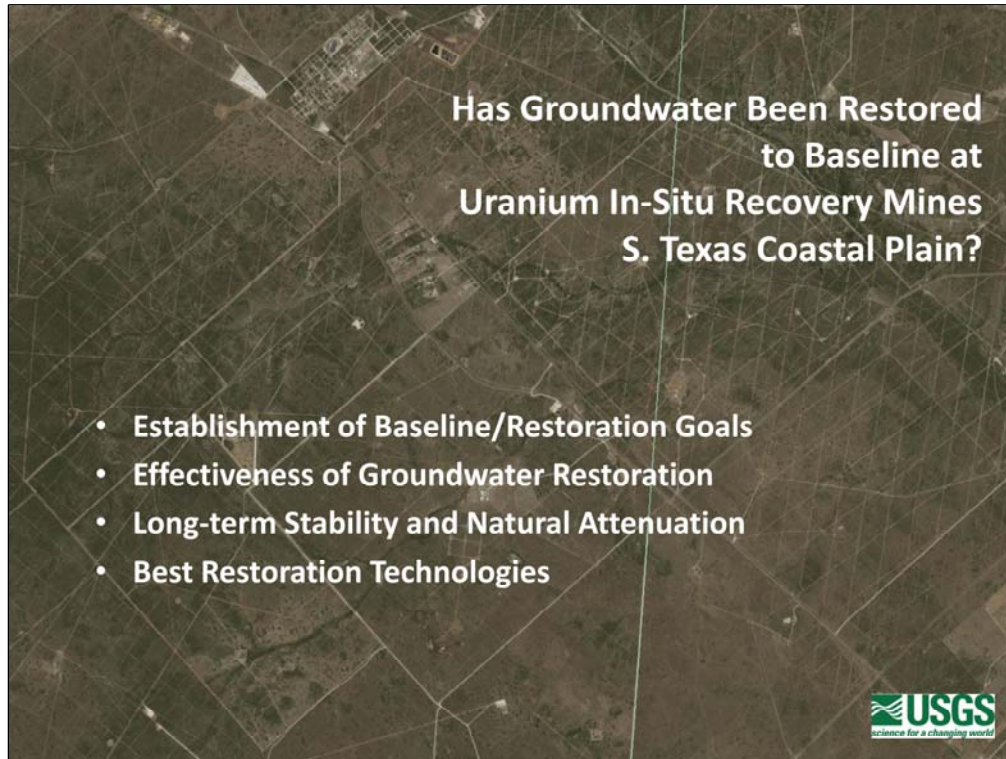
USGS Uranium ISR Studies

The USGS initiated a study of the effects on groundwater by ISR mining in 2008 in response to increased activity in uranium exploration and mining and the increasing number of applications for ISR mines to the U.S. Nuclear Regulatory Commission. USGS geologists were particularly intrigued with the widespread assertion that “Groundwater has never been returned to baseline at any ISR mine.”

USGS ISR studies are broken down into three phases:

1. Compilation of forensic chemistry: the examination of legacy projects.
2. Investigations of groundwater chemistry over time.
3. Development of improved restoration techniques.

The USGS is nearing completion of Phase 1, the forensic chemistry portion of our project, and these are some of the interim results of this work. The search for a suitable field site and funding to evaluate long-term impacts and natural attenuation of groundwater in ISR well fields (Phase 2) is underway, and preliminary testing of new restoration technologies for ISR well fields (Phase 3) has begun.



Outline of Presentation

To determine the effectiveness of groundwater restoration at ISR mines, the following topics will be addressed:

1. The establishment of baseline and restoration goals.
2. Effectiveness of groundwater restoration.
3. Long-term stability of well fields.
4. An evaluation of best restoration technologies, including:
 - (a) Pump and treat techniques (Texas),
 - (b) The addition of reductants (Wyoming and New Mexico), and
 - (c) Bioremediation (Nebraska and Wyoming).

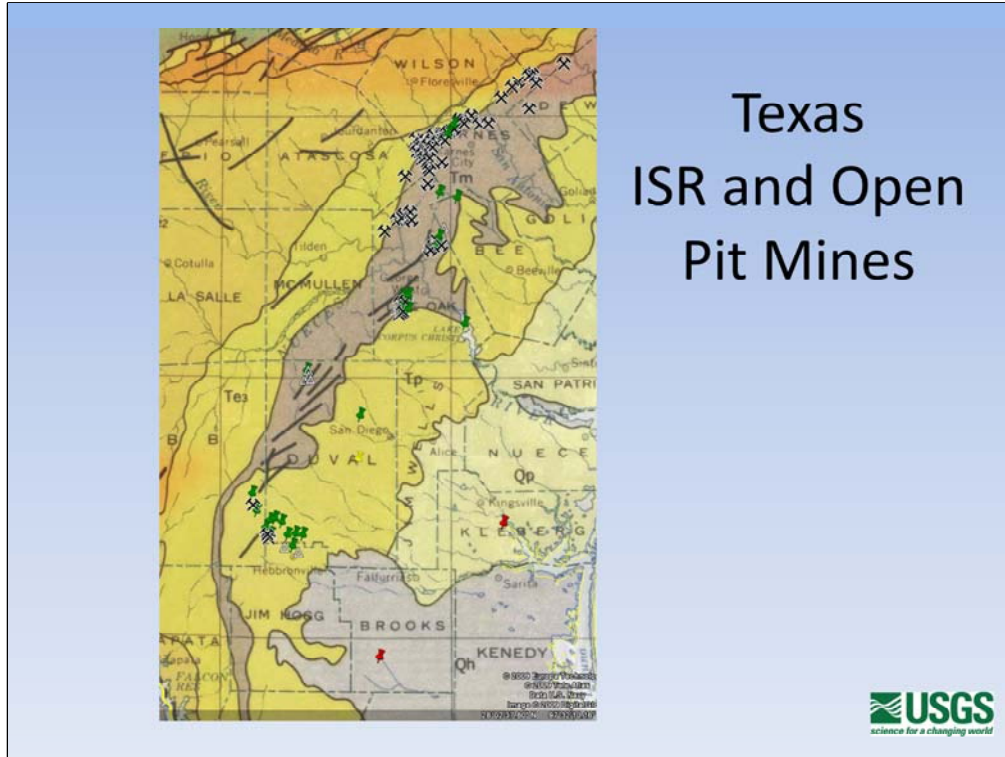


Background

The United States has been steadily producing uranium using ISR mining since the mid-1970s. In April 2009 there were four active mines in the United States (red markers): Cameco's Smith Ranch/Highland property in Wyoming and Crow Butte mine in Nebraska, and Mestena Uranium's Alta Mesa mine and URI's Kingsville Dome mine, both located in Texas.

Most uranium production from ISR mines has come from mines in Wyoming and Texas (green markers), with only pilot projects testing mining and restoration techniques developed in New Mexico (Crown Point, Mobil) and Colorado (Grover, Wyoming Minerals). More than 20 ISR mines anticipate or have begun the process of applying for licensing (yellow markers).

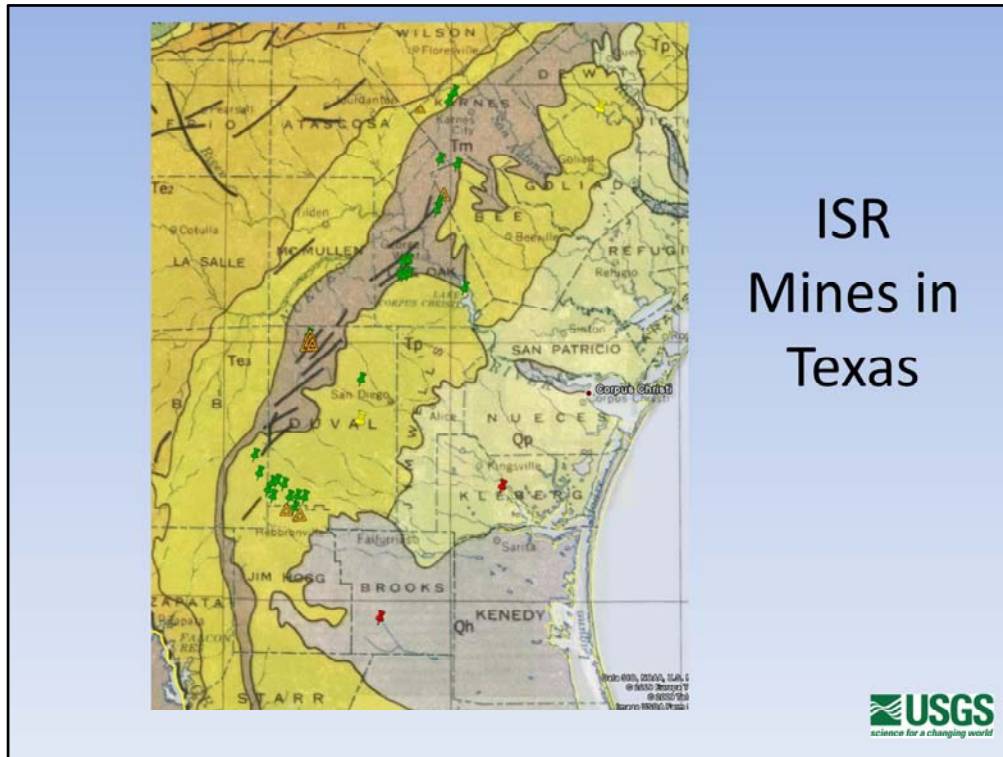
According to the Energy Information Agency, the United States imported 82 percent of its uranium in 2007 (Energy Information Agency, 2009) and 38 percent of U.S. uranium reserves are classified as ISR amenable (Nuclear Energy Agency, 2008). Thus, the safe and effective use of ISR technology in mining uranium deposits is a potentially critical element in the movement towards energy independence in the United States



Texas Coastal Plain Uranium District

Historically, uranium in Texas has been produced from Tertiary units along the southwest coastal plain. Uranium was first mined from a series of open-pit deposits developed in the Whitsett Formation (Jackson Group) and Catahoula Formation, starting in the late 1950s, when uranium was discovered during radiometric surveys in support of oil and gas exploration in Texas.

Black crossed mine symbols are uranium properties identified by the USGS Mineral Resources Data System database (<http://tin.er.usgs.gov/>) and show mostly historical open-pit mines located near Karnes City, Texas. The green markers represent closed ISR mines, and the red markers indicate operating ISR mines as of April 2009.



Along the southwest Texas coastal plain, uranium is mined, using ISR techniques, from the:

- Goliad Formation (Tp); a series of Miocene mudstone, conglomerates, and limestones, which is host to seven ISR mines
- Oakville Sandstone and Catahoula Formation (Tm); Miocene and Oligocene sandstone, clays, mudstones and Catahoula tuffs hosting 27 mines; 15 mines in the Oakville Sandstone and 13 mines in the Catahoula Formation
- Whitsett Formation (Te, Jackson Group); Oligocene mudstones, sandstones and tuffs which host two mines.

Thirty-six sites were authorized in Texas; seven were never mined (orange triangles), one was a tailings project (white square), and one was combined with another property. This leaves 27 mines (green markers) that were developed by construction of 77 well fields, termed Production Authorization Areas (PAAs) in Texas. The term “well field” and “PAA” will be used interchangeably throughout this presentation. Baseline and “amended restoration” values are available for all 27 mines/ 77 PAAs in TCEQ records.

Currently two mines are active in Texas: the Kingsville Dome mine in Kleberg County, operated by Uranium Resources International (URI), and the Alta Mesa mine in Brooks County, operated by Mestena Uranium (red markers). Two mines are in standby or shut down (green markers): the Vasquez and Rosita mines, both URI properties in Duval County. Two ISR mines are in the process of being permitted (yellow markers): Goliad in Goliad County (Uranium Energy Corporation) and La Palangana, a South Texas Mining Ventures property in Duval County.

Table 1: Baseline Water Quality for Zamzow PAA-1

ATTACHMENT G
BASELINE WATER QUALITY TABLE

TEXAS WATER COMMISSION
GROUNDWATER ANALYSIS REPORT SUMMARY
BASELINE WATER QUALITY—Solution Mining

Company: ICF Corp.
Mine Name: Zamzow
Mine Area: PAA-1 (New and Consolidated)
Data Summarized: October 31, 1998

PARAMETER	UNIT	NON-PRODUCTION ZONE**			PRODUCTION ZONE						WELL I.D. BY AREA*		
					MINE AREA**			PRODUCTION AREA					
		Low	Average	High	Low	Average	High	Low	Average	High	NON-PROD. ZONE	MINE	PROD. ZONE
1 Calcium	mg/l				122	317	552	196	259	310			
2 Magnesium	mg/l				15	38.4	84.2	3.0	21.1	50			
3 Sodium	mg/l				239	387	750	235	382	466			
4 Potassium	mg/l				19	30.3	49	18.9	26.7	50			
5 Carbonate	mg/l				0	0	0	0	0	0			
6 Bicarbonate	mg/l				128	297	400	157	269	346			
7 Sulfate	mg/l				454	733	1,520	441	601	860			
8 Chloride	mg/l				350	602	936	334	538	862			
9 Fluoride	mg/l				0.16	0.45	1.19	0.01	0.36	0.50			
10 Nitrate-N	mg/l				<0.01	0.16	0.9	<0.01	0.14	0.49			
11 Silica	mg/l				31	51.6	85	11	43.9	74			
12 pH	Std. unit				6.6	7.0	7.66	6.68	7.0	7.45			
13 TDS	mg/l				1,627	2,282	3,220	1,810	2,037	2,360			
14 Conductivity	umhos				2,720	3,204	4,300	2,680	3,049	3,430			
15 Alkalinity	Std. unit				105	275	400	206	238	304			
16 Acidity	mg/l				<0.001	0.009	0.03	<0.001	0.006	0.044			
17 Cadmium	mg/l				<0.0001	0.001	0.007	<0.0001	0.0010	0.013			
18 Iron	mg/l				0.01	0.915	8.0	0.03	0.075	0.26			
19 Lead	mg/l				<0.001	0.001	0.008	<0.001	0.009	0.02			
20 Manganese	mg/l				0.002	0.224	0.81	0.01	0.118	0.19			
21 Mercury	mg/l				<0.0001	0.0004	0.0018	<0.0001	0.0006	0.001			
22 Selenium	mg/l				<0.001	0.01	0.01	<0.001	0.004	0.01			
23 Uranium	mg/l				0.001	0.171	1.4	0.001	0.238	0.78			
24 Vanadium	mg/l				<0.001	0.121	1.7	<0.001	0.039	0.132			
25 Molybdenum	mg/l				<0.001	0.03	0.95	<0.001	0.226	2.1			
26 Radium-226	pCi/L				1.3	1.93	959	6.3	132	744			

* LIST THE IDENTIFICATION NUMBERS OF WELLS USED TO OBTAIN THE LOW, AVERAGE AND HIGH VALUES. ** MONITOR WELLS



TCEQ ISR Restoration Database

The ISR restoration database is housed in the TCEQ offices in Austin, Texas. The database consists of binders for each mine in a data room adjacent to regulator offices. TCEQ does not represent these data as validated. Official data are on microfiche in an adjacent building, but the data are poorly organized and difficult to search. A digital database, compiled by a retired TCEQ employee, was also made available to the USGS. This digital database was cross-checked against original data sheets from the TCEQ data room, which forms the basis of this research.

TCEQ employees were extremely helpful in allowing the USGS full access to their data and copying facilities and were always available to answer questions about the database or permitting process.

This table is a typical data sheet summarizing pre-mining groundwater baseline data for a Texas PAA. In Texas, 26 chemical constituents are measured before mining to establish a baseline, as shown in Table 1. Restoration values are initially set as baseline, with operators selecting the highest average concentration from either the production or mine area as their restoration goal. At this Zamzow well field, PAA-1, 0.171 milligram per liter uranium was the highest average value from the mine or production area for uranium, as highlighted in Table 1.

Table 2 : Initial Restoration Table for Zamzow PAA-1

Production Area Authorization
Permit No. URO2108-011

Page 3

ATTACHMENT A
RESTORATION TABLE

Parameter	Unit	Concentration
Calcium	mg/l	317
Magnesium	mg/l	38.4
Sodium	mg/l	387
Potassium	mg/l	30.3
Carbonate	mg/l	0
Bicarbonate	mg/l	297
Sulfate	mg/l	793
Chloride	mg/l	538
Fluoride	mg/l	0.54
Nitrate-N	mg/l	0.16
Silica	mg/l	61.6
pH	Std. Unit	7
TDS	mg/l	2,269
Conductivity	umhos	3,204
Alkalinity	Std. Unit	275
Arsenic	mg/l	0.009
Cadmium	mg/l	0.001
Iron	mg/l	0.915
Lead	mg/l	0.004
Manganese	mg/l	0.224
Mercury	mg/l	0.0006
Selenium	mg/l	0.01
Ammonia	mg/l	0.374
Molybdenum	mg/l	0.226
Uranium	mg/l	0.171



Table 2 is a copy of the initial restoration table for Zamzow PAA-1. Note that the restoration goal for uranium in groundwater is set as 0.171 milligram per liter, as highlighted on the table, which was the highest average uranium content from the PAA mine area, as shown on Table 1.

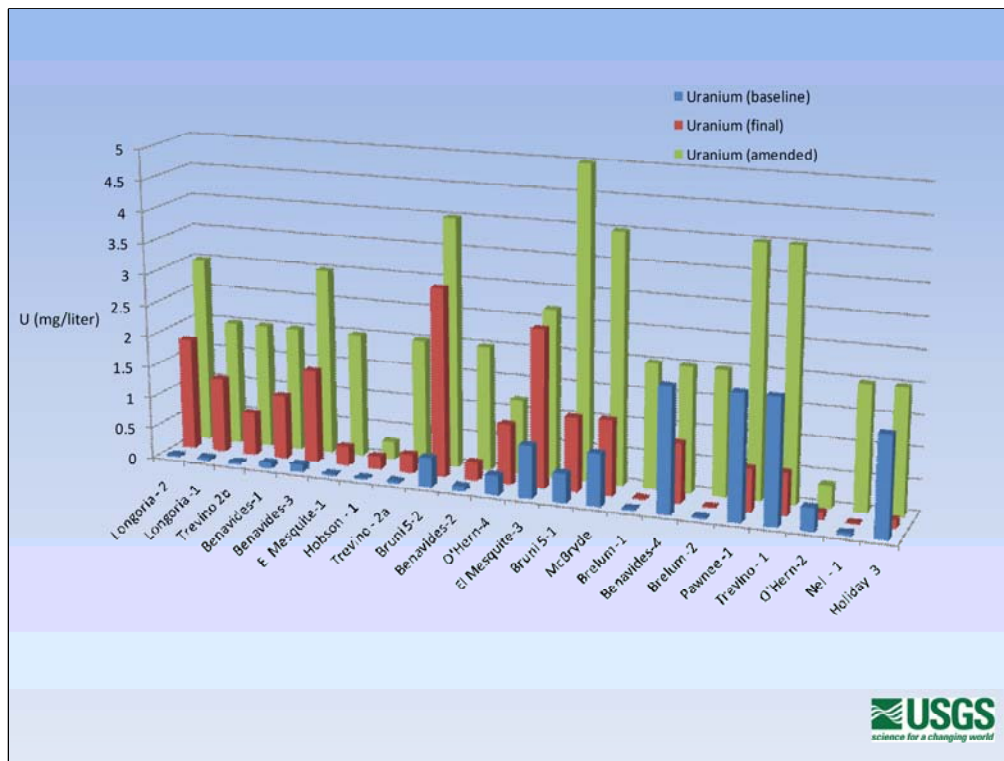
Table 3: Amended Restoration Table for Zamzow PAA-1

ATTACHMENT A
RESTORATION TABLE
(Amended)

Parameter	Unit	Concentration
Calcium	mg/l	317.
Magnesium	mg/l	38.4
Sodium	mg/l	450.
Potassium	mg/l	30.3
Carbonate	mg/l	0
Bicarbonate	mg/l	750.
Sulfate	mg/l	793.
Chloride	mg/l	538.
Fluoride	mg/l	0.54
Nitrate-N	mg/l	0.16
Silica	mg/l	51.6
pH	std. units	6.5 - 8.5
TDS	mg/l	2289.
Conductivity	µmhos	3204.
Alkalinity	std. units	500.
Arsenic	mg/l	0.2
Cadmium	mg/l	0.001
Iron	mg/l	0.915
Lead	mg/l	0.004
Manganese	mg/l	0.224
Mercury	mg/l	0.0006
Molybdenum	mg/l	5.
Selenium	mg/l	0.01
Uranium	mg/l	3.
Ammonia-N	mg/l	200.
Radium-226	pCi/l	200.



All PAAs in Texas have received amended restoration goals for at least one element after operators have expended a reasonable degree of effort to restore groundwater, as determined by TCEQ regulators, following established guidelines. The final restoration table for Zamzow PAA-1 shows an amended limit of 3.00 milligrams per liter for uranium. This amended restoration value is believed to be a relatively arbitrary value set by the regulators, as illustrated by the number of PAAs that set amended values at rounded whole numbers that were unrelated to any restoration level actually achieved in the PAAs. As there are no “final sample” data for Zamzow PAA-1, no information is available to describe the degree to which this well field was restored.



This graph of uranium concentration for various Texas PAAs illustrates the relationship between baseline, final values, and amended restoration goals in the PAAs where final values were available. The blue bars represent baseline restoration goals for uranium as set by the highest average uranium concentration in baseline samples from either the mine or the production area. Well-field designations are shown on the X-axis of this chart. Red bars represent “final values” for uranium prior to release of the PAAs, and green bars represent amended restoration goals for uranium. There is no clear relationship between the final value achieved for uranium in groundwater at the PAAs, and the amended restoration goals. Amended restoration goals do not reflect the degree of restoration achieved at the PAAs in Texas for which final values are available. Therefore, only those fields for which final values were available were chosen for this analysis.

Only 22 PAAs from 13 mines have final sample values. These 22 PAAs form the basis of the study of restoration at these well fields.

**Table 4: Baseline Groundwater in United States
ISR Mines – Constituents with EPA MCLs**

Baseline Groundwater Characteristics of U.S. Uranium ISL Projects								
Chemical Constituent (mg/L unless stated otherwise)	EPA MCL	Texas Baseline Range (71- 77 PAAs)	Texas - Number of PAAs Where Average Baseline Exceeds MCL/total # of PAAs & percentage	New Mexico Crown Point ISL Pilot	Colorado Grover ISL Pilot	Wyoming (SR WF1, CR MU2-6, Irigaray MU1- 5)	Nebraska Crow Butte (MU 1-5 & R&D Site)	
USEPA Primary Maximum Contaminant Levels (MCLs):								
Arsenic	0.010	0.0010 - 0.2000	45/73 62 %	0.004	0.01	0.006	0.001	
Barium	2	-	-	0.1	0.03	0.073	0.10	
Cadmium	0.005	0.0001 - 0.126	21/73 29%	0.006	0.002	0.016	0.006	
Chromium	0.1	-	-	0.007	0.003	0.259	0.01	
Copper	1.3	-	-	0.01	0.06	0.043	0.012	
Cyanide	0.2	-	-	0.088	-	-	-	
Fluoride	4	0.2 - 2.0	0/73 0%	0.39	0.7	0.307	0.69	
Gross Alpha (pCi/L)	15	-	-	-	87.67	-	-	
Gross Beta (millirems/year)	4	-	-	-	15.23	-	-	
Lead	0.015	0.001 - 1.970	35/73 48%	0.003	0.02	0.038	0.032	
Mercury	0.002	0.00003 - 0.44500	6/73 8%	0.00024	0.0002	0.001	0.0007	
Nitrate	10	0.01 - 12.0	1/77 1%	0.09	1.4	3.01	0.07	
Nitrite	1	-	-	-	-	0.168	0.004	
Radium (²²⁶ & ²²⁸ Ra: pCi/L)	5	5.45 - 1536.5	71/71 100%	<14.1	13.4	293.15	405.4	
Selenium	0.05	0.001 - 0.600	7/73 10%	0.01	0.01	0.015	0.002	
Uranium	0.03	0.002 - 2.913	66/73 90%	0.01	0.086	0.193	0.103	

Baseline Characterization of Groundwater in U.S. ISR Well Fields

Baseline standards for all 77 Texas PAAs can be used to characterize Texas ISR well fields that serve as a basis of comparison with baseline values determined for other ISR well fields in the United States. The argument is commonly made that before mining, groundwater in ISR well fields is so contaminated that it should not be used for human consumption. Before mining, these aquifers are typically granted exemptions from the Clean Water Act, termed aquifer exemptions, by the U.S. Environmental Protection Agency (USEPA).

In Texas, more than 25 percent of PAAs are characterized by baseline groundwater above the maximum contaminant level (MCL) for arsenic, cadmium, lead, radium, and uranium (shown highlighted on Table 4). MCL is set by the U.S. Environmental Protection Agency (USEPA; <http://www.epa.gov/safewater/contaminants/index.html>) for those elements with well-established links to negative human health effects. All PAAs contain radium above MCL, and 90 percent contain uranium above MCL. Although baseline is artificially elevated in this database because the operator is selecting the highest average value within the production or mine area, this value does serve to identify elements of concern in these well fields.

In the Crown Point pilot project in New Mexico, only cadmium was elevated above MCL. At the Grover pilot project in Colorado, baseline water showed gross alpha, gross beta, radium, and uranium above MCL. In Wyoming, averaged values for the Smith Ranch 1, Christensen Ranch 2-6, and Irigaray 1-5 mine units were elevated above MCL for cadmium, chromium, lead, radium, and uranium. In Nebraska (Crow Butte mine units 1-5 and the Crow Butte R&D site), average cadmium, lead, radium, and uranium were elevated above MCL. Elements above MCL are highlighted in the table.

With the exception of the New Mexico deposit (Crown Point), these well fields are characterized by groundwater elevated in multiple MCLs prior to mining. Radium is almost always elevated above MCL while uranium is typically elevated and cadmium and lead commonly elevated. These well fields would require pretreatment to be used as a source for drinking water.

Table 5: Baseline Groundwater in U.S. ISR Mines – Constituents with EPA Secondary (recommended) Standards

Baseline Groundwater Characteristics of U.S. Uranium ISL Projects								
Chemical Constituent (mg/L unless stated otherwise)	EPA Secondary Standard	Texas Baseline Range (71- 77 PAAs)	Texas - Number of PAAs Where Average Baseline Exceeds Secondary Standards/total # of PAAs & Percentage (highlighted if > 25% of PAAs Exceed Secondary Standards)	New Mexico Crown Point ISL Pilot	Colorado Grover ISL Pilot	Wyoming (SR WF1, CR MU2-6, Ingaray MU1- 3)	Nebraska Crow Butte (MU 1-5 & R&D Site)	
EPA Secondary Recommended Standards:								
Aluminum	0.200	-	-	-	0.02	0.537	0.117	-
Chloride	250	122.5 - 3505.0	64/77	83 %	20.3	7	9.8	202.6
Iron	0.30	0.01 - 6.3	32/72	44 %	0.67	0.7	0.648	0.04
Manganese	0.05	0.01 - 5.06	37/73	51%	0.05	0.02	0.018	0.03
Silver	0.10	-	-	-	<0.01	0.003	-	-
Sulfate	250	10.3 - 1197	10/77	13 %	38	38.3	300	353
Total Dissolved Solids	500	628 - 6349	73/73	100 %	357	295	616	1177
Zinc	5	-	-	-	0.01	0.04	0.073	0.017

Recommended secondary standards are set by the USEPA for constituents that, in high enough concentrations, negatively affect the esthetic quality of groundwater, but are not conclusively linked to any negative human health effect. Of those elements for which secondary standards are set by the USEPA, iron, sulfate, and total dissolved solids (TDS) are commonly elevated above recommended levels in pre-mining water at ISR facilities. Chloride and manganese are commonly high in Texas PAAs before mining, while TDS is elevated above the recommended standard in all pre-mining Texas PAAs. Elements elevated above secondary standards are highlighted in Table 5.

**Table 6: Baseline Groundwater in U.S. ISR Mines –
Constituents with no MCL or Secondary Standard**

Baseline Groundwater Characteristics of U.S. Uranium ISR Projects						
Chemical Constituent (mg/L unless stated otherwise)	USEPA MCL	Texas Baseline Range (71- 77 PAAs)	New Mexico Crown Point ISR Pilot	Colorado Grover ISR Pilot	Wyoming (SR WF1, CR MU2-6, Ingaray MU1-5)	Nebraska Crow Butte (MU 1-5 & R&D Site)
<i>No Established MCL or Recommended Secondary Standard:</i>						
Alkalinity (as CaCO ₃)	-	24 - 349	-	154.7	116.1	-
Ammonia-N	-	0.01 - 7.49	0.47	0.25	0.344	0.26
Bicarbonate	-	125 - 500	228	220.1	171.6	344
Boron	-	-	0.1	0.1	0.1	0.93
Calcium	-	0.2 - 395	5.8	9.1	29.4	12.97
Carbonate	-	0.10 - 38	-	4.31	22.4	369
Cobalt	-	-	<0.05	-	-	-
Conductivity (umhos/cm)	-	1,110 - 11,160	-	380.7	1051	1947
Magnesium	-	0.48 - 150.0	-	1.1	5.324	3.27
Molybdenum	-	0.01 - 2.53	0.172	0.02	0.100	0.05
Nickel	-	-	0.02	0.2	0.093	0.03
Phosphorous	-	-	-	0.05	-	-
Potassium	-	6.38 - 101.1	-	4.43	9.810	13.10
Silica	-	15 - 98	-	5.45	10.496	16.7
Sodium	-	174 - 2,356	114	85.2	155	410
Thorium	-	-	-	0.7417	-	-

Table 6 shows average concentrations and a range of concentrations in Texas PAAs, within pre-mining baseline groundwater for those analytes for which no primary or secondary standards have been set by the USEPA.

Table 7: Groundwater Chemistry of Texas In-situ Uranium Production Authorization Areas (22 PAAs where final analyses are available)							
Analyte	USEPA and TCEQ Drinking Water Standards (mg/l)	Baseline Range	Post-Restoration Range	PAAs with Baseline Above MCL or Recommended Standards	PAAs with Post-Restoration Water Above MCL or Recommended Standards	PAAs Where Post-Restoration Analyses Exceed Baseline	PAAs Where Post-Restoration Analyses are Below Baseline
USEPA and TCEQ Primary Maximum Contaminant Levels (MCLs):							
Arsenic	0.01	.004 - 0.23	.002 - .323	77%	55%	18%	82%
Cadmium	0.005	0.0001 - 0.0126	0.0001 - 0.01	45%	23%	27%	73%
Fluoride	4	0.21 - 1.8	0.29 - 1.6	0%	0%	31%	69%
Lead	0.02	0.003 - 1.97	0.001 - 0.05	81%	18%	9%	91%
Mercury	0.002	0.0001 - 0.445	0.0001 - 0.01	9%	0%	22%	64%
Nitrate	10	0.031 - 10.0	0.001 - 2.8	0%	0%	4%	96%
Selenium	0.05	0.001 - 0.049	0.001 - 0.102	18%	4%	54%	45%
Radium (226 & 228 Ra: Pci/l)	5 pci/l	9.36 - 429.8	5.2 - 149	100%	100%	4%	96%
Uranium	0.03	0.025 - 2.0	0.013 - 3.02	95%	86%	68%	32%
TCEQ Secondary Recommended Standards:							
Sulfate	300	15.8 - 250	78 - 3881	0%	18%	86%	14%
Chloride	300	196.9 - 3505	138 - 3326	86%	86%	22%	78%
Total Dissolved Solids	1000	785.7 - 6349	706.3 - 6155	81%	77%	31%	55%
Iron	0.3	0.04 - 5.49	0.01 - 2.7	54%	9%	4%	96%
Manganese	0.05	0.01 - 0.41	0.01 - 0.84	77%	50%	40%	60%
No Established MCL or Secondary Standards							
Calcium	-	4.13 - 241	14.7 - 191			77%	23%
Magnesium	-	0.477 - 125	2.27 - 53			72%	28%
Sodium	-	200 - 2356	169 - 2247			31%	65%
Potassium	-	6.38 - 101	6.1 - 70			14%	86%
Carbonate	-	0.1 - 17.9	0 - 14.6			50%	30%
Bicarbonate	-	160 - 500	160 - 500			66%	25%
Silica	-	16.3 - 76	13.4 - 77.6			19%	81%
Conductivity (umhos/cm)	-	1310 - 11160	1429 - 3697			76%	24%
Alkalinity (as CaCO3)	-	134 - 349	145 - 408			81%	10%
Molybdenum	-	0.01 - 0.2	0.0001 - 3.38			42%	54%
Ammonia-N	-	0.01 - 7.49	0.04 - 120			76%	24%
Baseline and post-restoration data was available for all 22 PAAs with the exception of: Ra, Mo, K, Si, Bicarbonate, Ammonia (21); Conductivity (14); Alkalinity (11) & Carbonate (10)							

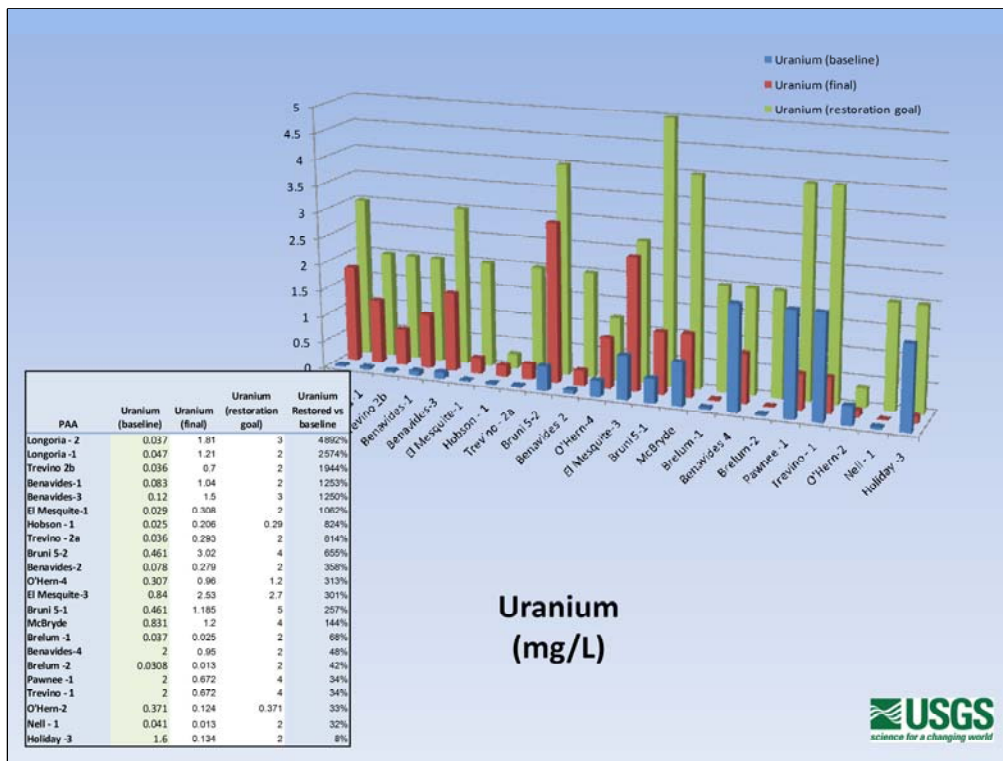
Restoration Results for Texas PAAs

Table 7 shows the average value, post-restoration, and baseline ranges of chemical constituents for all 22 well fields that have post-restoration analyses in the TCEQ records.

In general, at PAAs where post-restoration values exceed MCL, the elements elevated in baseline values (As, Cd, Pb, Se, Ra, and U) continue to be elevated after mining.

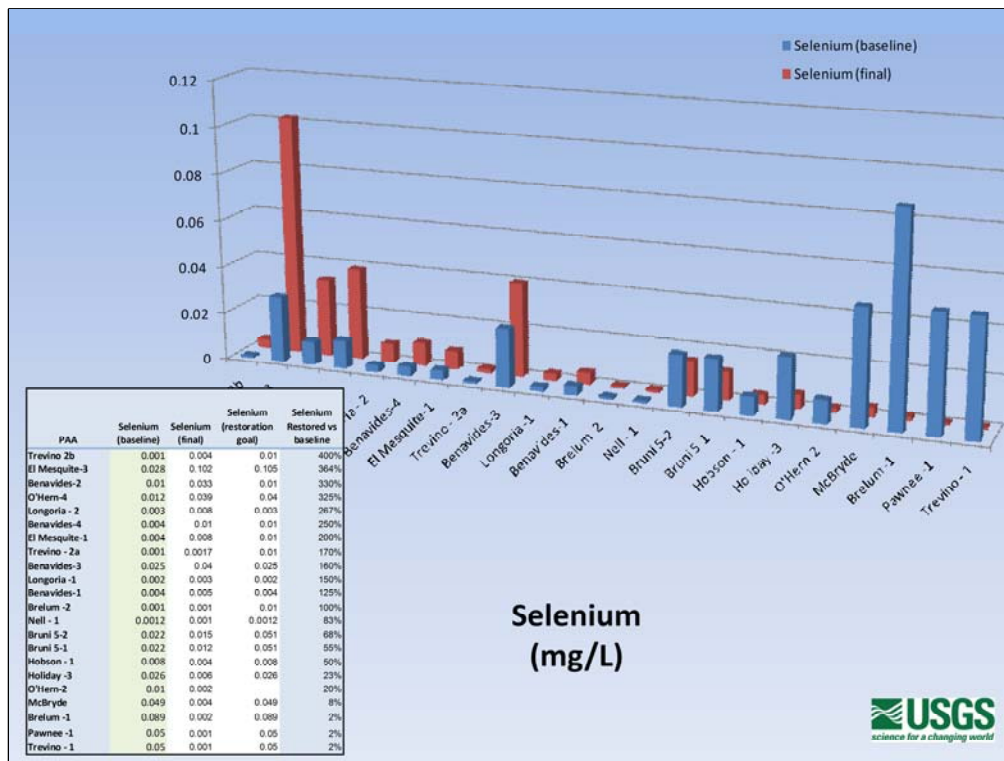
As compared to baseline values for the PAAs, uranium and selenium are elevated in the majority of PAAs. More than half of PAAs show a decrease in As, Cd, Fl, Pb, Hg, nitrate, and Ra after mining.

The following slides examine these trends in detail.

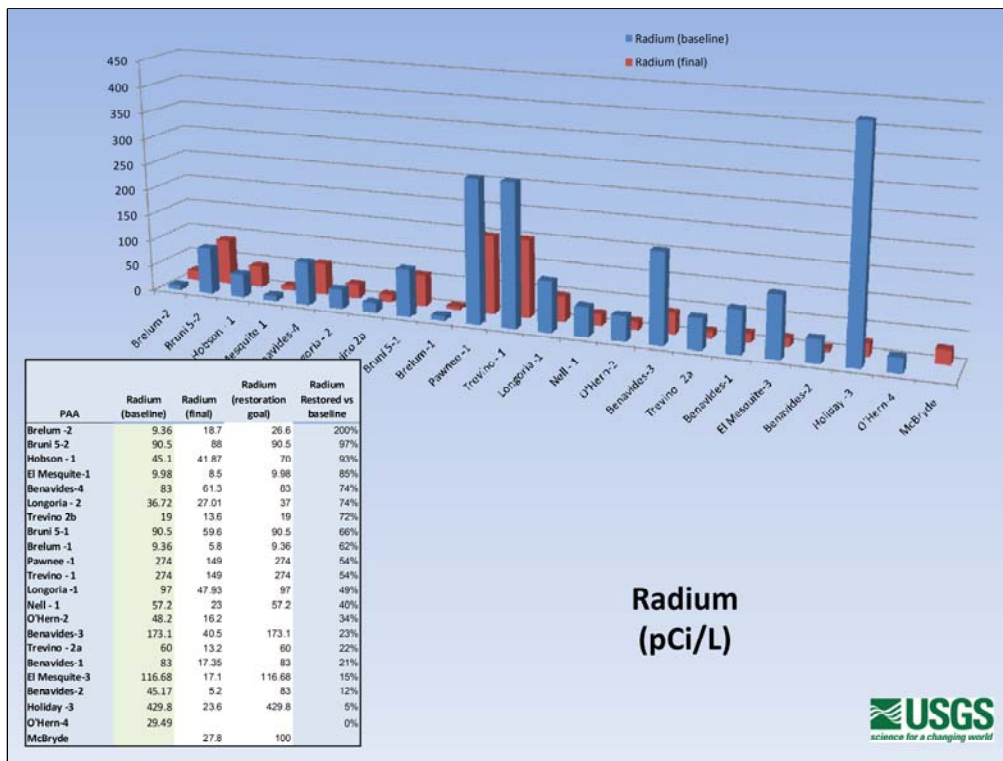


The USEPA-established MCL for uranium in drinking water is 0.03 milligram per liter. Ninety-five percent of Texas PAAs have a baseline value above MCL. Only the Hobson-1 and El Mesquite–1 PAAs were below the MCL for uranium and El Mesquite “rounded out” to equal MCL.

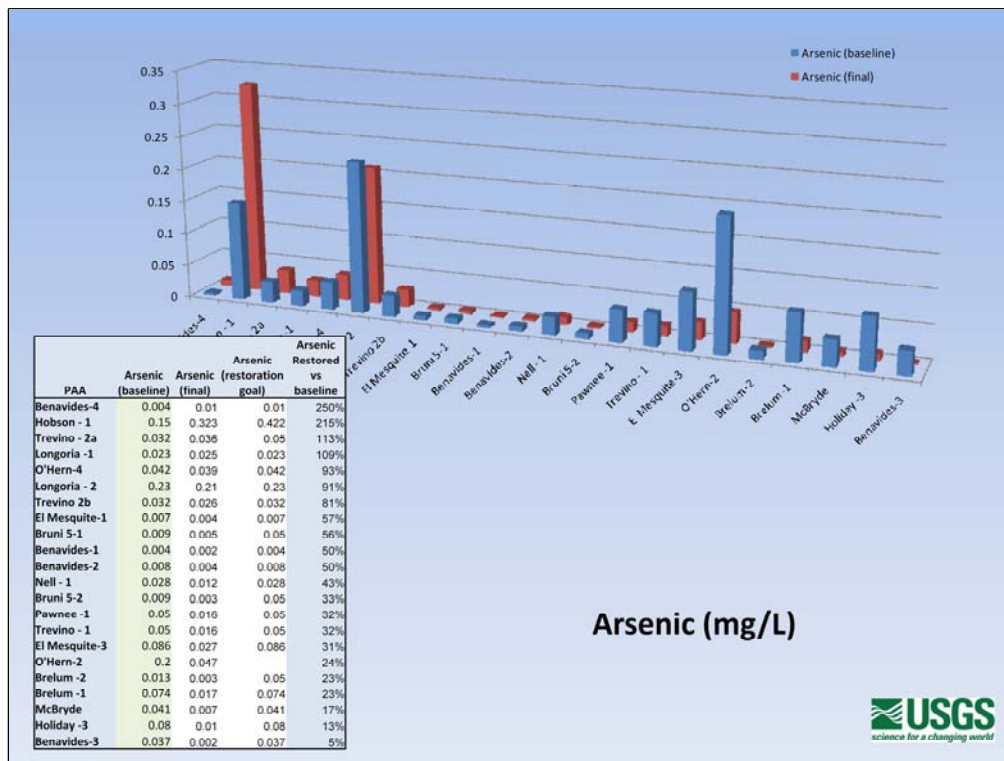
Eighty-six percent of Texas PAAs show a final restoration above MCL. In 68 percent of PAAs, final value exceeded baseline, and in 32 percent of PAAs, restoration was below baseline for uranium.



The MCL for selenium is 0.05 milligram per liter in drinking water. In 18 percent of PAAs, baseline of groundwater was above MCL, and in 24 percent of PAAs, the final restoration value was above MCL. After mining and restoration, 55 percent of PAAs exceeded baseline and 45 percent of PAAs were below baseline.

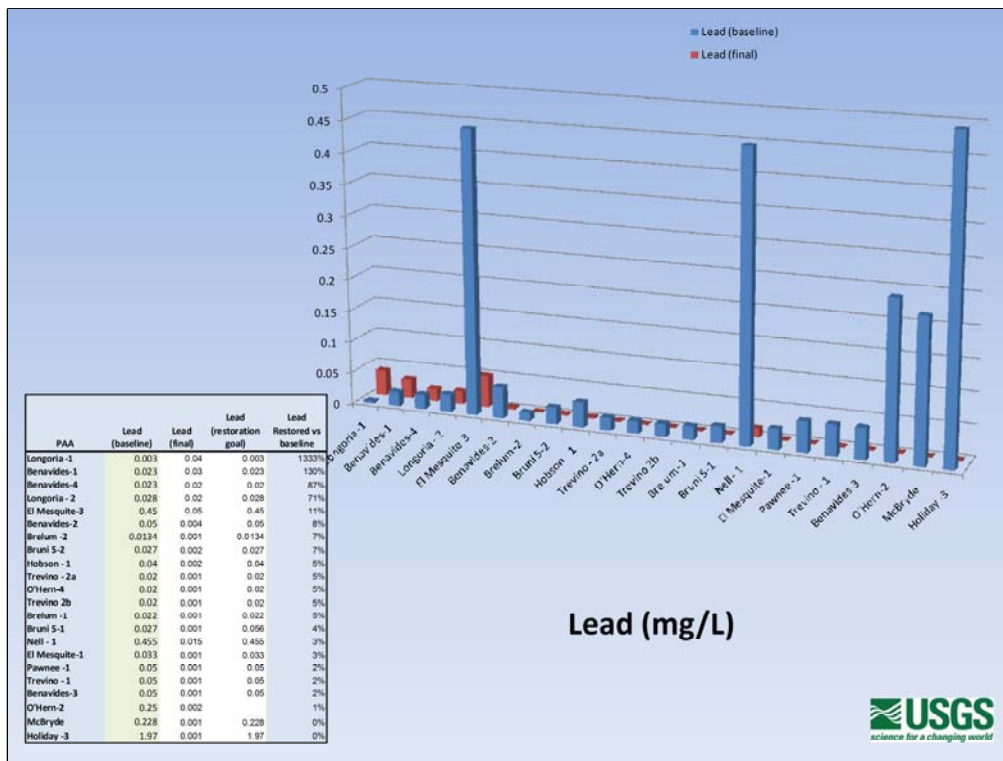


The MCL for radium (^{226}Ra and ^{228}Ra) is 5 pCi/L in drinking water. All PAAs are characterized by baseline and post-restoration radium concentrations above MCL. After mining and restoration, 4 percent of PAAs were above baseline, and 96 percent of PAAs were below baseline.



The MCL for arsenic is 0.01 milligram per liter in drinking water. Before mining, 77 percent of PAAs showed arsenic above the MCL, and after restoration 55 percent of PAAs were above the MCL.

After restoration, 18 percent of PAAs exceeded baseline and 82 percent of PAAs were below baseline.



The MCL for lead is 0.02 milligram per liter in drinking water. Eighty-one percent of PAAs have baseline levels above MCL, and 18 percent of PAAs are characterized by final restoration values above MCL.

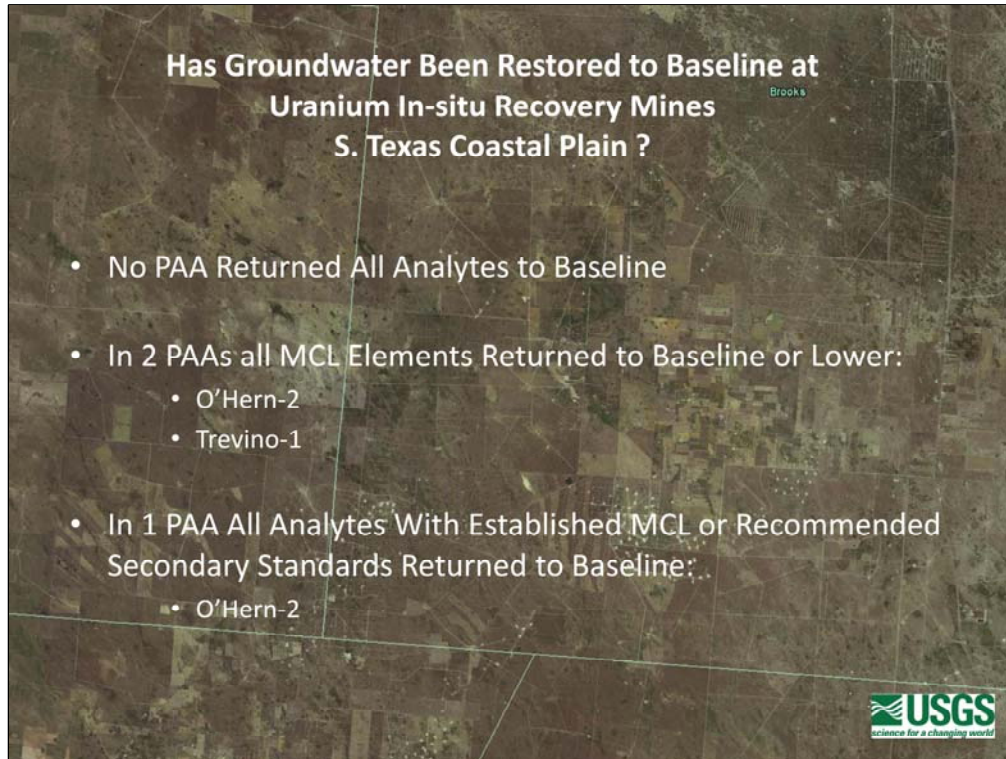
After mining and reclamation, 9 percent of PAAs were above baseline and 91 percent of PAAs were below baseline.

Table 7: Ground-water Chemistry of Texas In-situ Uranium Production Authorization Areas (22 PAAs where final analyses are available)							
Analyte	USEPA & TCEQ Drinking Water Standards (mg/L)	Baseline Range	Post-Restoration Range	PAAs with Baseline Above MCL or Recommended Standards	PAAs with Post-Restoration Water Above MCL or Recommended Standards	PAAs Where Post-Restoration Analyses Exceed Baseline	PAAs Where Post-Restoration Analyses are Below Baseline
USEPA & TCEQ Primary Maximum Contaminant Levels (MCLs):							
Arsenic	0.01	.004 - 0.23	.002 - .323	77%	55%	18%	82%
Cadmium	0.005	0.0001 - 0.0126	0.0001 - 0.01	45%	23%	27%	73%
Fluoride	4	0.21 - 1.8	0.29 - 1.6	0%	0%	31%	69%
Lead	0.02	0.003 - 1.97	0.001 - 0.05	81%	18%	9%	91%
Mercury	0.002	0.0001 - 0.445	0.0001 - 0.01	9%	0%	22%	64%
Nitrate	10	0.031 - 10.0	0.001 - 2.8	0%	0%	4%	96%
Selenium	0.05	0.001 - 0.049	0.001 - 0.102	18%	4%	54%	45%
Radium (226 & 228 Ra: Pci/L)	5 Pci/L	9.36 - 429.8	5.2 - 149	100%	100%	4%	96%
Uranium	0.03	0.025 - 2.0	0.013 - 3.02	95%	86%	68%	32%
TCEQ Secondary Recommended Standards:							
Sulfate	300	15.8 - 250	78 - 3881	0%	18%	86%	14%
Chloride	300	196.9 - 3505	138 - 3326	86%	86%	22%	78%
Total Dissolved Solids	1000	785.7 - 6349	706.3 - 6155	81%	77%	31%	55%
Iron	0.3	0.04 - 5.49	0.01 - 2.7	54%	9%	4%	96%
Manganese	0.05	0.01 - 0.41	0.01 - 0.84	77%	50%	40%	60%
No Established MCL or Recommended/Secondary Standard:							
Calcium	-	4.13 - 241	14.7 - 191			77%	23%
Magnesium	-	0.477 - 125	2.27 - 53			72%	28%
Sodium	-	200 - 2356	169 - 2247			31%	65%
Potassium	-	6.38 - 101	6.1 - 70			14%	86%
Carbonate	-	0.1 - 17.9	0 - 14.6			50%	30%
Bicarbonate	-	160 - 500	160 - 500			66%	25%
Silica	-	16.3 - 76	13.4 - 77.6			19%	81%
Conductivity (umhos/cm)	-	1310 - 11160	1429 - 3697			76%	24%
Alkalinity (as CaCO3)	-	134 - 349	145 - 408			81%	10%
Molybdenum	-	0.01 - 0.2	0.0001 - 3.38			42%	54%
Ammonia-N	-	0.01 - 7.49	0.04 - 120			76%	24%

Baseline and post-restoration data was available for all 22 PAAs with the exception of: Ra, Mo, K, Si, Bicarbonate, Ammonia (21), Conductivity (14), Alkalinity (11) & Carbonate (10).

Although restoration results vary widely for individual well fields, among the elements with an MCL, only selenium and uranium show overall increases in post-restoration groundwater in more than 50 percent of PAAs (Table 7). Of constituents for which secondary standards are established by the USEPA, sulfate increased in the majority of well fields after mining and restoration, whereas chloride, TDS, iron, and manganese decreased in the majority of well fields.

Of those chemical constituents for which there are no established MCLs or secondary standards, calcium, magnesium, bicarbonate, conductivity, carbonate, alkalinity and ammonia increased; sodium, potassium and silica decreased in the majority of well fields after mining and restoration. Statistically, molybdenum decreased in the small majority of well fields after mining.



Regarding the original question of whether or not groundwater has been restored to baseline in Texas uranium ISR well fields, it was observed that no well field for which final sample results were found in TCEQ records returned every element to baseline. However, two PAAs returned all elements for which USEPA has established MCLs to baseline: the O'Hern-2 and Trevino-1 PAAs.

Trevino-1, which was mined from the Oakville Sandstone and restored using electrodialysis, shows restored sulfate to 164 percent of baseline. Reclamation at O'Hern-2 returned constituents with secondary standards or MCLs to baseline values or below.

Table 8: Baseline and Final Chemistry of Groundwater at the O'Hern PAA-2 Well Field

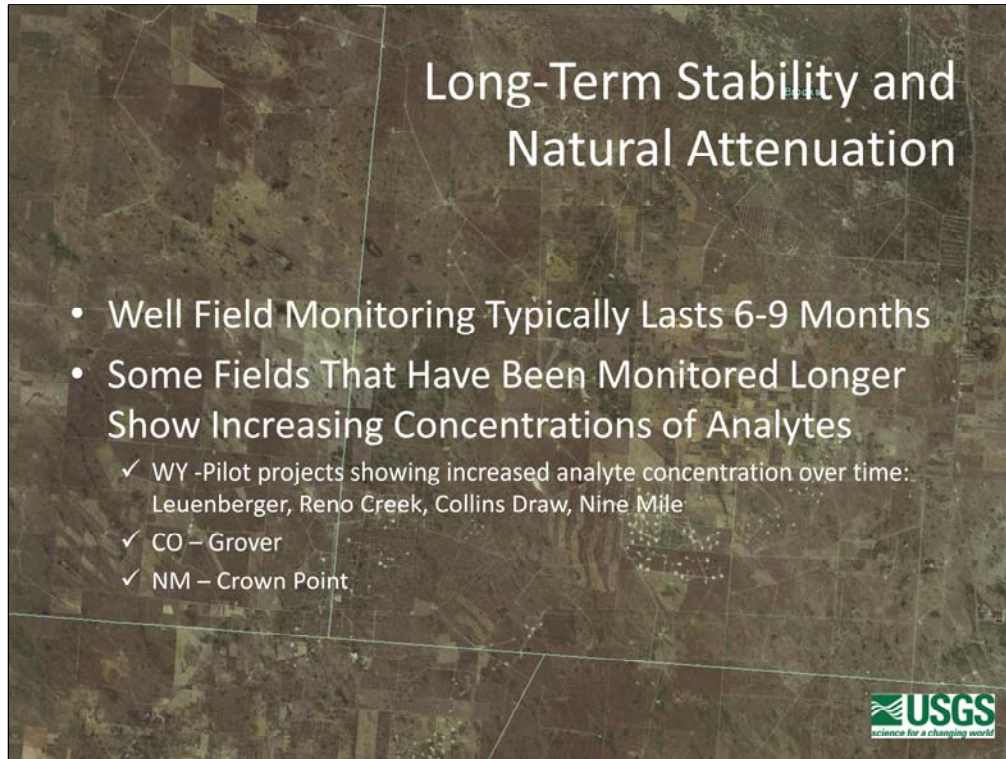
O'Hern-2 Groundwater Sweep and Reverse Osmosis	Analyte	Baseline	Final
Analytes for which EPA and TCEQ have set Maximum Contaminant Levels	Arsenic	0.2	0.047
	Cadmium	0.01	0.0005
	Fluoride	1.37	0.73
	Lead	0.25	0.002
	Mercury	0.445	0.0001
	Nitrate-N	0.86	0.47
	Selenium	0.01	0.002
	Radium	48.2	16.2
	Uranium	0.371	0.124
	Sulfate	129	102
Analytes for which TCEQ has set Secondary Recommended Upper Limits	Chloride	254	220
	TDS	979	890
	Iron	3.52	0.02
	Manganese	0.124	0.03
	Ca	13.7	14.7
	Mg	2.7	2.27
	Na	310	289
	K	9.7	6.6
	Carbonate	1.78	2.6
	Bicarbonate	347	
	Silica	43.7	35
	Conductivity	1626	1429
	Alkalinity		
	Ammonia-N	0.77	0.3
	Molybdenum	1.1	0.24



Specifically looking at restoration details from the O'Hern PAA-2 , this well field was developed by Cogema from 1979 to 1982 in the Catahoula Formation. Groundwater sweep and reverse osmosis were both used to restore groundwater after mining. Calcium and carbonate were both slightly elevated above baseline following mining and reclamation, as shown in Table 8 above.

The aquifer overlying O'Hern-2 is characterized by an average calcium of 27 milligrams per liter and carbonate of 10.1 milligrams per liter, so post-restoration elevation of these elements in the O'Hern-2 PAA seems inconsequential in the scheme of local hydrochemistry. No final values for bicarbonate or alkalinity were reported, so the specific degree to which this PAA was restored is unknown.

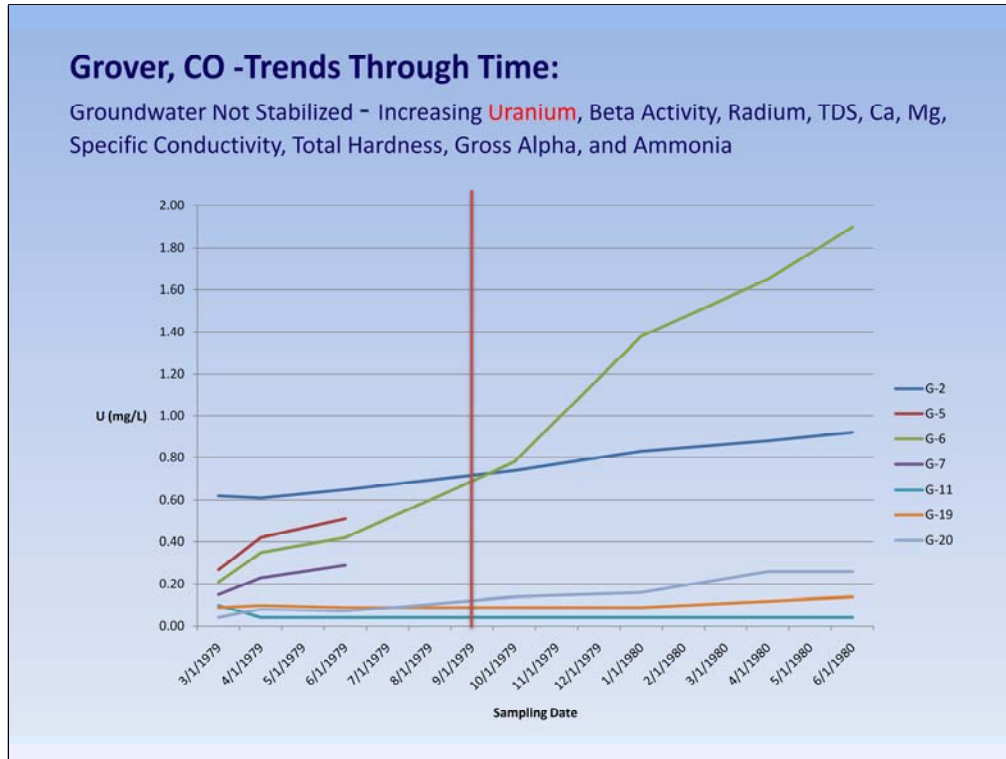
There is a notation in the TCEQ database that O'Hern PAA-3 did not receive any amendments. However, this could not be corroborated by TCEQ records.



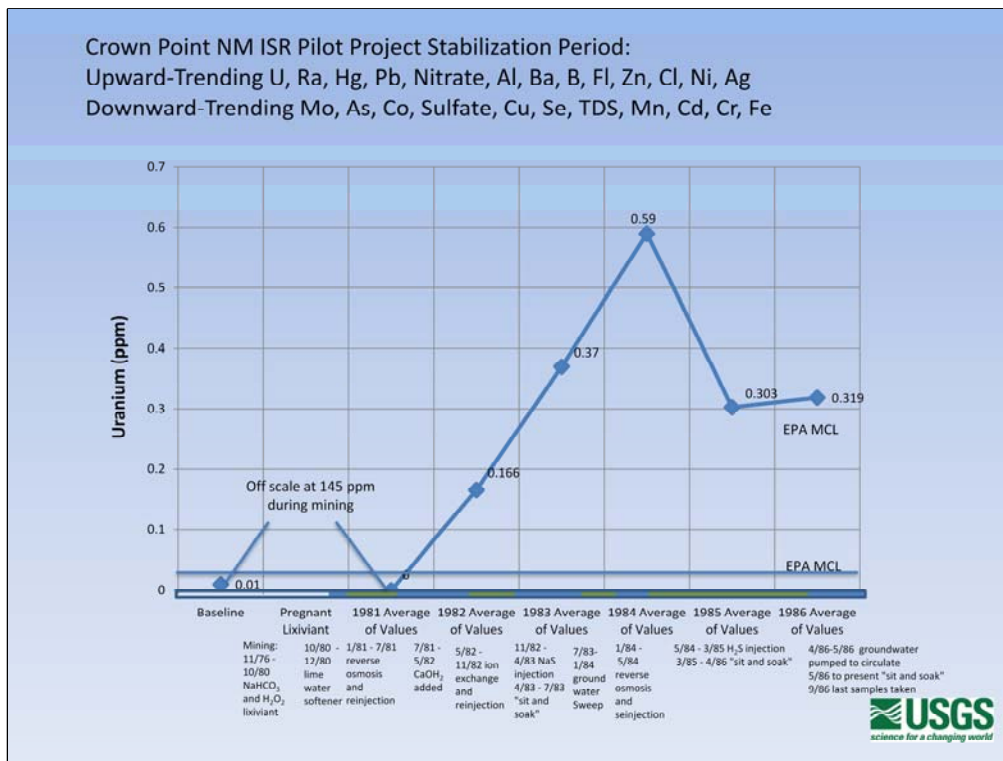
Long-Term Stability and Natural Attenuation

In Texas, after ISR mining ceased and restoration of the well fields was completed, PAAs were monitored for a minimum of 6 months. This period of monitoring has recently been increased to one year if no amendments to the restoration table are requested, and to two years if the operator requests an amendment to the restoration table.

Some well fields monitored for longer periods of time during the post-mining and remediation stability period show trends of increasing analyte concentration, as noted by USGS geologists while examining records at pilot projects in Colorado (Grover), New Mexico (Crown Point), and throughout Wyoming.

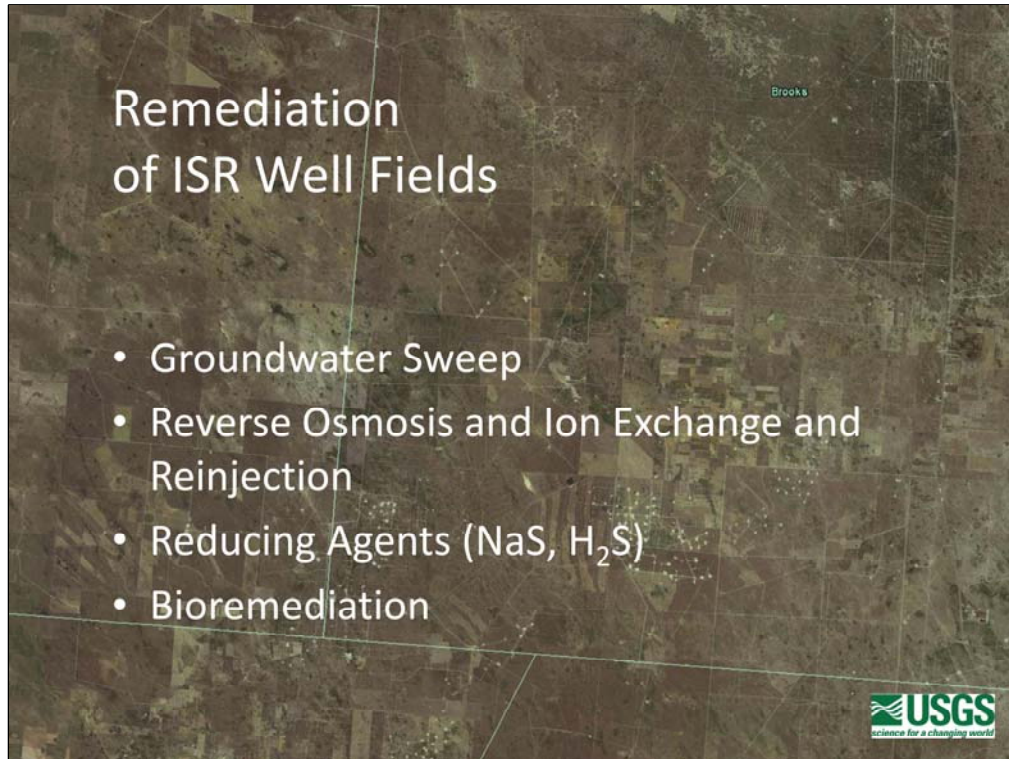


At the Grover, Colorado, pilot test site, pump and treat technologies did not return groundwater to baseline. Analysis of data collected by Colorado State regulators showed upward-trending uranium, beta activity, radium, TDS, calcium, magnesium, specific conductivity, total hardness, gross alpha, and ammonia. Results from individual wells differentiated using solid colored lines are shown above in the time series plot of uranium concentration. Note that the vertical red line indicates the end of the 6-month stabilization period required for Texas PAAs. These increasing concentrations of analytes indicate groundwater may not have stabilized when the Grover well field was released.



During the one-year stabilization period that followed restoration at Mobil's Crown Point, New Mexico ISR pilot project, both upward and downward trends in various chemical constituents were noted (Mobil, 1981). The Crown Point data are not detailed enough to analyze these trends, but the data indicate that groundwater may not have stabilized when the final samples were collected, similar to the Grover, Colorado, project.

Examples from Grover, Colorado, Crown Point, New Mexico, and ISR pilot projects in Wyoming indicate that the 6-month stability period mandated by Texas ISR rules may not have been long enough to adequately determine if groundwater in well fields had stabilized. Recent rule changes in Texas allow for longer term monitoring and could yield valuable data about the chemical stability of groundwater after ISR mining.



Effectiveness of Restoration Techniques

After mining has ceased, a restoration method called groundwater sweep can be used whereby groundwater in a mined aquifer is pumped from the well field either to a deeper aquifer, an adjacent well field where mining is being initiated, or to surface ponds where it is allowed to evaporate. Local groundwater then “sweeps in” to replace the displaced water. This is typically the first method of restoration applied to a well field (Mays, 1994).

Reverse osmosis and ion exchange are methods of removing contaminants from groundwater in well fields. The cleaned water is then reinjected into the well fields (Mays, 1994).

Reducing agents (H, NaS and H₂S) have been added to well-field groundwater in an attempt to return groundwater and host rocks to reducing conditions, thereby reversing the effects of oxidizing mining solutions (lixiviants) within the aquifer.

Bioremediation, the stimulation of native bacteria within the aquifer whose life processes fix metals from solution, is another remediation technique currently receiving much attention (Long and others, 2008).

Table 9: Elements with USEPA and TECQ Primary Maximum Contaminant Levels Restored vs. Baseline for Texas Well Fields With Known Restoration Methods										
PAA	Restoration Method	Arsenic	Cadmium	Fluoride	Lead	Mercury	Nitrate-N	Selenium	Radium	Uranium
Hobson - 1	GW Sweep Only	215%	1%	134%	5%	16%	9%	50%	93%	824%
Longoria -1	GW Sweep Only	109%	10000%	98%	1333%	333%	34%	150%	49%	2574%
Longoria - 2	GW Sweep Only	91%	10000%	82%	71%	333%	22%	267%	74%	4892%
McBryde	GW Sweep Only	17%	6%	50%	0%	10%	56%	8%		144%
Average for GW Sweep Only		108%	5002%	91%	353%	173%	30%	119%	72%	2109%
Benavides-4	RO	250%	3333%	77%	87%	100%	3%	250%	74%	48%
Bruni 5-1	RO	56%	2%	143%	4%	11%	15%	55%	66%	257%
Bruni 5-2	RO	33%	4%	155%	7%	11%	22%	68%	97%	655%
O'Hern-4	RO	93%	91%	63%	5%	13%	NR	325%	NR	313%
Average for RO only		108%	858%	110%	26%	34%	13%	175%	79%	318%
El Mesquite-1	RO and Ion Exchange	57%	17%	117%	3%	50%	22%	200%	85%	1062%
El Mesquite-3	RO and Ion Exchange	31%	83%	74%	11%	40%	19%	364%	15%	301%
Holiday -3	RO and Ion Exchange	13%	200%	94%	0%	100%	53%	23%	5%	8%
Average for RO and ion exchange		34%	100%	95%	5%	63%	31%	196%	35%	457%
Brelum - 1	GW Sweep and RO	23%	6%	107%	5%	10%	3%	2%	62%	68%
Brelum -2	GW Sweep and RO	23%	1%	97%	7%	11%	5%	100%	200%	42%
O'Hern-2	GW Sweep and RO	24%	5%	53%	1%	0%	55%	20%	34%	33%
Average for GW Sweep and RO		23%	4%	86%	4%	7%	21%	41%	99%	48%
Trevino - 1	Electrodialysis	32%	1%	82%	2%	5%	5%	2%	54%	34%
Trevino - 2a	Electrodialysis	113%	1%	83%	5%	33%	6%	170%	22%	814%
Trevino 2b	Electrodialysis	81%	1%	81%	5%	33%	19%	400%	72%	1944%
Average for Electrodialysis		75%	1%	82%	4%	24%	10%	191%	49%	931%

Pump and Treat Technology

Texas provides a database that can be used to examine the effectiveness of the “pump and treat” technologies of groundwater sweep, reverse osmosis, ion exchange, and electrodialysis. Historically, pump and treat techniques were the only restoration techniques used in ISR mines developed in Texas.

Uranium in groundwater is 2,109 percent of baseline in well fields using groundwater sweep only, yet is 48 percent of baseline when groundwater sweep is combined with reverse osmosis (Table 9). Similar trends are shown for arsenic, cadmium, lead, mercury, and selenium. Trends for fluoride and nitrate are not as clear.

Analysis of patterns in Texas PAAs show restoration using groundwater sweep coupled with reverse osmosis results in the greatest decrease in concentration of chemical constituents. These coupled techniques are commonly used in many well-field restoration projects nationwide.



Table 10: Summary of ISR Mines Where Chemical Reduction Was Used to Remediate Groundwater

Type of Reductant	Sites	Pros	Cons
H ₂ S	Smith Ranch, Irigaray and Collins Draw, WY; Crown Point, NM	Good Reducer	Volatile, difficult to use, mixed results, well clogging
Na ₂ S	Crown Point, NM; Highland, WY	Less expensive than bioremediation	Overall mixed results, likely doesn't have reducing capacity necessary to effect any noticeable improvement in groundwater quality, may produce transitory effects
H ₂	Kingsville Dome, TX	Good Reducer	2009 pilot project, results not yet available



Chemical Reduction

Inorganic chemical reductants are designed to reverse the effects of oxidizing lixiviant solutions on host rock and groundwater. Overall, these techniques when used in remediation of U.S. ISR mines, show mixed results (Table 10). Crown Point and Irigaray did not appear to significantly benefit from the addition of reductants into groundwater at the levels applied (LQD/DEQ Response Document, 2005; Mobil, 1981). Uranium Resources International is completing a pilot project in Texas to test the restoration effectiveness of hydrogen gas in removing analytes from groundwater (M. Pelliza, oral commun., May 2009). Results of this study are not yet available.

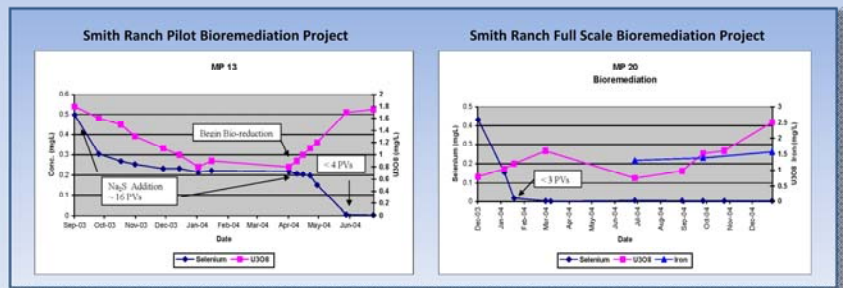
Bioremediation

Crow Butte, NE

- Jan. 2009: Emulsified oil substrate added to six production wells in Mine Unit 4 after groundwater sweep, ion exchange

Smith Ranch, WY

- 2003 – Methanol and molasses (Highland Well field B)
- Selenium rapidly to non-detection levels, uranium shows upward trend

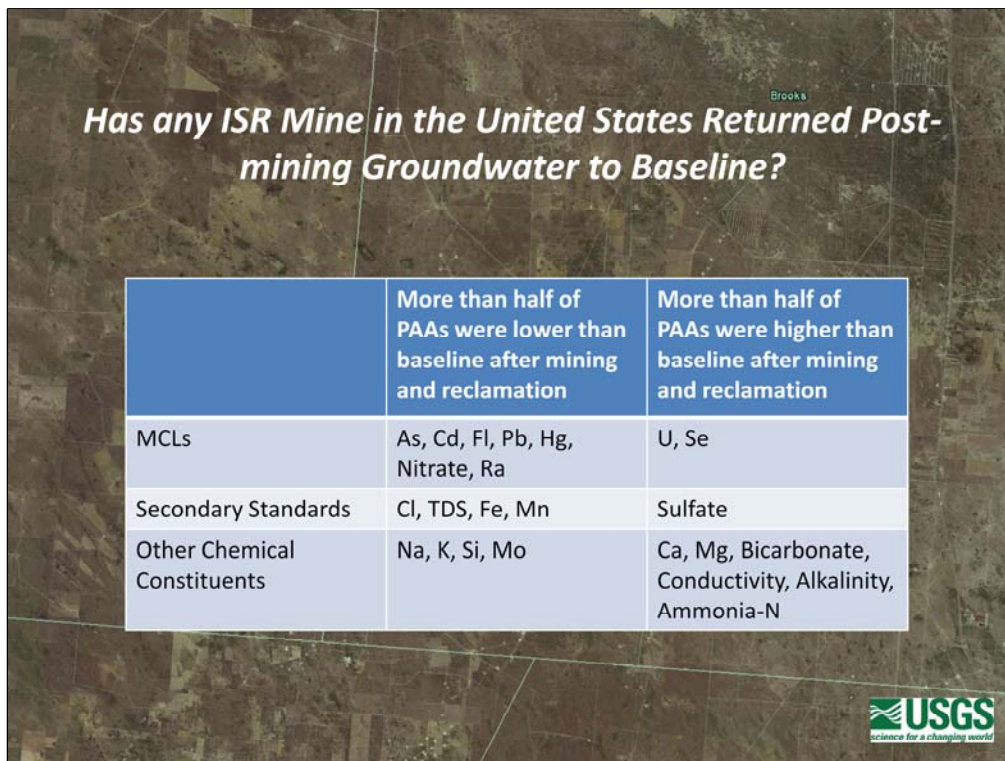


Bioremediation

Nutrients, such as acetate, methanol, and molasses, can be added to groundwater as a food source to stimulate native bacteria populations. As bacteria populations rise in response to increased food, metal concentrations decrease in groundwater; however the exact mechanism is uncertain.

In January 2009, an emulsified oil substrate was added to 6 production wells at the Crow Butte ISR mine as part of remediation of groundwater in Mine Unit 4 (NDEQ, 2009). The first 4 months of preliminary results do not show a significant reduction in uranium. At a Smith Ranch/Highland ISR remediation project in 2003, methanol and molasses were added to wells in the Highland B well field, first as a pilot project following chemical reduction (Na₂S) and then in a full-scale remediation project without prior chemical reduction (Reimann and Huffman, 2005). Selenium in groundwater was rapidly reduced in both the pilot (MP13) and full-scale (MP20) fields, although uranium concentration initially increased (see graphs above). Uranium increases noted in groundwater after bioremediation had been initiated may be attributable to the dissolution of iron oxyhydroxides and the concomitant release of their contained uranium in response to increasingly reducing conditions created during bioremediation (Reimann and Huffman, 2005). In subsequent bioremediation projects at Smith Ranch, cheese whey coupled with methanol has been used as a biostimulant.

The USGS continues to gather and process records from State agencies to track the effectiveness of these bioremediation methods.



Conclusions

Can we answer the question: “Has any ISR mine in the United States returned post-mining groundwater to baseline?”

Answer: Not based upon analysis of the Texas database because “final value” records were found for only 22 of 77 PAAs (13 of 36 mines).

We can conclude that in Texas, ISR mines are characterized by high baseline arsenic, cadmium, lead, selenium, radium, and uranium. After mining and restoration, for those well fields that reported “final values” in TCEQ records, more than half of the PAAs had lowered levels of many elements, including some that dropped below MCL.

Of those elements for which MCL is established, the majority of PAAs showed increases in uranium and selenium after mining and restoration and decreases in arsenic, cadmium, fluoride, lead, mercury, nitrate, and radium to below baseline for the majority of well fields.

Analytes for which secondary standards have been established show that sulfate is the only constituent that increased in the majority of well fields after mining and remediation, whereas chloride, TDS, iron, and manganese decreased. Chemical constituents for which no MCL or secondary standards were set are higher than baseline for calcium, magnesium, bicarbonate, conductivity, alkalinity, and ammonia. Sodium, potassium, silica, and molybdenum were lower than baseline in the majority of well fields after mining and remediation.

For More Information Contact:

Susan Hall
U.S. Geological Survey
Central Energy Resources Science Center
Box 25046, MS 939
Denver, CO 80225

susanhall@usgs.gov

303-236-1656

References Cited

- Energy Information Agency, 2009. EIA – Nuclear Data, Reports, Analysis, Surveys, 11 May 2009, accessed data at <http://www.eia.doe.gov/fuelnuclear.html>.
- Long, P.E., Yabusaki, S.B., Meyer, P.D., Murray, C.J., N'Guessan, A.L., 2008, Technical basis for assessing uranium bioremediation performance: NUREG/CR-6973, U.S. Nuclear Regulatory Commission Office of Nuclear Research, 128 p.
- LQD/DEQ Response Document, January 10, 2005 Comments, 2005, Irigaray Well field Restoration Report TFN 4 1/170 prepared by Cogema Mining Inc., Petrotek Engineering Corporation, and Resource Technologies Group.
- Mays, W.M., 1994, Restoration of groundwater at three in-situ uranium mines in Texas, IAEA Technical Committee Meeting, Vienna Austria, Oct. 5-8, 1992 as reviewed in Nuexco Review, May 1994; Groundwater Restoration of In-Situ Uranium Mines.
- Mobil, 1981, Internal company reports describing Mobil Oil Corporation's Crown Point ISR Pilot Test Project.
- NDEQ, 2009, Nebraska Department of Environmental Quality Monthly Restoration Reports Crow Butte Mine Unit 4.
- Nuclear Energy Agency, 2008, Uranium 2007 Resources, Production and Demand: a Joint Report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency, 420 p.
- Reimann, L. and Huffman, L., 2005, Biological reduction of metals during ground water restoration: presented at the Global Uranium Symposium, July 13, 2005, Casper, Wyoming.

DOMINIQUE-JANINE EXTENSION, McCLEAN LAKE PROJECT, AND MIDWEST JOINT VENTURE

Report of the Joint Federal-Provincial Panel
on Uranium Mining Developments in Northern Saskatchewan

OCTOBER 1993



Saskatchewan

Canada

**Uranium Mining
Developments in
Northern Saskatchewan:
Dominique-Janine
Extension,
McClean Lake Project, and
Midwest Joint Venture**

**Report of the Joint Federal-Provincial
Panel on Uranium Mining Developments
in Northern Saskatchewan**

October 1993



@Minister of Supply and Services Canada 1993

Cat. No. En106-21/1 993E

ISBN O-662-21 044-4

JOINT FEDERAL/PROVINCIAL PANEL ON URANIUM MINING DEVELOPMENTS IN NORTHERN SASKATCHEWAN

The Honourable Pierre Vincent
Minister of the Environment
Room 581, Confederation Building
House of Commons
Ottawa, Ontario
K1A 0A6

The Honourable Bernhard Wiens
Minister of Saskatchewan Environment
and Resource Management
Room 348, Legislative Building
Regina, Saskatchewan
S4S 0B3

The Honourable Barbara Sparrow
Minister Designate for Natural
Resources
Room 322, West Block
House of Commons
Ottawa, Ontario
K1A 0A6

Mr. J. G. **McManus**
Secretary General
Atomic Energy Control Board
270 Albert Street, P. O. Box 1046
Ottawa, Ontario
K1P 5S9

Panel Report on the Dominique-Janine Extension, the McClean Lake Project and the Midwest Joint Venture Project

In accordance with the mandate announced in April, 1991, the Joint Federal/Provincial Panel on Uranium Mining Developments in Northern Saskatchewan is pleased to submit the attached report.

Our review has been completed under the terms of reference provided at the time of our appointment in August, 1991. The documents supplied by the proponents have been subjected to a thorough technical review and public meetings have been held in **La Loche, Ile-à-la-Crosse**, Buffalo Narrows, Prince Albert, La Ronge, Wollaston Lake, Black Lake, Saskatoon and Regina.

On the basis of this review, we recommend that the Dominique-Janine Extension should be allowed to proceed, subject to certain conditions stated in the report. This recommendation is based on the conclusion that the project will provide substantial benefits in the form of employment, business opportunities and royalties, while causing only a small incremental increase to existing environmental and health risks.

We further recommend that the Midwest Joint Venture project not be allowed to proceed. The expected benefits from this project are meagre, while the chances for negative health and environmental impacts are great.

For the McClean Lake Project, we have concluded that the socio-economic benefits to northern Saskatchewan could be increased and the health and environmental risks reduced to an acceptable level by a modest delay, primarily to provide time for education, training and research. We recommend, therefore, that this project be delayed for at least five years, and that its approval at that time be subject to the conditions outlined in the report.

The panel also recommends that the findings and conclusions described throughout the report be given careful consideration by governments, the proponents and other interested parties.

Respectfully,

A handwritten signature in black ink, appearing to read 'Donald G. Lee', with a stylized, flowing script.

Donald G. Lee
(Chairperson)

TABLE OF CONTENTS

	<i>Page</i>
EXECUTIVE SUMMARY	1
1 .O INTRODUCTION	3
1.1 Review Process	3
1.2 Panel	3
1.2.1 Membership	3
1.2.2 Mandate	5
2.0 GENERAL ISSUES AND RECOMMENDATIONS	7
2.1 Nature of the Recommendations	7
2.2 Participation of Northern People	7
2.2.1 Revenue Sharing	8
2.2.2 Human Resource Development Agreements	9
2.2.3 Definition of a Northerner	9
2.2.4 Education and Training	10
2.2.5 Northern Business Opportunities	10
2.2.6 Monitoring Committees	11
2.3 Biophysical and Related Concerns	11
2.3.1 Monitoring	12
2.3.2 Liquid Effluent	13
2.3.3 Air Emissions	14
2.3.4 Tailings	14
2.3.5 Decommissioning and Post-Decommissioning.. ..	15
2.3.6 Cumulative Effects	15
2.4 Health Issues	16
2.4.1 Occupational Health and Safety	17
2.4.1.1 Radiation Health Risks	17
2.4.1.2 Combined Effects of Radiation and Heavy Metals	17
2.4.1.3 Epidemiological Studies	18
2.4.1.4 Noise Reduction	19
2.4.1.5 Importance of Worker Involvement	19
2.4.1.6 The Need for Occupational Health Professionals	19
2.4.1.7 Socio-Economic Related Health Impacts	20
2.4.1.8 The Psychological Health of Workers	20
2.4.2 Community Health Impacts	20
2.4.2.1 Contamination of Air, Water and the Food Chain	21
2.4.2.2 Transportation of Dangerous Goods	21
2.4.2.3 Socio-Economic Impacts on Health	21
2.4.2.4 Environmental Protection, Development and Health	21
2.4.2.5 The Acceptability of Risk	22
2.4.2.6 Disease Causation and Community Health Data	22
2.5 Larger Issues	23
25.1 Sustainable Development	23
25.2 Alternative Energy Sources	24
25.3 Local and Global Economics of Uranium Mining	24
25.4 Regulatory Agencies	25
2.5.4.1 Northern Involvement	25
2.5.4.2 Harmonization of Government Activities	25
2.5.4.3 Foreign Ownership	25

2.55 The Nuclear Fuel Cycle	25
2.5.5.1 Nuclear Power	25
2.5.5.2 Non-Proliferation Treaty	26
2.5.5.3 High Level Waste Disposal	26
2.5.6 Joint Review Process	26
2.5.7 Public Acceptance of Uranium Mining	27
3.0 THE DOMINIQUE-JANINE EXTENSION	29
3.1 Project Description and Site Map	29
3.2 Recommendations	29
3.3 Biophysical Concerns	31
3.3.1 Air Quality	31
3.3.2 Hydrogeology	31
3.3.3 Waste Rock Management	31
3.3.4 Surface Waters and Fisheries	32
3.3.5 Wildlife and Terrestrial Habitat	32
3.3.6 Monitoring	32
3.3.7 Cumulative Effects	32
3.3.6 Decommissioning and Site Reclamation	33
3.4 Socio-Economic Concerns	33
3.4.1 Human Resource Development Agreement	33
3.4.2 Revenue Sharing	33
3.4.3 Monitoring Committee	33
3.5 Health Concerns	33
3.5.1 Occupational Health	33
3.5.2 Community Health	34
4.0 MIDWEST JOINT VENTURE	35
4.1 Project Description and Site Map	35
4.2 Recommendation	35
4.3 Potential Risks	35
4.3.1 Unacceptability of Mining Methods	37
4.3.2 Radiological and Chemical Toxicity of Ore	37
4.3.3 Uncapped Bore Holes	37
4.3.4 Transportation Hazards	38
4.3.5 Surface Water Impacts	38
4.3.6 Hydrogeological Impacts	38
4.3.7 Disposal of Mill Tailings	38
4.3.8 Cumulative Impacts	38
4.4 Potential Benefits	39
4.4.1 Employment	39
4.4.2 Business Opportunities	39
4.4.3 Royalties and Taxes	39
4.5 Risks Versus Benefits	39
5.0 McCLEAN LAKE PROJECT	41
5.1 Project Description and Site Map	41
5.2 Recommendations	41
5.3 Biophysical Concerns	43
5.3.1 Air Quality	43
5.3.2 Hydrogeology	43
5.3.3 Waste Rock Management	44
5.3.4 Surface Waters and Fisheries	44
5.3.5 Tailings Management	45
5.3.6 Wildlife and Terrestrial Habitat	45

53.7 Monitoring	45
5.3.8 Cumulative Biophysical Effects	45
5.3.9 Decommissioning and Site Reclamation	46
5.4 Socio-Economic Concerns	46
5.4.1 Education and Training	46
5.4.2 Human Resource Development Agreement	46
5.4.3 Revenue Sharing and Monitoring Committee	47
5.4.4 Inherent Rights	47
5.4.5 Cumulative Effects	47
5.5 Health Concerns	48
5.5.1 Occupational Health	48
5.5.2 Community Health	48

APPENDICES

A Panel Member Biographies	51
B Terms of Reference for the Environmental Assessment Review of Uranium Mining Development	52
• Mandate	52
• Review Procedures	52
• Technical Experts	52
• Stages of the Review	52
• Linkage to Other Policy Processes	53
• Schedule A	53
C Panel Activities	54
D Submissions to Panel	55
D-1 Referenced by All Three Reviews	55
D-1.1 Oral Presentations Made At Public Hearings	55
D-1.2 Written Submissions	58
D-2 Dominique-Janine Extension	59
D-2.1 Oral Presentations Made at Public Hearings	59
D-2.2 Written Submissions	59
D-3 McClean Lake	59
D-3.1 Oral Presentations Made at Public Hearings	59
D-3.2 Written Submissions	59
D-4 Midwest Joint Venture	60
D-4.1 Oral Presentations Made at Public Hearings	60
D-4.2 Written Submissions	60
E Bibliography of Key Review Documents	60
E-1 Referenced by All Three Reviews	60
E-2 Dominique-Janine Extension	61
E-3 McClean Lake	61
E-4 Midwest Joint Venture	62

EXECUTIVE SUMMARY

The major recommendations arising from our review of the Dominique-Janine Extension, the **McClean** Lake Project, and the Midwest Joint Venture are summarized in this section. These recommendations have been formulated by assessing the balance between the potential benefits and risks to the region and to the province.

Because the people who live in northern Saskatchewan would experience the greatest impacts of these projects, particular importance has been placed on their concerns and aspirations. An improvement in educational levels would permit northerners to take greatest advantage of the employment opportunities presented by development of these mines. A spacing of the start-up dates of approved projects over a number of years would allow education programs to keep pace with the labour demands. A delay in some of the projects would also leave time for the implementation of monitoring regimes, the completion of baseline health studies, and the improvement in tailings management systems.

This report is presented with the understanding that its existence will not limit our ability to review the two additional projects contained in our mandate—the Cigar Lake and **McArthur** River developments. Readers should not assume that these recommendations prejudice, in any way, those that might be made on the basis of these forthcoming reviews.

The information in chapter 1 of the following report defines the scope of the report; the discussion in chapter 2 provides a summary of the important issues associated with uranium mining in general; and chapters 3, 4 and 5 deal with the specific projects.

The Dominique-Janine Extension

The socio-economic benefits associated with the proposed extension of the Dominique-Janine mine at Cluff Lake would be significant. The health and environmental risks, incremental to those already in existence, could be reduced to acceptable limits provided certain conditions are met. The proponent has, in the past, demonstrated respect for the local environment, concern for worker health, and interest in the socio-economic well-being of the residents of the impacted communities. We recommend approval of this project subject to implementation of the following conditions:

1. establishment of a new Human Resource Development Agreement in which Cogema be required to select a minimum of 50% of its new employees from residents of the primarily-impacted communities and a minimum of 30% from residents of the secondarily-impacted communities. These conditions should also apply to contractors and sub-contractors;
2. agreement on a form of revenue sharing that is acceptable to the majority of the impacted communities;
3. establishment of a monitoring committee (as described in section 2.2.6) for the Cluff Lake Mine;
4. provision of a financial guarantee to cover decommissioning and post-decommissioning costs;
5. adoption of the exposure standards recommended in Publication 60 of the International Commission on Radiation Protection (ICRP-60) without allowing the collective dose to increase;
6. completion of a review of worker health training programs;
7. establishment of mechanisms for conducting an **epidemiological** study of the health of current and former workers at the Cluff Lake mine;
8. establishment of an air quality monitoring program using moss pillows and development of a system for monitoring the quality of the groundwater in the vicinity of the Claude pit;
9. evaluation and selection of a different option for deposition of waste rock. Only innocuous waste should be disposed of in Cluff Lake. Options for disposing of other waste rock in the Claude and Dominique-Janine pits should be evaluated. The Claude pit should be decommissioned by filling it with rock capped by clean overburden;
10. establishment of a research fund to support the search for innovative ways of reducing the volume of effluent released and the quantity of chemicals required to treat contaminated water;
11. development of site-specific water quality objectives, establishment of a program to reduce contaminated mine water inflows, and assessment of the possible impacts to the Island Lake watershed;
12. specification of total environmental loading for the mine, and development of a material-balance for contaminants in all liquid effluent;
13. evaluation of alternative oxidants that could replace sodium chlorate in the leaching process and thereby permit recycling of mill effluent;
14. use of the Environmental Transfer Pathway model (**ETP/AECB**) as the focus for an integrated monitoring program, and the assessment of cumulative effects;
15. agreement that the decommissioned Dominique-Janine pit not be connected to Cluff Lake, and that Claude Creek not be rerouted to flow through the decommissioned pit; and
16. evaluation of alternative methods of tailings disposal, with the goal of closing down the present tailings management facility as soon as possible.

The Midwest Joint Venture

The Midwest Joint Venture project, as described in the EIS and its Amendment, is not acceptable; the benefits that could be obtained are insufficient to balance the potential risks. It is,

therefore, recommended that permission to proceed should not be granted for reasons that are presented in chapter 4.

The McClean Lake Project

It is recommended that the **McClean** Lake project be delayed for at least five years.

This would allow time to obtain more experience with previous surround tailings management facilities, to acquire comprehensive community health information, to **maximize** employment opportunities to northerners through education and training, to discuss further the larger issues, and to assess cumulative biophysical and socio-economic impacts.

Its approval at that time should be contingent on fulfillment of the following conditions:

1. evaluation, by the regulatory agencies, of the previous surround tailings pit at Rabbit Lake after several more years of operation;
2. collection and evaluation of baseline data on groundwater flow patterns and water quality. In particular, the panel recommends that accurate flow rates be determined for the streams in the Collins Creek watershed and that the modelling of predicted impacts on the receiving waters be revised accordingly;
3. development of plans to reduce contaminated mine-water inflows;
4. evaluation of alternative oxidants that could replace sodium chlorate in the proposed milling process;
5. participation in the establishment of a research fund to support the search for innovative ways to reduce the volume of effluent and quantity of chemicals required to treat contaminated water. The panel also recommends that site-specific water quality objectives be developed for the **McClean** Lake project. In addition, the total environmental loading should be specified and a material-balance developed for all contaminants in the liquid effluent;
6. use of the Environmental Transfer Pathway model (**ETP/AECB**) as the focus for integrating the monitoring program at McClean Lake. The general design of the monitoring program should be the same as that at other uranium mines. This would guarantee a consistent replication of treatments for biological effects monitoring and eventually produce the database required for the study of cumulative effects. The results of biophysical monitoring at **McClean** Lake should be reviewed by the independent monitoring committee recommended in section 54.3;
7. assessment of cumulative effects using the **ETP/AECB** model and validation of the results by use of a whole ecosystem approach to monitoring, as specified in section 2.3.1 and section 5.3.7;
 - a. decommissioning plans that include filling of mined-out pits with waste rock capped by clean overburden;
9. adoption of sediment quality guidelines for Saskatchewan and institution of a program to monitor sediment quality in the Wollaston Lake drainage system;
10. adoption of a Human Resource Development Agreement that includes employment objectives of 30% (75 workers) of the initial workforce from the Athabasca Basin and 40% (100 workers) from the rest of northern Saskatchewan, with the balance (**30%**, 75 workers) coming from southern Saskatchewan or elsewhere. After the mine has been in operation for three years, these objectives should be changed to require the selection of a minimum of 50% of all new employees from residents of the primarily-impacted communities and a minimum of 30% from the residents of secondarily-impacted communities. These conditions should also apply to contractors and sub-contractors;
11. agreement on a form of revenue sharing that is acceptable to the majority of impacted communities;
12. establishment of a monitoring committee (as described in section 2.2.6) for the McClean Lake Project;
13. provision of a financial guarantee to cover decommissioning and post-decommissioning costs;
14. adoption of the exposure standards recommended in Publication 60 of the International Commission on Radiation Protection (**ICRP-60**), without allowing the collective dose to increase;
15. implementation of a program to collect and **analyze** changes in indicators of community health for the impacted communities, and formulation and implementation of remedial health strategies; and
16. further public discussion of the larger issues identified in section 2.5 of this report.

1.0 INTRODUCTION

1.1 Review Process

In April, 1991, the governments of Canada and Saskatchewan announced a joint federal-provincial environmental assessment review to study uranium mine developments in northern Saskatchewan (see figure 1). To be included in the review were proposals for the Dominique-Janine Extension, **McClean** Lake, and Midwest Joint Venture. The review was also to include proposals for operating mines at **McArthur** River and at Cigar Lake. Each project proposal was at a different stage of development, and would progress through the sequences of the review process when appropriate. A panel was appointed in August, 1991.

Three proposals are being considered in this part of the review: the Dominique-Janine Extension at Cluff Lake; a proposed new mine at **McClean** Lake; and a proposed new mine, the Midwest Joint Venture (MJV), at South **McMahon** Lake.¹

For the three proposals being considered, Environmental Impact Statement (EIS) Guidelines were drafted by Saskatchewan Environment and Public Safety² in November, 1989, December, 1989 and March, 1990, respectively, in accordance with the provincial *Environmental Assessment Act*.

Subsequently, the Atomic Energy Control Board (AECB) referred the new uranium mine proposals (the MJV and **McClean** Lake projects) to the federal Minister of the Environment for public review under Section 12(b) of the *Environmental Assessment and Review Process (EARP) Guidelines Order*.

The proposed expansion of an existing uranium mine (the Dominique-Janine Extension) was also referred for review. Because the AECB had concluded that the adverse environmental effects of the proposal might be significant, it cited Section 12(e) of the *EARP Guidelines Order* as the basis for the referral.

The proposals for the Dominique-Janine extension, the **McClean** Lake new mine, and the Midwest Joint Venture new mine were at similar stages of development. The panel decided, on behalf of all stakeholders, that it would be most expeditious to combine the public hearing phase of the review for these three proposals.

The panel reviewed the Environmental Impact Statements (**EISs**) from the three proponents and their subsequent responses to the panel's requests for additional information,

The panel also reviewed comments provided by government agencies and public presenters.

Participant funding of \$200,000 was made available to help the public take part effectively in the review. The funds were intended to assist recipients in reviewing **EISs** and in preparing for and participating in the public hearings.

As required by its terms of reference, the panel then conducted public hearings in March, April and May of 1993. The sessions were held in Regina, Saskatoon, Black Lake, **Wollaston** Lake, La Ronge, Prince Albert, Buffalo Narrows, **Ile-à-la-Crosse** and La **Loche**.

After the public hearings, the panel prepared the following report, which assesses the acceptability of the proposed Dominique-Janine Extension, the **McClean** Lake new mine, and the Midwest Joint Venture new mine. In accordance with our terms of reference, recommendations are made on whether or not each project should be allowed to proceed, and in each case reasons are provided.

This report is submitted to the federal Minister of Environment, and the designated Minister of Natural Resources;³ the Saskatchewan Minister of Environment and Resource Management; and to the Atomic Energy Control Board.

1.2 Panel

1.2.1 Membership

The Joint Federal-Provincial Panel on Uranium Mining Developments in Northern Saskatchewan was appointed on August 22, 1991. Donald Lee, Head of the Department of Chemistry at the University of Regina, is Chairperson of the panel. Other panel members are:

- James Archibald, Associate Professor of Mining Engineering, Queen's University;
- John Dantouze, Vice-chief, Prince Albert Tribal Council;
- Richard Neal, Associate Dean (Academic), and Professor of Biology, College of Arts and Sciences, University of Saskatchewan; and
- **Annalee** Yassi, Associate Professor and Director of Occupational and Environmental Health, Faculty of Medicine, University of Manitoba.

¹ The proponent of the extension at Cluff Lake is the Cluff Mining Partnership, comprised of Cogema Resources Ltd. (80%) and Corona Grande Exploration Corporation (20%).

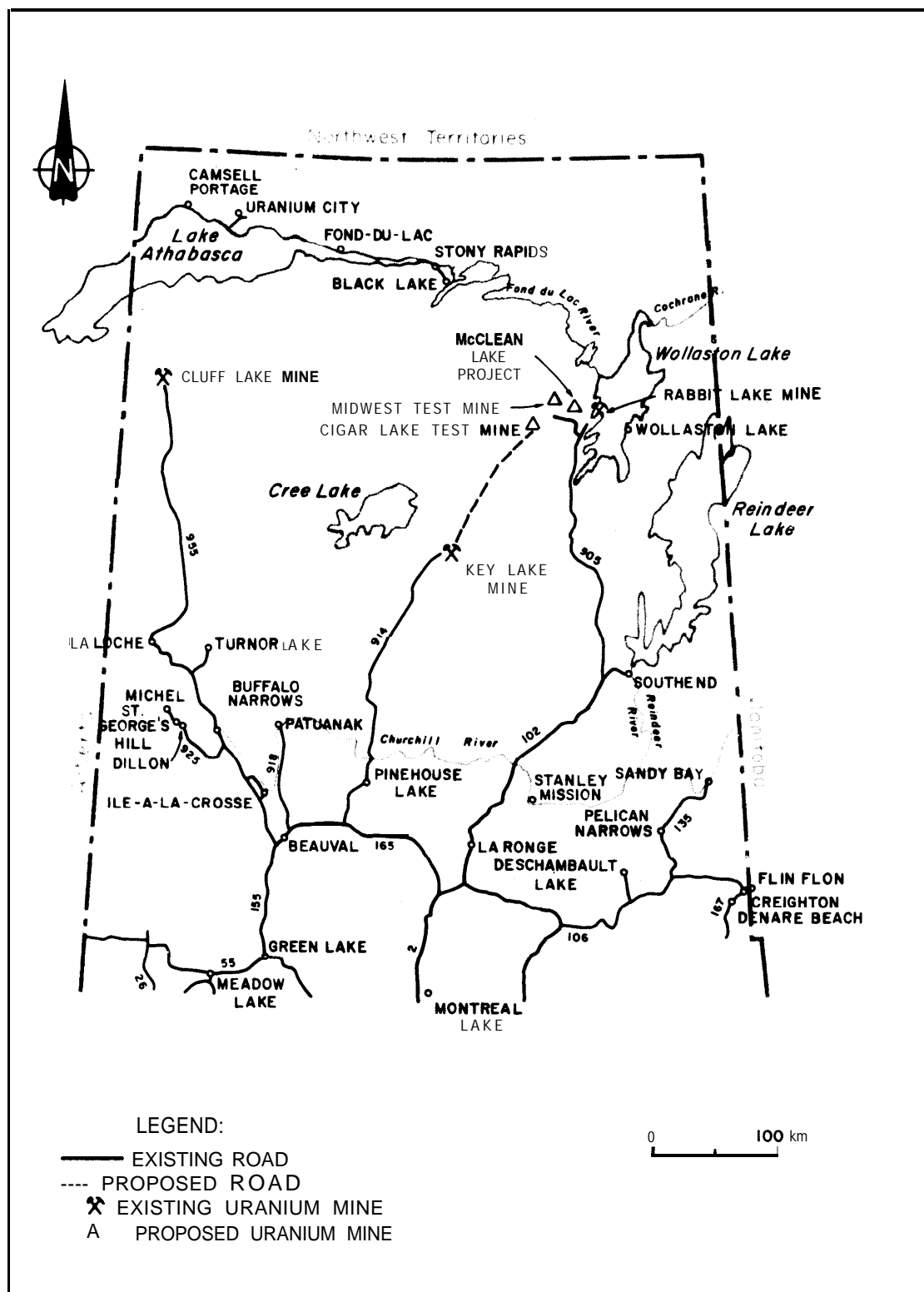
The proponent of the **McClean** Lake project, at the time of the public hearings, was Total Minatco. Other participants in the joint venture were Denison Mines Limited (22.5%) and OURD (7.5%). At the start of the public hearings, the proponent for the Midwest Joint Venture was Denison Mines Limited. During the public hearings, Total Minatco became project operator and major shareholder (56%), with Denison Mines Limited (19.5%) OURD (4.5%)

and **Uranerz** Exploration and Mining Limited (20%) as other shareholders.

² Saskatchewan Environment and Public Safety became Saskatchewan Environment and Resource Management in March, 1993.

³ Natural Resources is a new department and includes the previous department of Energy, Mines and Resources. The Minister of Natural Resources is the Minister responsible for the Atomic Energy Control Board (AECB). It was the AECB which requested the Minister of the Environment to conduct a public review.

Figure 1
Location of Existing and Proposed Projects



Biographies of the panel members are in Appendix A.

1.2.2 Mandate

The panel was given a three-fold mandate: to review the environmental, health, safety and socio-economic impacts of the proposed uranium mine developments; to determine from its review whether each project was acceptable or unacceptable; and to provide full opportunities for public consultation and review.

Complete terms of reference for the panel are in Appendix B.

This report on our review of the Dominique-Janine Extension, the **McClean** Lake project, and the Midwest Joint Venture is presented with the understanding that its existence will not limit our ability to review the Cigar Lake and **McArthur** River projects. Readers are cautioned not to assume that these recommendations will in any way prejudice those which will be made in the future reports. We reserve the right to complete a full and fair review of the Cigar Lake and **McArthur** River projects in a fashion that is independent from, and unbiased by, the reviews described in this report.

2.0 GENERAL ISSUES AND RECOMMENDATIONS

During the public hearings many participants raised issues that are relevant to all of the proposed projects. While some of these issues are very general (e.g. the educational levels of people living in northern Saskatchewan) and others more specific (adoption of ICRP-60, for example), they are the same or similar for all of the projects and are, therefore, most efficiently addressed in a collective fashion. These common issues are described in this chapter along with the presentation of a number of recommendations that flow from their consideration. Descriptions of the individual projects and recommendations pertaining to each are presented in subsequent chapters.

2.1 Nature of the Recommendations

Assessing the acceptability of a project under environmental review involves a balancing of potential benefits against potential risks. While establishing such a balance is never easy, it is more straightforward when a majority of the benefits are expected to accrue to the same people who are required to accept the greatest risks. In the case of uranium mining, however, a proper balance is more **difficult** to reach because northern people are expected to accept the greatest environmental and health risks while the economic benefits are shared more universally. Many of the recommendations in this report are made in an attempt to rectify this situation. To do so, it is necessary to minimize the potential for environmental damage and to maximize the likelihood that a substantial portion of the socio-economic benefits derived from uranium mining will remain in not-them Saskatchewan. Regional risks, associated with the possible contamination of air, land and water, must be exceeded by socio-economic benefits to justify a continuation or expansion of the uranium industry.

Concerns were raised regarding end uses and other larger issues impacting on whether uranium mining should be allowed to proceed in northern Saskatchewan. However, the terms of reference provided to us prohibit such considerations from influencing our recommendations, and we have proceeded accordingly.

We have made a positive recommendation for the acceptance of one project (chapter 3) because substantial benefits in the form of employment, business opportunities and royalties may be obtained with only a small incremental increase to existing environmental and health risks. For another (chapter 4), we have made a negative recommendation because the potential benefits are meagre and the chances for negative health and environmental impacts great. For the third project (chapter 5), we have determined that the socio-economic benefits to northern Saskatchewan could be increased and the health and environmental risks reduced to an acceptable level by a modest delay, primarily to provide some time for education, training and research.

⁴ R. M. Bone, *The Geography of the Canadian North* (Toronto: Oxford University Press, 1992), p. 38-70.

2.2 Participation of Northern People

*But we did not give up either our right to govern our lives, or the right to make our living from the resources that dene **nené** (our land) can provide. This means that, regardless of issues about jurisdiction, we insist on being directly included in all aspects of determining how the resources are used.*

Black Lake and Fond du Lac First Nations
Represented by Chief J. Martin, D. Deranger,
E. Boneleye, P. Robillard and A. Adam, *Transcript of
Public Hearings, Saskatoon, Saskatchewan, May 19,
1993, p. 208.*

Few people have had to adapt to new economic and social situations more quickly and completely than the people of northern Saskatchewan. Circumstances have forced them to change from a nomadic hunting economy (in effect prior to contact with Europeans) through a fur trapping/trading economy, and into the present resource-based wage economy, in about 300 years.⁵ It is not surprising that they have found the transition difficult and that many are now forced to rely on transfer payments (welfare) from central governments.

When one reviews the conditions that many northern people must endure, it is natural to ask the question, "What could have been done to avoid this situation?" However, it is much more important to consider questions such as, "What can now be done to improve conditions?", and "What is a fair and reasonable response to the current aspirations of northern aboriginals to regain a measure of ownership over their traditional lands and take control of their own destiny?" A wise and generous answer to the latter two questions on the part of the people of Canada, as represented by their governments, could go a long way toward righting past injustices and allowing the people of northern Saskatchewan to create a brighter future for themselves and their descendants. We recognize that a Royal Commission⁵ is currently assessing aboriginal issues, and look forward, along with the people of northern Saskatchewan, to their recommendations. Our report focuses only on the impacts of uranium mining; the Commission's mandate with respect to aboriginal issues is larger.

We must realize that measures taken with respect to the mining industry in general, and uranium mining in particular, can provide, at best, only a small portion of the solution to the problems associated with northern development. However, they could be part of the total solution and, since the mining companies appear to be genuinely committed to working for

⁵ *The Royal Commission on Aboriginal Peoples*, co-chaired by René Dussault and Georges Erasmus.

an improvement of conditions in northern Saskatchewan, an opportunity to explore creative alternatives exists.

Throughout the public hearings, people in northern Saskatchewan continuously lamented their lack of control in an area that had traditionally been "their land". It is apparent that the wish by aboriginal peoples to be in charge of their own region is partly an economic issue and partly a spiritual longing to be reunited with their cultural history.

We support the people of northern Saskatchewan in their wish to be accepted as equals (if not masters) when developments are being planned for their region of the province. Although as a consequence of the 1930 Resources Transfer Agreement legal ownership rests with the Crown (i.e. the people of Saskatchewan), we do not believe that it is in Canada's best interests to continue to deny the people of northern Saskatchewan a measure of ownership over their traditional lands and/or the resources contained therein. Because the economic and social problems faced by the people of northern Saskatchewan are so severe and encompassing, there is little doubt that, if allowed to remain unresolved, they will eventually have a highly adverse effect on the entire provincial economy. It is, therefore, incumbent upon us from both a compassionate and a materialistic point of view to take whatever measures are available to provide the people of northern Saskatchewan with an opportunity to secure their own future. Existing treaties, that were likely executed between two very unequal partners, should not be allowed to prevent governments from taking actions that would empower the northern people to be responsible stewards of their traditional lands. Outright or joint ownership could provide northerners with an economic base and, at the same time, foster a sense of dignity and responsibility that would be hard to achieve in any other way.

*... You know, the treaties promised us that as long as the sun shines, the **rivers** flow, even rocks are not moved, that we would continue to use the land and **utilize** the land **forever...and** if we were given free roam and access to the land, that also gives us certain rights to do whatever we wanted to with the land. We didn't give up those rights....*

Senator Chicken (translated by A. Adam), *Transcript of Public Hearings*, Black Lake, Saskatchewan, April 13, 1993, p. 107.

In the following paragraphs, we have restated a number of suggestions that were brought to our attention and which we believe would assist northern people to govern their lives and to make a living from the resources that their land can provide, as expressed in the quotation that opened this section.

2.2.1 Revenue Sharing

There's all different kinds (of) ideas about revenue sharing. Our region is so different between Black Lake, Fond du Lac, Wollaston, Uranium City...If there's any revenue sharing. ..it should be brought down to a community, each community.

P. Bougie, *Transcript of Public Hearings*, Black Lake, Saskatchewan, April 13, 1993, p. 89.

To establish a formula for revenue sharing and ensure that it is directed in an orderly manner is difficult but it is possible. We would like to have the opportunity to participate; it would be a good problem for northern people to have.

T. Tornquist, *Transcript of Public Hearings*, La Ronge, Saskatchewan, April 16, 1993, p. 6.

An increase in economic activity usually leads to an increase in jobs and business opportunities, and the benefits extend far beyond those directly employed in an industry. However, it is important to **recognize** that these benefits are much more limited in northern Saskatchewan. Only a small proportion of the northern labour pool can be hired by the uranium mines, and the business opportunities for northerners, while important, are much more limited than for southern Saskatchewan. Furthermore, much of the money that is paid to northern workers and businesses by the uranium mines will flow south because goods in the south are cheaper and more available. Thus, most northerners receive little, if any, benefit from the uranium mining industry because the economic system of the region fails to redistribute the wealth. A new method of sharing the wealth created by the uranium mines is required, to allow more people of the region to benefit.

It is essential that an equitable form of revenue sharing be worked out with northern people before additional projects are approved. This need has been consistently advocated by panels such as ours for the past fifteen years. Both the Cluff Lake⁶ and the Key Lake Boards of Inquiry⁷ made strong recommendations in this regard, and, in our report on the McArthur River Underground Exploration Program, we have noted that, "it is northern people who must tolerate the intrusion of

⁶ *Final Report, Cluff Lake Board of Inquiry*, E. D. Bayda, Chairman, 1978, p. 206.

⁷ *Key Lake Board of Inquiry Report*, R. W. Mitchell, Chairman, 1981, p. 50.

mines, and it is they who bear the greatest **risk** of environmental damage or social disruption by these developments.”⁸ They should, therefore, share more generously in any benefits (royalties, crown mineral disposition fees, corporation capital taxes and surcharges, corporate income taxes, municipal property taxes and crown surface lease fees) that are derived from the mines. Disbursement of the net revenues, estimated conservatively at **\$488.3-million** for the years 1980-1992,⁹ into the general provincial coffers does not seem equitable and leaves the residents of northern Saskatchewan with the impression that resources are being taken from “their land” with no direct compensation. The mechanism by which this compensation should take place will likely pose a difficult problem for the provincial government and we will not attempt to offer advice on how revenue sharing should be achieved. However, we **recommend that no new uranium mining developments be undertaken until a form of revenue sharing, acceptable to the majority of impacted communities, has been agreed upon.**

2.2.2 Human Resource Development Agreements

Human Resource Development Agreements are the instruments through which northerners are guaranteed an equitable share of the jobs that will be made available in these projects. Despite a high rate of unemployment among northerners, the mining companies have only succeeded in obtaining, at best, about 50% of their workforce from northern Saskatchewan. Cogema stated that 52% of the current workforce at its Cluff Lake mine are **northerners**,¹⁰ while the **Cameco** Corporation has established a goal of having 50% northern employment by 1995.”

Increasing northern participation in the workforce appears to be a fairly complex problem. On one hand, we heard that workers, some of them with experience, were available and anxious to work in the mines, while on the other hand, we were told that, because educational levels are low, companies have difficulty recruiting qualified personnel. If this information is correct, there is an abundant supply of unskilled labour available, but a scarcity of people in northern communities who have **sufficient** training to fill many of the positions that exist at the mine sites and in the company offices. This problem can only be solved, as discussed below, by provision of appropriate training for northern people. An orderly, planned increase in mining activity (as opposed to a rapid expansion) would most likely be of the greatest benefit to northerners as far as employment is concerned. **We are, therefore, recommending that the start-up of any approved projects be**

spread over a number of years and that the companies work together with the appropriate agencies to ensure that training keeps pace with development. Using this approach, the Human Resources Development Agreements could be renegotiated to guarantee that a much larger percentage of the **new** employees hired for these projects come from northern communities—a goal of 80% would seem obtainable. These goals should apply to all levels of employment, including administrative and executive positions. The employment objectives should also apply to on-site contractor or sub-contractor employees.

2.2.3 Definition of a Northerner

A question closely related to the human resources agreements is the way in which a “northerner” is defined for purposes of calculating employment percentages. The present definition—a person who has spent one-half of his/her life, or at least ten years, as a resident of northern Saskatchewan—was **criticized** on several occasions because it includes many people who are now residents of southern Saskatchewan, and because it does not give any preference to people of aboriginal descent.

Formulation of a new definition will be a difficult task because it must not be a racist statement, and because it should not restrict, in any way, a person's freedom of movement within the province. Some of these difficulties may be resolved through the natural flow of human activities. For example, since most residents of the northern communities expressed a wish to remain there, the current tendency to move south once they become regular wage-earners will be reduced when northern communities have better schools and services available. Similarly, there appears to be little need to distinguish between aboriginals and non-aboriginals because an increasing majority of residents of most northern communities can claim at least partial aboriginal **ancestry**.^{12,13} The question ultimately becomes, “Which communities should be considered when defining a northerner, and how should persons be counted who were formerly residents of the north and now live in the south?” This could also prove to be a difficult question to resolve by consultation with northern people because each community wishes to have the most-favoured status. For example, the people of La Loche, since theirs is the closest community to Cluff Lake, believed that they should be given priority for jobs at that mine,¹⁴ while the Athabasca communities expressed the opinion that they should have first chance

⁸ *McArthur River Underground Exploration Program*, report by the Joint Federal/Provincial Panel on Uranium Mining in Northern Saskatchewan, January, 1993, p. 4.

⁹ *Interim Report: Information from the Government of Saskatchewan requested by the Joint Federal/Provincial Panel on Uranium Mining in Northern Saskatchewan for the Cigar Lake and McArthur River Projects*, SERM, May, 1993, p. 83.

¹⁰ L. Bear, *Transcript of Public Hearings*, Regina, Saskatchewan, March 22, 1993, p. 71.

¹¹ J. McIntyre, *Transcript of Public Hearings on the McArthur River Underground Exploration Program*, Saskatoon, Saskatchewan, December 4, 1992. p. 8.

¹² Ft. M. Bone, *The Geography of the Canadian North*, (Toronto: Oxford University Press, 1992), p. 190, reports that 75.1% of the population of northern Census Divisions in 1986 were of aboriginal origins.

¹³ E. Weick, *Health in the Context of Uranium Mining in Northern Saskatchewan*. (Ottawa: ESAS Inc., 1992), p.6, notes that only the four larger urban centres (Air Ronge, La Ronge, Creighton and Flin Fion) have substantial non-aboriginal populations.

¹⁴ Despite being the closest community to the Cluff Lake Mine, only one person from La Loche is currently employed by Cluff Mining according to L. Bear, *Transcript of Public Hearings*, La Loche, Saskatchewan, April 20, 1993, p. 26.

at the available jobs because all of the mines are located somewhere in the Athabasca Basin?

We believe that it would be preferable to reduce the emphasis placed on the definition of a northerner and replace it with a regulation requiring the companies and their contractors to select a substantial percentage of their new employees from the impacted communities. Each mine should be required to define, in consultation with the province, a number of primary and secondary impact communities (located north of the old Department of Northern Saskatchewan boundary) from which they would hire primarily and in which they could offer incentives for the people to obtain appropriate training. Most of the new employees would then be expected to come from the communities of greatest impact; for example, 50% would come from the primary impact communities and 30% from the secondary impact communities. Workers from other parts of northern Saskatchewan and those who move south could still be counted as northerners for statistical purposes, but would not be considered as residents of the impacted communities when new hiring took place. This arrangement would encourage the mining companies to focus their educational and training programs more directly toward those communities that are expected to experience the greatest environmental and social impact of each particular mine.

2.2.4 Education and Training

Improved education and training opportunities are required if northern people are to become equal partners in the development of that part of Saskatchewan. The ability to obtain a sound kindergarten to grade 12 (K-12) education without having to leave home has long been taken for granted by people living in southern Saskatchewan. Similar opportunities should be made available to the citizens of northern Saskatchewan. It is unfair, for example, to expect students to come south to complete their high school grades. Teenagers and their parents experience enough stress without also having to adjust to a different culture. The inevitable consequence of such a system is an unusually large number of drop-outs. The situation with respect to drop-outs is improving where schools are **available**,¹⁵ but all communities do not have access to a high school. We also heard that the teaching of science and mathematics in northern schools is considered by some parents to be below the standards maintained in southern Saskatchewan? If this is true, every effort should be made to correct the situation; a resource-based economy requires graduates who have a good understanding of science and technology.

It is clear that every effort is being made to improve both the quality and accessibility of K-12 education. This work should be supported and encouraged to the maximum extent possible. A good basic education, in addition to equipping northern people to become leaders in their own territory, allows for the possibility of employment beyond the boundaries of northern

Saskatchewan and provides entrance requirements for institutions of higher education. With a very large population of children and young adults,¹⁶ it seems likely that not all of the young people in northern Saskatchewan will be able to find employment without venturing out into the larger world. A K-12 education will enable northerners to do that more easily and more successfully.

It is also important to provide post-secondary training for specific jobs and occupations. At the present time, training for mine-related employment is facilitated by the *Mineral Sector Task Team* which includes representatives from the northern mineral industry, Northlands College, Employment Canada, the Prince Albert Tribal Council, the **Métis** Society and the provincial Departments of Economic Development, and Education, Training and Employment. Through close cooperation with the mining companies and careful planning, an attempt is being made to **"maximize the hiring, training and advancement of northern people in the region's mineral sector"**.¹⁷ We applaud this initiative and encourage its continuation. When coupled with a planned expansion of the industry, it should be possible to obtain a majority of new employees from the impacted communities.

Programs that enable and encourage northerners to enter apprenticeship programs should also be promoted. In addition to employment in the mining industry, an individual with appropriate qualifications in one of the trades has opportunities for employment beyond the boundaries of northern Saskatchewan. Competent electricians, plumbers, etc. are in widespread demand. The presence of tradespeople in local communities could also lead to an improvement of the standard of living in the North.

2.2.5 Northern Business Opportunities

*The continuing development of the uranium industry in Northern Saskatchewan is integral to the improvement of economic conditions to the north. It's a development that not only provides direct benefits, but it a/so creates the wealth, **workforce**, and attitude necessary to start improving the economy.*

J. Roberts, *Transcript of Public Hearings*, La Ronge, Saskatchewan, April 15, 1993, p. 72.

A number of northern residents indicated that increased participation in the mining industry by local businesses could be beneficial to the development of northern communities. The ability to call on local people for services could also be an asset for the mining companies in certain instances.

¹⁵ J. J. Mercredi, *Transcript of Public Hearings*, Black Lake, Saskatchewan, April 13, 1993, p. 30; G. Fern, *ibid*, p. 36.

¹⁶ R. McKay, *Transcript of Public Hearings*, Saskatoon, Saskatchewan, May 3, 1993, p. 169.

¹⁷ D. Dewar, *Transcript of Hearings*, Buffalo Narrows, Saskatchewan, April 19, 1993, p. 67.

¹⁸ E. Welck, *A Socio-Economic Overview of Uranium Mining in Northern Saskatchewan*, (Ottawa: ESAS Inc., 1992), p. 3.

¹⁹ R. McKay, *Transcript of Public Hearings*, Saskatoon, Saskatchewan, May 3, 1993, p. 165.

Participation by local contractors would be encouraged by the establishment of company information offices staffed by people who, in addition to informing northerners of employment and business opportunities, were capable of providing assistance in the preparation of bids and/or proposals. In some cases, it might also be advantageous to all concerned if preferential treatment were given to bids received from northern contractors. The availability of start-up capital for business ventures (provided either by governments or proponents) would also assist northerners in their attempts to participate in mining activities, or in other business ventures of their choice.

These mining developments are in a region traditionally used and controlled by northern people and it seems only fair that they should be provided with an opportunity to benefit, not only through employment and revenue sharing, but also by the development of business expertise within their communities. **We therefore urge proponents and governments to create conditions under which the ability of northerners to participate in available business' opportunities is maximized.**

2.2.6 Monitoring Committees

How can we have our elders better understand what is going on here? How can they be more involved?

E. Benoanie, *Transcript of Public Hearings, Wollaston Lake, Saskatchewan, April 14, 1993, p. 106.*

There is a need for the people of Saskatchewan to be reassured that the mines are operating in compliance with all regulations and that northern economic benefits are being maximized through appropriate hiring practices and policies related to business opportunities. However, it is clear from the hearings that neither the word of company executives nor of officials from the regulatory agencies will be accepted without a certain amount of scepticism. To be completely believed, information must come from knowledgeable and trusted members of the local communities. It would therefore appear that the objective of providing the citizens of Saskatchewan with accurate and believable information concerning the mines could be achieved most effectively by formation of a monitoring committee for each mine. Such a committee, composed of members elected by each of the primary impact communities, along with one or two knowledgeable persons appointed by the provincial government, could meet at the mine site with mine officials and representatives of the regulatory agencies two or three times a year to receive and **scrutinize** reports on the operation of the mine, and to observe site conditions. In turn, the **committees**,²⁰ which could derive their legal standing from regulations introduced by the appropriate government

departments, would be required to issue annual public reports on their findings.

The regulations governing the committees should be stated in such a way that it is clear the committees can neither interfere with the operation of the mine nor attempt to formulate or influence policy. Their function would be one of receiving, evaluating and transmitting information in an understandable and unbiased fashion.

In addition, as the levels of education improve in northern Saskatchewan, the regulatory agencies would be wise to recruit members for their boards and technical staffs from the regions in which the mines are located. Having people from the northern communities actually involved in the regulation of the mines would help to demystify the work of the agencies and increase public confidence.

2.3 Biophysical and Related Concerns

The primary biophysical concern expressed by the public was contamination of the environment by radionuclides and heavy metals. Other contaminants, such as sulphates and chlorides, were of less concern. Contaminants can be released into the environment during the operational phase of the mines and long into the future. Consequently, proper decommissioning of the mines and long-term containment of contaminants were also major issues. Residents of the Athabasca region should be able to hunt, fish, harvest plants, drink the water, and use the land throughout the region without fear of being poisoned by past, present or future mining activity.

The following is a sample of the questions asked by the public.

- What are the background, i.e., pre-mining development, levels of the various contaminants in the region?
- What changes have occurred at the existing mine sites?
- Are the air, soil, water, sediments and biota being monitored adequately?
- Who checks to see that monitoring is done properly?
- How can the air and liquid effluent emissions be reduced?
- Are the air and water quality objectives appropriate for the region?
- Are there guarantees to ensure that the mine sites will be properly decommissioned?
- How will contaminants, especially the radionuclides and heavy metals in the tailings, be contained in the long term?
- What plans are there for the long-term monitoring of decommissioned mine sites?

transportation and accommodation. Alternatively, a more **arms-length** arrangement of costs could be made by providing grants that would be administered by a third party such as one of the Tribal Councils.

²⁰ We suggest that these committees could consist of six people appointed for six-year terms (on a staggered basis to ensure continuity). Costs could be shared by government and the mines with government providing per *dies* and the mines providing

- **Do the effects of different mines overlap and accumulate to produce regional effects? What are the cumulative effects?**

In summary, the biophysical **issues of most concern to the public were monitoring of the environment; the effects of liquid effluent and aerial emissions on the biota; the long-term containment of contaminants in the tailings; decommissioning; and cumulative effects. Each of these concerns is expanded upon in the following sections.**

2.3.1 Monitoring

The reasons for monitoring the environment at each mine site have been discussed by Swanson²¹ and Dirschl et al.²² It is important to know what is there before mining begins; what changes will or have occurred during the operation of the mine; and how the environment will recover or be restored after decommissioning. This should include data on changes in the biota, and on the concentration of various radionuclides and heavy metals in specific ecosystem components.

Monitoring at the existing mines has concentrated on water, and then, with decreasing emphasis, on air, aquatic sediments, soil, and biota. Researchers have developed a voluminous database on chemical contaminants, but with little understanding of the impact of the various chemicals on the surrounding biota²³ and local inhabitants (section 2.4.2.1). There is a lack of integration in the monitoring of the various aspects of the environment and a possible lack of understanding of the rationale for monitoring some ecosystem components.

The panel recommends that a common model such as the **Environmental Transfer Pathways model (ETP/AECB)²⁴ be used as the focus for integrating the monitoring program.** This model is powerful, flexible and easy to use. It integrates airborne and water-borne emissions from multiple sources and predicts contaminant concentrations through time in specific components (air, water, sediment/soil, plant and animal species) at specific locations. The model may be used to predict the concentrations of a specific contaminant, such as arsenic, to which biota or humans may be exposed. This allows an assessment of environmental impacts or probable health risks, providing the biological effects of the contaminant are known. Alternatively, the cumulative radiation dose from all radionuclides may be estimated for humans obtaining their food and water from the immediate area of a mine-site. Thus, the main "purpose of the proposed modelling is to **determine if the food chains within local ecosystems could transfer significant quantities of radionuclides or other contaminants to any possible future inhabitants, so that their natural ecosystems can be fully protected from any potential...damage...The objective of the modelling is to protect future generations, their**

native food sources and the entire sustaining ecosystem from any deleterious effects"²⁵

The **ETP/AECB** model is of limited value by itself. It is vital that it be validated by a carefully designed monitoring program which can determine whether the predictions of the model have any resemblance to reality. The model can help design the monitoring program in three main ways. First, it can identify key components that should be measured (monitored). Second, it can identify key processes, such as the transfer rates of contaminants between components, which may require quantification or further study. Third, it may suggest where permanent monitoring sites should be located relative to the expected concentration gradients of contaminants, as well as identify potential control (unimpacted) monitoring sites.

The **ETP/AECB** model and similar models used by the proponents in their Environmental Impact Statements suggest that the following components should be monitored: air, soil, terrestrial plants, a terrestrial vertebrate such as the snowshoe hare, groundwater, surface water, aquatic sediments, benthic invertebrates, and fish. Air and water should be monitored throughout the year. The remaining ecosystem components should be monitored on a two-year cycle, until the various sampling problems have been overcome, and then on a longer cycle as the changes slow down. In the post-decommissioning phase, the cycle may be five to ten years or even longer.

A carefully designed monitoring program will help to determine the impacts of the various emissions on the biota. However, it is difficult to isolate the impacts of mining on the biota from impacts on the biota caused by other factors. Therefore, an adequate monitoring program must include simultaneous monitoring of control areas, replication of treatments at independent sites, careful selection of sample sites and components, and use of standard methodologies to provide data that can be compared between sites and through time. **The panel recommends that the general design of the monitoring programs should be the same for all uranium mines. This will guarantee the consistent replication of treatments required to determine biological impacts and eventually produce the database necessary for the study of cumulative biophysical impacts (see section 2.3.6).**

The design of the monitoring program is the responsibility of the regulatory agencies in consultation with the mine operators. At present, data collection is the responsibility of the mine operators, with periodic independent samples collected by the regulatory agencies acting as an audit. This operates effectively for chemical monitoring, but monitoring of the biota will require a different audit. For the latter, the panel suggests

²¹ S.M. Swanson, *Cluff Lake: Status of the Environment Report*, (Saskatchewan Research Council Publication No. E-2200-2-E-91, 1991).

²² H.J. Dirschl, N.S. Novakowski, and L.C.N. Burgess, *An Overview of the Biophysical Environmental Impact of Existing Uranium Mining Operations in Northern Saskatchewan* (Ottawa: ESAS Inc., 1992).

²³ Swanson, *Cluff Lake: Status of the Environment Report*.

²⁴ Atomic Energy Control Board, *Cumulative Impact of Uranium Mining in Northern Saskatchewan*, Submission to Public Hearings, Saskatoon, Saskatchewan, May 4, 1993. B. Zgola, *Transcript of Public Hearings*, Saskatoon, Saskatchewan, May 4, 1993, p. 1-22. D. Lawson, *Transcript of Public Hearings*, Saskatoon, Saskatchewan, May 4, 1993, p. 22-45.

²⁵ Environment Canada, Western and Northern Region, Submission to the Public Hearings, Saskatoon, Saskatchewan, May 4, 1993.

that species' samples be retained permanently so that identifications and counts can be confirmed independently.

Finally, there is the issue of trust as discussed in section 2.2.6. Can one trust a company to monitor its own activities, and are the regulatory agencies too involved with the companies to provide independent, objective assessment of the data? The natural tendency of the proponents is to interpret the data in the most favourable and optimistic way. For this reason, the panel recommends **that biophysical monitoring be among the subjects reviewed by the independent monitoring committees, proposed in section 2.2.6.**

2.3.2 Liquid Effluent

Mines deal with large volumes of contaminated water. The contaminated water comes from mine water inflow; from precipitation collected after it has percolated through ore stockpiles and special wastes; from the milling process; and from pore water expressed from the tailings. Treatment with chemicals precipitates most of the radionuclides and heavy metals which are then deposited in the tailings management facility. The resulting effluent has a high concentration of total dissolved solids (TDS) and a low concentration of radionuclides and heavy metals.

The method of water treatment involves an environmental trade-off, whereby the mitigation of one problem (containment of metals and radionuclides) creates or exacerbates another problem (increased salinity). The effluent is saline because the high TDS content consists largely of chloride and sulphate salts. This is fatal for some organisms and adversely affects others, particularly in a region such as northern Saskatchewan where the water normally has an extremely low TDS content. The environmental impact of increased salinity is acceptable for two reasons. It is less harmful than elevated concentrations of radionuclides and metals, and the salinity change in the receiving waters is not permanent. After decommissioning, when water treatment stops and the concentration of TDS drops to background levels, those organisms that have been eliminated because of the change in salinity can reinvade and become reestablished.

The dispersal of radionuclides and metals is not entirely prevented by the method of water treatment because the total environmental loading²⁶ of various contaminants can still be considerable if sufficiently large volumes of effluent are released. Even though the concentrations of radionuclides and metals are very low, the large volume of effluent means that surprisingly large amounts of these elements are released. For example, at Cluff Lake a total of 12,816 kg of uranium was released in **8,181,769 m³** of water during the seven-year period, 1982-1988.²⁷ Similarly, the Department of Fisheries and Oceans has calculated that **"...over the anticipated life of the project, this will result in the discharge of approximately**

103,230 kg of uranium"²⁸ in treated effluent discharged from the McClean Lake project.

The spread of radionuclides and metals is limited because they are adsorbed by the sediments and suspended particulate matter, to a degree determined by factors such as the nature of the sediments and the speed of water flow. Contaminants will spread less if the effluent is released into a bog or lake where the water is in contact with rich organic sediments for a long period, than if released into a river or lake with a large turnover rate.

The two problems posed by liquid effluent are antagonistic; a decrease in one (salinity) leads to an increase in the other (total environmental loading of radionuclides and metals). Moreover, they are resolved in incompatible ways. In the first case, the effluent should be diluted as rapidly as possible to flush the salts from the system; in the second, the aim is to confine the effluent for as long as possible to allow time for contaminants to be adsorbed from solution.

One procedure that is compatible for both problems is to reduce the volume of effluent by decreasing mine-water inflow and by recycling water in the milling process as much as possible. A second compatible resolution is to remove radionuclides and metals from the contaminated water by other processes, such as adsorption onto organic particles or ion exchange columns.²⁹ Both solutions require further research.

The panel has three recommendations regarding the release of liquid effluent. **First, a research fund should be established to support the search for innovative ways to reduce the volume of effluent and the quantity of chemicals required to treat contaminated water.** The objectives should be a "zero effluent" mill, and liquid effluent from the other mining operations with low concentrations of all contaminants, not just radionuclides and metals. The research fund could be established at either the federal or provincial level and be administered by the appropriate regulatory agency. Funds could be obtained by placing a modest environmental tax on the total environmental loading of key contaminants in the liquid effluent.

Second, site-specific surface water quality objectives, appropriate for the Athabasca region rather than for Saskatchewan as a whole, should be developed. The present Saskatchewan Surface Water Quality Objectives (SSWQO), applicable for southern Saskatchewan where there is often a high concentration of TDS in the water, are not always appropriate for the Athabasca region. Where the SSWQO and the Canadian Water Quality Guidelines differ, the more stringent should apply. In addition, the new objectives should include a uranium water quality guideline for aquatic biota, and guidelines for any other significant ions or elements which are presently excluded.

²⁶ Total environmental loading = concentration of contaminant in effluent x volume of effluent released.

²⁷ T. P. Hynes, *The Impacts of the Cluff Lake Uranium Mine and Mill Effluents on the Aquatic Environment of Northern Saskatchewan*, M.Sc. Thesis, University of Saskatchewan, p. 40.

²⁸ *Position and Technical Review Of the Response to the Uranium Mines Review Panel Request for Additional Information concerning the Complementary McClean Lake and Midwest Projects, McClean Lake Project*, Department of Fisheries and Oceans, Central and Arctic Region, Submission to Panel, March, 1993.

²⁹ *Technical Position on Dominique-Janine Extension*, Environment Canada. Submission to Panel, May, 1993.

Third, the total environmental loading should be specified for all contaminants. Each mine should be required to develop a material-balance for all contaminants released in its effluent. The mines should be able to account for the spread of contaminants in the watershed. The estimates could be checked by the monitoring program.

2.3.3 Air Emissions

The primary concern expressed by the public with respect to aerial emissions was the release of radon (and the subsequent deposition of radon progeny) from mine ore bodies, ore stockpiles, waste rock, the mill, water treatment facilities and tailings. Radioactive dust was also a concern.

For many people, the central question, however, is to what extent do radon and radon progeny from mining activity represent a regional or even global health hazard? On the one hand, *... radon mixes very rapidly with the atmosphere, and the presence of even large radon sources cannot readily be detected a short distance away. Furthermore radon has a short radiological half life (less than four days) and the /eve/s therefore cannot build up over a long period of time.*³⁰ *"On the other hand, the tailings continue to release radon for over 100,000 years. And if the tailings are not isolated from the atmosphere, the sum of exposures for all those years could be large in absolute terms. . . Basically, . . . radionuclides are pumped out of the tailings area and over very large areas of land. And what we have is radioactive fallout onto vegetation, consisting mainly of those polonium iso topes. . ."*³¹

Regional radon concentration data³² indicate that the values for northern communities are as low as, or lower than, those for southern communities in Saskatchewan. However, elevated concentrations of radon progeny, particularly polonium-210, near the uranium mines could present a health risk if incorporated into food chains.³³ If the levels of radon progeny are elevated within a 5-10 km radius of a mine, and mines are developed so that tailings pits are in close proximity to one another, measurable cumulative effects could result. This could have a significant impact for inhabitants of the region choosing to obtain a substantial part of their food from the area, as noted in section 2.4.2.1.

This risk is difficult to assess because of inadequate monitoring of the aerial deposition of contaminants around the mine sites.³⁴ An improved monitoring program (see section 2.3.1) would address this problem. Secondly, the flux of radon from tailings management areas in the long term will depend on how they are decommissioned (see section 2.3.4). Finally, the future spatial pattern of development of uranium mines is not known, although several mines may be developed in the area to the west of Wollaston Lake. Future-risks from the combined

effects could be investigated by cumulative effects modelling (see section 2.3.6).

Because of its potential negative impact on the environment, all reasonable measures should be taken to minimize the release of radon and to thereby mitigate health risks by reducing the deposition of radon progeny. Measures should also be taken to reduce the creation and release of radioactive dust to a practical minimum.

2.3.4 Tailings

Most of the radionuclides and metals contained in the ore body are deposited in the tailings management facility. The long-term containment of these dangerous contaminants is vital.

There are two tailings management design concepts used in Saskatchewan. The first stores the tailings above ground. Contaminants are contained in the long term by covering the tailings and encapsulating them above the water table. However, some seepage of precipitation through the cover will always occur, resulting in continuous seepage through the tailings and the lowest seal of the downstream impermeable barrier. *"... there is no known way to achieve near absolute contaminant immobility and thus a maintenance-free condition"*³⁵

The second type stores the tailings in a pit below the water table using a pervious surround method. This involves lining the pit with a very permeable layer and placing the tailings in the centre. The enclosed tailings are expected to consolidate and become more dense than the surrounding layer. The contaminated water expressed from the tailings as they consolidate is pumped from the bottom of the pit to the water treatment plant. After the site is decommissioned, water ideally will move around the tailings through the more permeable surroundings so that, theoretically, contaminants will only be released by diffusion, a very slow process. *"...through this method, the radionuclides and other chemical contaminants can be virtually immobilized within the tailings deposit. In theory, the method appears to be flawless but only time will tell and, as yet, not enough time has passed to enable a final assessment?"*

Both methods of tailings management must contain contaminants for tens of thousands of years before they will cease to be a radiological hazard. Moreover, the non-radioactive toxic metals, such as arsenic, will persist forever. Perhaps wisely, the public fears that whatever can go wrong, will go wrong. For example, the cover or dikes encapsulating the above-ground tailings may erode and fail, allowing rapid dispersal of contaminants into the air and surface waters. Thus, the long

³⁰ L. D. Brown, *Risk Assessments for Exposure of the Public to Ionizing Radiation*, Submission to Public Hearings, Saskatoon, Saskatchewan, May 7, 1993, p. 3.

³¹ G. Edwards, *Transcript of Public Hearings*, Saskatoon, Saskatchewan, May 19, 1993, p. 80.

³² *A Cross-Canada Outdoor Radon Survey*, B. Grasty (1991), together with the results from a follow-up survey completed in 1992. Submitted to the panel by Mineral Industry Environmental Protection Branch, SERM, April 26, 1993.

³³ M. Shiell, *Biophysical Aspects of High-Grade Uranium Mines*, Submission to Public Hearings, Saskatoon, Saskatchewan, May 5, 1993.

³⁴ H.J. Dirschl et al, *Biophysical Environmental Impact*, p. 81.

³⁵ H.J. Dirschl et al, *Biophysical Environmental Impact*, p. 77.

term storage of these harmful substances needs to be studied very carefully.

One suggestion made to improve the safety of the tailings storage would be to remove thorium-230 and radium-226 from the **tailings**.³⁶ These two elements have half-lives of 60,000 and 1,622 years, respectively, whereas the other elements in the uranium decay series have half-lives ranging from a fraction of a second (polonium-214) to a few decades (lead-210). Thus, the removal of thorium-230 and radium-226 would reduce the radiological hazard of the long-term storage of the tailings. The concentrated thorium and radium would comprise a small volume, permitting more expensive methods of containment to be considered for these elements.

A second suggestion concerns the cover for the in-pit, pervious surround **method**.³⁷ If the tailings were covered with successive layers of glacial till, waste rock and overburden rather than with water, the tailings should consolidate still further as a result of the increased pressure. This should make it even more difficult for water to flow through the tailings and **disperse** contaminants, and should minimize the flux of radon to the atmosphere (see section 2.3.3).

Such suggestions require careful study and research. **The panel concludes that research funds are required to examine innovative techniques for the management of the tailings.** Funds could be created and administered in a similar way to that proposed for funding research on liquid effluent (see section 2.3.2).

And now here the uranium companies are asking us to increase the level of experimentation in a major way when the verdict isn't nearly in on the first round of experiments in waste management.

V. Drummond, Transcript of *Public Hearings*, Prince Albert, Saskatchewan, April 21, 1993, p. 146.

2.3.5 Decommissioning and Post-Decommissioning

Following uranium extraction, the mine site and surrounding environment should be restored to approximately their original state. The inhabitants of the Athabasca region should be able to use the territory in traditional ways: hunting, fishing, trapping, and gathering berries and herbal medicines. The way in which the site is decommissioned should be in part under the control of the inhabitants of the region. For example, they should be involved in decisions about whether open pits should be allowed to fill with water (contaminated at least in

the short term), or whether they should be filled with waste rock topped by glacial till.

The public was adamant that decommissioning costs are the financial responsibility of the mining companies and not of the government (i.e., the taxpayer). Much of this concern stems from the unsatisfactory way in which mines near Uranium City were abandoned when they were no longer profitable. For example, it **appears** that it is going to be costly to complete corrective work at the Gunnar Mine **site**.³⁸ Furthermore, because of poor initial planning, it seems likely that it will not be possible to restore the site as completely as is desirable and in as acceptable a fashion as the public expects for modern mining operations. This situation must not be allowed to re-occur.

The projects under consideration have been described in such a **way** that preliminary plans for decommissioning and site restoration have been established and agreed upon in advance; however, it is also necessary to have a guarantee that corporate funds will be available to execute these plans regardless of the financial health of the owners. Without such guarantees the public would not be protected from future costs if the mine owners were unable to provide the required funds. The guarantee should cover the possibility of an unexpected cessation of operations prior to completion of the project as well as the costs associated with decommissioning and site-restoration after the ore has been completely extracted as envisaged in the Environmental Impact Statements.

The public was also insistent that, because of the long-term hazard of contaminants, the mine-site should be monitored long after the mines have closed. Clearly, funds are also required for post-decommissioning monitoring.

During the public hearings, we were told that there are several ways in which a company could provide such guarantees. Insurance, performance bonds, trust funds, an irrevocable letter of credit and a pledge of assets were mentioned as **possibilities**.³⁹ Other jurisdictions, such as British Columbia, have introduced programs that require deposition of "reclamation securities" at the commencement of a project and a periodic re-evaluation to ensure that potential decommissioning and post-decommissioning costs have not expanded to exceed the value of the securities on **deposit**.⁴⁰ While not wishing to suggest the exact form it should take, we **recommend that a financial guarantee to cover the decommissioning and post-decommissioning costs of a project be secured from the proponent before that project is approved.**

2.3.6 Cumulative Effects

Cumulative biophysical effects are complex because the effects may be cumulative in several **ways**.⁴¹ Effects may:

³⁶ G. Edwards, *Transcript of Public Hearings*, Saskatoon, Saskatchewan, May 19, 1993, p. 62.

³⁷ Environment Canada, Western and Northern Region. Submission to the Public Hearings, Saskatoon, Saskatchewan, May 4, 1993, p. 26-28.

³⁸ R. Barsi, *Transcript of Public Hearings*, Regina, Saskatchewan, March 23, 1993, p. 111.

³⁹ K. Haapanen, *Transcript of Public Hearings*, Regina, Saskatchewan, March 23, 1993, p. 388.

⁴⁰ *Guidelines for Mineral Explorations: Environmental, Reclamation and Approval Requirements*, Ministry of Energy, Mines and Petroleum Resources, Province of British Columbia, 1992.

⁴¹ H. Sadar et al, *Assessing Cumulative Effects of Saskatchewan Uranium Mines Development*, December, 1992.

- be cumulative through time;
- be cumulative in space (multi-sources of contaminants from a single mine, several mines, or mines plus other activities in an area);
- be a combination of several different contaminants on a single species; and/or
- impact one or more species through ecosystem alterations.

A good example of cumulative effects through time is shown with the issue of total environmental loading, discussed in section 2.3.2. The concentration of a contaminant may be extremely low in the liquid effluent but the total amount of the contaminant released may be large because of the enormous volume of effluent. If the contaminant is adsorbed by aquatic sediments, its concentration may increase in the sediment to levels above that observed in the water column. This process of concentration of contaminants by aquatic sediments has been observed for molybdenum and uranium at the Cluff Lake mine,⁴² although the biological effects are unknown at this time. Thus, compliance with regulations, such as Saskatchewan Surface Water Quality Objectives, does not necessarily prevent the accumulation of some contaminants, over time, to potentially harmful concentrations. There is a need for limits on total environmental loading of contaminants and for an accounting of the fate of all contaminants released, as recommended in section 2.3.2. **The panel recommends that the Saskatchewan government adopt sediment quality guidelines similar to those of the Ontario government.**

A contaminant may also be released from several sources at a single mine, or from different mines, resulting in spatial cumulative effects. One example is the release of radon from mine workings, waste rock, ore stockpiles, the mill, the tailings management area, and the water treatment plant at a single mine. The various emissions must be considered together to determine how they overlap and potentially augment one another. Another example is the release of liquid effluent from different mines into the same watershed or convergent watersheds. In considering the cumulative impacts of different mines it has been argued that, *"In provincial monitoring procedures, existing sources are monitored to the point where measures do not exceed background. This provides the point at which the potential for cumulative impacts is generally considered to be zero. Provided there is no overlap in areas, there is no cumulative or 'combined' impact?"* This is true for most species in ecosystems because the individual members of those species live entirely within the sphere of influence of a single mine. However, it is not necessarily true for the few species, such as barren ground caribou or humans, which range over an area that may include several mines. In the latter case it can be argued that the exposure to contaminants is additive if there is more than one mine in an individual's home range. For example, exposure would be approximately

doubled if there were two mines rather than a single mine in an individual's home range, and so on. Thus, spatial cumulative effects need to be assessed carefully on a case-by-case basis.

Organisms are not affected on a contaminant-by-contaminant basis but by the combined effects of all contaminants, and other forms of disturbance. For example, an organism may be very sensitive to changes in **salinity**,⁴⁴ although the precise mix of ions may also be important. The interactive effects of the various contaminants are extremely varied. They may be greater than the sum of the individual effects taken independently (i.e., synergistic), such as the health risk of radiation and arsenic discussed in section 2.4.1.2. In contrast, the effects of different contaminants may also be antagonistic. For example, the toxic effects of ammonia and many other contaminants are reduced as the **hardness**⁴⁵ of the water increases.

The cumulative effects through time and space, and between different contaminants, can be modelled and assessed in a preliminary way by the Environmental Pathway model (ETP/AECB) discussed in section 2.3.1. However, the cumulative biological effects are impossible to predict in detail because the effects on organisms are species-specific, and ecosystem processes are extremely complex. Moreover, ecosystems can compensate for some environmental changes. For example, if an increase in the salinity causes the elimination of a species, the effect on the structure and function of the ecosystem may be minimal if that species is replaced by a similar, more salinity-tolerant species. From a practical point of view, the main assessment of cumulative biological effects will require a well-designed monitoring program. The latter requires that whole ecosystems be studied by monitoring key components and processes, as discussed in section 2.3.1. Such a program should identify major changes in ecosystem structure and function, and measure contaminant concentrations in important species that may be harvested by humans.

We recommend that a program designed to monitor cumulative biological effects be implemented for the Cluff Lake site and the west side of Wollaston Lake before further development is allowed.

2.4 Health Issues

Health is widely accepted as being more than the absence of disease; it is a state of physical, mental and emotional well-being. The terms of reference of the panel reflect this broad understanding by encompassing socio-economic effects along with environmental and health considerations. All three potential impacts on health (i.e. direct physical effects, socio-economic effects, and psychological effects) have, therefore, been included in our analysis of the possible effect of the proposed uranium mines on worker and community health.

⁴² T. P. Hynes, *Impacts on Aquatic Environment*. S. Swanson, *Cluff Lake: Status of the Environment Report*.

⁴³ R. Zukowsky, *Perspectives on Cumulative Impact Assessment in Saskatchewan*. Submission to Public Hearings, Saskatoon, Saskatchewan, May 4, 1993, p. 4.

⁴⁴ Salinity is defined as a measure of the total amount of soluble salts (ions) in water or soil.

⁴⁵ Hardness is defined as the concentration of calcium and magnesium in soil and water.

2.4.1 Occupational Health and Safety

The occupational health and safety hazards facing uranium miners include those associated with all mining operations as well as those specific to uranium mining. Thus, in addition to musculoskeletal injuries; respiratory diseases, including **silicosis**; heavy metal toxicity; and vibration and noise-induced injuries, uranium miners encounter radiation-related diseases.

2.4.1.1 Radiation Health Risks

It is now internationally accepted that ionizing radiation carries a greater risk per dose of exposure than had been thought previously. This acceptance is based on new scientific evidence, which recognizes that each **milliSievert (mSv)** of exposure is actually associated with 2-4 times greater risk than had been appreciated when the former standard was applied. The International Commission on Radiation Protection (ICRP), therefore, has recommended decreasing the allowable occupational exposure from **50 mSv** annually, to **20 mSv** per year averaged over 5 years. The new standard also includes contributions from all sources of radiation exposure. The level of acceptable risk was chosen because it corresponds to a one in 10,000 mortality risk per year (0.4% lifetime risk of occupationally-induced death). This is comparable to occupational risk in other industries and is therefore thought to be **acceptable**.⁴⁶ However, some labour organizations and environmental groups believe it is still unacceptably high, and continue to question the science on which it is **based**.⁴⁷

... relatively low doses spread among a relatively high population of workers do not produce fewer detriments than a high dose spread among a small group of workers.

D. Anderson, *Transcripts of Public Hearings*, Saskatoon, Saskatchewan, May 17, 1993, p. 24-25.

In 1991, the AECB published Consultative Document C-122 to invite public comment on the adoption of the ICRP-60 exposure standards. A presenter pointed out that some of the proposed workplace designs would exceed the proposed **20 mSv/year** limit, and another urged caution in adopting the ICRP-60 standards because, *"In the case of uranium mining*

*where the ability to modify exposure of workers is limited, imposition of lower dose limits is unlikely to reduce the collective dose. In fact, it may be that by forcing uranium mining companies to adopt job rotation schemes, the collective dose, and the consequent risk, may be increased."*⁴⁸ Another presenter cited the *Ham Commission's*⁴⁹ warning that using miners for shorter time periods without reducing the total exposure would probably increase the number of cancer victims.*

We agree with these cautionary comments, but also **recognize** that there is a consensus of scientific opinion indicating that a tightening of standards is warranted. It is, therefore, recommended **that** measures be taken to implement the standards recommended by **ICRP-60** before approval of **any** additional uranium mines; measures must also be taken to ensure **that collective doses are not permitted to rise**.

In addition to complying with established radiation standards, uranium mining companies are required to implement the concept of **ALARA** (As Low As Reasonably Achievable) **risks**.⁵¹ It is not permissible to use a certain method if a comparable, but safer, method is available. This principle recognizes that unnecessary exposure is unacceptable, even if regulations are not exceeded. In our opinion, **ALARA** is an important concept, one that the proponents and regulators should vigorously promote. During the hearings, it appeared that some proponents had not used their past experience to develop a good understanding of the significance of health effects attributable to radiation exposures. This is worrisome given the importance of this understanding as a motivator in applying the **ALARA** principle.

Of equal importance to the application of good regulations and the observation of the **ALARA** principle is the insistence upon maintaining actual (not approximate, estimated or average) exposure records. Instrumentation for this purpose is now available and we **recommend that the use of personal dosimetry which measures both alpha and gamma radiation become standard practice in uranium mines**.

2.4.1.2 Combined Effects of Radiation and Heavy Metals

Some Saskatchewan mines contain high concentrations of arsenic and nickel, both known to be carcinogenic, as well as uranium. A study of Ontario miners has suggested that there is a synergistic effect between radiation and arsenic exposure? This finding implies that the risk of lung cancer to

⁴⁶ M. Measures; D. Brown. *Transcript of Public Hearings*, Saskatoon, Saskatchewan, May 7, 1993.

⁴⁷ M. Schmidt, "The New Recommendations of the International Commission on radiological Protection-No Progress for Radiological Protection", *International Perspectives in Public Health*, Vol. 7, (1991), p. 20-28; 'Permitting Unacceptable Risks: The New international Commission on Radiological Protection Radiation Safety Standards', *Friends of the Earth*, London, England, (February, 1991).

⁴⁸ T. Meadley, *Transcript of Public Hearings*, Saskatoon, Saskatchewan, May 19, 1993, p. 230.

⁴⁹ Report of the Royal Commission on the Health and Safety of Workers in Mines, James Ham, Chairperson, 1976.

⁵⁰ S. Helliar, *Transcript of Public Hearings*, Saskatoon, Saskatchewan, May 17, 1993, p. 199.

⁵¹ D. Brown, *Transcript of Public Hearings*, Saskatoon, Saskatchewan, May 7, 1993, p. 200-201.

⁵² R.A. Kusiak, A.C. Ritchie, J. Muller, J. Springer, 'Carcinoma of the Lung in Ontario Gold Miners: Possible Aetiological Factors.' *British Journal of Industrial Medicine*, April, 1991.
R.A. Kusiak, A.C. Ritchie, J. Muller, J. Springer, 'Lung Cancer Mortality in Ontario Uranium Miners', draft paper issued for comment, October 15, 1991; subsequently accepted for publication in the *British Journal of Industrial Medicine*, 1993.

miners employed in mines with both a high grade of uranium and a high concentration of arsenic may be considerably greater than predicted from the sum of the individual exposures. A similar situation may also exist for nickel and other mining exposures, although this has not been well studied (see section 2.4.1.3).

Whether the risks of arsenic, and possibly **nickel**,⁵³ in the presence of radiation **are** synergistic or additive, it is clear that miners **working** in such mines are likely at greater risk than their counterparts in mines **which contain little or none of** these heavy metals. It would, therefore, seem reasonable that the regulated exposure limits should be adjustable to account for variations in mining conditions. **It is recommended that the proponents voluntarily reduce exposure limits for underground mines containing high concentrations of arsenic, and that regulators establish site-specific combined exposure limits that would approximate an acceptable risk?**

The hazards posed by the high-grade uranium ore are exceedingly multiplied by the intimately associated very large amounts of high-grade arsenic..

J. Stmad, Speaking Notes for Public Hearings, Saskatoon, Saskatchewan, May 5, 1993.

... the Saskatchewan limits will probably be amended to reflect the evidence of increased cancer risk from inorganic arsenic..

J. Alderman, Speaking Notes for Public Hearings, Saskatoon, Saskatchewan, May 4, 1993, p. 3.

2.4.1.3 Epidemiological Studies

Much of the information regarding the health effects of mining has come from epidemiological studies. These studies of the distribution and determinants of disease have served as the basis for identifying hazards, quantifying risk and setting standards to control these risks. During the late 1940's and into the 1950's, as uranium mining expanded, excess lung cancer was documented in US uranium miners as a result of an epidemiological study conducted by the US Public Health Service? Since then, many other groups of underground miners

have been documented to have increased risk of lung cancer. This has generally been thought to be related to the radon contamination in underground mines. Recently, however, the role of other cancer-causing exposures in mines has also been actively explored.

To date, four epidemiological studies of Canadian uranium miners have been conducted and all have shown increased risk of lung cancer.⁵⁶ The Ontario Miners' study followed the mortality experience of over 50,000 miners who worked in Ontario uranium mines by linking the list of miners to the Canadian National Mortality Database, internationally renowned for its comprehensiveness. The exposure to radon progeny for the period before 1968 had to be estimated by linking work histories with area measurements, as personal dosimetry information was not available during the early years. The uranium miners **showed a significant increase** in overall deaths and specifically deaths from lung cancer. Excess mortality from lung cancer in Ontario gold miners (exposed to large concentrations of arsenic) was also **found**.⁵⁷ This is when the authors **realized** that exposure to arsenic and radon decay products **was** particularly problematic. A **follow-up** of these miners confirmed that the risk of death due to lung cancer was greatest among uranium miners, who had also worked in gold mines?

Workers employed in the Port Radium mine were also found to have a significant excess in lung cancer deaths. A study of over 8000 workers employed between 1948 and 1980 at Beaverlodge Uranium Mines was also conducted. A much greater excess of lung cancer was found in Beaverlodge miners compared to the Ontario and Northwest Territories miners, which has raised many questions. Smoking appeared unlikely to have accounted for much greater risks. Apparently, a follow-up study of these miners has been conducted, but it is not known to the **panel**⁵⁸ whether the much greater risk (per working level) experienced by these miners was related to faulty exposure estimates or other explanations.

There have been major improvements in mining techniques and ventilation standards in mines during the past few decades. Exposure standards have also been reduced and it would appear that mining conditions are now better than ever before. Without appropriate study, however, it is impossible to provide quantitative verification of this assumption. As discussed in the previous section, some of the changes may, in fact, be detrimental to the overall health of miners. The only way that one can properly ascertain the consequence of any changes is through a thorough epidemiological study. Such a

⁵³ Internationally respected committees on cancer have consistently concluded that there is strong evidence that some types of nickel are carcinogenic. While the Ontario-based studies have confirmed increased cancer with some types of nickel exposure, and have also found increased lung cancer in nickel miners, the carcinogenic agent in nickel mines is still the subject of investigation.

⁵⁴ Acceptable risk is considered to be one in 10,000 occupational-induced mortalities per year as recommended in ICRP60.

⁵⁵ National Research Council, Biological Effects of Ionizing Radiation Committee (BEIR IV), *Health Risks of Radon and Other Internally Deposited Alpha Emitters*, (Washington, DC: National Academy Press, 1966).

⁵⁶ M. Measures, 'Exposure and Dose Limits for Workers and Members of the Public in Canada,' *Submission to Public Hearings*, Saskatoon, Saskatchewan, May 7, 1993, p.9.

⁵⁷ R.A.Kusiak, A.C. Ritchie, J. Muller, J. Springer, "Carcinoma of the Lung in Ontario Gold Miners: Possible Aetiological Factors", *British Journal of Industrial Medicine*, April 6, 1991, p. 808-817.

⁵⁸ R.A.Kusiak, A.C. Ritchie, J. Muller, J. Springer, "Lung Cancer Mortality in Ontario Uranium Miners". Draft paper issued for comment, October, 15, 1991; later accepted for publication in the *British Journal of Industrial Medicine*, 1993.

⁵⁹ At the time of the hearings, this report was unavailable.

study would compare the health impacts on miners from the Uranium City era with those from the more modern mines at Rabbit Lake, Key Lake and Cluff Lake. It would compare open-pit and underground mines and provide data on whether the effects of various miner rotation/shift patterns could be evaluated from a health perspective. It could also be used to predict future risks and perhaps suggest ways in which they could be mitigated. While an adequate latency period is required before any results could be truly reassuring, beginning a study now (15 years after commencement of the modern mines) would still be useful.

With the introduction of personal dosimetry monitoring, as recommended in section 2.4.1.1, the continuation of this epidemiological study into the future would permit comparisons to be made using actual, not average or estimated, exposures. Proper monitoring would also provide the data required to gain insight on questions surrounding the possible additive or synergistic effects of arsenic, nickel, or other mining exposures. **For these reasons, it is recommended that arrangements be made to conduct an on-going epidemiological study of all Saskatchewan uranium miners (past, present, and future). It is recommended that the study begin as soon as possible, and that the results be promptly communicated to the public.**

The reality for workers has been that when experts disagree, the worst case scenario has generally proven to be the one that is closest to the truth.

Communications, Energy and Paperworkers Union of Canada, *Submission to the Public Hearings*, Saskatoon, Saskatchewan, May 18, 1993, p. 4.

2.4.1.4 Noise Reduction

The control of noise in mines is an occupational health and safety issue that merits particular comment. Excessive noise is a safety factor because it can cause fatigue, and interfere with communication, thereby increasing the chance of an accident or an injury. It is also a direct health concern because it can cause hearing loss or damage.

Saskatchewan Labour's brief indicated that *"...amendments to the Occupational Health and Safety Regulations will probably place more emphasis on noise reduction".⁶⁰ We agree with this objective and urge that regulations which place emphasis on noise reduction be introduced.*

⁶⁰ J. Alderman, *Speaking Notes for Public Hearings*, Saskatoon, Saskatchewan, May 4, 1993, p. 3.

⁶¹ G. Telfer, *Transcript of Public Hearings*, Saskatoon, Saskatchewan, May 4, 1993, p. 201-204.

2.4.1.5 Importance of Worker Involvement

... If education, monitoring and dose reduction programs are to be effective, ... they must be developed and implemented with full participation of the worker who knows better than anyone else what is going on in the workplace, and how conditions can be improved.

G. Telfer, *Transcript of Public Hearings*, Saskatoon, Saskatchewan, May 4, 1993, p. 203.

As workers have to accept a risk, they should do so on the basis of full participation and a complete understanding of the issues involved.

J. Alderman, *Speaking Notes for Public Hearings*, Saskatoon, Saskatchewan, May 4, 1993, p. 2.

Worker education and formal worker involvement in health and safety are crucial to worker protection. Saskatchewan's proposed new *Act Respecting Occupational Safety and Health* (Bill 56) will **recognize** this reality and require the establishment of joint workplace safety and health committees with defined responsibilities. **The proposed legislation (Bill 56) would promote a higher level of assurance in the health and safety of the proposed new mines and its timely adoption is recommended.**

A union representative who appeared before the panel indicated that union members wanted mining jobs, but believed that much could be done to further reduce risks to workers? He also contended that occupational health and safety committees function best in unionized workplaces, and expressed particular concern for health and safety of workers of non-unionized mine contractors.

The brief from the union also referred to a computer-based training course on radiation **safety**,⁶² which has been used at Cluff Lake. We suggest that this type of learning tool should continue to be developed, adapted as needed, and made available to all workers in this industry.

2.4.1.6 The Need for Occupational Health Professionals

With the advent of the Workplace Hazardous Materials Information System (WHMIS) and other worker right-to-know initiatives, workers are asking more questions about health hazards and the potential work-relatedness of their health problems. Occupational health matters, important in any workplace, are particularly fundamental with respect to uranium

⁶² *All About Radiation*, a self-teaching interactive video produced by the Canadian Institute for Radiation Safety, **Saskatoon**.

mines, because of radiation-related health issues. While physicians working in northern Saskatchewan have taken initiatives to assist workers/patients with such concerns, the resources and training needed for these often complex assessments seem to be insufficient? Limited availability of occupational physicians' time may severely restrict the number of visits and the extent to which occupational health concerns can be addressed. **The proponents should ensure adequate availability of knowledgeable occupational health professionals.**

2.4.1.7 Socio-Economic Related Health impacts

Proposed **workcamp** amenities and site facilities have been described in the EIS, along with a discussion of issues related to worker lifestyle. The latter included existing or proposed **measures regarding** alcohol, tobacco and drugs, recreation and entertainment needs, and food and accommodation. We note that the impact of the mines in these areas is likely to be positive. In **workcamp** situations, however, attention should be paid to both primary prevention measures, and to early identification of problems followed by counselling and rehabilitation as needed.

The way in which workers are hired, fired or promoted can either increase or reduce stress depending on the perceived fairness of the process followed. This is particularly important when minorities are involved. **The need for culturally-sensitive orientation and counselling to ease the adjustment of aboriginal people into full-time industrial employment is evident.**

Most workers who addressed the issue of worker lifestyle strongly supported the 7 day-in/7 day-out shift concept. Although there are hardships associated with the commuting lifestyle, there are also problems related to boom-and-bust mining towns. **On balance, the panel finds the 7 day-in/7 day-out concept acceptable. There is, however, a need for the proponents to provide on-site counsellors who can help workers resolve family/work conflicts and related issues.**

The proceedings of a conference held in Saskatoon⁶⁴ reported a number of cautionary observations about the 7 day-in/7 day out rotation. For example, it noted that health and safety implications of rotational schedules and the extended workday are still not well understood and need further study. The conference also noted that diet is an important issue associated with the employment of a native labour force; to avoid digestive problems, it was advised that country foods (fish and game) be included in the diet. With respect to family stress, the conference summary cited a survey in which three-quarters of the respondents had an overall negative view of the commuting system and about 66% of the remainder had some negative comments, with spouses more negative than miners. It was noted that 67% of long-distance commuting miners were married, and 92% were male. The conference urged the hiring

of more women, the hiring of couples, subsidized and private telephone lines and social events for families.

The panel also noted that very few of the women presenters supported uranium mining development, and that few women have been hired in this industry. More obvious opportunities for women in this industry might offset some of their concerns.

The panel concludes that flexibility to accommodate family needs should be encouraged and that special attempts should be made to provide employment opportunities for a growing pool of well-qualified northern women.

2.4.1.8 The Psychological Health of Workers

The importance of traditional harvesting and gathering activities to the spiritual well-being of aboriginal people was stressed throughout the public hearings. Many people stated that working at the mines does not negate these activities; in fact, some presenters noted that uranium mining development can actually enhance the potential for continued traditional activities. In any event, work arrangements that permit employees to engage in traditional activities will promote their health and well-being.

Risk, or the perception of risk, can also have a strong effect on the psychological health of workers. Everyone accepts certain risks daily; driving a car, walking across a street and almost everything else we do involves risk. Usually such risk does not impact on health from either a physical or a psychological perspective. However, if, in order to find employment, one is forced to accept risk or engage in an activity which he or she may feel is potentially detrimental, it may have a psychological effect on his/her health and sense of well-being. It is, therefore, important to understand those factors that contribute to the acceptability of the risks associated with uranium mining. These are discussed further in section 2.4.2.5.

2.4.2 Community Health Impacts

... the data from Saskatchewan Environment and Resource Management, as well as Saskatchewan Labour, indicates that within a few kilometres of existing uranium mining sites that radiation levels are back to background. Therefore, unless there is an emergency spill, there should be no direct negative impact on the physical health of people who live in the areas surrounding the mines... Even though it is much easier to study a biomedical impact like cancer than a socio-health impact like employment, both issues are relevant and important to the health of northern residents.

J. Lyster, *Transcript of Public Hearings*, Saskatoon, Saskatchewan, May 7, 1993, p. 207.

⁶³ D. Dewar, *Transcript of Public Hearings*, Buffalo Narrows, Saskatchewan, April 19, 1993, p.104-105.

⁶⁴ *Long Distance Commuting in the Mining Industry: Conference Summary*, edited by M. Shrimpton, K. Storey, Centre for Resource Studies/Energy Mines and Resources Conference, November 1990, Saskatoon, Saskatchewan.

2.4.2.1 Contamination of Air, Water and the Food Chain

There is a fundamental concern that chemicals from uranium mines may enter surface or groundwater, thereby contaminating drinking water, and fish. The potential terrestrial contamination of edible local foods (including terrestrial wildlife), and the consequent effect on human health must also be considered. In this regard, the need for proper environmental monitoring (section 2.3) is evident.

Some presenters raised concern about a potential link between uranium mining and adverse health effects such as cancer, 'birth defects, spontaneous abortion and a myriad of other problems. A calculation of health risk to someone eating caribou daily was conducted by experts from the Bureau of Radiation and Medical Devices, Health and Welfare Canada.⁸⁵ Various tissues from the caribou in Baker Lake were found to contain elevated concentrations on polonium-210 and lead-210, which were associated with a calculated total dose to the consumer of 1.41 mSv/year. Using the ICRP-60 risk coefficient, a lifetime cancer risk of 0.5% is calculated, compared to the background cancer risk of about 20%. This level of increased risk is small, roughly equivalent to the risk associated with natural background radiation. Whether or not this incremental level of risk is acceptable is the subject of debate. The lack of environmental health risk assessment data makes any conclusions regarding the health concerns of the impacted communities problematic. **Appropriate studies are needed to more fully assess environmental health risk to human populations caused by the possible contamination of air, water and the food chain.** Such studies should be conducted as part of the comprehensive community health studies recommended in section 2.4.2.6.

2.4.2.2 Transportation of Dangerous Goods

Residents of some of the villages along northern highways raised concerns related to the transportation of dangerous goods over roads that pass near or through their communities. We also heard from individuals familiar with the trucking industry who described precautions taken during the transportation of dangerous goods. Although we do not wish to recommend new legislated requirements in this area, we urge that care be taken to ensure the safe handling of materials, and that emergency training and response capabilities be available to all impacted communities. It is the proponents' responsibility to share information concerning the materials being transported, and their safe handling and emergency response measures, with the communities.

... whatever you get out of the uranium mine is transported within the town of La Loche...if there was a spill here... What kind of precautions are we going to take within the community?

I. LeMaigre, Transcript of Public Hearings, La Loche, Saskatchewan, April 20, 1993, p. 107.

2.4.2.3 Socio-Economic Impacts on Health

Some concern was expressed that mine employment could cause community health problems through the influx of money, drugs and alcohol into the communities. For example, the presence of a few large wage-earners may increase the despair of those unable to obtain employment and thereby contribute to community disharmony. On the other hand, the panel heard from many young people who want the jobs and business opportunities provided by the mines, and who look to those who have been employed in the mines as positive role models.

In some of the communities, living conditions are poor, often lacking basic sanitation and infectious disease control measures. Depressed social, psychological and economic conditions have produced a situation that is inadequate from a health perspective.

Rapid population growth in some communities has resulted in the presence of a number of young people who need to establish their self-worth either through traditional land-use activities or employment. **Recognizing this reality, the panel concludes that economic development is imperative to the health and well-being of northern peoples.**

The role uranium mining could play in this needed development was the subject of many presentations. In addition to jobs and business opportunities, positive benefits reported include the establishment of an air transport system and the creation of roads which presently link many northern communities. Such transportation networks have found strong acceptance by most communities.

On the other hand, public concern was expressed that some of the community health problems may be partially attributable to the increasing development of public roads, and the consequent availability of alcohol, etc. No studies are available, however, to assess concerns that increasing community health risk has developed as a direct result of mining activity. This **emphasizes** the need for the comprehensive health studies recommended in section 2.4.2.6.

2.4.2.4 Environmental Protection, Development and Health

The importance of preservation of the environment to the health and well-being of individuals, their communities and future generations was a common theme at the public hearings.

Several presenters discussed various socio-economic philosophical perspectives; one stated that **developmentalists** see their goal as creating a comfortable and efficient lifestyle

⁸⁵ Health Assessment of Po-210 in Caribou from the NWT, memo submitted to the Public Hearings by D. Lawson, Saskatoon, Saskatchewan, May 4, 1993.

through an understanding of how things work (science), producing the most efficient tools (technology), and advancing as quickly as possible (progress). She contrasted this with environmental and native traditionalist values which stress responsibility as stewards of the earth-locally, regionally and globally in this and future generations. She and other presenters challenged the developmentalist values as seeing □ ... *the environment as existing to serve humanity's need to prosper*.⁶⁶ The dichotomy between the wish for a pristine environment and the need for economic development may cause internal conflict and consequent health problems. Decision makers should **recognize** that the ideology of development is not embraced by all.

2.4.2.5 The Acceptability of Risk

The presence of health risk can have a profound effect on the physical and psychological health of a community. The acceptance of such a risk is usually linked to a variety of factors, some that may have little to do with scientifically quantifiable exposures, doses or documented effects. The perception of a risk can often be just as damaging as its actual presence. Every effort should therefore be made to provide impacted communities with a sound basis for judging the extent of a risk or the lack thereof. The following principles should be carefully considered when proponents and governments expect communities to accept the risks associated with the intrusion of uranium mines onto their lands.

- The most important determinant of acceptability of risk is whether or not that risk is voluntary. The right to say no makes saying yes much more acceptable. Letting people of the north decide was a major theme in numerous presentations.
- The distribution of risks and benefits must be perceived to be fair; those who must endure the greatest risks should reap the greatest benefits.
- Trustworthiness is an essential element in the acceptability of uranium mining. Monitoring committees, composed largely of people from the impacted communities, may be able to provide information that northerners will trust.
- Health risks associated with memorable catastrophic events are more feared. The fact that the world first learned of nuclear technology from Hiroshima and Nagasaki cannot be ignored.
- Health risks from "natural" versus "man-made" sources cannot be compared. The fact that radon levels in basements may be greater than radon levels in some mines is irrelevant to many people.
- A risk is deemed more acceptable if there is a good moral reason for accepting it; conversely, if a risk offends an individual's moral standards, it is unacceptable. The possibility

that uranium mining may contribute to global problems has caused many people to view it as an immoral activity. Few communities would wish to accept a risk that could contribute to the proliferation of nuclear weapons or similar problems.

- Some of the uncertainties regarding the potential long-term health impacts of uranium mining relate to the inherent complexity of the issues and the absence of sufficient study. Education could lead to a better understanding of this industry and a consequent decrease in the uncertainty of its impacts by the public. It is not clear to the panel how this information could best be conveyed nor whether a more sophisticated understanding would lead to better acceptance or more widespread rejection of uranium mining.

Proponents and regulators should take these factors into consideration when they are dealing with impacted communities.

Many people feel an uneasiness when uranium mining is mentioned. They don't have anything definite that they can put their finger on.

C. Bradek, *Transcript of Public Hearings*, Prince Albert, Saskatchewan, April 21, 1993, p. 139.

2.4.2.6 Disease Causation and Community Health Data

Some northerners raised questions about possible links between a wide variety of health problems in their communities and the existence of uranium mines. While some of the health concerns in question are not likely attributable to the mines on toxicological or radiological grounds, a more indirect link may exist. The unexplained increase in congenital **anomalies**,⁶⁷ for example, while based on very small numbers, demands study and consequent prevention. However, the lack of baseline health data on northerners has made the evaluation of the health impacts of uranium mining difficult.

The social health impact of uranium mining, positive or negative, defies assessment without a comprehensive community health study. The panel, therefore, recommends **that a comprehensive health study of northern people be conducted as a "baseline" against which any future impact of uranium mining can be assessed.** This will require a combined effort of federal and provincial authorities, together with extensive participation by the communities. We also urge federal and provincial community health educators to seek better understanding of community perceptions of disease causation and to work with the community leaders to formulate remedial strategies.

⁶⁶ C. Stang, *Transcript of Public Hearings*, Saskatoon, Saskatchewan, May 17, 1993, p. 4.

⁶⁷ J. Irvine, D.C. Gillis, L. Tan, S. Chiu, L. Liu, D. Robson, 'Lung, Breast and Cervical Cancer Incidence and Survival in Saskatchewan Northerners and Registered Indians (1967-86)', (Whitehorse, Yukon: 6th. International Congress on Circumpolar Health, 1990).

Surely, from a common sense point of view, the evaluation of health of people who must frequent either the mines or their environs is more important than any other aspect of mine operation.

B. Forgay, *Transcript of Public Hearings*, Regina, Saskatchewan, March 22, 1993, p. 314.

The Bayda Inquiry, many years ago, came out with the suggestion that there should have been a baseline health study done of northerners before further uranium development proceeded.

D. Dewar, *Transcript of Public Hearings*, Buffalo Narrows, Saskatchewan, April 19, 1993, p. 86.

2.5 Larger Issues

Here we are asked to break down the nuclear industry, frame by frame, to examine only three uranium mining proposals and their artificially discrete impacts. We are asked to view uranium mining as though it occurs in isolation from nuclear power, nuclear weapons, and the scramble to find a high level waste repository in Canada.

S. Fortugno, *Speaking Notes for Public Hearings*, Saskatoon, Saskatchewan, May 17, 1993, p. 5.

2.5.1 Sustainable Development

Saskatchewan's Round Table on Environment and Economy recently published a report outlining eight principles of sustainable development for the province.⁶⁸ Of the principles enunciated (environmental/ economic reality, environmental/economic integration, adaptability, renewability, efficiency, stewardship, sufficiency and accountability), the one most difficult to apply to mining is "renewability". It is, of course, impossible to mine ore in a fashion that is completely renewable. Once the ore has been removed, refined and used elsewhere, it will never again be renewed in the sense, for example, that a forest which has been harvested can be replanted. The report of the Round Table puts it this way:

The concept of sustainable development applies to non-renewable resources in a different way than it does to renewable resources. The mining of any given ore body is not sustainable, but the mining industry as a whole can continue over time. As mineral deposits are mined, new deposits are discovered while new technologies and products reduce the need for these minerals.⁶⁹

⁶⁸ *Conservation Strategy for Sustainable Development in Saskatchewan*, Province of Saskatchewan, 1992, p. 5.

⁶⁹ *Ibid*, p. 29.

In addition, it is possible to apply the principle of renewability in the sense of site decommissioning and reclamation. Restoration of the land, water and air to predevelopment quality will allow nature to again flourish and renew the mine site.

The *Mining Advisory Committee* of the Round Table has expanded on the concept of sustainability as it applies to mining and published a list of seven characteristics of sustainable mining developments, the central one being:

Sustainable mining balances economic growth and protection of the environment by sensible trade-offs that consider all costs and benefits in the decision-making process.⁷⁰

During the public hearings, there was considerable discussion of whether or not uranium mining could be considered a sustainable development. Although the arguments were substantial on both sides of the question, we are of the opinion that uranium mining can, if properly done, meet the criteria of the province as expressed in the report of the Round Table. However, it is clear that whether or not uranium mining will be significant in the future of northern Saskatchewan, it is not indefinitely sustainable and it will not be the entire answer to northern development. Governments would, therefore, be wise to simultaneously promote other forms of economic activity.

If it is indeed the case that northerners are being given a choice only between uranium mines and continued desperate poverty, then I'd say they're being given no choice at all.

J. McPherson, *Transcript of Public Hearings*, Saskatoon, Saskatchewan, May 8, 1993, p. 2.

Several opponents of these projects suggested a variety of possible alternatives to uranium mining (for example, **ecotourism**, fisheries, native crafts, expanded wild rice farms and other forms of agriculture such as berry picking) that are more in keeping with the objectives of sustainable development. However, many of these possibilities are not mutually exclusive with uranium mining and should be actively promoted and encouraged regardless. **The best future for sustainable development in northern Saskatchewan lies in a planned and diversified economy. Uranium mining may be one of its components.**

Many presenters noted that the World Commission on Environment and Development, which popularized the concept of sustainable development, called for a broadening of environmental assessment to include strategic policy issues and their implications. As was noted in section 2.4.2.5, some

⁷⁰ *Sustainable Development in Mining*, Province of Saskatchewan, 1991) p. 3.

presenters have taken issue with the limits of the panel's mandate.

sustainability	<i>Board of Inquiry to choose sustainability d our children and grandchildren.</i>
Regina, Sask.	Taylor, <i>Transcript of Public Hearings</i> , Regina, Sas- katchewan, March 22, 1993, p. 294.

2.5.2 Alternative Energy Sources

Several members of the public pointed out that selection of alternative energy sources could reduce the need for nuclear power and the consequent environmental damage associated with uranium mining. Coal, hydro, natural gas, wind, solar, biomass and geothermal are alternatives that could be considered as possible replacements for nuclear power. However, as detailed in the report of another review panel,⁷¹ each of these possibilities also comes with certain environmental or economic disadvantages—burning coal or natural gas contributes to the greenhouse effect, hydro electric dams cause flooding, wind is site-specific, solar is currently uneconomical, and so on. It is apparent that there are certain risks and trade-offs associated with the generation of power from any source of energy.

There is, however, one approach that is completely benign as far as the environment is concerned; conservation is an effective way of reducing the need for additional energy. It is apparent that this is a favoured option of large segments of the population and it is one that should receive serious consideration from government.

*We do not need nuclear power,
And we do not need uranium mines.
We need to learn to use the
power of the wind and the sun,
And leave consuming ways behind.*

O. Dancer and J. Dancer, *Transcript of Public Hearings*,
La Loche, Saskatchewan, April 20, 1993, p. 50.

2.5.3 Local and Global Economics of Uranium Mining

Representatives from the provincial and federal governments reported that the demand for new uranium ore (in excess of present inventories, fuel stocks from Western countries available for re-processing, and material originating from the former Soviet Union) will exceed supply for at least the next decade.^{72,73} At present, however, nuclear power utilities worldwide maintain an inventory of uranium sufficient to meet power generating demands for a minimum period of two years. Similarly, large proven uranium reserves exist in Australia and countries of the former Soviet Union which could affect the demand for Saskatchewan uranium if they were brought into production. In addition, large uranium ore bodies other than those under current review have been delineated in northern Saskatchewan.

Offsetting potential impediments to the sale of Saskatchewan uranium are factors which will contribute to a slow, but steady, rise in world demand for uranium. According to information provided to the panel, several countries, such as Japan, South Korea and France, are expanding their nuclear power industries and will continue to require additional guaranteed sources of uranium supply. Elsewhere, older nuclear reactors are being dismantled and replaced by fewer but larger units with significantly greater power generating capacities than those which they are replacing.⁷⁴

Australia has a legislated policy restricting production of uranium to only three mines to **minimize** environmental loading and to maintain a high price for the **product**.⁷⁵ Australia also had a floor price policy until about 1988 whereby uranium could only be sold at prices above a certain level, thus assuring minimum guaranteed royalty returns to the government. By restricting the inventory of uranium available for international sale, and maintaining a minimum sale price, Australia limited its capability to produce and sell uranium. This may have favoured Saskatchewan producers.

Existing inventory will ensure a surplus of uranium until at least the middle of the present decade. However, some predictions suggest that supplies of newly-mined uranium will be unable to meet demand in the following ten- to fifteen-year period. Some projections show a steady, though moderate, increase for nuclear power demand, of approximately 1.8% per year until 2010.⁷⁶ Based upon this and varied production scenarios, the average annual growth rate of Western world uranium requirements until 2005 is also estimated to approximate 1%. It is therefore feasible that, after approximately 1995, increased uranium production may be necessary to keep pace with world uranium demand.

⁷¹ *Saskatchewan Electrical Energy Options*, Saskatchewan Electrical Energy Options Review Panel Final Report to SaskPower, November, 1991.

⁷² R. Williams, *Transcript of Public Hearings*, Regina, Saskatchewan, March 22, 1993, p. 207-208.

⁷³ R. Clayton, *Transcript of Public Hearings*, Regina, Saskatchewan, March 23, 1993, p. 222-223.

⁷⁴ R. Williams, *Submission to Public Hearings*, Saskatoon, Saskatchewan, March 22, 1993, Figure 12 and p.(iii) - Summary.

⁷⁵ R. Williams, *Submission to Public Hearings*, Saskatoon, Saskatchewan, May, 1993, p.33.

⁷⁶ R. Williams, *Submission to Public Hearings*, Regina, Saskatchewan, March 22, 1993, Figures 7 and 8.

*... existing operational facilities in the traditional supplier countries cannot meet **projected** Western world reactor requirements. The shortfall in production may be met by the expansion of certain existing operations, by the development of a small number of new projects....*

R. Williams, Submission to Public Hearings, Saskatoon, May 18, 1993, p.34.

The forecast of increased demand implies that uranium prices should remain at, or increase above, present commodity levels. Historically, however, prices have tended to be lower than predicted; no proven method for accurately predicting price levels has been developed.

The panel recommends that control of industry production be considered. As well, the establishment of a minimum pricing policy should be examined. The Australian model permitted that country to retain its share of the world uranium market and to maintain a reasonably high commodity price. If similar pricing controls were to be established in Saskatchewan, the province would **realize** higher royalty returns on the product sold, even if unregulated production throughout the world were to result in a lowering of the international commodity price. With a planned development of Saskatchewan's reserves, sufficient to meet anticipated world demands, the province might retain its share of world production while maintaining a firm product price.

2.5.4 Regulatory Agencies

2.5.4.1 Northern Involvement

There is a perception that regulatory groups, at both federal and provincial levels, deal too intimately with proponents of uranium mining ventures to maintain objectivity. Without participation, northerners feel excluded from the regulatory process.

Regulatory agencies such as Saskatchewan Labour, the Mineral Industry Environmental Protection Branch and the Atomic Energy Control Board appear to have few northern employees. Coincidentally, northern communities lack information concerning mine occupational mishaps, regulation implementation, regulation enforcement and penalty assessment. **Regulatory agencies should endeavour to recruit aboriginals into their operations to mitigate perceptions of bias and to facilitate public confidence.**

2.5.4.2 Harmonization of Government Activities

Many federal and provincial government agencies are involved in the regulation of the uranium mining industry. Although each has a specific mandate, they attempt to work together for the common good of the uranium mining industry and the public. In some cases, regulators may be duplicating effort, at unnecessary cost. Currently, guidelines and regulations governing radiation safety, surface water quality and

other factors exist at both federal and provincial levels. Such regulations may have differing standards, and may not incorporate the most recent internationally-recognized limits. **The panel perceives a need for the harmonization of federal and provincial activities relating to mine regulation and enforcement.**

2.5.4.3 Foreign Ownership

A 50% Canadian ownership rule applies to all companies operating in Canada. This regulation states that companies which are more than 50% owned by foreign nationals (Cogema and Total Minatco, for example) require either special dispensation (called *grand-fathering* for previously-operating companies) or federal ministerial waivers. **All proponents, venture participants and operating uranium mining companies which are being reviewed in this report have been exempted from the ownership regulations, with the result that approval of these projects would place a substantial portion of the uranium industry under the control of foreign ownership.** Some presenters stated that this is an unhealthy situation and that federal ministerial waivers should be used more restrictively.

2.5.5 The Nuclear Fuel Cycle

We regard the nuclear industry as the major health hazard to the people of the world. . .

M. Repo, Transcript of Public Hearings, Saskatoon, Saskatchewan, May 19, 1993, p. 249.

2.5.5.1 Nuclear Power

The concept of nuclear energy as a source of power is one with a relatively short history of application; it is also the least understood and least trusted of all available energy options. Despite the observation that nuclear power does not contribute to atmospheric pollution by the production of carbon dioxide and other flue gases, significant public concern about nuclear power issues was communicated. For example, the report of another panel, referred to us, notes:

It should be clearly appreciated that there are widely held and deeply felt concerns about nuclear safety, waste disposal and other issues which must be recognized and addressed. . . There are. . . some fundamental philosophical objections to nuclear power generation which are held by a significant proportion of the general public. These concerns are much broader than the generation of electrical energy within Saskatchewan. They initiate with the mining of

uranium in Saskatchewan and its utilization in various forms throughout the world.⁷⁷

2.5.5.2 Non-Proliferation Treaty

Although nuclear weapons proliferation is outside the mandate of the panel review, many participants expressed concern regarding this topic. Many perceive the end uses of Saskatchewan uranium to be detrimental to the general public good. Rather than being used solely to benefit society through power/energy production, uranium is and has been seen to be **utilized** for weapons production.

...perhaps the greatest shortcoming of Saskatchewan's involvement in uranium mining is that any benefits gained from uranium mining are experienced by the current generation of Saskatchewan residents while the problems created are left behind for future generations of Saskatchewan residents and citizens of the globe to grapple with.

P. Prebble, Transcript of *Public Hearings*, Regina, Saskatchewan, March 23, 1993, p. 291.

Participants noted that specific proponents, such as Cogema, are wholly-owned subsidiaries of foreign governments heavily involved in military weapons research, fabrication and testing. Accordingly, mining proponents are viewed as a direct part of the chain leading to weapons production. Should such companies be given approval for mining, they will continue, in the perception of some members of the public, to enhance the development of weapons and promote proliferation. The **Nuclear Non-Proliferation Treaty**, of which Canada is a signatory, prohibits the use of uranium in the production of enriched uranium for military applications. However, there is no process whereby exported Canadian uranium can be separated from uranium derived from other sources. Therefore, no proven method exists for preventing incorporation of Canadian uranium into military applications.

Current Canadian limitations on end uses of uranium provide no reassurance to the public that Canadian uranium is used solely for non-military applications by purchasers. **The panel wishes to bring concerns related to the possible use of Saskatchewan uranium for weapons to the attention of the government.**

2.5.5.3 High Level Waste Disposal

Many members of the public perceive that there is no safe method of long-term storage or disposal of nuclear fuel wastes. Under existing regulations, used nuclear fuel from Canadian reactors is stored at the reactor site either by submerging it in water pools, or by placing it in above-ground

caskets. Such storage requires continuous monitoring and care by site staff in perpetuity.

A generic **waste storage** concept is the subject of review for a separate FEARO panel.⁷⁸ Intended for permanent disposal, the concept is based on a non-retrievability scenario with nuclear fuel waste being placed in deep underground repositories.

Neither nuclear waste storage nor an examination of the Canadian nuclear fuel storage concept is part of our panel's mandate.

2.5.6 Joint Review Process

Members of the public raised the following specific concerns about the efficacy of the Environmental Assessment Review process for judging the proposals submitted.

- The degree of participation by provincial and federal government departments was uneven. The panel received considerable technical information from some government agencies, but was unable to obtain sufficient information from others. Of the information received, some was extensive, technically suitable and well prepared, whereas other information was of limited benefit to either the public or the panel.
- Some participants found the length of time provided during technical sessions insufficient for asking questions and obtaining information from available experts. Similarly, technical presenters did not always have sufficient time to present all relevant information or to respond to public and panel questions.
- Some participants were concerned that undue emphasis would be placed on technical rather than non-technical considerations such as values, theological and spiritual beliefs, morality, and fairness. The panel has endeavoured to ensure that this was not the case.
- In the northern communities visited, only the proponents were allotted time to make presentations at each and every location. Since the proponents presented primarily the beneficial impacts of the proposals, an unrealistic image may have been created for members of the public. The suggestion was made that, if opponents of proposals were given similar time to present the negative factors of the proposals, fairer public consideration of issues could be achieved.
- The panel maintains its position that procedures which permitted only local residents to make presentations at community public hearings were fair and just. This participation format avoided public appearances by out-of-community residents that would have been repetitive for the panel. At many sites, due to the large number of local participants eager to make presentations, the addition of extra-community speakers would have taken up considerable time, and might have inhibited local participation.

⁷⁷ *Saskatchewan Electrical Energy Options*, Saskatchewan Electrical Energy Options Review Panel Final Report to **SaskPower**, November, 1991, Section 3.3.2.4, p. 21-22.

⁷⁸ Environmental Assessment Panel on the Nuclear Fuel Waste Management and Disposal Concept.

- A concern was raised that only three of the uranium mining proposals were being reviewed at this time, with other mining proposals being reviewed separately. Particular concern was expressed that it might not be possible to **properly** assess cumulative effects.
- The lack of legal process by which the public hearings were conducted was considered a positive feature. In particular, members of northern communities participated with less perceived restraint. The panel believes that legal procedures during public hearings require considerable expense to develop and maintain, and inhibit public input.
- The EIS review process should be streamlined to prevent unnecessary and lengthy delays in the approval or rejection process. Present review intervals may take in excess of **3-5** years. In the Midwest Joint Venture proposal, for example, initial project review began in 1989, and has only now reached the public hearing review phase. Proponents are concerned that lengthy review processes may detrimentally affect the economic viability of ventures. Fixed contract intervals and development start-up schedules often determine the financial success of ventures, as well as the long term cost to establish, maintain and conduct the EIS review itself.
- Many of the recommendations of the earlier Key and Cluff Lake inquiries, following public consultation and reviews similar to those conducted by this panel, have not been acted upon. The public perception is that recommendations made by the present panel may also not be acted upon by government. This would defeat the intent of the review process and negate the considerable efforts made by the panel, members of the public, proponents, and government departments to conclude a full and fair review.

Future environmental review panels and both federal and provincial branches of government should evaluate these public concerns. Government response should be prompt to all issues brought forward in this report. Reasons for accepting or rejecting recommendations should be clearly stated for public dissemination.

... the frustrations you may hear today...is because there's been so many promises, so many panels, but basically nothing has been done.

His Worship **B. Belanger**, *Transcript of Public Hearings, Ile-à-la-Crosse, Saskatchewan, April 16, 1993, p. 36.*

2.5.7 Public Acceptance of Uranium Mining

A public opinion survey ascertained that approximately **three-quarters** of the provincial population were in favour of the continuation of uranium mining.⁷⁹ It was noted that **women were less supportive than men. General opposition to this industry by 25% of the population suggests that opponents can not be dismissed as a small group of environmental or anti-nuclear activists. Moreover, as noted by one presenter, a *Star Phoenix* poll found that more than two-thirds (67.4%) of the respondents did not want uranium sold for use in nuclear weapons.**⁸⁰

The "deep ecologist" view would suggest that a moratorium on all such activity be instituted; persons should strive to live in harmony with the pristine environment, avoiding any potential for disruption. On the other hand, the "pragmatic" view suggests that poverty is currently a greater threat to the health of northerners than is radiation.

Ideally there should be no necessity to choose between jobs and the environment; sustainable development principles suggest that the two can coexist. Some environmentalists argue that uranium mining could be rejected, with the needed economic development provided through alternative **non-mega-project** options. Uranium mining proponents, on the other hand, insist that the environment can be maintained and restored to an almost pristine state, posing no direct or indirect threats to human health or well-being.

Thus, the philosophy brought to the specific recommendations in the following chapters is one of proceeding with cautious development. This should be done to ensure the maximum benefit to the people of Saskatchewan, and particularly to the impacted communities.

Saskatchewan is a leader in the uranium industry. It has developed competitive mines, a highly skilled workforce, and the technical expertise second to none.

E. J. Hinz, *Transcript of Public Hearings, Saskatoon, Saskatchewan, May 14, 1993, p. 271.*

⁷⁹ D. Fast, *Transcript of Public Hearings, Saskatoon, Saskatchewan, May 4, 1993, p. 233-246.*

⁸⁰ *Star Phoenix*, October 22, 1988, p. 1.

3.0 THE DOMINIQUE-JANINE EXTENSION

3.1 Project Description and Site Map

The Cluff Mining Partnership is seeking authorization for an extension to its open pit mining operation at Cluff Lake. The Cluff Mining Partnership is comprised of Cogema Resources Ltd. (80%), which is the operator of the partnership, and Corona Grande Exploration Corporation (20%). In the balance of the report, Cogema Resources Ltd. will be referred to as the responsible party for the proposal under review.

The proposed Dominique-Janine Extension is approximately 75 km south of Lake Athabasca and 15 km east of the provincial border with Alberta, in the southern portion of the **Carswell Structure**. The water systems in the area of the site drain through interconnected lakes and small rivers into the Douglas River, which flows northwest, eventually emptying into Lake Athabasca.

Since early 1980, the Cluff Mining Partnership had been mining and milling ore from several deposits adjacent to the proposed Dominique-Janine Extension. Open-pit extraction of ore from the northern part of the Dominique-Janine ore body began in early 1989, and was completed by the end of December, 1991.

Data from a drilling exploration program indicated that the zone of mineralization for the Dominique-Janine ore body extended continuously southward from the open pit to the edge of Cluff Lake. Mining this additional mineralization, a **10-million cubic metre open pit project**, is the purpose of the **Dominique-Janine Extension** proposed for review by Cogema (see figure 2).

The Dominique-Janine Extension, approximately 650 m long by 350 m wide, would extend **100-150 m** into Cluff Lake. The southern rim of the pit would be approximately 25 m below the current lake level, and the final pit floor might be as much as 125 m below. Construction of a perimeter dam around the southern rim of the Dominique-Janine Extension open pit, to control the inflow of lake water into the pit, has been proposed. Dewatering wells would be installed between the dam and the pit rim to control seepage which might pass under or through the barrier wall; water collected in these wells during the mining period would be pumped back to Cluff Lake. Additional rock mined from the proposed extension would be placed under water in Cluff Lake. Although the original EIS envisaged also putting special waste in the dike, the revised project description proposes to dispose of the special waste in the mined-out Claude Pit. The rationale for underwater waste disposal is to minimize oxidation of the waste rock and subsequent generation of acid.

During decommissioning, Cogema proposes the reclamation and revegetation of ground surface areas after the removal of all constructed surface structures and buildings. Accumulated waste rock in Cluff Lake would create a new dry land area which would also be reclaimed and vegetated. The dam structure would be left intact, with water flooding the pit progressively until the level reached that of Cluff Lake. Cogema would

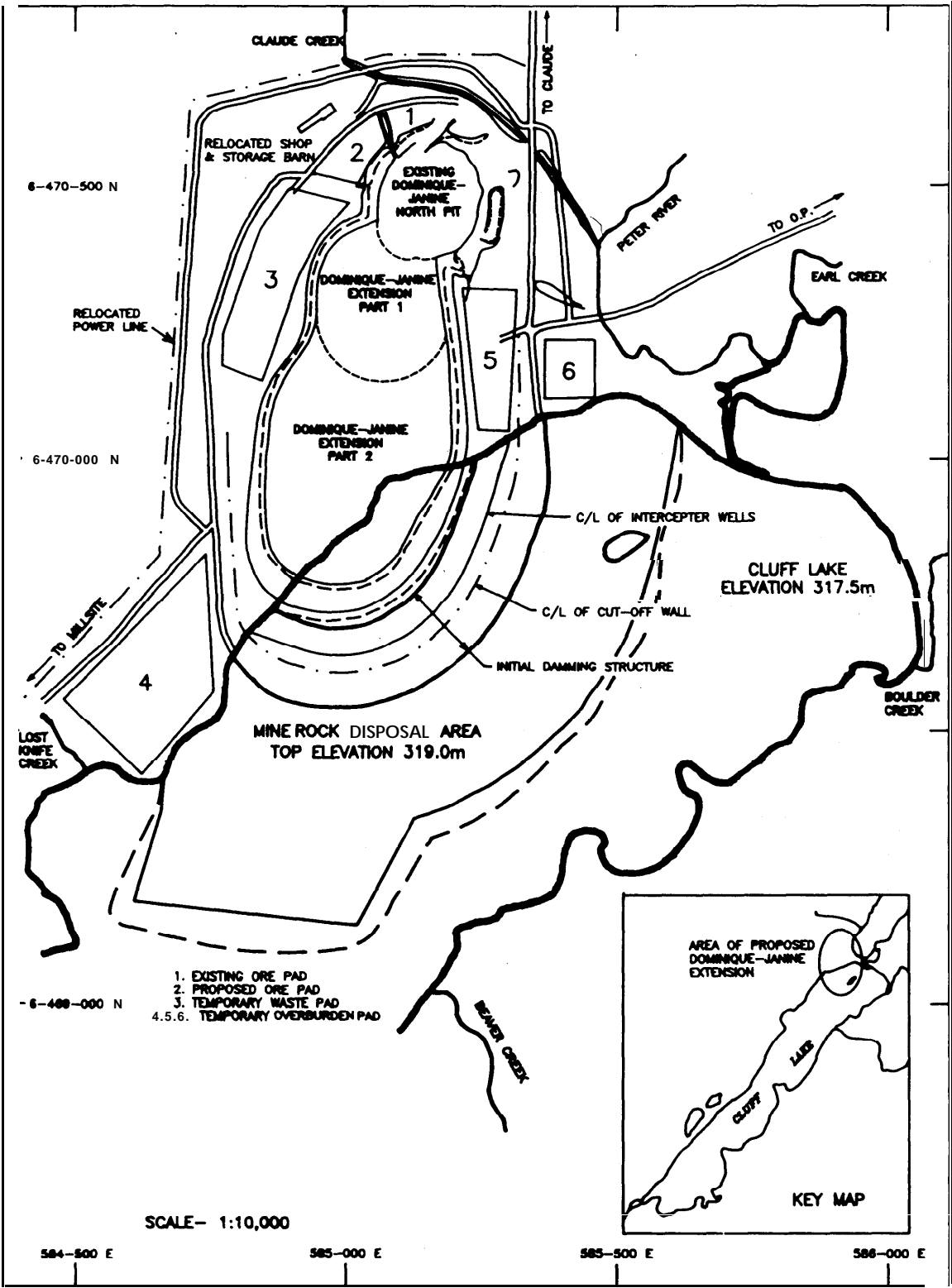
monitor the quality of the pit water until provincial regulatory limits were met. At that time, it is proposed that a channel be constructed to connect the pit with Cluff Lake.

3.2 Recommendations

The socio-economic benefits associated with this proposed extension to the Dominique-Janine mine at Cluff Lake will be significant. The health and environmental risks, incremental to those already in existence, could be reduced to acceptable limits provided certain conditions are met. The proponent has, in the past, demonstrated respect for the local environment, concern for worker health, and interest in the socio-economic well-being of the residents of the impacted communities. With the expectation that these positive attitudes will continue, we recommend approval of this project subject to implementation of the following conditions:

1. establishment of a new Human Resource Development Agreement in which Cogema be required to select a minimum of 50% of its new employees from residents of the primarily-impacted communities and a minimum of 30% from residents of the secondarily-impacted communities. These conditions should also apply to contractors and sub-contractors;
2. agreement on a form of revenue sharing that is acceptable to the majority of the impacted communities;
3. establishment of a monitoring committee (as described in section 2.2.6) for the Cluff Lake Mine;
4. provision of a financial guarantee to cover decommissioning and post-decommissioning costs;
5. adoption of the exposure standards recommended in Publication 60 of the International Commission on Radiation Protection (ICRP-60) without allowing the collective dose to increase;
6. completion of a review of worker health training programs;
7. establishment of mechanisms for conducting an **epidemiological** study of the health of current and former workers at the Cluff Lake mine;
8. establishment of an air quality monitoring program using moss pillows and development of a system for monitoring the quality of the groundwater in the vicinity of the Claude pit;
9. evaluation and selection of a different option for deposition of waste rock. Only innocuous waste should be disposed of in Cluff Lake. Options for disposing of other waste rock in the Claude and Dominique-Janine pits should be evaluated. The Claude pit should be decommissioned by filling it with rock capped by clean overburden;

Figure 2
Dominique-Janine Extension



10. establishment of a research fund to support the search for innovative ways of reducing the volume of effluent released and the quantity of chemicals required to treat contaminated water;
11. development of site-specific water quality objectives, establishment of a program to reduce contaminated mine water inflows, and assessment of the possible impacts to the Island Lake watershed;
12. specification of total environmental loading for the mine, and development of a material-balance for contaminants in all liquid effluent;
13. evaluation of alternative oxidants that could replace sodium chlorate in the leaching process and thereby permit recycling of mill effluent;
14. use of the Environmental Transfer Pathway model (ETP/AECB) as the focus for an integrated monitoring program, and the assessment of cumulative effects;
15. agreement that the decommissioned Dominique-Janine pit not be connected to Cluff Lake, and that Claude Creek not be rerouted to flow through the decommissioned pit; and
16. evaluation of alternative methods of tailings disposal, with the goal of closing down the present tailings management facility as soon as possible.

3.3 Biophysical Concerns

3.3.1 Air Quality

Public concern over the release of radioactive dust and radon (along with the subsequent deposition of radon progeny) has been discussed in section 2.3.3. This concern could be assessed more critically if a better designed monitoring program were prepared.

The results of monitoring air quality at Cluff Lake have been reviewed by Swanson⁸¹ who concluded that high-volume sampling should be continued, but that the use of dustfall jars for monitoring aerial deposition should be replaced by a system using "lichen/moss pillows". Preliminary use of the latter in 1985-86 yielded interesting results. Some data suggest that most aerial deposition of contaminants occurs within 3 km of the mill but other data indicate a much larger radius of deposition. A better designed monitoring program would settle this issue.

The panel recommends that air quality monitoring be augmented by the use of "moss pillows" to map the aerial deposition of contaminants. Such a procedure need not be conducted yearly, but could be part of a comprehensive system of ecosystem monitoring conducted two or three times each decade.

⁸¹ Swanson, *Cluff Lake: Status of the Environment Report*.

⁸² *Review of the Cogema Environmental Impact Statement, Dominique-Janine Extension, Addendum A and B*, Atomic Energy Control Board, submission to the panel, March 18, 1993, p. 2.

3.3.2 Hydrogeology

Cogema proposes to dewater the extended Dominique-Janine (D-J) pit using interceptor wells in the dam and pumping from sumps in the bottom and walls of the pit. Uncontaminated water would be discharged into Cluff Lake, and contaminated water diverted for water treatment before discharge into Island Lake. The volume of contaminated mine-water that would require treatment prior to discharge to the environment is not known at this time. There is a possibility of exceeding the capacity of the water treatment facility; it would need to be more than doubled if all of the intercepted water required treatment. Cogema has stated that it would expand the water treatment plant, if necessary, but has not evaluated the overall impacts to the aquatic environment should this scenario become a reality. The panel notes that this concern is shared by the AECB⁸² and will, therefore, be addressed during the normal licensing procedure. A recommendation to reduce the volume of contaminated mine-water inflow is made in section 3.3.4.

There is also a concern that water from Claude pit, which will have special wastes placed in it, may flow and pollute nearby water bodies.⁸³ **The panel recommends that groundwater around Claude pit be monitored to determine if contaminants would move from the pit.**

3.3.3 Waste Rock Management

For management purposes the waste rock is classified into one of three categories: special waste (containing 0.05%-0.1% U_3O_8 , and readily soluble material); other waste rock, with a potential acid-generating capacity; and clean waste rock. The clean waste rock would be used to construct a dam to separate the D-J pit from Cluff Lake; the special waste would be placed in the mined-out Claude pit and covered with till or other waste rock; and the bulk of the other waste rock would be placed in Cluff Lake to form a large flat area reaching to 1-2 m above lake level. The objective of the subaqueous disposal for the majority of the waste rock is to prevent its oxidation and subsequent generation of acid.

There are three main concerns. First, the classification of waste rock is an issue. The Mineral Industry Environmental Protection Branch of Saskatchewan considers special waste to be 0.03%-0.1% U_3O_8 rather than the criterium used by Cogema. In addition, it may be difficult to separate clean waste rock from waste rock with acid-generating potential under field conditions. Second, the placement of the bulk of the waste rock in Cluff Lake may cause problems of turbidity that would adversely affect the water quality of the lake. Third, if the disposal of rock in Cluff Lake fails to prevent acid generation, it would be an extremely difficult problem to mitigate.

These concerns, together with others relative to the decommissioning plans for the D-J and Claude pits (see section 3.3.8), would be addressed if all of the waste rock, with the

⁸³ *Technical Review of the Dominique-Janine Extension*, Department of Fisheries and Oceans, submission to panel, January, 1993.

exception of that required for the dam, were disposed of in the Claude and mined-out D-J pits. Special waste could be disposed of in both pits allowing Claude to be decommissioned prior to the complete excavation of the D-J extension. With a suitable cover of clean overburden, it might not be necessary to separate innocuous and potentially acid-generating waste rock. Waste rock disposed of in this fashion would not be exposed to atmospheric oxygen, nor subject to wind and wave erosion, as would be the case if it were placed in Cluff Lake.

The panel recommends that only innocuous waste be disposed of in Cluff Lake and that options for disposing of other waste rock in the Claude and Dominique-Janine pits be fully evaluated. The Claude pit should be decommissioned by filling it with rock, capped with clean overburden, as opposed to allowing it to flood.

3.3.4 Surface Waters and Fisheries

The panel has requested additional information on the Island Lake watershed (specifically on cumulative environmental impacts, aquatic community structure, aquatic bioaccumulation, and predicted impacts to the aquatic environment).⁸⁴ The proponent is currently conducting a field study, but the final report will not be available until the end of 1993 or early 1994.⁸⁵ The panel notes, however, that sufficient background information to assess impacts to the Island Lake watershed will have been collected prior to any expansion of mining at Cluff Lake and recommends that the regulatory agencies evaluate the impacts before a licence is granted.

Issues relating to the release of liquid mine effluent (in this instance into the Island Lake watershed) are discussed in section 2.3.2. That section provides the rationale for the following three recommendations. First, the panel recommends that the Cluff Lake mine participate in the establishment of a research fund to support the search for innovative ways of reducing the volume of effluent released and the quantity of chemicals required to treat contaminated water. Second, the panel recommends that site-specific water quality objectives be developed for the Cluff Lake mine. Third, the panel recommends that the total environmental loading be specified for the Cluff Lake mine and that a material-balance be developed for all contaminants in the liquid effluent.

There are two further specific recommendations related to reducing the volume of effluent. First, it may be possible to reduce the volume of contaminated mine-water inflow by placing a network of dewatering wells around the entire pit, not just in the dam structure. If the intercepted water were sufficiently clean to be released directly into Cluff Lake, effluent loading to the Island Lake watershed would be reduced. The panel recommends that attempts be made to reduce contaminated mine-water inflows. Second, because the Cluff Lake mill uses sodium chlorate as an oxidant in the leaching circuit, the mill effluent contains a high chloride content and,

therefore, cannot be recycled. There may be alternative oxidants that could be used in the leaching circuit which would allow the mill effluent to be recycled, thereby reducing effluent loading to the receiving environment. **The panel recommends evaluation of alternative oxidants that could replace sodium chlorate in the Cluff Lake mill.**

3.3.5 Wildlife and Terrestrial Habitat

It is unlikely that the D-J extension by itself would have major impacts on the terrestrial environment. Rather the concern is with possible cumulative effects (see section 3.3.7) and whether certain rare plants, that are known to occur in the Cluff Lake area, might be affected by mining activity. The panel notes that Cogema Resources Ltd. has undertaken an inventory of rare plants around Cluff Lake, the results of which should be available to the regulatory agencies before licences to proceed are granted.

3.3.6 Monitoring

The panel's general recommendations on monitoring are dealt with in section 2.2.6. Some of the particulars of air quality monitoring have been recommended in section 3.3.1. Monitoring of the aquatic environment should focus on the Cluff Lake drainage system and the Island Lake watershed. In keeping with the arguments advanced in section 2.3.1, the panel recommends that the Environmental Transfer Pathway model (ETP/AECB) be used as the focus for integrating the monitoring program at Cluff Lake. The general design of the monitoring program should be common to all uranium mines. This will guarantee the consistent replication of treatments required to determine biological effects monitoring and eventually produce the database necessary for the study of cumulative biophysical impacts.

3.3.7 Cumulative Effects

The location of the Cluff Lake mine is such that cumulative biophysical effects involving other uranium mines are likely to be so small as to be undetectable. Thus, the cumulative effects of concern will be those involving a single mine; these have been discussed in section 2.3.6.

Probably the most significant cumulative effect at Cluff Lake would be that generated by the liquid effluent over time. Metals and radionuclides are being concentrated in the sediments and it is not known how this would impact aquatic ecosystems in the Island Lake watershed (see sections 2.3.6 and 3.3.4). **The panel recommends cumulative effects be assessed using the ETP/AECB model and that a whole ecosystem approach to monitoring be adopted, as specified in section 2.3.1.**

Sediment quality guidelines should be established, as discussed in section 2.3.6.

⁸⁴ Request for Additional Information on the Dominique-Janine Extension, Joint Federal/Provincial Panel on Uranium Mining Developments in Northern Saskatchewan, October, 1992.

⁸⁵ Dominique-Janine Expansion Project Request for Additional Information by the Joint Federal/Provincial Panel, Terrestrial Aquatic Environmental Managers Ltd., May, 1993.

3.3.8 Decommissioning and Site Reclamation

Cogema proposes to decommission the mined-out **Dominique-Janine** pit by allowing it to fill with water. Once the quality of the pit water meets the Saskatchewan Surface Water Quality Objectives, the proponent plans to breach the dam wall, connect the flooded pit to Cluff Lake, and to reroute Claude Creek so that it drains through the flooded pit.

As indicated in section 3.3.3, the panel recommends that the Claude pit be filled with waste rock and capped with till. The balance of the waste rock would then be deposited in the D-J pit. However, since there would not be enough rock to completely fill the D-J pit, it would be partially flooded. In such an event, it is recommended **that the Dominique-Janine pit not be connected to Cluff Lake and that Claude Creek not be rerouted to flow through the decommissioned pit.** Containment of contamination is more desirable than dilution.

There is also concern about the long-term containment of tailings and associated contaminants in above ground structures (see section 2.3.4). **The panel recommends that Cogema evaluate alternative methods of tailings disposal that are less subject to surface erosion and infiltration by precipitation than the present tailings management facility.** The objective is to close down the use of the present tailings management facility as soon as possible.

The need for a decommissioning fund, guaranteed to be available regardless of the financial capabilities of the mine owners, has been discussed in section 2.3.5. In keeping with the arguments advanced therein, it **is recommended that a financial guarantee to cover decommissioning and post-decommissioning costs be secured before the D-J Extension is approved.**

3.4 Socio-Economic Concerns

With the economic times so uncertain, mining and exploration in northern Saskatchewan is one of the very few bright spots the province has.

L. Wolkowsky, *Transcript of Public Hearings, La Ronge, Saskatchewan, April 16, 1993, p. 24.*

3.4.1 Human Resource Development Agreement

During the public hearings, Cogema indicated that it anticipated a large percentage of the new employees for the expansion of the D-J pit would be **northerners.**⁸⁶ **It is, therefore, recommended that a new Human Resource Development Agreement be established in which Cogema be required to select a minimum of 50% of its new employees from residents of the primarily-impacted communities and a**

minimum of 30% from the secondarily-impacted communities. (A further rationale for this recommendation can be found in section 2.2.2.)

3.4.2 Revenue Sharing

The need for governments to establish a mechanism for sharing revenues with the impacted communities has previously been discussed in section 2.2.1 and it is **strongly recommended that the Dominique-Janine Extension not be allowed to proceed until a form of revenue sharing, acceptable to the majority of impacted communities, has been agreed upon.**

3.4.3 Monitoring Committee

The establishment of a monitoring committee for the mine site would provide a mechanism through which the public could receive information from an independent source about the operation of the mine with respect to biophysical impacts, results of health studies, compliance with regulations, employment practices and other economic opportunities for northerners. **It is, therefore, recommended that the provincial government establish a monitoring committee (as described in section 2.2.6) for the Cluff Lake mine.**

3.5 Health Concerns

3.5.1 Occupational Health

The panel was favourably impressed with the safety record of Cogema, and with its efforts to train workers regarding health hazards. However, it is important to continue to promote the highest possible level of worker health, safety and well-being. The proponent's commitment to this area, along with the involvement of its union, the vigilant efforts of the regulators, and the watchful eye of a community monitoring committee should permit this project to proceed with an acceptable degree of risk.

The general comments in section 2.4.1. apply to this project as well. Specifically, **the exposure standards recommended in ICRP-60 should be adopted, without allowing an increase in the collective dose, and mechanisms for conducting an epidemiological study of worker health should be promptly put into place.**

The workers from Cogema who appeared before the panel spoke highly of the worker monitoring and notification program at Cluff Lake. **Nonetheless, the panel believes that improvements can be made in worker notification; i.e. by providing more easily understandable explanations of the significance of the reported numbers.** Consultation with adult educators in the impacted communities may assist the authorities at Cluff Lake in identifying methods to best accomplish this goal. The proponent should also ensure sufficient availability of occupational health practitioners to address worker health concerns.

⁸⁶ M. Poissonnet, *Transcript of Public Hearings, La Loche, Saskatchewan, April 20, 1993, p. 132.*

3.5.2 Community Health

The proponent has made efforts to inform the impacted communities concerning mine issues. With the assistance of the

proposed monitoring committee, similar attention should be directed to the other health concerns discussed in chapter 2.

4.0 MIDWEST JOINT VENTURE

4.1 Project Description and Site Map

At the time public hearings began, Denison Mines Limited, as project operator for the Midwest Joint Venture (MJV), was seeking approval to develop an underground uranium mine at South **McMahon** Lake. The MJV was comprised of Total Minatco Ltd. (56%), Denison Mines Limited (19.5%), OURD [Canada] (4.5%), and Uranerz Exploration and Mining Limited (20%). During the hearings, the panel learned that Cogema Resources Ltd. would be purchasing the project. At the close of the public hearings on May 20, 1993, the panel was unclear with respect to the ultimate ownership of the Midwest Joint Venture.

The uranium deposit which MJV proposes to develop is located close to Points North and about 20 km west of the **McClellan** Lake site. It is connected to Highway 905 by a 2 km local access road.

Mineralization was discovered in 1977 and by 1980, 442 holes had been drilled in an attempt to delineate the deposit. An Environmental Impact Statement was submitted in 1981 for a proposal including open pit mining and on-site milling of the ore. A formal review was not initiated in 1981, due to a corporate decision to defer development of the project. Ownership of the project changed in 1987 with Midwest Joint Venture acquiring the property and becoming the operator.

Midwest Joint Venture obtained approvals in 1988 to proceed with an exploration program to assess underground conditions including the geotechnical and hydrogeological environment, and to gather data to evaluate potential mining methods. MJV's 1991 proposal and its subsequent amendment are based on information collected from the test mining project.

In 1991, Midwest Joint Venture applied for approval to construct and develop an underground mine, a mill and a tailings disposal area. This proposal was amended in September, 1992, to reflect the decision by the MJV and Total Minatco to develop their respective ore bodies on a complementary basis. The Midwest Joint Venture now proposes to mill its ore at the proposed **McClellan** Lake mill or at Cameco's Rabbit Lake mill. Its tailings would be disposed of in either the JEB open pit, (enlarged to provide the required capacity), or the Rabbit Lake pit. The MJV proposal now also includes the building of a plant at the mine site for treatment of contaminated surface and underground water (see figure 3).

The Midwest ore body lies under the Mink Arm of South **McMahon** Lake. Because most of the exploration holes drilled into the ore body were not cemented off, it is proposed that Mink Arm be dewatered to minimize flow of surface water into the underground workings.

The shaft sunk for the test mine would be deepened a further 60 metres, and used for initial underground development from

the west side of Mink Arm. This shaft would later become the primary ventilation exhaust shaft, in conjunction with a smaller shaft specifically constructed for additional ventilation capacity. A production/air intake shaft would also be sunk to a depth of 220 metres on the east side of Mink Arm.

It is proposed that the mine would be developed on three levels: the drill level, the haulage level, and the drainage level.

Ore mining would occur during a six-month "summer" period. The main Midwest ore body, with an average grade of 6.2% uranium, would be mined from above, with drillers protected from radiation by a layer of barren rock. High grade ore would be removed on a lower level by shielded or remotely operated machinery. Lower grade ore would be mined manually by benching, a modified conventional method.

Ore would be either transferred directly to trucks for haulage to a mill, or stockpiled temporarily on the surface near the headframe.

4.2 Recommendation

The Midwest Joint Venture project, as described in the EIS and its Amendment, is not acceptable; the benefits that could be obtained are insufficient to balance the perceived risks. It is, therefore, recommended that permission to proceed should not be granted for reasons summarized in the following sections.

4.3 Potential Risks

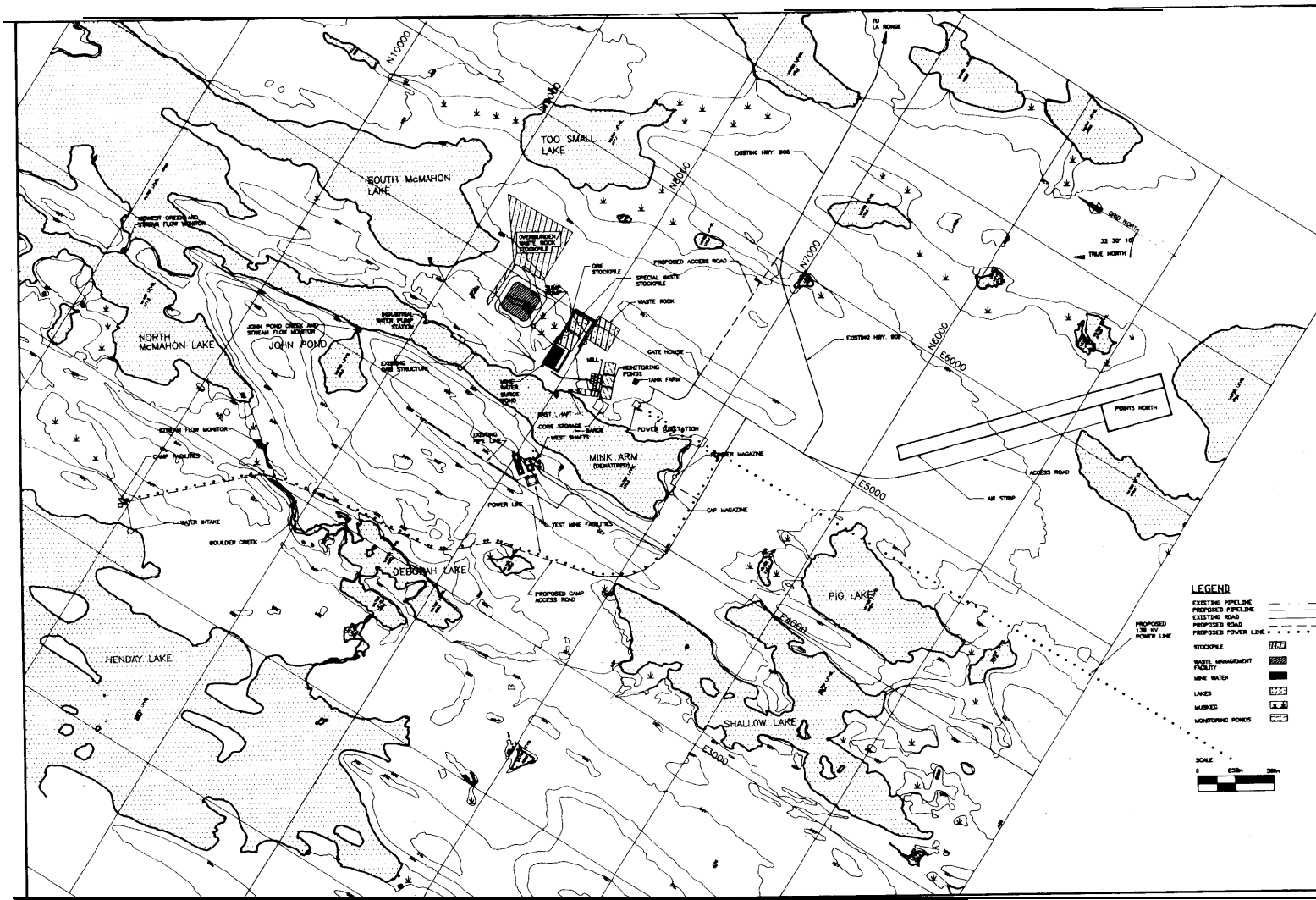
Presenters at the public hearings raised several concerns about the acceptability of this project. Those project-specific concerns determined to be most significant include:

- the use of unacceptable mining methods;
- mining, in confined underground spaces, of an ore that contains high concentrations of uranium, arsenic and nickel;
- the existence of over 600 exploration bore holes, most of them uncapped, in the vicinity of the ore body;⁸⁷
- the need to transport high grade ore on a public highway;
- the potential for environmental damage through the release of contaminated effluent into the Smith Creek watershed and the need to dewater an area of several square kilometres around the mine site;
- uncertainties in the disposal of mill tailings containing high concentrations of toxic heavy metals; and
- the contribution of this proposed mine to the combined effects of all of the mines (existing and proposed) in a relatively small area on the west side of Wollaston Lake.

between 1978 and 1980; and on page 5-I 1, the number has increased to "more than 600", due to additional exploration.

⁸⁷ Midwest Uranium Project Environmental Impact Statement, August, 1991, Volumes 1 and 2. On page I-I, it states that three holes were drilled in 1977; on page 1-2, it mentions 439 more

Figure 3
Midwest Joint Venture Site Plan



Each of these concerns and their attendant risks is briefly discussed below.

4.3.1 Unacceptability of Mining Methods

Midwest Joint Venture proposes the use of two underground mining methods for ore extraction. The first technique, a standard manual benching method that requires direct worker access, is proposed for use in low grade ore zones. The second, the Nqn-Entry Vertical Panel (NEVP) method in which workers are not in direct contact with the ore, is proposed for mining in higher grade ore zones. For manual benching, some mining analogs exist at the Cluff Lake Mine where it has been shown that implementation of appropriate ventilation and dust control strategies can restrict worker radiation exposure to acceptable limits. However, MJV has indicated that the average geological grade of low-grade ore approximates 1.8% U_3O_8 with some spot grades being higher? The indicated low-grade ore composition is approximately double that of Cluff Lake ore and eighteen times that of the average ore grade mined in Elliot Lake, Ontario. The EIS does not justify the use of the manual benching method nor satisfactorily indicate ore grade limits to differentiate site selection between the two principal mining techniques. Thus, the proposed benching method would expose workers to elevated risks due to gamma radiation and radon progeny.

During test mining of the Midwest deposit, high grade ore was removed using the blind raise boring technique. However, this method was eventually rejected for full-scale mining in favour of the NEVP method proposed in the EIS. Using this technique, underground workers are restricted from direct access to the **orebody** by a considerable thickness of inert waste through which remote drilling of blast holes and ore extraction operations are conducted. Broken ore is removed on an underlying haulage level utilizing either remotely controlled or shielded equipment. Any mechanical breakdowns of equipment, excavation failures or ore blockages at extraction sites would, however, require worker access to the equipment and sites to permit removal and repair. Under such conditions, workers who are not adequately shielded, either by design or by accident, would be likely to incur excessive gamma exposure.

Substantial risk to worker health is, therefore, associated with the proposed mining methods.

4.3.2 Radiological and Chemical Toxicity of the Ore

The MJV ore reserves, currently estimated at 361,000 tonnes, contain high concentrations of both arsenic (As) and nickel (Ni) as well as uranium (U).⁹⁰ Typical core samples contained

1.08 - 9.62% As, 0.94 - 4.80% Ni and 0.25 - 11.8% U.⁹⁰ Since arsenic and nickel are toxic and uranium is both toxic and radioactive, inhalation or ingestion of ore dust could cause chemical and radiological health impacts on the workers. All three exposures (arsenic, nickel and alpha radiation) have been linked to elevated risks of lung cancer, as discussed in section 2.4.1.

Of particular concern is the possible synergistic effect resulting from occupational exposure to high concentrations of both uranium and arsenic as discussed in section 2.4.1.2. The potential health risk when all three exposures are present has not been adequately studied. In confined underground spaces, workers might undergo continuous exposure to toxic, radioactive dusts causing an unacceptable level of occupational health risk.

4.3.3 Uncapped Bore Holes

During the exploration phase of this project, over 600 bore holes were drilled in an attempt to define the location and quality of the ore body. These holes, the majority of them remaining uncapped and open, now present a **sizeable** risk to the health of miners attempting to remove ore from below, as they create a potential for unrestricted flow of surface and subsurface radioactive water into the mine **workings**.⁹¹

Ground water at the Midwest Joint Venture site characteristically exhibits the presence of high concentrations of radon which can pose serious worker exposure and health problems if adequate interception and drainage is not provided. Despite the proposed dewatering of Mink Arm, significant groundwater inflows would continue to occur through the overlying, altered Athabasca sandstones, especially during the development stage of the proposed mine.⁹² The installation of dewatering wells to systematically drain the overlying rock strata would reduce, but not eliminate, inflow through these drill holes. Any undrained portions of subsurface waters and additional quantities of surface waters due to local rainfall would remain unaffected by dewatering. Such radon-bearing water would, therefore, pose a hazard to underground workers.

Should failure of all or part of the dewatering system occur, rapid build-up of mine water inflows might result? During test mining, three water-bearing drill holes were intercepted by the single access drift that was being advanced. Such holes were successfully capped, at depth, and it was possible to transport water flows away from worker-occupied sites. However, should drill hole interceptions occur within unoccupied sites, where remotely controlled equipment must be used, the ability to cap them becomes problematic. Consequent excess water and radon/radon progeny inflow to the mine would create an additional exposure risk to workers.

⁹⁰ Midwest Uranium Project *Environmental Impact Statement*, August, 1991, Volume 2, "Project Description", Section 5.3.7, p. 5-74.

⁹⁰ Midwest Uranium Project *Environmental Impact Statement*, August, 1991, Volume 2, "Project Description", Section 5.2.1.3, p. 5-9.

⁹⁰ Midwest Uranium Project *Environmental Impact Statement*, August, 1991, Volume 2, "Project Description", Section 5.2.2.1, Table 5.2.1.3, "Analyses of Typical Ore Samples."

⁹¹ Midwest Uranium Project *Environmental Impact Statement*, August, 1991, Volume 2, *Project Description*, Section 5.3.2.2, p. 5-47

⁹² Midwest Uranium Project *Environmental Impact Statement*, August, 1991, Volume 2, *Project Description*, Section 5.2.3.3, p. 5-32

⁹³ Midwest Uranium Project *Environmental Impact Statement*, August, 1991, Volume 2, *Project Description*, Section 5.2.3.4, p. 5-33

4.3.4 Transportation Hazards

Midwest Joint Venture proposes to transport mined ore over a considerable distance (30-50 km) for milling. This might put worker health at risk due to possible radiation exposure created by release of radioactive dust and the proximity of truck drivers to large volumes of high grade, gamma-emitting ore. While the concept of complementary utilization of existing or proposed mills is commendable, the potential exposure of transport workers to radiation and dust must be considered.

The need to transport large volumes of ore using Highway 905 could also present a significant health risk to the public. Increased traffic, along with the inevitable accidents and spills, could cause both physical and psychological effects on community health. In addition, mine-related traffic accidents could inconvenience travellers and could have a serious impact on various local businesses that depend on Highway 905.

The proponent has indicated that a plan to directly link the Midwest and McClean Lake sites, thereby reducing road length and consequent driver exposure, was considered and rejected. Adoption of such a closed, direct haul route to the McClean Lake mill would also have reduced potential public exposure to possible radioactive contaminants, and decreased traffic disruption on Highway 905. No reason has been presented by the proponent for rejecting this transport option.

4.3.5 Surface Water Impacts

In order to reduce mine water inflows, MJV proposes to pump the water in Mink Arm over an already constructed dam into South McMahon Lake and to remove subsurface water by the installation of a number of dewatering wells in the vicinity of the mine. In the short-term, this would have a drastic effect on the environment; all aquatic life in Mink Arm would be destroyed, bogs and fens would dry up, and terrestrial vegetation would suffer from the lack of moisture in the soil. The long-term effects, although difficult to predict, would depend to a large extent on the decommissioning and restoration programs employed.

During mining, all treated mine water would be released into North McMahon Lake. Such releases, projected to range between 61,000 - 400,000 m³/month during the entire project lifetime, would contain substantial amounts of various dissolved solids. The achievable effluent concentrations of the sixteen principal contaminants to be released into North McMahon Lake have been modelled and several metals, such as cadmium, copper, and nickel (as well as ammonia) are expected to exist at levels higher than provincially-legislated standards.

Furthermore, as discussed in section 2.3.2, surface water impacts reflect only the transient state of water quality. In many respects, total loading to the watershed, and particularly to the sediments therein, is more important. These have not been adequately addressed by the proponent.

4.3.6 Hydrogeological Impacts

Midwest Joint Venture proposes to dewater the Mink Arm of South McMahon Lake, as well as subsurface zones about the Midwest orebody. The consequences of dewatering would be a depression of the existing groundwater table and reduction of hydrogeologic flows over at least the eleven-year period of mining.

As with the other mine proposals, the panel and regulators consider the assessment of baseline hydrogeologic data to be very important in determining the impacts of a mining operation on the environment. Midwest's assessment of existing hydrogeologic conditions is based on data collected over one decade ago, and limited to data from areas lying largely within the MJV lease boundaries. The proponent has not evaluated recent hydrogeologic conditions of its lease or of regional areas adjacent to it. Nor has MJV done an assessment of the predicted hydrogeologic flow disruptions expected to result from dewatering. Accordingly, the baseline data and flow modelling presented are inadequate for the purpose of environmental assessment.

4.3.7 Disposal of Mill Tailings

Because the MJV ore is laden with toxic heavy metals, particularly arsenic and nickel, the mill tailings and effluent would necessarily contain the same elements. The problems associated with the disposal of such dangerous tailings have not been adequately addressed by the proponent. Their suggestion that disposal would take place at either the JEB or the Rabbit Lake sites overlooks the fact that neither of these disposal facilities has been approved to accept MJV tailings.

Safe disposal of mill tailings, a major environmental concern of several presentations at the public hearings, has not been adequately addressed by the proponent.

4.3.8 Cumulative Impacts

Cumulative impacts on that portion of the Athabasca Basin west of Wollaston Lake and south of Hatchet Lake (approximating the Smith Creek and Collins Creek watersheds) might be considerable. Several existing or potential mining operations are close to the MJV site. While the area actually used by the mining operations would be small, the overall effect of the operations, with the possibilities for interconnecting roads and power lines, would be widespread. Some of the lakes and streams would become unsuitable for fish and it is likely that most of the game animals would leave the area. As a result, the entire area might become unproductive for traditional hunting, fishing and gathering activities. Even if opportunities for such activities were not eliminated, local people might choose not to use land adjacent to the mines as a source of food. Approval of the MJV project would further increase this problem.

When this portion of the Athabasca Basin is viewed in a regional context, it is evident that several existing and potential mining operations are close to the Midwest Joint Venture/McClean Lake sites. The risk of air pollution, particularly by the release of radon and its progeny, increases when several mining sites are located in the same area.

Similarly, cumulative impacts to the Smith Creek and Collins Creek **watersheds have not been examined in sufficient detail**. Total **downstream** deposition quantities, sites of deposition and the capabilities of sediments, biota, etc. to absorb such discharges have not been adequately addressed. In particular, little attention has been paid to the possibility that milling of the MJV ore, with its high nickel and arsenic content, could cause an increase of contaminants in the mill effluent. As discussed in section 5.3.4, this could result in enhanced risk to the Collins Creek watershed.

When we look around in our communities here in the Athabasca region, we have a lot of water which we still enjoy...our water is still fresh. When you look at the water and rivers in south Saskatchewan, and North and South Saskatchewan River, how many people are going to go down to the shore and make tea with that water? That's why when we see those types of things, we see that you can't enjoy a cup of tea from that water, that we want to protect our future water resources as well.

B. Sandypoint, *Transcript of Public Hearings, Black Lake, Saskatchewan, April 13, 1993, p. 62.*

4.4 Potential Benefits

Benefits associated with this project include the following:

- employment, particularly for northerners;
- business opportunities; and
- royalties and taxes.

The potential for each of these benefits to contribute to improved socio-economic conditions is briefly discussed in this section.

4.4.1 Employment

The complementary Midwest Joint **Venture/McClean** Lake mining proposal forecasts the creation of approximately 95 new jobs at the MJV site. It is not clear how many of these jobs would be seasonal since mining is proposed only for summer months. Some positions at the JEB mill would also be extended. Based on present hiring practices by mining companies within the Athabasca Basin, about 50% of these positions would be filled by northerners. An obvious benefit would **result**.

4.4.2 Business Opportunities

Approval of this project would provide mining contractors, engineering firms, and related businesses with an opportunity for more work. Presenters at the public hearings indicated that

such possibilities would be welcomed by the Saskatchewan business community, particularly in the present economic climate. This project could, therefore, provide needed economic benefits.

It appears, however, that the work associated with the MJV mine would be of most benefit to firms operating from the southern part of the province; the proposal does not offer substantial business opportunities to the north, nor does the EIS propose contracting practices or surface lease agreement clauses significantly favouring northern development. Direct benefits to the northern economy through increased business opportunities for northerners would, therefore, appear to be minimal.

...objectivity is difficult to maintain after seeing years and years of so-called northern development result in continual poverty, social problems, unemployment, substandard health services, etc.

His Worship B. Belanger, *Transcript of Public Hearings, Ile-à-la-Crosse, Saskatchewan, April 16, 1993, p. 31.*

4.4.3 Royalties and Taxes

Low uranium prices during the last decade have provided little assurance that present and future uranium mining ventures can remain economically viable. Oversupply of uranium, with consequent low prices, has caused the provincial royalties during the period of 1978-1992 to be much less than expected. Several public hearing participants expressed concern that, if prices remain low (or drop even further), negligible benefits from this non-renewable resource would accrue.

Although the MJV mine was initially proposed in 1991 as a stand-alone project, the Amendment issued in October, 1992, suggested the situation had significantly changed in a period of only a few months. It appeared that an independent mine was now no longer viable as indicated by the statement, *"...given the conditions of today's markets, it is doubtful that the Midwest project would be economical on a stand-alone basis".*⁹⁴ The impression is thereby left that the financial viability of the project is tenuous. It is difficult to justify the environmental damage this project would cause when its profitability may be doubtful. Low profitability would also reduce possible revenue sharing with northern communities.

4.5 Risks Versus Benefits

An objective assessment of the risks and benefits described in the preceding sections requires the conclusion that the project not be allowed to proceed. The substantial risks to worker and community health, along with significant potential for environmental damage, are not balanced by the projected economic benefits.

⁹⁴ *Complementary McClean Lake and Midwest Projects, Midwest Project Environmental Impact Statement Amendment, 1992, p. 1-3.*

5.0 McCLEAN LAKE PROJECT

5.1 Project Description and Site Map

At the time public hearings began, Total Minatco Ltd. was proposing development of uranium ore reserves at **McClean Lake**. Total Minatco Ltd. is a wholly owned subsidiary of TOTAL, an integrated oil and gas company based in Europe, and, with 70% interest, was to be the project operator of the McClean Lake Joint Venture. The other participants in the joint venture were Denison Mines Limited, with a 22.5% interest, and OURD (Canada), with 7.5%. During the hearings we were informed that the project would be purchased by Cogema Resources Ltd. At the close of the public hearings on May 20, 1993, the panel was unclear with respect to the ultimate ownership of the McClean Lake project.

The McClean Lake site is in northern Saskatchewan about 12 km northwest of the existing Rabbit Lake mine, and about 350 km north of the town of La Ronge. Access to the project site is by a private road from Provincial Highway 905, or by use of the airstrip at Points North.

Mineralization was discovered at McClean Lake (the McClean Lake North deposit) in January, 1979. Further exploration resulted in the discovery of the McClean Lake South deposit; the Sue A, B and C deposits, about 2.5 km to the east; and the JEB deposit, about 9 km north. Total Minatco proposes the development of the McClean Lake deposits as an underground mine and the JEB and Sue A, B and C deposits as open pit operations.

The McClean Lake deposits, at a depth of about 160 m, would be accessed by a ramp. Vertical shafts would be used for ventilation, minewater pumping and backfill transport. An ore transfer pad would be built to store ore from the underground mine temporarily before it is transported to the main stockpile. Contaminated water would be pumped approximately 2 km to the water treatment plant at the Sue site.

The open pit mining operations for the JEB and Sue A, B and C deposits would involve overburden stripping and waste rock mining, followed by mining of the ore zones. A lined ore storage pad for the stockpiling of ore would be located close to the JEB pit. The pad would be used by mining operations at all six ore bodies. Waste rock and overburden would be placed in prepared areas close to the open pits, and might be used subsequently for construction activities if tests showed the material to be suitable.

The Sue A, B and C pits would have a waste rock disposal site, a water treatment plant, contaminated-water holding ponds, and treated-water monitoring ponds.

The McClean Lake proposal includes the building of a mill complex where ore would be processed to produce **yellowcake**. A water treatment facility would be built at the mill complex, located near the JEB pit. Water collected by the drainage systems for the ore storage pad would be processed here, as would JEB minewater, collected runoff, and tailings seepage water. It would also treat mill process waste streams and tailings decant water from the mill. Treated water would be

pumped to Sink Lake for regulated discharge through Vulture Lake to McClean Lake (see figure 4).

Tailings from the milling process would be deposited in the mined-out JEB pit for disposal using the pervious surround concept. This would require that the ore from JEB be removed and stored while the pit is being prepared to receive the tailings.

Ancillary facilities would include a shop and change rooms at the Sue site: offices, warehouses, shops, change rooms, a power generator plant, contaminated water storage ponds and treated water monitoring ponds at the mill site; fans and air heaters, electric power generators, minewater sedimentation ponds, a waste rock disposal area and an ore transfer pad at the McClean Lake underground mine site; and a camp designed to accommodate construction and production crews for all sites, to be built 800 m from the mill.

All active areas would be linked by roads and power lines. Pipelines would be used to transport minewater from the **McClean Lake** underground mine to the Sue Water treatment plant, and from the Sue and JEB treatment plants to Sink Lake.

It is proposed that the McClean Lake project and the Midwest Joint Venture be developed in a complementary way, with the McClean Lake site developed first, and the Midwest Joint Venture brought into production by 1999. Ore from the Midwest site would be milled at the JEB mill; tailings from the Midwest operation would also be disposed of in the mined-out JEB pit.

5.2 Recommendations

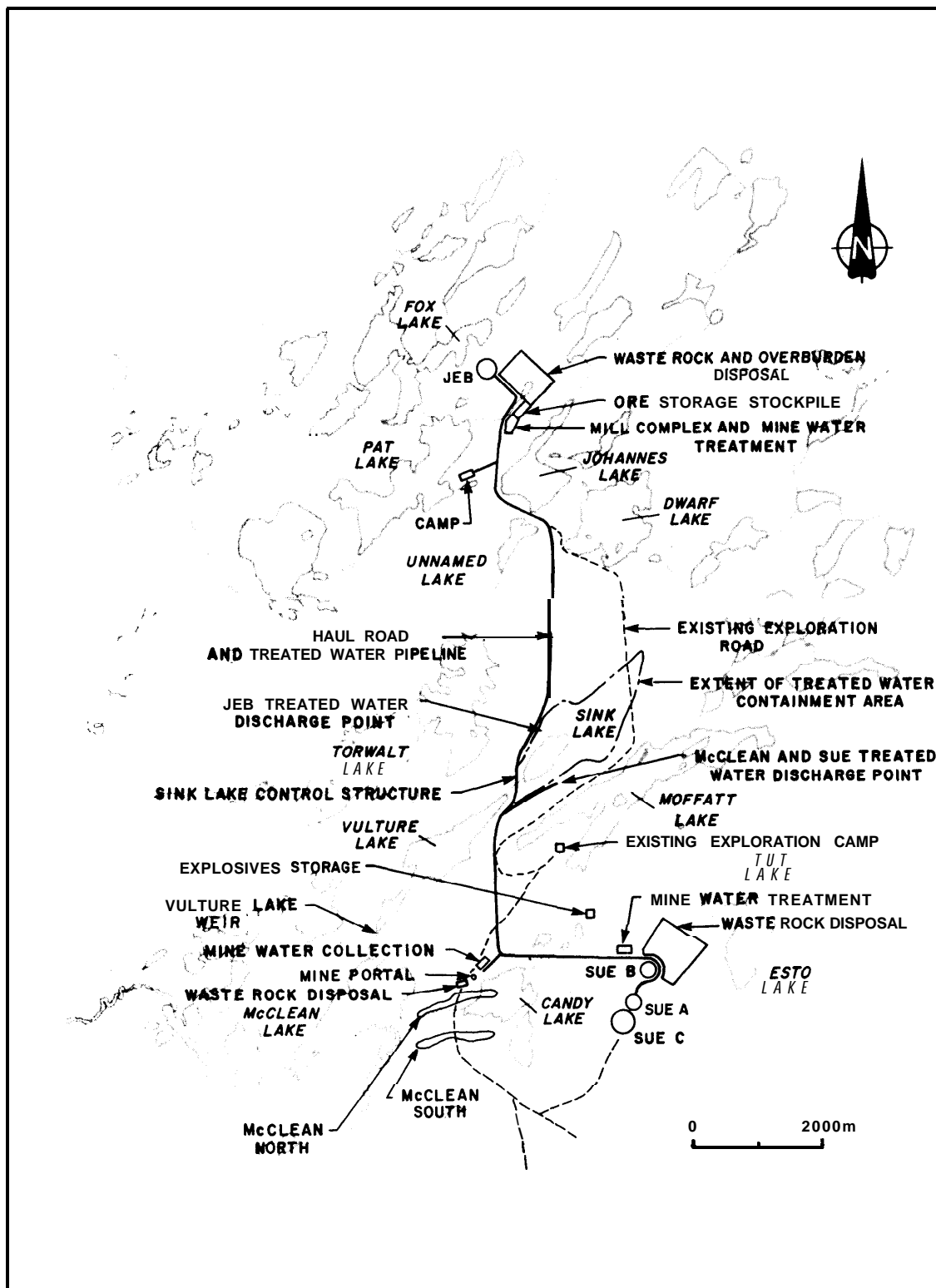
It is recommended that the McClean Lake project be delayed for at least five years.

This would allow time to obtain more experience with pervious surround tailings management facilities, to acquire comprehensive community health information, to maximize employment opportunities to northerners through education and training, to discuss further the larger issues, and to assess cumulative biophysical and socio-economic impacts.

Its approval at that time should be contingent on fulfillment of the following conditions:

1. evaluation, by the regulatory agencies, of the pervious surround tailings pit at Rabbit Lake after several more years of operation;
2. collection and evaluation of baseline data on groundwater flow patterns and water quality. In particular, the panel recommends that accurate flow rates be determined for the streams in the Collins Creek watershed and that modelling of predicted impacts on the receiving waters be revised accordingly;
3. development of plans to reduce contaminated mine-water inflows;

Figure 4
McClean Lake Project



4. evaluation of alternative oxidants that could replace sodium chlorate in the proposed milling process to permit recycling of mill effluent;
5. participation in the establishment of a research fund to support the search for innovative ways to reduce both the volume of effluent and quantity of chemicals required to treat contaminated water. The panel also recommends that site-specific water quality objectives be developed for the **McClellan Lake** project. In addition, the total environmental loading should be specified and a material-balance developed for all contaminants in the liquid effluent;
6. use of the Environmental Transfer Pathway model (ETP/AECB) as the focus for integrating the monitoring program at **McClellan Lake**. The general design of the monitoring program should be the same as that at other uranium mines. This will guarantee a consistent replication of treatments for biological effects monitoring and eventually produce the database required for the study of cumulative effects. The results of biophysical monitoring at **McClellan Lake** should be reviewed by the independent monitoring committee recommended in section 54.3;
7. assessment of cumulative effects using the ETP/AECB model and validation of the results by use of a whole ecosystem approach to monitoring, as specified in section 2.3.1 and section 5.3.7;
6. decommissioning plans that include the filling of **mined-out** pits to surface with waste rock capped by clean overburden;
9. adoption of sediment quality guidelines for Saskatchewan and institution of a program to monitor sediment quality in the Wollaston Lake drainage system;
10. adoption of a Human Resource Development Agreement that includes employment objectives of 30% (75 workers) of the initial workforce from the Athabasca Basin and 40% (100 workers) from the rest of northern Saskatchewan, with the balance (30%, 75 workers) coming from southern Saskatchewan or elsewhere. After the mine has been in operation for three years, these objectives should be changed to require the selection of a minimum of 50% of all new employees from residents of the primarily-impacted communities and a minimum of 30% from the residents of secondarily-impacted communities. These conditions should also apply to contractors and sub-contractors;
11. agreement on a form of revenue sharing that is acceptable to the majority of the impacted communities;
12. establishment of a monitoring committee (as described in section 2.1.5) for the **McClellan Lake** Project;
13. provision of a financial guarantee to cover decommissioning and post-decommissioning costs;
14. adoption of the exposure standards recommended in Publication 60 of the International Commission on Radiation Protection (ICRP-60) and measures to prevent the collective dose from increasing;
15. implementation of a program to collect and **analyze** changes in indicators of community health for the impacted communities, and formulation and implementation of remedial health strategies; and
16. further public discussion of the larger issues identified in section 2.5 of this report.

5.3 Biophysical Concerns

5.3.1 Air Quality

There is general concern over the release of radioactive dust and radon, with the subsequent deposition of radon progeny, as discussed in section 2.3.3. This concern could be assessed more critically if a well designed program, such as the one proposed by the proponent, were used to monitor radon and dust, together with radionuclide and metal uptake in soil, lichen, vascular plants and the snowshoe hare. The monitoring of vegetation and wildlife should occur on a three-year cycle and start before mine excavation to provide required baseline information.⁹⁵ **The panel notes the commitment given by Total Minatco to establish a comprehensive air quality and aerial contaminant deposition monitoring program.** A delay in the start-up date of this project will provide the proponent with an opportunity to accumulate comprehensive air quality baseline data before mining begins.

The issue of cumulative effects associated with aerial emissions from a complex of mines or proposed mines to the west of Wollaston Lake is dealt with in section 5.3.8.

5.3.2 Hydrogeology

Review participants expressed concern about the lack of information on groundwater patterns, retardation factors, etc. While such information appears to be of little more than academic interest to the **proponent**,⁹⁶ the Saskatchewan Mineral Industry Environmental Protection Branch considers background and baseline data to be very important in determining the effects of an operation on the **environment**.⁹⁷ **The panel shares this latter assessment and recommends that baseline data be collected on groundwater flow patterns and water quality.** Further rationale is provided for this recommendation in section 5.3.4.

⁹⁵ Complementary **McClellan Lake and Midwest Projects, McClellan Lake Project, Environmental Impact Statement, Additional Information Requested by Uranium Mines Review Panel**, Total Minatco Ltd., November, 1992, Deficiency Number 3.35.

⁹⁶ Complementary **McClellan Lake and Midwest Projects, McClellan Lake Project, Environmental Impact Statement, Additional Information Requested by Uranium Mines Review Panel**, Total Minatco Ltd., November, 1992, Deficiency Number 3.28, p. 2.

⁹⁷ Technical Review of **McClellan Lake Project - Additional Information Requested by Uranium Mines Review Panel**, Saskatchewan Mineral Industry Environmental Protection Branch, January 28, 1993.

5.3.3 Waste Rock Management

The proponent proposes to dispose of most of the waste rock, mined from the JEB and Sue sites, in surface rock **piles adjacent** to the mined-out open pits. About 2% of **the waste rock** would be classified as special waste (**0.03%-0.1% U_3O_8**) and would be disposed of mainly in the Sue C open pit. Most of the waste rock from the **McClean Lake underground mine** would be used as backfill as the ore body is mined out.

The main consideration for the management of waste rock seems to be cost; it is least expensive to dispose of it on the surface. However, concerns about contaminated **leachate** from the rock piles affecting the water quality of the adjacent flooded pits have not been addressed. There has been no consideration of using the waste rock from one open pit as fill for another, even where there are closely situated open pit mines to be developed in sequence (as in the Sue A, Sue B, and Sue C mines).

The management of waste rock needs to be considered as part of an integrated decommissioning of the mines. As discussed in section 5.3.9, we favour filling all mined-out pits with waste rock, capped by clean overburden.

5.3.4 Surface Water and Fisheries

Surface waters are affected in three main ways by the proposed mining activity. First, liquid effluent (derived from the mill, the tailings treatment facility, the stockpiles and contaminated mine water) would be released into Collins Creek by way of Sink Lake, Vulture Lake and **McClean Lake**. Second, Candy Lake would be drained while the **McClean** underground mine is being constructed and in operation. The lake would be refilled and restocked with fish after the mining operation is completed. Third, surface water bodies would be created in the flooded Sue open pits and above the tailings in the JEB pit.

The impact of the release of liquid effluent would be major and will be considered at length below. The draining of Candy Lake would be of a temporary nature and is subject to the *Fish Habitat Compensation Agreement* which is the mandate of the Department of Fisheries and Oceans. The creation of lakes by the flooding of open pits should be avoided, as discussed in section 5.3.9.

In assessing the impact of liquid effluent on the receiving waters, it is important to know the flow rates for streams in the Collins Creek watershed. Unfortunately, the historic data are of questionable value. Thus, the proponent **has** developed a synthetic set of data, based on flow rates for Thyme Hill River, that seems to correlate well with the limited available data. However, **the** uncertainties associated with this approach are considerable. For example, is the storage capacity of Sink Lake sufficient to delay the release of effluent during periods of low water flow? **in an attempt to avoid unacceptable impacts on the quality of the surface water, the proponent should determine accurate flow rates for the streams in the Collins Creek watershed and model the predicted impacts on the receiving waters accordingly.**

Some of the general issues relating to liquid effluent are discussed in section 2.3.2. The discussion therein is particularly relevant to McClean Lake because of the large volume of effluent that would be created by that proposed project. The volume is estimated to average approximately **3,760,000 m³** a year over the 18 years of the project, but in some years it would be almost double this **amount**.⁹⁸ Using the proponent's **data it is possible** to calculate the average total environmental loading (total mass released in effluent) for various contaminants. For example, almost 400 kg each of arsenic and nickel, more than 2,000 kg of uranium, and more than 13,000 tonnes of total dissolved solids would be released on average each year. Thus, the release of contaminants in the liquid effluent would be substantial. It is not surprising to learn that the Saskatchewan Surface Water Quality Objectives would be exceeded for many contaminants in Sink Lake, Vulture Lake and even part of McClean Lake.

The proposed impacts to Sink Lake, Vulture Lake, McClean Lake and Collins Creek are not acceptable because there is good evidence to suggest that the volume of effluent could be lowered substantially in at least two ways. First, the volume of contaminated mine-water requiring treatment could be decreased by intercepting groundwater with a network of **de-watering** wells around each open pit. Uncontaminated groundwater could be released directly into the watershed. **The panel, therefore, recommends that contaminated mine-water inflows be reduced.** Second, the proponent plans to use sodium chlorate as an oxidant in the milling process for ores with a low arsenic content. If this is done, it will not be possible for the mill effluent to be recycled because of its high chloride content. The use of alternative oxidants, which allow the mill effluent to be recycled, would reduce chloride loading in the effluent. **The panel, therefore, recommends the evaluation of alternative oxidants that could replace sodium chlorate in the proposed mill, to permit recycling of mill effluent.**

The rationale for the following three recommendations may be found in section 2.3.2. First, the panel recommends **that the McClean Lake mine participate in the establishment of a research fund to support a search for innovative ways to reduce both the volume of effluent and quantity of chemicals required to treat contaminated water.** Second, the panel recommends that site-specific water quality objectives be developed for the McClean Lake mine. Third, the panel recommends that total environmental loading be specified for the McClean Lake mine and that a **material-balance** be developed for all contaminants in the liquid effluent.

I must stress that you have to watch the water because water is how we sustain our life.

T. Dzejlion, *Transcript of Public Hearings*, Wollaston Lake, Saskatchewan, April 14, 1993, p. 128.

⁹⁸ *McClean Lake Project, Environmental Impact Statement Amendment*, Total Minatco Ltd., September 1992, Section 2.

53.5 Tailings Management

Tailings management can also have a substantial deleterious effect on the quality of surface water downstream from the mine site. For this project, it has been proposed that the mined-out JEB pit be used as a pervious surround disposal facility to contain mill tailings from both the McClellan Lake project and the Midwest Joint Venture mine. The use of one tailings facility for two projects should be environmentally beneficial because it would reduce the proliferation of such sites. Placement of the tailings in a pit would also decrease the likelihood of surface water contamination (but raises the spectre of possible ground water contamination).

Despite these theoretical advantages, we were reminded by the public that the pervious surround method for tailings containment has not yet been adequately tested. The only such pit in the Athabasca Basin, the nearby Rabbit Lake facility, has not been in operation long enough to demonstrate its viability. It is the panel's opinion that it would be prudent to observe the operation of that facility for a few more years before deciding on whether or not to license another. **This is one of the primary reasons why we are recommending a delay in the start-up of this project for at least five years. The time interval will provide the regulatory agencies with an opportunity to observe and evaluate the facility at Rabbit Lake; it will also undoubtedly provide the proponents with information that can be used to improve the design of the JEB facility.**

...no new pervious surround tailings until the pilot project at Rabbit Lake is proven. That's my position.

M. Shiell, Transcript of Public Hearings, Regina, Saskatchewan, March 22, 1993, p. 269.

5.3.6 Wildlife and Terrestrial Habitat

The area of the proposed McClellan Lake project is not highly productive and wildlife populations are low. The main concerns of the public related to possible widespread contamination of the area, including the vegetation and wildlife, by radionuclides and metals. This concern is discussed in sections 5.3.7 and 5.3.8.

One rare plant has been found in wetland habitats in the project area and could be impacted by mining development. The panel concludes that this risk is acceptable, given that these habitats are commonly found throughout the region. However, the proponent should undertake to implement all reasonable measures to protect such habitats from disruption.

⁹⁹ Complementary McClellan Lake and Midwest Project, McClellan Lake Project, Environmental Impact Statement, Additional Information Requested by Uranium Mines Review Panel, Total Minatco Ltd., November, 1992, Deficiency Number 3.33 and Deficiency Number 3.36.

5.3.7 Monitoring

The proponent has developed a comprehensive monitoring program that would start before mine excavation in order to provide adequate baseline information.⁹⁹ While the proposed monitoring program for the terrestrial environment is satisfactory, the corresponding program for the aquatic environment requires modification. In particular, the division of monitoring activities into core and second-level components, whereby the latter would only be monitored if certain, unspecified action levels in core components were exceeded, is not acceptable. It is suggested, instead, that all of the second-level components be monitored on the same basis as core components, with the possible exception of radionuclide and heavy metal content of benthic invertebrates. Otherwise, the overall design and rationale of the proposed monitoring program is consistent with the general philosophy discussed in section 2.3.1. In keeping with the arguments therein, **the panel recommends that the Environmental Transfer Pathway model (ETP/AECB) be used as the focus for integrating the monitoring program at McClellan Lake.** The general design of the monitoring program should be the same as that at other uranium mines. This will guarantee a consistent replication of treatments for biological effects monitoring and eventually produce the database required for the study of cumulative effects. The results of biophysical monitoring at McClellan Lake should be reviewed by the independent monitoring committee recommended in section 5.4.3.

A delay in the start-up date for this project would allow the proponent to establish a monitoring program and obtain considerable baseline data before mining starts.

5.3.8 Cumulative Biophysical Effects

There is considerable potential for cumulative effects arising from the McClellan Lake project. It involves five mines (JEB, Sue A, Sue B, Sue C, and McClellan underground) which are located within a 10-20 km radius of several other ore bodies that have been or could be mined in the future (Dawn Lake, Midwest, Eagle Point, Collins Bay A, Collins Bay B, Rabbit Lake, Horseshoe, and Raven). Indeed, it is not a question of whether or not there will be cumulative environmental impacts, but of their magnitude.

Three cumulative biophysical impacts are of potential concern: impact on surface waters; concentration of contaminants by aquatic sediments; and airborne dispersal of contaminants.

Liquid effluent from the McClellan Lake project would drain via Collins Creek into the west side of Wollaston Lake, approximately 40 km north of where effluent from the existing Rabbit Lake mine is discharged via Effluent Creek into Hidden Bay on Wollaston Lake. Preliminary assessments¹⁰⁰ suggest that cumulative effects from the two mines (and also from the two more distant mines at Cigar Lake and Key Lake) on the water

¹⁰⁰ "Cumulative Impact of Uranium Mining in Northern Saskatchewan", Atomic Energy Control Board, Submission to Public Hearings, Saskatoon, Saskatchewan, May 4, 1993. McClellan Lake Project, Environmental Impact Statement, Amendment, Total Minatco Ltd., September, 1992, Section 3.

quality of Wollaston Lake would be impossible to detect. Nevertheless, the McClean Lake project would add one more polluted watershed to the west side of Wollaston Lake. Consequently, there would be a worsening in water quality in this region which might affect the traditional use of the land by local communities (see section 5.4.4).

The enormous volume of effluent expected to be discharged by the project and high total environmental loading of many contaminants (see section 5.3.4) would result in large quantities of metals and radionuclides being accumulated in the sediments of Sink, Vulture, **McClean** and Keweenaw Lakes. Furthermore, contamination would mainly occur in the top 10 cm of the sediments. This is where aquatic macrophytes are rooted and is also the environment for bottom-living animals. The proponent's EIS indicates that by the end of the project the sediment quality in Sink and Vulture Lakes would exceed the "severe effects level" of the Ontario Sediment Quality Guidelines for arsenic, cadmium, copper, and nickel. This level indicates concentrations at which prolonged disturbance of the sediment dwelling community can be expected, with resultant harmful effects on the majority of bottom-living species. This impact on the sediment-dwelling community is expected to persist for a long time. The proponent's modelling analysis of sediment quality indicates that sediment quality in Sink and Vulture Lakes would exceed the Ontario Sediment Quality Guidelines for arsenic and cadmium for at least 100 years following the proposed decommissioning of the project. Clearly, plans should be developed to minimize or mitigate these effects before mining begins. We also note that Saskatchewan has no guidelines for sediment quality.

The remaining cumulative impact of concern is that radon, radon progeny, and radioactive dust emissions would overlap with those of nearby mines to produce a wider, regional effect. Preliminary modelling by the proponent indicates that radon from McClean Lake, at concentrations elevated above background levels, would overlap with radon from the proposed Midwest mine and the existing Rabbit Lake mine. Similarly, there would also be overlap of elevated dust concentrations from the McClean Lake and Rabbit Lake mines. However, the zone of overlap is predicted to be at very low concentrations, at about one-thirtieth of background levels for radon, for example.

Residents of the Athabasca region, particularly those in the Wollaston Lake area, will continue to be concerned about the possible deterioration of water and air quality, and whether the plants, fish and wildlife that they harvest are contaminated. **The panel shares these concerns and recommends that cumulative effects be assessed using the ETP/AECB model and that the results be validated by using a whole ecosystem monitoring approach, as specified in sections 2.3.1 and 5.3.6. We also recommend that the Saskatchewan government adopt sediment quality guidelines similar to those of the Ontario government.**

¹⁰¹ R. McKay, *Transcript of Public Hearings*, Saskatoon, Saskatchewan, May 3, 1993, p. 163.

53.9 Decommissioning and Site Reclamation

The flooding of the Sue pits and the tailings-filled JEB pit is objectionable. For example, the proponent's model for the flooded Sue pits suggests that the Saskatchewan Surface Water Quality Objectives for arsenic, copper and nickel would be exceeded for at least 500 years. Moreover, in assessing the water quality of the flooded pits, the effect of **leachate** from the surface waste rock piles has not been included. There would be sufficient waste rock to completely fill all of the pits and thereby reduce the problem of **leachate** from this source to a minimum, as well as eliminate the concern over water quality in the flooded pits. **The panel recommends that all open pits be filled to surface with waste rock and capped with clean overburden.**

Plans for the reclamation of Candy, Sink, Vulture, McClean and Keweenaw Lakes would require the approval of the Department of Fisheries and Oceans.

It is recommended that a financial guarantee to cover decommissioning and post-decommissioning costs be secured before the McClean Lake Project is started. The need for such a guarantee for all mines has previously been discussed in section 2.3.5.

5.4 Socio-Economic Concerns

5.4.1 Education and Training

During the public hearings, the Executive Director of Northern Education described a Consortia Training Plan¹⁰¹ that has been developed to address emerging labour market and training issues. This plan requires cooperation between employers and educators to ensure that there will be an approximate balance between the number of jobs available and the number of trained personnel. Such a plan will work best if sufficient time is made available to design the project and train the workers. In order for this Consortia Training Plan to work most effectively, several new projects should not begin at the same time. It will be easier to prepare for a gradual increase in employment opportunities. **Many of the workers required for the McClean Lake project will require more extensive training than, for example, the new workers at the Dominique-Janine extension at Cluff Lake.** This is one of the reasons why we are recommending that the Dominique-Janine Extension be allowed to proceed as soon as the specified conditions are met, but that the start-up of the McClean Lake Project be delayed for at least five years. Given sufficient lead time for training, it should not be difficult for the operating company to meet the employment objectives outlined in the proposed Human Resource Development Agreement described below.

5.4.2 Human Resource Development Agreement

In section 2.2.2 we have recommended that the Human Resource Development Agreements include provisions requiring

80% of all new employees for existing mines to be drawn from the primary and secondary impact communities. However, for a new mine this goal may be too ambitious. In their submission to the panel, officials of the McClellan Lake Project suggested that hiring would include 40-75 workers from the Athabasca Basin, 50-100 workers from other northern Saskatchewan communities and 75-160 workers from southern Saskatchewan, for a total of 250 employees.¹⁰² Delaying this project for approximately five years would provide a greater opportunity for education and training prior to start-up and thereby give the company a better chance of meeting its upper estimates for hiring from the Athabasca Basin and northern Saskatchewan. **It is, therefore, recommended that the Human Resource Development Agreement for the McClellan Lake Project include employment objectives of 30% (75 workers) of the initial workforce to be recruited from the Athabasca Basin and 40% (100 workers) from the rest of northern Saskatchewan with the balance (30%, 75 workers) coming from southern Saskatchewan or elsewhere. After the mine has been in operation for three years, these objectives would be replaced by those pertaining to existing mines, i.e. 50% of all new employees must be from the primarily-impacted communities and 30% from the secondarily-impacted communities, as described in section 2.2.2.**

5.4.3 Revenue Sharing and Monitoring Committee

Delaying the start-up of this project by at least five years would also provide sufficient time for the province to work out a revenue-sharing program that is acceptable to the impacted communities, and to establish the regulations required to govern the selection and activities of a monitoring committee. **It is recommended that the project not be allowed to proceed until a form of revenue sharing acceptable to the impacted communities has been implemented and a monitoring committee for this project has been appropriately established.** It should be noted that McClellan Lake officials have already indicated their concurrence with the suggestion that a monitoring committee be established for the project with representation from the impacted communities,¹⁰³ similar to the recommendation we have made in section 2.2.8.

5.4.4 Inherent Rights

Before a new mine site is established, there must be a clear understanding of any residual inherent rights that may exist and how compensation would be provided for the loss of those rights if mining interferes with the use of the land for traditional hunting, fishing, trapping and gathering activities. The province of Saskatchewan has acknowledged that the *Natural Resources Transfer Agreement* which is part of the

Constitution Act, 1930 "... guarantees Indian people the right to hunt, fish and trap for food on unoccupied Crown land or other lands to which they have a right of access".¹⁰⁴ The way in which aboriginal people are to be compensated for the loss of these rights when land, which had traditionally been unoccupied, is used for other purposes should be clearly established before developments are allowed to begin. In the specific case of the McClellan Lake Project, a substantial area of dry land, as well as several lakes, streams and bogs, would be affected and it is our opinion that, although the area may not be in current use by any specific person, it is still a parcel that would be subtracted from the total amount of land available for traditional uses. **The panel recommends that the loss of inherent rights on that particular parcel of land be recognized and the families or communities involved be compensated by the province.**

It is **recognized** that arriving at an acceptable form of compensation for the loss of these inherent rights may take considerable time, and a delay in the project would provide an opportunity for this concern to be settled before start-up. We are aware that these and similar issues may be considered by the *Royal Commission on Aboriginal Peoples*, and a delay would permit governments to also have the benefit of its recommendations before approval of this project is considered.

5.4.5 Cumulative Effects

Mining of any non-renewable resource cannot be sustained indefinitely. To be sustainable development, within the definition of the Brundtland Report, the mining of uranium must "...**meet the needs of the present without compromising the ability of future generations to meet their own needs**".¹⁰⁵ Sustainability of the industry as a whole can, however, be achieved over a long period of time by sequential development of various **deposits**.¹⁰⁶

Mineral reserves are depleted as deposits are mined out, and are subsequently replenished by new discoveries, or by technological advances that make lower grade deposits economic to develop. Innovations in developing alternate energy sources may even eventually eliminate the demand for uranium. However, it is important not to mine out current reserves unless the market demand coincides with the amount of ore being produced. **Otherwise**, the natural environment will have been disrupted for no sound cause.

Coinciding with the cycle of development of mineral resources is the accompanying employment and spin-off economic development which result from mining activity. The side benefit of direct and indirect employment is the positive impact most often cited by those supporting the continuation of expansion of uranium mining. Negative impacts can thus be accepted,

¹⁰² W. Keyes, *Submission to Public Hearings*, Saskatoon, Saskatchewan, March 19, 1993.

¹⁰³ K. Haapanen, *Transcript of Public Hearings*, Regina, Saskatchewan, March 23, 1993, p. 155.

¹⁰⁴ *Interim Report: Information from the Government of Saskatchewan requested by the Federal/Provincial Panel on Uranium Mining in Northern Saskatchewan for the Cigar Lake and McArthur River Projects*, SERM, 1993, p. 4.

¹⁰⁵ G. Brundtland, *Our Common Future*, World Commission on Environment and Development, Oxford University Press, 1987.

¹⁰⁶ *Conservation Strategy for Sustainable Development in Saskatchewan*, Saskatchewan Round Table on Environment and Economy, 1992.

within regulatory standards, provided there are offsetting positive impacts, such as employment.

The potential positive effect, i.e., more employment for northern aboriginals, would be greatly diminished if the projects were allowed to proceed before there were enough trained and educated northern aboriginals available to fill the jobs created. **Therefore, the McClean Lake project should be delayed until a sufficient supply of skilled and educated workers from the impacted communities exists to satisfy the employment demands of this project and existing mines.**

A delay in development would have a second advantage; the overall amount of job dollars being injected into the northern economy from uranium mining could be sustained at a more constant level by a postponed development at McClean Lake. **If the latter project were phased into production as others, i.e. Ciuff Lake and Rabbit Lake, were mined out, a continuity of employment would occur, thereby avoiding a boom-bust cycle.**

5.5 Health Concerns

5.5.1 Occupational Health

The comments and recommendations discussed in section 2.4 apply to this project. While several of the components of the project do not pose health risks that are greater than those posed by existing uranium mines, some components of the project are troublesome. From an occupational health viewpoint, Sue C and the underground mine constitute situations of high grade uranium ore and high arsenic concentration. The underground mine poses particular concerns in

this regard, as underground mines tend to be associated with higher levels of worker exposure. Section 2.4.1.2 addressed the issue of the synergism of arsenic and radiation. The complexities of dose, dose rate, age at exposure, and concomitant risk factors such as cigarette smoking, as well as arsenic and radiation, all affect the health risks associated with this project. Before approval is granted, the proponent and the regulators must be able to address these complexities and assure the public that the level of health risk associated with the combined exposures in these mines is within acceptable limits.

55.2 Community Health

Several community health concerns were identified in section 2.4.2. The extent to which uranium mining has had a positive, negative or no impact on health in the impact communities cannot be evaluated due to the unavailability of sufficient environmental health risk information and the lack of community health data. The panel therefore recommends that **a community health assessment be undertaken before the McClean Lake project is approved.** The community health concerns may be surmountable, with the use of appropriate technology and monitoring. However, the uncertainty factor (as discussed in section 2.4.2.6), the public uneasiness concerning larger issues (section 2.5), and the likelihood of watershed contamination (section 5.3.4) make the assessment of the potential community health risks impossible at the present time. Provision of sufficient time for further public discussion could also promote consensus among the people of Saskatchewan concerning the issues surrounding uranium mining.

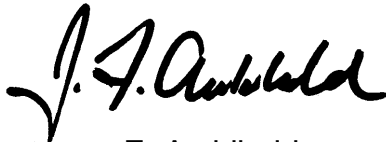
JOINT FEDERAL-PROVINCIAL PANEL

ON

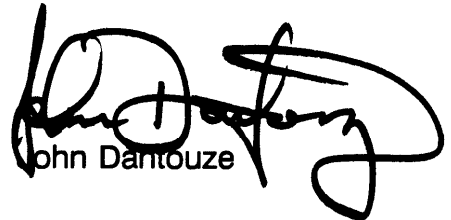
URANIUM MINING DEVELOPMENTS IN NORTHERN SASKATCHEWAN



Donald Lee
(Chairperson)



James F. Archibald



John Dantouze



Richard Neal



Annalee Yassi

APPENDIX A

PANEL MEMBER BIOGRAPHIES

DONALD LEE (Chairperson)

Dr. Lee is Head of the Chemistry Department at the University of Regina and Past President of Luther College. A native of Saskatchewan, he has a Master of Arts degree from the University of Saskatchewan, a Ph.D. in Chemistry from the University of British Columbia and has completed post doctoral studies at Harvard University. Dr. Lee has been a member of the faculty at the University of Regina since 1967 and has served as a visiting professor at Stanford University and as a visiting scientist at the University of Oslo. He has published over ninety scientific papers and numerous non-scientific articles.

Active in community affairs for many years, Dr. Lee has been Chairman of the Saskatchewan section of the Chemical Institute of Canada, Executive Member of the Saskatchewan Association of Independent Schools, a national official of the Canadian Amateur Swimming Association, and President of the Regina Optimist Dolphin Swim Club.

JAMES F. ARCHIBALD

Dr. Archibald received his Ph.D. in Mining Engineering at Queen's University and is now an Associate Professor in the Department of Mining Engineering at Queen's. His work experience is primarily in the academic field with some associated private consultation. Dr. Archibald is a member of the Canadian Institute of Mining and Metallurgy (CIM), the CIM Backfill Sub-Committee (Rock Mechanics Group) and the American Institute of Mining Engineers.

Dr. Archibald's research interests include measurement and control of radiation hazards in underground mines, mine ventilation systems, in-situ stress analysis, rock burst prediction and structural mine design evaluation. Dr. Archibald is a member of the High Level Waste Disposal Scientific Review Group examining the concept of deep geologic disposal of nuclear fuel waste.

JOHN DANTOUZE

Mr. Dantouze is a Vice-chief of the Prince Albert Tribal Council, with responsibilities encompassing treaty issues, First Nations self-government, and a variety of program, service, and policy areas. Previously, Mr. Dantouze was Prince Albert Tribal Council Community Planning Advisor for the Athabasca Indian Bands of Fond du Lac, Black Lake and Hatchet Lake in northern Saskatchewan.

Mr. Dantouze also sits as an advisor on the Caribou Management Board and the Athabasca Task Force Committee on

northern Health Services. He recently participated in the Saskatchewan Environmental Assessment Review Commission formed to review the province's environmental assessment review process, and acted as a Dene interpreter when the Commission visited the Athabasca region of northern Saskatchewan.

RICHARD NEAL

Dr. Neal is Associate Dean (Academic) and Professor of Biology in the College of Arts and Science, University of Saskatchewan. He received both his Bachelor of Science and Ph.D. in Zoology from the University of Southampton, U.K. Dr. Neal has been a member of the Department of Biology at the University of Saskatchewan since 1968, and has taught extensively in the field of Biology.

Dr. Neal's research interests include population ecology and a broad range of environmental issues, including impacts of uranium mine and mill effluent on the aquatic environment in northern Saskatchewan, effects of pesticides on prairie ponds and duck populations, and revegetation of lands **salinized** by potash mine tailings. Dr Neal is actively involved in a number of professional organizations and has been the Chairman of **the** Environmental Advisory Committee for the City of Saskatoon.

ANNALEE YASSI

Dr. Yassi is an Associate Professor and Director of the Occupational and Environmental Health Unit, in the Department of Community Health Science, University of Manitoba. She is also the Director of the Department of Occupational and Environmental Medicine at the Health Sciences Centre in Winnipeg. Dr. Yassi received her Bachelor of Science **degree** in 1974 from McGill University and her M.D. in 1977 from **McMaster** University. She obtained a Master of Science degree in Community Health, (Epidemiology/Occupational and Environmental Health) in 1985 from the University of Toronto, and is a Royal College Fellow in both Community Medicine and Occupational Medicine.

Dr. Yassi has served as an occupational physician for the Manitoba Federation of Labour Occupational Health Centre; **she** has also served as **the** principal medical consultant **for** the Manitoba Hazardous Waste Management Corporation. She has conducted numerous health hazard evaluations and has been involved in several environmental impact assessments affecting **Native** communities. **She** was also a member of the Canadian Public Health Association's Task Force on Human and Ecosystem Health.

APPENDIX B

TERMS OF REFERENCE FOR THE ENVIRONMENTAL ASSESSMENT REVIEW OF URANIUM MINING DEVELOPMENT

MANDATE

1. The panel shall review the environmental, health, safety and **socio-economic** impacts (hereinafter referred to as "impacts") of the proposed uranium mine developments (listed in Schedule A) in northern Saskatchewan and assess their acceptability.

In assessing the acceptability of the proposed developments, the panel will include in its review and consider:

- a) the historical experience with past and existing uranium mining operations in Saskatchewan;
 - b) the cumulative impacts of existing operations and the proposed developments;
 - c) the short and long term impacts of the proposed projects, spanning their construction phase, operating period, decommissioning phase and post-decommissioning phase;
 - d) the impact of employment and socio-economic opportunities afforded northern residents by the proponents and the measures necessary for implementation of those opportunities;
 - e) the adequacy of measures proposed by the project proponents to protect environmental quality and to safeguard worker health and safety, and whether the measures can be expected to meet the requirements of Canadian and Saskatchewan law, regulations and policies applicable to uranium mine developments;
 - f) the adequacy of monitoring, enforcement and compliance systems to ensure that measures necessary for mitigating adverse impacts can be implemented; and
 - g) the benefits afforded by the proposals.
2. The panel shall determine from its review whether a project is acceptable or unacceptable.

In concluding that a project is acceptable, the panel may recommend that specified minimum terms and conditions, including any mitigative measures or any other measures relating to the impacts under the panel's review, be implemented where it considers these necessary for the protection of health, safety and the environment or for dealing responsibly with **socio-economic** concerns. The panel may also suggest measures that it considers would enhance the acceptability of the proposals.

If the panel concludes a project is unacceptable, it shall provide its reasons for this conclusion.

3. In fulfilling its mandate, the panel shall provide full opportunities for public consultation and review.

REVIEW PROCEDURES

Detailed written procedures for conducting the review shall be established by the panel and made available to the public.

TECHNICAL EXPERTS

The panel may secure the services of independent technical experts to assist and advise on complex technical and/or socio-economic issues related to its mandate. Such experts will also be available to respond to inquiries from review participants.

STAGES OF THE REVIEW

Schedule A lists the five proposals to be reviewed by the panel. The five proposals have been referred due to potentially significant or unknown adverse environmental effects and public concern.

While all of the proposals are in the planning stage, some are further advanced than others. Environmental Impact Statements (EIS) have been prepared for the first three proposals listed in Schedule A, one of which (Dominique-Janine extension) is associated with the existing operating uranium mining facility and two of which are for new uranium mining facilities. EIS documents have yet to be prepared for the last two proposals listed in Schedule A. The panel will take the differing stages of these projects into consideration in scheduling its review.

The panel will seek public comment on the three available **EIS's** and determine their adequacy before proceeding to public hearings. When the panel is satisfied with the information provided, including that with respect to the cumulative impacts, it may report on one or more of these projects to the Ministers as described in the following stages of the review. The panel shall submit its final report(s) on these proposals within 18 months of its appointment.

In reviewing the remaining two proposals, the panel will conduct scoping sessions in appropriate communities to solicit public comment and, based on these comments and its own consideration, prepare and issue Guidelines to the respective proponents for the preparation of **EIS's**. The cumulative impacts of these two proposals will be considered when the EIS

documents have been submitted. The stages of the review following submission of these documents to the panel are outlined below. The panel shall submit its final report(s) on these two proposals within 18 months of receipt of the **proponents' EIS's**.

1. Review of Information

- a) Review of the available information on the environmental, health, safety and socio-economic impacts of the uranium mining industry in Saskatchewan to date. The information and any related reports prepared will be made available to the public.
 - b) Review of the past performance of the uranium mining industry in providing employment and socio-economic opportunities to northern residents. The information and any related reports prepared will be made available to the public.
 - c) Review by the panel of Environmental Impact Statements (**EISs**) submitted by the proponents. The **EISs** will also be made available to the public for review and written comment.
 - d) The panel may draw on proponents, technical agencies from within federal or provincial governments, independent experts and the public for available information.
2. Should the panel, after reviewing the above information and considering public comments, deem an EIS deficient it may request additional information from the project proponent.
3. Once the panel is satisfied with the information provided, it will announce public hearings for the project in question. If appropriate, the hearings may be structured to address more than one project.
- For the purposes of promoting public awareness and facilitating public comment, the panel will hold meetings and/or hearings in the appropriate northern communities, Regina, Saskatoon and in such other Saskatchewan communities as the panel may think necessary.
4. When the panel is in a position, following the completion of **public** hearings, to **provide a report** on its findings.

conclusions and recommendations relevant to a specific project, it will submit the report to the federal Ministers of Environment and of Energy, Mines and Resources and to the Saskatchewan Minister of Environment and Public Safety.

The panel should, to the extent possible, ensure that the timely review of a specific project is not jeopardized by delays in the review of another project included **in its mandate**.

LINKAGE TO OTHER POLICY PROCESSES

The panel is not expected to interpret its mandate so as to duplicate the work of other public inquiries and policy processes or to focus on national or international issues which are not directly related to the impacts of the proposals.

However, concerns may be raised by the public which extend beyond the impacts of direct concern to the panel, and in such cases the panel will ensure that the public is provided a reasonable opportunity to express these concerns.

SCHEDULE A

EIS Submitted

1. Dominique-Janine Extension
Amok Ltd.¹⁰⁷
2. South **McMahon** Lake Project
Midwest Joint Venture (Denison Mines Ltd.¹⁰⁸)
3. **McClean** Lake Project
Minatco Ltd.

EIS to be Prepared

4. **McArthur** River Project
McArthur River Joint Venture (**Cameco** Corporation)
5. Cigar Lake Project
Cigar Lake Mining Corporation

¹⁰⁷ Responsible party for Dominique-Janine Extension is now **Cogema** Resources Ltd.

¹⁰⁸ Responsible party for Midwest Joint Venture is now Total Minatco.

APPENDIX C

PANEL ACTIVITIES

-
- Joint public review announced and Terms of Reference issued by Robert de **Cotret**, Minister of the Environment, and Grant **Hodgins**, Minister of Saskatchewan Environment and Public Safety, April 18, 1991
 - Joint Review Panel members appointed by **Beattie** Martin, Minister of Saskatchewan Environment and Public Safety and Jean Charest, Minister of the Environment, August 22, 1991
 - Panel toured all proposed mine development sites, October 1-6, 1991
 - Panel's Operational Procedures released December 19, 1991
 - **EISs** received and released for a **90-day** public review as follows:
 - Midwest Joint Venture, December 19, 1991
(deadline date for submissions-March 20, 1992)
 - McClean Lake Project, January 13, 1992
(deadline date for submissions-April 13, 1992)
 - Dominique-Janine Extension at Cluff Lake, March 31, 1992
(deadline date for submissions-June 30, 1992)
 - Deadline date for public submissions for MJV and McClean Lake extended to May 29, 1992
 - Scoping Meetings for Cigar Lake and McArthur River announced January 7, 1992, to begin February 7, 1992
 - Dates and locations of Scoping Meetings announced January 22, **1991**, as follows:

February 7, 1992	Ben McIntyre School, Uranium City
February 8, 1992	Fond du Lac Band Hall, Fond du Lac
February 10, 1992	Community Hall, Stony Rapids
February 10, 1992	Community Hall, Black Lake
February 11, 1992	Hatchet Lake Band Hall, Wollaston Lake
February 12, 1992	Arena Hall, La Loche
February 13, 1992	Complex Hall, Buffalo Narrows
February 14, 1992	Community Hall, Ile-à-la-Crosse
March 2, 1992	Ramada Renaissance, Regina
March 3, 1992	Holiday Inn, Saskatoon
March 4, 1992	Marlboro Inn, Prince Albert
March 5, 1992	Kikinahk Centre, La Ronge
 - Modifications to the Midwest Joint Venture and McClean Lake projects issued May 6, 1992
 - Technical Reviews of Midwest Joint Venture and McClean Lake projects, as prepared by Ecologistics Limited, issued May 29, 1992
 - Draft Guidelines and Government Information Requests for Cigar Lake and McArthur River issued June 1, 1992, for public review until July 3, 1992
 - Summary Report on Scoping Meetings for Cigar Lake and McArthur River, prepared by Quadra Planning Consultants Ltd., issued August 19, 1992
 - Guidelines for the Preparation of Environmental Impact Statements and Government Request for the Cigar Lake and McArthur River projects issued September 11, 1992
 - Request for Additional Information issued to Amok Ltd. on October 7, 1992
 - EIS Amendments for Midwest Joint Venture and McClean Lake issued October 30, 1992, for a public review period ending November 30, 1992
 - EIS on McArthur River Project Underground Exploration Program, July 1992, and Addendum, October, 1992, referred to Joint Panel for public review on October 29, 1992, with review period ending December 2, 1992
 - Dates and locations for Public Hearings on McArthur River Underground Exploration Project announced November 1, 1992, as follows:

December 3, 1992	Hotel Saskatchewan, Regina
December 4-5, 1992	Holiday Inn, Saskatoon
December 6, 1992	Community Hall, Fond du Lac
December 7, 1992	Community Hall, Black Lake
December 8, 1992	Hatchet Lake Band Hall, Wollaston Lake
December 9, 1992	Community Hall, Pinehouse
December 10, 1992	Kikinahk Centre, La Fionge
 - Response to Panel's Request for Additional Information from Total Minatco on the **McClean** Lake project issued on December 15, 1992, for a public review period ending January 15, 1993
 - Panel issued commissioned reports December 15, **1992**, as follows:
 - *Health in the Context of Uranium Mining in Northern Saskatchewan*, Ed **Weick**, ESAS

-
- *An Overview of the **Biophysical** Environmental Impact of Existing Uranium Mining Operations in Northern Saskatchewan*, Dr. Herman Dirschl, ESAS
 - *A **Brief** Historical Review of the **Beaverlodge** Mining Area of Northern Saskatchewan*, R. Barsi and Dr. A.W. Ashbrook
 - *A Socio-Economic Overview of Uranium Mining in Northern Saskatchewan*, Ed Weick, ESAS
 - *Review of the **Cluff** Lake and Key Lake Reports*, L. Vigrass
- Response to Panel's Request for Additional Information from Midwest Joint Venture issued on December 23, 1992, for a public review period ending January 22, 1993
 - Panel issued specialists' report, *Assessing Cumulative Effects of Saskatchewan Uranium Mines Development*, on January 8, 1993
 - Panel submitted **McArthur** River Underground Exploration Program report to federal and provincial governments, on January 15, 1993
 - Cogema's (formerly AMOK) Response to the Panel's Request for Additional Information issued February 8, 1993, for a public review period ending March 5, 1993
 - Public Hearings dates and locations announced on February 19, 1993, and extended dates announced March 26, 1993. An additional change in the dates of the Hearings was announced on April 26, 1993. Hearings were held as follows:
- | | |
|-------------------|---|
| March 22-24, 1993 | Hotel Saskatchewan, Regina |
| April 13, 1993 | Community Hall, Black Lake |
| April 14, 1993 | Hatchet Lake Band Hall, Wollaston Lake |
| April 15-16, 1993 | Kikinahk Centre, La Ronge |
| April 16, 1993 | Friendship Centre, Ile-à-la-Crosse |
| April 19, 1993 | Complex Hall, Buffalo Narrows |
| April 20, 1993 | Arena Hall, La Loche |
| April 21, 1993 | John M. Cuelenaere Library, Prince Albert |
| May 3-5, 1993 | Holiday Inn, Saskatoon |
| May 7-8, 1993 | Holiday Inn, Saskatoon |
| May 17-20, 1993 | Holiday Inn, Saskatoon |
-

APPENDIX D

SUBMISSIONS TO PANEL

APPENDIX D-I

REFERENCED BY ALL THREE REVIEWS

D-I.1 Oral Presentations Made At Public Hearings

Alam, Rabbi

Algoma Manitoulin Nuclear Awareness (Ed Burt)

Alto Construction (Ron Kunkel)*

Anderson/Fast Marketing Solutions (Doug Fast)*

Association of Consulting Engineers of Saskatchewan (E.J. Hinz)*

Athabasca Airways (Jim Glass)

Atomic Energy Control Board (George Jack, Mary Measures, Dalsu **Baris**, Bernie Zgola, Tom Viglasky, Larry Chamney, Kevin **Scissons**, Rick McCabe, Ron Moore, Fred **Ashly**)*

Augier, Danny

Ayotta, Ivan

Battlefords Awareness Movement (Laird **Brittin**)*

Batty, Linda

BCP Engineering Ltd. (Gary **Cabalt**)*

Beauvin, Marie

Beaver Eye, Joe

Bell, Jack*

Benoanie, Ed

Bethel United Church, Council of (Judy **Howsam**, Helen Smith-McIntyre, Mary Jean Roy)*

Big Eye, J.B.

Big Eye, Maurice

Black Lake and Fond du Lac Bands (Chief Joe Martin, Pierre Robillard, Donald Deranger, Edwin **Boneleye**)*

Boan, Derek*

Bougie, Paul

Bouvier, **Vye***

Brade k, Carla

Brady Development Corporation, Pathway to Success Program (Michelle Harding)

Brent Construction (Russ Clunie)

Brucy, Martin
Bryce, Elizabeth*
Bryson, Mike*

Canadian Coalition for Nuclear Awareness (Gordon Edwards)
 Canadian Labour Congress and the Saskatchewan Federation of Labour (Don Anderson)
 Canadian Nuclear Association (The Honourable John Reid, Ian Wilson)*
 Canadian Union of Public Employees, Saskatchewan Division (Glen **Makahonuk**)*
 Carle, Gordon
 Case, **Leila**
 Chambers, Doug
 Chary, Srinii'
 Cheecham, Roy
 Chevalier, Malann
 Chicken, Senator Louis
 Christie, Larry
 Churchill **Métis** Labour Management Board (Max Morin)
 Cisyk, Dave
 Citizens Concerned about Free Trade (Marjaleena Repo, David Orchard)*
 Clark, Peter
 Clay, Colin **P.***
 Cominco Engineering Services Ltd. (Will **Brandsema**)*
 Communications, Energy and Paperworkers' Union of Canada (R.E. **Neilsen**)*
 Communications, Energy and Paperworkers' Union, Local 46 (Geoff Case and **Del** Josephson on behalf of John Case, Sid Schmidt, John Case)*
 Community Services Health Clinic (Michael Wilson, Michael **Murphy**)*
 Conlon, Art (on behalf of Sharon Aubin)*
Conwest Construction (Oliver (Bob) Cromwell)*
 Crush, Terry
 Cummings, Rick
 Curry, Bill
 Cusitar, Murray
 CUSO (Don Kossick, Marlene Larocque, Jacqui Barclay)*

 Daigneault, Tony
 Dancer, Joys
 Dancer, Oriole
 Deranger, Donald*
Denechezhe, Sophie*
 Denison Mines Ltd. (Andy **Rickaby**)*
 Dewar, Dale
Dillen, Ken*
 Dobbin, Murray (presented by David Geary)
 Drummond, Val
 Dumais, William
 Dzeyllion, Martin
 Dzeyllion, Tony

 Energy, Mines and Resources Canada (Richard Williams, Greg **McGuire**, Grant Feasby, Ron Edwards)*
 Environment Canada (Dennis Lawson, Bill Howard)*
 Environmental Engineering Research Unit, University of Saskatchewan (Lee **Barbour**, John **Gillis**)*
 Epp, William*
 Favel, Brian

Favel, Jim
 Favel, William
 Federation of Saskatchewan Indian Nations (Vikas Khaladkar on behalf of Chief Roland Crowe)
 Fern, George
 Fisher, Linda*
 Fisheries and Oceans Canada (Bruce **Fallis**)*
 Fitzsimmons, Michael
 Flood, Peter'
Forgay, Beryl*
 Fortugno, **Maria***
Fortugno, Stefania*
Francis, Mai
 Froese, Dan'
 Froese, Joe

Gagne, Louise*
 Garrett, Jim*
 Geary, David*
 George, **Isabelle***
 George, Chief Louis
 GML Integrated Environmental Management Ltd (Raymond Van de **Woestyne**)*
 Gramiak, Connie*
 Greenfield, Dave
 Greenpeace (Stan **Gray**)*
 Guillet, Raymond

Harding, Jim*
 Hardy, Naomi
 Harrison, Phil
 Hauta, Shirley*
 Hawkins, Valerie*
 Health and Welfare Canada (Jerry **Shaw**)*
 Helliard, Stephen*
 Hellmuth, Ralph*
 Herman, **Cecile**
 Herman, Emil
 Herman, Lester
Holden, Joe'
 Howe, Eric*

Ile-à-la-Crosse, Town of (His Worship Buckley **Belanger**)*
 IndEx'93 (**Barb Klassen**)*
 Indian and Northern Affairs Canada (George Cornwell)*
 Inter-Church Uranium Committee (**Phillip Penna**, Michael **Poellet**)*
 Interprovincial Association on Native Employment (Roberta Burns)*
 Inuit Tapirisat of Canada (Jamie **Kneen**, Joan **Scotti**)*
 Iron, Joe Sr.
Irvine, J.*

J.P. Enterprises (J.P. Proulx)
Jacek, Sister Regina
 Jack, Bob
 Janvier, Diane
 Janvier, Jacob
 Jensen, Debbie
 Johnson, Harold
 Josie, Martin
 Josie, Sarazine

Kennedy, Ray
 Kilborn Western Inc. (Ted Bassett)*
 Kirshner, David
 Kitsaki Development (J.P. Roberts)
 Klassen, Cameron
 Kramer Ltd. (**Garry** Ewen on behalf of Tim Kramer)
 Kyle, Croft

Laban, Jimmy
 La **Loche** Airways (Craig Schnell)
 Lamont, Tom'
LaRiviere, Tom*
 La **Ronge** and District Chamber of Commerce (Peter Kelly)'
 La Ronge Economic Development Committee, Town of (Scott Robertson)*
 La Ronge, Town of (His Worship Morris Gabrush)'
 Lau, Victor
 Le Maigre, Ida
 Le Maigre, Mark
 Lindner, Degen*
 Loewer, Roland
 Logue, Maureen

McDonald, **Bart**
 McIntyre, Lawrence
 McKay, Norma
 Paul McKay
 McPherson, Jean*
 Malboeuf, Norma
 Meadow Lake Heritage and Future Development Association,
 and Meadow Lake District Chamber of Commerce
 (Eric Roberts)
 Mercredi, Germaine
 Mercredi, John James
 Mercredi, Robert
Métis Society of Saskatchewan (Norman Hansen)
Métis Society of Saskatchewan, Local 126 (**Robert** Doucette,
 Deb Hopkins)*
Metke, Bill*
 Montgrande, Sharon
 Montour, L.
 Morin, Jeff
 Morin, Gordon
 Morin, Sharon
 Morin, Vital
 Mumm, Maggie*
 Murphy, Linda
 Myers, David*

Naldzil, Alfred
 Norsask Native Outreach Inc. (Vicky Marinuk, Antoinette Le
 Maigre, Doreen **Morin**)*
 North Saskatoon Business Association (Ed Stevens)'
 Northeast Economic Development Association (Torance
 Tomquist)*
 Northern Explosives Ltd. (Larry Wolkowsky)
 Northern Mining Coordinators (Les **Erikson**)*
 Northern Resource Trucking Ltd. (Roger Olyowsky, Chief
 Harry Cook, Dwayne **Hounsel**)*
 Northwatch (Lloyd Greenspoon)
 Northwest Credit Union (Bill Jeffrey)

O'Conway, **Marcie**

Onyskevitch, Morris*

Parrott, Dan
 Partnership, The (Betty Anne Latrace-Henderson)*
 Pedersen, **Gil***
 Pedersen, John'
 Pedersen, Yens (on behalf of Jean Sloan)*
 Peerenboom, Laurie*
 Pelican Narrows, Northern Village of (Torance Tornquist for
 Ron **Canada**)*
Penna, James'
Pinehouse, Village of (His Worship Peter Smith, Greg Ross)
 Pokebusters (Karen Weingeist)
 Porcupine Plain Opportunities Programs (Carl Kwiatkowski)
 Powder, Danny
 Powder, Dennis
 Powder, Steve
 Prince Albert Citizens for Energy Alternatives (Steve
 Lawrence)*
 Prince Albert Development Corporation, Security Services
 (Raymond Sanderson)*
 Project Plow Shares (Ellen Gould)
 Pronteau, Gilbert

Quigley, Tim*

Rachar, Paul
 Ratt, Brian
 Regan, Gerald
 Regnier, Bob
 Robillard, **Archie**
 Robillard, Chief Dan
 Robillard, Dennis
 Robillard, Henry
 Robillard, Mervin
 Robillard, Simon
 Robillard, Ted
 Rogalla, Dieter'
Rushton, Michael*

Sachacherl, Ugo*
 Salt, **Reg***
 Sanderson, Lillian
 Sandypoint, Billy
 Saskatchewan Association of Rural Municipalities (Val **Kono-**
 noff, Jim Angus)*
 Saskatchewan Conference of the United Church of Canada,
 The Church in Society Committee (Sylvia Thompson)*
 Saskatchewan Construction Association Inc. (Jim Chase)*
 Saskatchewan Education, Training and Employment (Ray
Mackay)*
 Saskatchewan Energy and Mines (Ray Clayton, Jane
 Forester)*
 Saskatchewan Environment and Resource Management (Ron
 Zukowsky, Ron **Barsi**, Bruce Smith, Greg Vogelsang,
 George Lucas)*
 Saskatchewan Environmental Society (Peter **Prebble**)*
 Saskatchewan Executive Council (Frank **Bogdasavich**)*
 Saskatchewan Government Employees' Union (Fiona Bishop,
 Dale **Holmberg**)*
 Saskatchewan Health (Danni Boyd, Jane Lyster, Kathy
 Chisholm, Gloria Sills, Leonard Hamm)'
 Saskatchewan Indian and **Métis** Affairs (Victor Taylor)*

Saskatchewan Labour (John Alderman, Denis Brown)*
 Saskatchewan Mining Association (Bob Cunningham)*
 Saskatchewan Municipal Government (Ron Styles, Brian Goff in)*
 Saskatchewan Natural History Society (Jim Elliott)*
 Saskatchewan Social Services (Brenda Righetti)*
 Saskatchewan Urban Municipalities Association (Alderman Ted Cholod, His Worship Buckley Belanger)*
 Saskatchewan Young New Democrats (Keith Jorgenson)*
 Saskatoon Chamber of Commerce (Albert Johnson)*
 Saskatoon, City of (Peter McCann)*
 Saskatoon Economic Development Authority (Dick Pinder)*
 Saskwatch (Paul Hanley, Larry Morris)*
 Sayezi, Donald
 Sayezi, Jimmy
 Sayezi, Max
 Scarfe, Albert
 Schlichemeyer, Cheryl
 Senior Environmental Organization of Regina (Verena Catikkas)*
 Sentar Consultants Ltd. (Donald Somers on behalf of Stella Swanson)*
 Septre Controls Ltd. (Stan Powell, Larry Bohn)*
 Shiell, Maisie*
 Shumard, Shirley
 Siemens Transport (Brian Smith)*
 Simpson, Graham
 Six Seasons Catering (William Smith)*
 Smillie, Adelle*
 Sproule, Cathy
 Stang, Carol
 Strnad, J. G.
 Swider, Rick
 Sydiaha, Stephanie
 Sylvester, Donnie
 Sylvester, Linda
 Symis, Marie
 Synergy Today (His Worship Bill Childerhose)
 Tavini-Huiraatira-Polynesian Liberation Front (Remuna Tufariua)*
 Taylor, Allan S.
 Telesis³ (John Scharf, Bud Burrell)*
 Thyssen Mining Construction of Canada Limited (Andrew Fearn)*
 Tron Power Ltd. (Ron Hemeon)*
 Tsannie, Chief Joe
 Twin Rivers Educational Environmental Society (read by Yens Pedersen for Val Shockey)*
 United Steelworkers of America, Local 8914 (Gordon Telfer)*

University of Saskatchewan (Bill Stolte)*
 Uranium Coalition (Marvin Resnikoff)*
 Uranium Saskatchewan Association Inc. (Tim Meadley)*

Vector Enterprises (Bob Heath)*

Wartman, Mark
 Watson, Ron
 Wells, Stewart
 West Wind Aviation (Dennis Goll)*
 Whitehawk, Joe
 Weingeist, Karen
 Wiercinski, Criss*
 Winnipeg Coordinating Committee for Disarmament (Philip Kienholz)
 Woods, Bob
 World Uranium Hearings (Guenter Wippel)*

N. Yanke Transfer Ltd. (Russell Marcoux)*
 Yole, Sharon

'A written submission was supplied to accompany the oral presentation, and is available for public review.

D-1.2 Written Submissions

Beverly and Kaminuriak Caribou Management Board (Jerome Denecheze)
 BIG MOUNTAIN Aktionsgruppe, Team Frankfurt (Wolfgang Sandkühler)
 Breti, Sybil
 Concerned Citizens of Manitoba (Anne Lindsey, Dave Taylor)
 Fort Qu'Appelle Peace and Justice Committee (N.L. Rowell)
 Fortugno, Frances
 Government of the Northwest Territories (Titus Allooooloo)
 Huculak, Jim
 Indigenous Women's Network (Lea Fouchée)
 McConnell, Madage
 NO-Candu Coalition (Diana Chown)
 NUEXCO Information Services (Thomas C. Pool)
 Orchard, R. Lyle
 PA Foundry Ltd. (Merriett Hewitt)
 Penna, Marion
 Peoples' Organization Against Nuclear Power and Nuclear Weapon, Gävle, Sweden (Thorild Dahlgren)
 Pike, C.
 Pomroy, Brent
 Thomas, Patricia
 Trendocher, Loretta
 UNECO (Ken Smith)

APPENDIX D-2

DOMINIQUE-JANINE EXTENSION

D-2.1 Oral Presentations Made at Public Hearings

Buffalo Narrows Airways (Dennis O'Brien)
 Cogema Resources Inc. (**Michel** Poissonnet, Liz Quarshie,
 Lyle Bear, Stan Penner)*
 Communications, Energy and Paperworkers' Union, Local 48
 (Geoff Case and **Del** Josephson on behalf of John Case,
 Sid Schmidt, John Case)*
 Forester, John
 Gardiner, Abraham
 Gardiner, Rodney (read by Joe Whitehawk)
LaFleur, Jim
Meneley, W. A.
 Piercy and Associates (read by **A.R.** Garden of McPherson,
 Leslie and Tyerman, for Harold Piercy)
 Petit, Frank
 Quarshie, Ellis*

D-2.2 Written Submissions

Atomic Energy Control Board (George Jack)
 Beaver Foods Ltd. Limited (**R.** J. Henderson)
 Environment Canada, Western and Northern Region (B. M.
 Burns)
 Fisheries and Oceans, Central and Arctic Region (P.H.
 Sutherland)
Flett, Alex, Edward, and **Timmy**
 Health and Welfare Canada (Jerry Shaw)
 Inuit Tapirisat of Canada (Jamie Kneen)
 Saskatchewan Environment and Public Safety (Technical
 comments from provincial departments and agencies)
 Saskatchewan Environmental Society (Peter **Prebble**)
 Saskatchewan Natural History Society (Jim Elliott, Donald
 Harron)
Shiell, Maisie
 The Uranium Coalition (prepared by Radioactive Waste Man-
 agement Associates)

APPENDIX D-3

McCLEAN LAKE

D-3.1 Oral Presentations Made at Public Hearings

Brown, Adrian
Corman, Jim
Halbert, Bruce
 Hamlet of Wollaston Lake/Hatchet Lake Band Joint Commit-
 tee (Chief Joe Tsannie, Jack Bell)*
 La **Ronge/Air** Ronge Economic Development Committee
 (Scott Robertson)*
 Points North Freight, (George Eikel)
 Total Minatco Ltd. (Ken Haapanen, Al Morrish, Dennis
DeWinter, Walter Keyes)*
 Visions North Community Futures Committee (Angus Pratt)*

D-3.2 Written Submissions

Atomic Energy Control Board (George Jack)
 Environment Canada, Western and Northern Region (B. M.
 Burns)
 Fisheries and Oceans (P.H. Sutherland)
 Fond du Lac Indian Band, Black Lake Indian Band, and Prince
 Albert Tribal Council Health and Welfare Canada (Tim
 Bonish)
 Indian and Northern Affairs Canada (Clifford S. Starr)
 Inuit Tapirisat of Canada (Jamie Kneen)
 Joint Review Committee, Hamlet of Wollaston Lake and
 Hatchet Lake Indian Band (Her Worship Flora **Nato-**
magen, Chief Joe Tsannie)
 Saskatchewan Environment and Public Safety (Technical
 comments from provincial departments and agencies)

Saskatchewan Environmental Society (Peter Prebble)
Saskatchewan Natural History Society (Jim Elliott, in cooperation with Donald E. Harron))

Shiell, Maisie
The Uranium Coalition (Prepared by Radioactive Waste Management Associates)

APPENDIX D-4

MIDWEST JOINT VENTURE

D-4.1 Oral Presentations Made at Public Hearings

Hamlet of Wollaston Lake/Hatchet Lake Band Joint Committee (Chief Joe Tsannie, Jack Bell)
La Ronge/Air Ronge Economic Development Committee (Scott Robertson)*
Midwest Joint Venture (Joe Anderson, Herb Fredericksen)
Montell, Jacques
Points North Freight (George Eikel)*
Rickaby, Andy
Visions North Community Futures Committee (Angus Pratt)

Environment Canada (B.M. Burns)
Fisheries and Oceans (P.H. Sutherland)
Fond du Lac Indian Band, Black Lake Indian Band, and Prince Albert Tribal Council
Health and Welfare Canada (Jerry Shaw)
Joint Review Committee, Hamlet of Wollaston Lake and Hatchet Lake Band (Chief Joe Tsannie)
Saskatchewan Environment and Public Safety (Technical comments from provincial departments and agencies)
Saskatchewan Natural History Society (Jim Elliott, in cooperation with Donald E. Harron)
Shiell, Maisie

D-4.2 Written Submissions

Atomic Energy Control Board (George Jack)

APPENDIX E

BIBLIOGRAPHY OF REVIEW DOCUMENTS

APPENDIX E-I

REFERENCED BY ALL THREE REVIEWS

- *A Brief Historical Review of the Be8 veriodge Mining Area of Northern Saskatchewan*, by R.G. Barsi and Dr. A.W. Ashbrook, October, 1992
- *An Overview of the Biophysical Environmental Impact of Existing Uranlum Mining Operations in Northern Saskatchewan*, prepared by Environmental-Social Advisory Services Inc. (Herman J. Dirschl, Principal), October, 1992

-
- ***A Socio-Economic Overview of Uranium Mining in Northern Saskatchewan***, prepared by Environmental-Social Advisory Services Inc. (Ed Weick, Principal), October, 1992
 - ***Assessing Cumulative Effects Of Saskatchewan Uranium Mines Development***, prepared by an independent team of specialists (Principal authors: M. Husain Sadar, David R. Cressman, and Dianne C. Damman)
 - ***Health in the Context of Uranium Mining in Northern Saskatchewan***, prepared by Environmental-Social Advisory Services Inc. (Ed Weick and Dr. John O'Neil, Principals)
 - Review ***of the Cluff Lake and Key Lake Reports***, by L. W. Vigrass, September, 1992
 - Uranium Library, compiled by D.W. Lawson, L. Raymond, D.M. Shiskowski, Environment Canada
-

APPENDIX E-2

DOMINIQUE-JANINE EXTENSION

-
- ***Environment81 impact Statement: Dominique-Janine Extension, Main Document***, Amok Ltd/Ltée, February, 1992.
 - ***Environmental Impact Statement: Dominique-Janine Extension, Addendum***, Cogema Canada Ltd/Ltée, January 1993.
 - ***Cluff Lake Status of the Environment Report***, Stella Swanson, Editor, October 29, 1990
-

APPENDIX E-3

McCLean Lake

-
- ***McCLean Lake Project, Environmental impact Statement***, Total Minatco Ltd., August 1991.
 - ***Complementary McCLean Lake and Midwest Projects, McCLean Lake Project Environmental Impact Statement***, Total Minatco Ltd., September 1992.
 - ***Complementary McCLean Lake and Midwest Projects, McCLean Lake Project Environmental impact Statement, Additional information Requested By Uranium Mines Review Panel***, Total Minatco Ltd., November 1992.
 - ***McCLean Lake Project, Environmental Impact Statement, Additional information Transmission Line Tap***, Total Minatco Ltd., March 1993.
 - ***Technical Review of the Minatco Limited Environmental Impact Statement for the Proposed McCLean Lake Uranium Development***, prepared by Ecologistics Limited, May 21, 1992.

APPENDIX E-4

MIDWEST JOINT VENTURE

- ***Midwest Uranium Project, Environmental Impact Statement***, Midwest Joint Venture, Denison Mines Limited (Operator), August, 1991.
- ***Complementary McClean Lake and Midwest Projects, Midwest Project Environmental Impact Statement Amendment***, Midwest Joint Venture, September, 1992.
- ***Complementary McClean Lake and Midwest Projects, Midwest Project, 1991 Environmental Impact Statement***,
Additional Information Requested By Uranium Mines Review Panel, Midwest Joint Venture, November, 1992.
- ***Technical Review of the Midwest Uranium Project Environmental Impact Statement***, prepared by Ecologistics Limited, May 25, 1992.



Uranium mining in the North Bohemia, Straz, Czech Republic and geological evaluation prior to remediation

P. Kopecky, J. Slezak

DIAMO, Straz pod Ralskem, Czech Republic

Abstract. The Straz uranium deposits are located in sedimentary rocks and within important aquifers. One of these is of drinking water quality. The deposits were exploited by both conventional and in situ leach (ISL) methods in two mines: the Hamr-North underground and the Straz (ISL) mine. They are located in an aquifer within sedimentary Cenomanian formation. Between 1967 and 2000 the Straz ISL mine produced over 16 000 tonnes U by injecting a total of 4.1 million tonnes of sulphuric acid, 315 000 t of nitric acid, 112 000 of ammonia, 26 000 of hydrofluoric acid, and 1400 of hydrochloric acid. This enormous amount of acid is creating a major rehabilitation problem and a potential risk for another aquifer: the Turonian drinking water quality aquifer. The problem is now being addressed by completing a complete hydrogeological assessment. Contaminated water is being treated to reduce the present contamination levels of 5-110g/l TDS to less than 10g/l TDS. The rehabilitation will be influenced by economic factors, as well as the development of new technologies.

The North Bohemian uranium bearing region was detected at the beginning of the 60s as a result of a systematic well log re-examination in the area Hamr na Jezere.

Based on geological exploration work the deposit area was identified as a stratiform deposit in sedimentary rock having sub-horizontal tabular position with variable changeable thickness. Uranium deposits of the Straz block in the northbohemian Cretaceous are fundamentally different from other formerly exploited uranium deposits in the CR. It is a region with complicated and unfavourable hydrogeological conditions for mining. Moreover, significant potable groundwater resources are located in the territory.

The deposits are generally flat or gently inclined with irregular mineralized thickness that varies from several dm to several m. Mineralization is associated with several kinds of rock such as sandstone, breccia, conglomerate, and siltstone in which fortress in pressure varies from 2 MPa to 30 MPa.

Choosing a suitable mining method required the consideration of specific criteria, such as, an underground mining method that prevents subsidence or working with a deposit that has an impermeable strata above the mining area. These criteria limited the choices to either essentially complete backfilling in an underground mine or an in situ leaching technique.

Eventually both methods were used. The Hamr and Brevinstek deposits were mined by underground methods and the Straz deposit by in situ leaching.

The “room and pillar” (panel and fill) method was chosen for the underground mining operation. This choice was based on tests conducted between 1972 and 1975. Specifically, the method adopted retains pillars to support the roof in the mined out area. The open space or room is then backfilled with a low compressible solidifying material that is brought into the mine from the surface. The mining thickness varied from 2.2 m to 5 m. Each mining block had a width of up to 250 m and a maximum length of 150 m.

Each room had a maximum width of 5 m. Both a three-room system and a four-room, system were used. With the three-room system, a 10 m pillar was retained between the rooms, and a 15 m pillar was retained when the four room system was used. Mining of the secondary room was initiated after the primary room was mined out.

If the mineralized thickness was greater than 5 m, the ore was mined by panel slicing, and the open space was backfilled before mining the subsequent panel slice.

For mining relatively narrow ore seams, a variant of the room and pillar method was used, in which each mined out room was totally backfilled before proceeding to the next room. A long-wall technique similar to that used in coal mines was also tested.

Both dewatering of each mining block prior to actual mining and continuous mine drainage during operations was required. Dewatering was achieved both through drifts below the ore block and through drill holes above the ore block. During mining operations at the Hamr mine, it was necessary to pump approximately 15 m³ of mine water annually.

The underground mining operations produced about 42.3% of the total uranium recovered from the northbohemian area; the balance (57.7%) came from ISL operations.

After laboratory and field-test verification, ISL technology has been used since the second half of the 60s. The first batch of concentrate from leach field VP-3 was transported to the MAPE chemical mill in Mydlovary on 13 Dec.1967. Leach field VP-3 consisted of two interconnected 8 m hexagons. The field contained 12 wells (10 perimeter and 2 center wells).

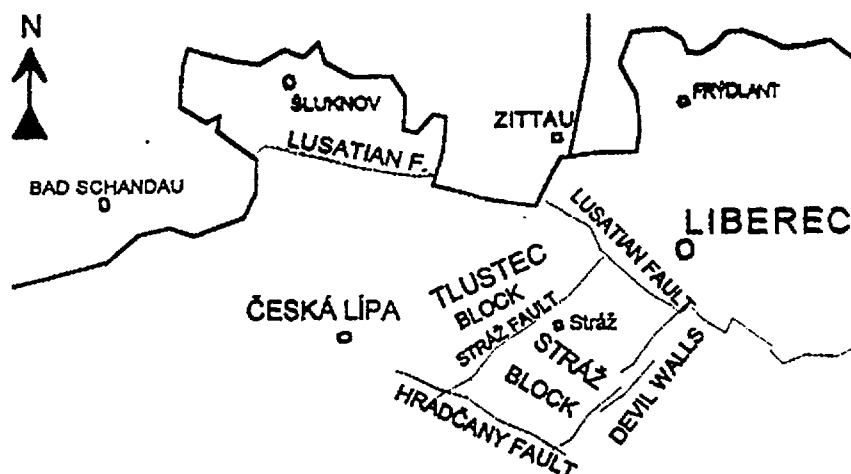


FIG. 1. Situation scheme of Northbohemian area.

After 1971, the pace of ISL development increased significantly. Step by step, the ISL method gradually replaced uranium production from the traditional mining districts. Much of this change occurred when production stopped at the Hamr-North deep mine due to flooding when the mining operations crossed the saturated Agnes tectonic zone. In 1975, ISL operations covered a total area of almost 210 ha; in 1980 the extent was over 300 ha.

Substantial changes in well construction have occurred. Single casing wells were replaced by double cased wells with outer casings. The small diameter pumping wells were replaced by wide-diameter wells.

The straz ISL operations below the Ralsko hill were stopped in 1993. In total it had 42 leaching fields containing 7500 wells and extended over 650 ha.

Between 1967 and 2000 the ISL mines produced over 16 000 t uranium. Reagent consumption totalled 4.1 million tons of sulphuric acid, 315 thousand tons of nitric acid, 112 thousand tons of ammonia, 26 thousand tons hydrofluoric acid and 1400 tons of hydrochloric acid.

ISL and deep mine production methods require different hydrogeological conditions for successful development:

- dry deposits benefit deep-mine operations;
- deposits with Cenomanian water levels favour ISL operations.

The existence of both mining methods in a relatively small area led to ISL leach solution excursions towards the centre drainage of the deep mine. Thereby, the contaminants reached the so-called "dispersion area" of acid ISL mine waters. A stable situation was reached after installing a hydraulic barrier between ISL area and the deep mine. Water injection creates an artificial compressive watershed in Cenomanian aquifer.

The ISL wellfields were developed using a series of isometric polygon well patterns (at first hexagonal, later square) with varying distances between wells.

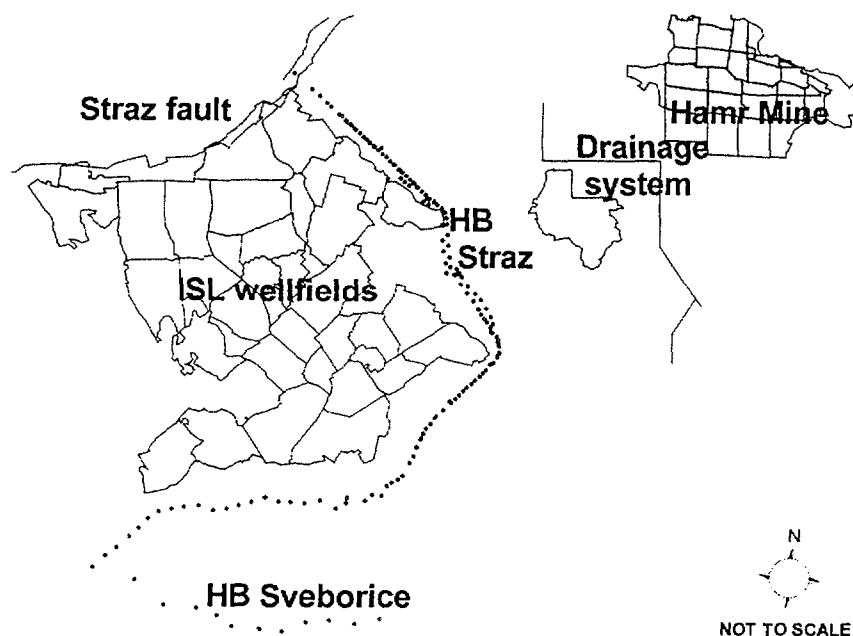


FIG. 2. Situation scheme of mining area.

A number of different well patterns were tried on one hectare plots of the leaching field. The highest density of 15 to 30 wells/ha was achieved using the square pattern; the lowest density of 4-8 wells/ha was realized with wide-spaced wells.

At present, the contaminated ground water in the Straz deposit and its surroundings (approx. 24 km² with about 270 mil. m³) contains 4.8 mil. t of dissolved substances. Approximately 99.5% of dissolved solids are concentrated in the Cenomanian aquifer; the remaining 0.5% of the contamination is dispersed in 80 mil. m³ of groundwater in the turonian aquifer.

The contaminated ground waters are not naturally attenuated in the aquifers. If the situation is not actively addressed, it will in time lead to dispersal of the contamination and to negative impacts on the groundwater quality over a wide area.

In 1996, a treatment facility (SLKR) was installed to decontaminate the acid solutions. One unit of this facility treats the turonian waters using membrane technology, and the second operation uses evaporation for the Cenomanian waters. At present, the SLKR operation is showing its positive influence by reducing the volume of the contaminated ground water in the cenomanian formation.

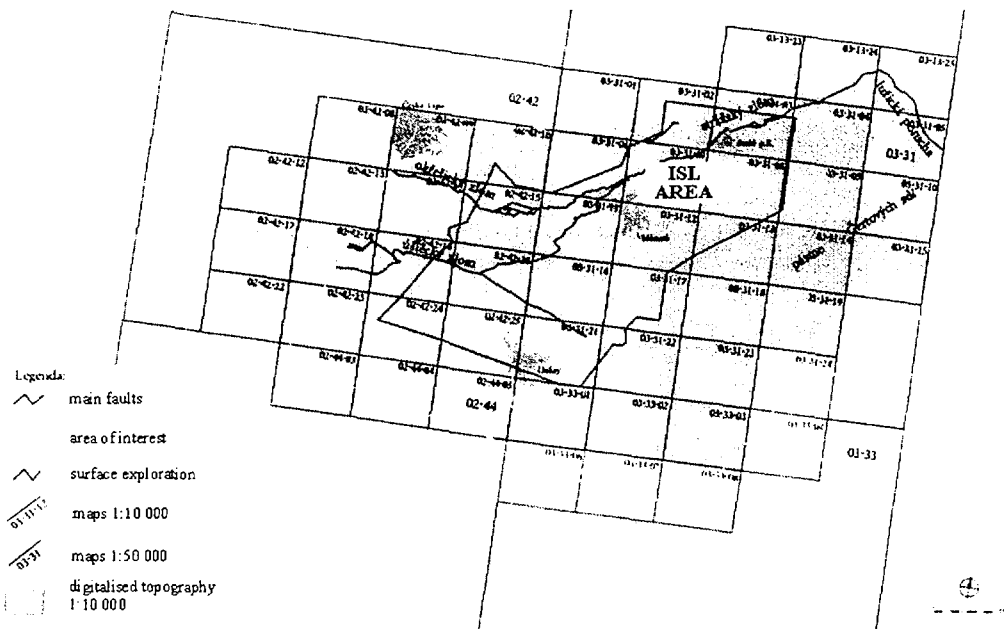


FIG. 3. Explored area.

The ISL production of uranium from the Cenomanian sandstones in Northern Bohemia was carried out in a part of the geological structure which has two main aquifers with one aquiclude between them. Mining activities have influenced both the quantity and quality of the groundwater. After 1990, the environmental point of view changed rapidly. During an analyses of ISL and deep mining impact, the large amount of contaminated water from ISL (approx. 200 000 000 m³ having approx. 50 g/l TDS) was determined to be the greatest potential risk in the area.

At the beginning of the 1990's, extensive geological exploration work was done in the area south-west of the ISL plant, which is the direction of natural groundwater flow from the ISL area. This work was conducted to determine whether there was a geological risk that contaminated groundwater could transfer from the Cenomanian aquifer to the overlying Turonian aquifer or to the surface.

A complex of exploration methods ranging from small to comprehensive scale was established to qualify and quantify the risks. This complex approach answered the questions in a very short time. The applied methods had a logical sequence.

The first phase consisted of synoptic methods such as:

- satellite imaging photos and their evaluation,
- air-borne geophysics and their evaluation,
- re-interpretation of older geological and geophysical data,
- regional hydraulic mathematical models of groundwater flow.

The second phase concentrated on the areas, which appeared risky after the first phase. The work consisted of:

- surface geophysics,
- surface geological exploration

Phase 2 focussed on the most risky parts of the geological structures, such as faults with significant vertical movement etc. Results of this exploration were gradually put into the regional hydraulic mathematical model.

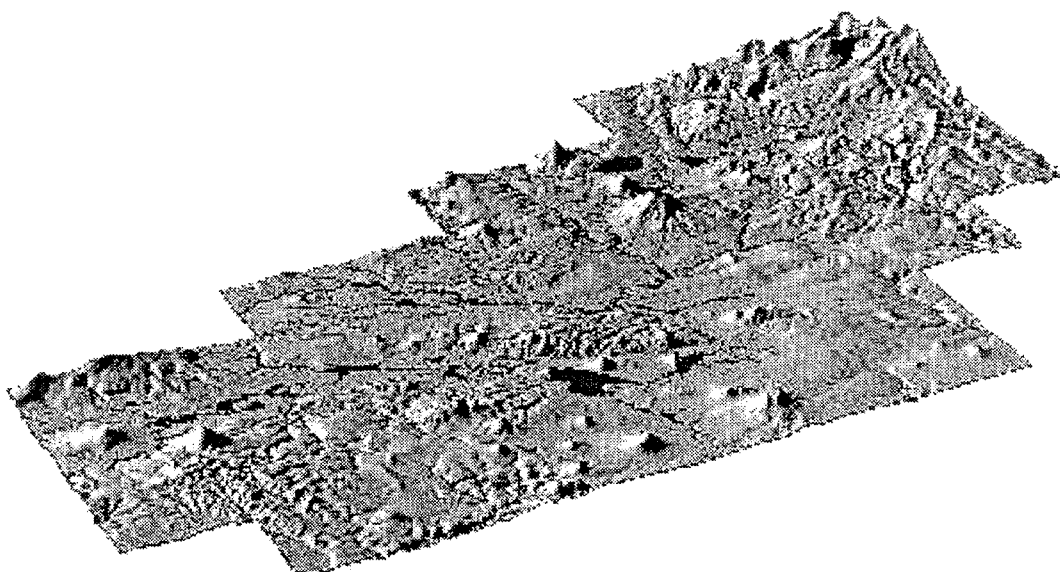


FIG. 4. Surface 3D map of the area from GIS data.

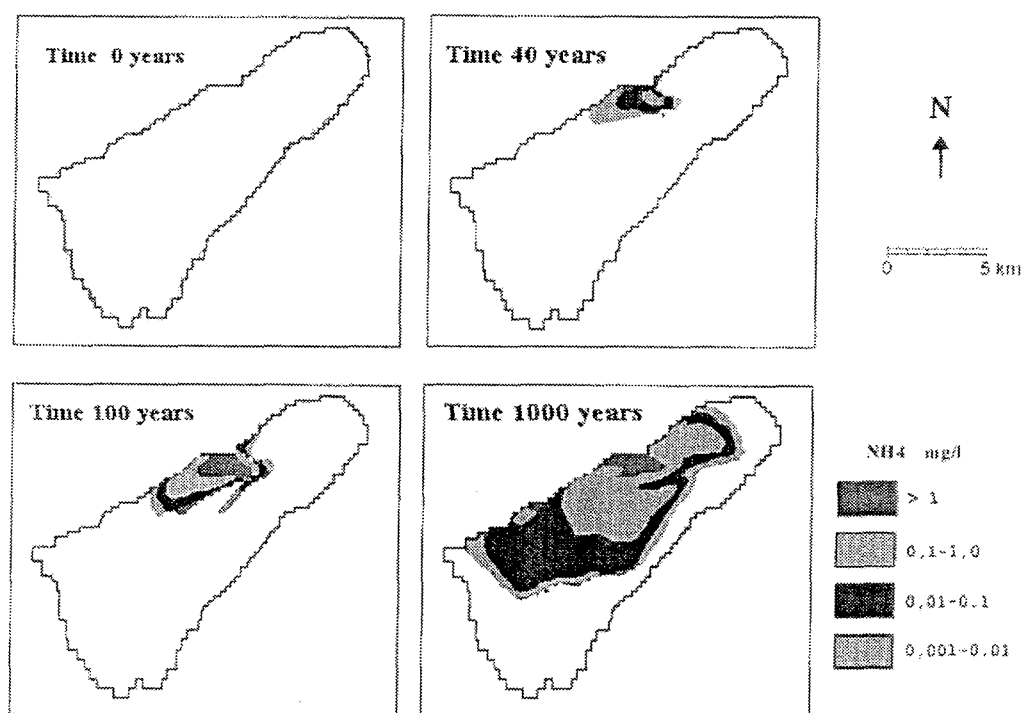


FIG. 5. Calculated contamination caused by ammonia ions in time.

The results showed the necessity for confining the contaminated groundwater to the ISL area and supported remediation targets such as:

- recovery of solutions from the cone of depression in the area of ISL,
- time-spatial course of contaminated water recovery,
- preliminary setting of limits for final content of contaminants.

The following main targets influenced the systematic implementation of the exploration work:

- **final exploration output** (more accurate structural-geological knowledge in the area of interest, determination of geological risk elements),
- **deadline for the problem resolution** (before decision on further remediation actions and setting the clearance levels),
- **financial requirements** (approximately US \$1.3 million between 1992 to 1998. It was covered by the Ministry of Economics, Ministry of the Environment and by DIAMO itself),
- **initial knowledge of the geological and hydrogeological conditions** (different in individual parts of the area of interest – the highest level of knowledge was of course in the area of uranium deposits, the lowest level was in the former military training area situated SE),
- **availability of exploration methods** (there was sufficient number of external suppliers).

The results of exploration works showed the high importance of hydrogeological works for evaluation of old reminders, especially in sedimentary complexes.

Contamination caused by ISL operations constitute a potential risk to the Turonian aquifer water sources in the area ($n \cdot 10^2 \text{ km}^2$) over a long period of time ($n \cdot 10^2 - 10^3$ years). The area and time will be influenced by final clearance level for the Cenomanian aquifer. It is expected the water must be treated to reduce the present contamination levels (5-110 g/l TDS) to less than 10 g/l TDS. The remediation will also be influenced by economic factors, time and development of new treatment technologies in the future.

BIBLIOGRAPHY

FIEDLER, J. ed., “Zaverecna zprava geologicko pruzkumneho ukolu - Jz. predpoli loziska Straz - geologicko-geofyzikalni a hydrogeologicky pruzkum“ č. 22 93 2008 1 2 250 3000 1 (Final Report on Geological Exploration Task – SW Forefield of the Straz Deposit – Geological-Geophysical and Hydrogeological Exploration No. 22 93 2008 1 2 250 3000 1), MS DIAMO, Straz pod Ralskem (1995).

KOPECKY, P. ed., “Zaverecna zprava geologicko pruzkumneho ukolu - Jz. predpoli loziska Straz - geologicko-geofyzikalni a hydrogeologicky pruzkum – II. etapa“ č. 22 93 2008 1 2 250 3000 1 (Final Report on Geological Exploration Task – SW Forefield of the Straz Deposit – Geological-Geophysical and Hydrogeological Exploration No. 22 93 2008 1 2 250 3000 1 - II. stage), MS DIAMO, Straz pod Ralskem (1998).

Review

A Review of In Situ Leaching (ISL) for Uranium Mining

Guihe Li ^{1,2} and Jia Yao ^{1,*} ¹ College of Engineering and Physical Sciences, University of Wyoming, Laramie, WY 82071, USA; guiheli@alumni.upenn.edu² School of Engineering and Applied Science, University of Pennsylvania, Philadelphia, PA 19104, USA

* Correspondence: jyao46@asu.edu

Abstract: Uranium, a cornerstone for nuclear energy, facilitates a clean and efficient energy conversion. In the era of global clean energy initiatives, uranium resources have emerged as a vital component for achieving sustainability and clean power. To fulfill the escalating demand for clean energy, continual advancements in uranium mining technologies are imperative. Currently, established uranium mining methods encompass open-pit mining, underground mining, and in situ leaching (ISL). Notably, in situ leaching stands out due to its environmental friendliness, efficient extraction, and cost-effectiveness. Moreover, it unlocks the potential of extracting uranium from previously challenging low-grade sandstone-hosted deposits, presenting novel opportunities for uranium mining. This comprehensive review systematically classifies and analyzes various in situ leaching techniques, exploring their core principles, suitability, technological advancements, and practical implementations. Building on this foundation, it identifies the challenges faced by in situ leaching and proposes future improvement strategies. This study offers valuable insights into the sustainable advancement of in situ leaching technologies in uranium mining, propelling scientific research and practical applications in the field.

Keywords: uranium mining; in situ leaching (ISL); acid leaching; alkaline leaching; neutral leaching; bioleaching; blasting-enhanced permeability (BEP); reactive transport model (RTM)



Citation: Li, G.; Yao, J. A Review of In Situ Leaching (ISL) for Uranium Mining. *Mining* **2024**, *4*, 120–148. <https://doi.org/10.3390/mining4010009>

Academic Editors: Mostafa Benzaazoua and Yassine Ait-Khouia

Received: 31 January 2024

Revised: 26 February 2024

Accepted: 29 February 2024

Published: 2 March 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

While fossil fuels, represented by coal, oil, and natural gas, continue to dominate the global energy landscape and meet the majority of energy demands, the escalating concern regarding climate change and environmental issues [1,2] has brought attention to the negative impacts associated with their production and utilization [3–10]. Specifically, the combustion of fossil fuels releases substantial amounts of greenhouse gases, intensifying global warming [3,5]. In response to the challenges, there is a worldwide momentum toward accelerating the advancement of clean energy, with nuclear energy, which is rooted in uranium mining, emerging as a noteworthy and environmentally friendly energy source [11,12]. Nuclear energy undergoes the process of fission, converting it into thermal energy, which is subsequently transformed into electricity through successive steps. Nuclear energy stands out as a clean and efficient energy suitable for diverse applications in power generation and beyond [13–15]. Its high energy density enables the provision of sustained and stable electricity supply [12,16]. In comparison to traditional fossil fuels, nuclear energy serves as a low-carbon energy source, avoiding the generation and emission of carbon dioxide (CO₂) during its utilization [17]. It also minimizes air pollutants, such as nitrogen oxides, during operation, underscoring its significant environmental benefits [12].

Uranium, as the foundational material for nuclear energy, is commonly distributed throughout the Earth's crust at relatively low concentrations [11]. Globally, economically viable uranium deposits are unevenly distributed, with sandstone-hosted uranium deposits being the most prevalent [18–22]. Based on the latest data updated by the World Nuclear Association (WNA) in 2023, the total recoverable identified resources have reached

7.918 million tonnes U (tU) [23]. The top five countries with the largest uranium reserves are Australia (28%), Kazakhstan (13%), Canada (10%), Russia (8%), and Namibia (8%) [23]. The Organisation for Economic Co-operation and Development (OECD) reports that as of 2020, uranium production was carried out in 17 countries worldwide, with a total output of 47,342 tU. The top five uranium-producing countries are Kazakhstan (41.1%), Australia (13.1%), Namibia (11.4%), Canada (8.2%), and Uzbekistan (7.4%) [24]. Given the imperative transition toward sustainable energy, the OECD predicts a continual rise in global uranium demand [24]. Therefore, it is crucial to improve uranium mining technologies to meet this escalating need. This endeavor supports the sustainable development of the nuclear energy industry while creating a more stable global energy foundation, promoting the widespread adoption of clean energy.

The traditional uranium mining methods include open-pit mining [25] and underground mining [26]. In recent years, heap leaching [27] and in situ leaching (ISL, also known as in situ recovery, ISR) [28,29] have emerged as two breakthrough technologies utilized in uranium mining. In comparison to open-pit and underground mining, these two mining technologies offer distinct advantages such as environmental sustainability, efficient extraction, and cost-effectiveness [28,29]. Furthermore, it is crucial to emphasize that low-grade sandstone-hosted uranium deposits, which were previously economically unviable for extraction, can now be economically and efficiently mined using these two mining technologies. Regarding the heap leaching technology, some research has been conducted [27,30–34]. Ghorbani et al. have conducted a thorough and detailed review of its current development status, technological innovations, and future directions [32]. Peterson has provided a comprehensive introduction to this technology as a key method for extracting minerals from low-grade ores [27], highlighting the significance of heap leaching. Regarding the in situ leaching technology, its value is reflected in its increasingly widespread practical application in recent years. In 2021, approximately 63% of uranium was produced via in situ leaching [24,35].

The annual publication statistics offer valuable insights into the evolving research landscape concerning in situ leaching and its associated fields. As depicted in Figure 1, the volume of pertinent academic literature demonstrates a pronounced upward trajectory, signifying an escalating interest in the domain of in situ leaching. These studies associated with in situ leaching for uranium mining may have different emphases. Seredkin et al. comprehensively compare in situ leaching with traditional mining technology from the perspectives of exploration, environmental impact, and economics, emphasizing its advantages as an alternative to conventional methods of mining [36]. Bhargava et al. elucidate the fundamental principles of in situ leaching for uranium extraction and analyze factors that may influence its effectiveness [37]. Mudd provides the detailed application measures and resulting impacts of in situ leaching [38,39]. Furthermore, certain studies focus on the practical application effects of in situ leaching in specific uranium deposits [40–42]. While research on in situ leaching for uranium mining continues to expand, there is currently a lack of comprehensive studies providing systematic summaries of its sub-techniques for different conditions, the associated principles, and its recent advancements. Therefore, this study aims to thoroughly review the most recent progress of in situ leaching for uranium mining, addressing a gap in the existing research.

This review study was conducted through a systematic process of information collection, classification, analysis, and summarization. The information was sourced extensively, primarily from peer-reviewed journal papers and conference proceedings evaluated through databases such as Web of Science, Scopus, and China National Knowledge Infrastructure (CNKI). It was complemented by relevant information from international organizations, government reports, and company websites. The timeline of these publications spans over a century, from the early 20th century to the year 2023. Subsequently, the collected information was categorized based on different sub-techniques and their underlying principles, technological advancements, and practical application status. A meticulous analysis was conducted on this basis, summarizing the applicable conditions,

advantages, and disadvantages of these in situ leaching sub-techniques, including acid leaching, alkaline leaching, neutral leaching, and bioleaching. Additionally, the recent technological advancements and the real-world field application of in situ leaching are introduced. Furthermore, the current challenges faced by in situ leaching are clarified, and future improvements are proposed. This comprehensive review offers researchers and practitioners a nuanced understanding of the latest developments in in situ leaching for uranium mining, precisely delineating the practical application scope of the technology. Through an in-depth analysis of the current technological landscape, this study aims to steer future research directions and facilitate technological enhancements. The continued development of in situ leaching techniques for uranium mining will play a pivotal role in maintaining the long-term sustainability of nuclear energy as a primary clean energy source going forward on a global scale.

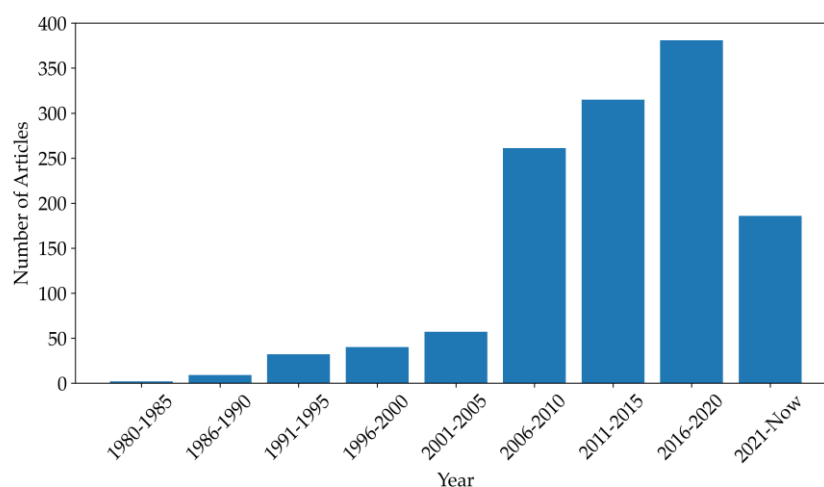


Figure 1. Dynamics of scientific publications on in situ leaching from 1980 to 2023.

2. Overview of Uranium Mining Methods

The formation of uranium deposits is influenced by various factors such as geological structures, sedimentary processes, rock types, and fluid interactions [20,22,43–49]. The combined effect of these factors may lead to significant variations in the burial depth of uranium deposits, ranging from near-surface locations to several hundred meters or more underground. Open-pit mining and underground mining, which are traditional uranium mining methods, are classified based on the suitability for the burial depth of uranium deposits. Open-pit mining is primarily employed for uranium deposits with shallow burial depths [50–52]. Figure 2 illustrates the open-pit mining process for uranium mines. Its core procedures involve excavating and removing the topsoil and overburden covering the uranium directly to expose the ore body [53]. The exposed ore body is then ripped and transported to the stockpile and mill sit for subsequent processing to obtain uranium products. On the other hand, underground mining is applied to deeper-buried uranium deposits or those where open-pit mining is not feasible [54–56]. The method involves sinking a shaft or driving an adit near the ore body to extend levels at various depths, allowing miners to access and remove the ore to the surface for subsequent processing. The schematic diagram illustrating the utilization of underground mining for uranium extraction is depicted in Figure 3.

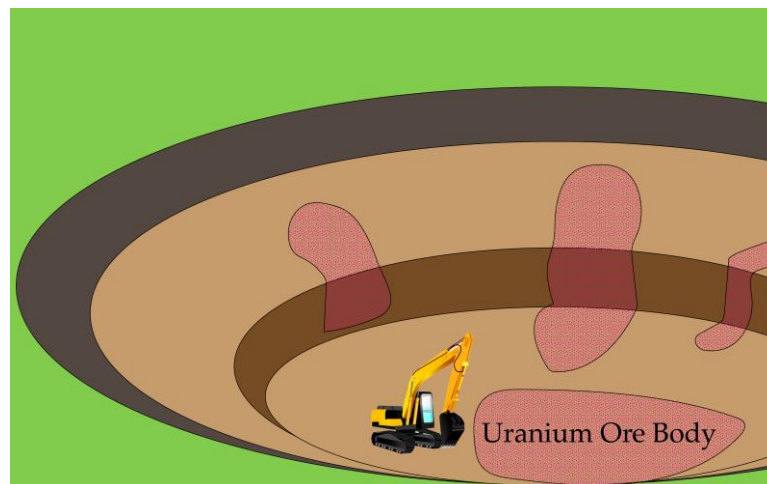


Figure 2. Schematic diagram of open-pit mining.

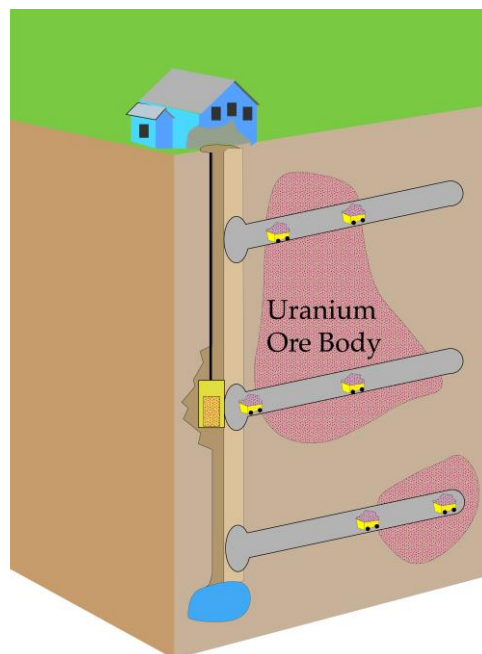


Figure 3. Schematic diagram of underground mining.

At present, in situ leaching stands as another extensively employed mining technique [2,35,48,57], alongside open-pit and underground mining. Unlike open-pit and underground mining, in situ leaching does not rely on burial depth as a criterion but is based on the properties of the uranium deposit. As a mining technique conducted under the natural conditions of ore deposits, in situ leaching is well-suited for uranium deposits situated within aquifers and characterized by favorable permeability [58–60]. This method involves strategically arranging and drilling wells, including injection wells and production wells (or recovery wells), within the uranium deposit. The leaching solution (or lixiviant) is injected to react with the ore, dissolving uranium. The uranium-bearing solution, known as the pregnant solution, is then brought to the surface for further treatment. Table 1 presents the applicable conditions for these three uranium mining methods, along with their respective advantages and disadvantages.

Table 1. Comparison of uranium mining methods.

Method	Applicable Condition	Advantage	Disadvantage	Reference
Open-pit Mining	Shallow burial depths of main ore bodies	Short construction period; Large mining space and high labor productivity; Safe working conditions	Subject to climate conditions; High infrastructure and equipment investment; Large land footprint and environmental damage	[50,61]
Underground Mining	Significant burial depths or surface conditions unsuitable for open-pit mining	Limited climate disruption; Minimal impact on surface ecosystems; High mining efficiency	High extraction costs; Complex and challenging construction and maintenance of underground mining facilities; Potential impact on underground geological environment; Elevated safety risks	[26,53,54]
In Situ Leaching	Situated in aquifers with favorable permeabilities	Safe and simple mining process; Short construction period and minimal infrastructure investment; Low labor intensity and high automation level; Less environmental pollution due to avoidance of waste rocks; Capability to process low-grade ore deposits	Requirements for geological and hydrogeological conditions; Slow extraction rate; Underground water management challenges	[58–60,62]

Compared to open-pit and underground mining, in situ leaching offers distinctive advantages. By operating directly within natural ore deposits, this mining method avoids extensive surface disruption and excavation. Consequently, it lowers the input costs, shortens the mining process, and entails a more minimal environmental impact. Moreover, in situ leaching involves the direct injection and cyclic utilization of leaching solution into uranium deposits, effectively eliminating the generation of unwanted by-products such as waste rock, radioactive dust, and emissions. This prevents health hazards for personnel in addition to reducing the expenses associated with waste disposal. Furthermore, while leaching uranium elements, the leaching solution also facilitates the extraction of uranium-associated elements such as selenium (Se), scandium (Sc), and molybdenum (Mo), thereby enhancing the overall recovery rate of valuable minerals [63].

In addition, in situ leaching significantly enhances the industrial value of low-grade sandstone-hosted uranium deposits. These deposits are widely distributed globally, encompassing countries like Australia, Canada, and Kazakhstan [11], constituting a vital component of the world’s uranium resources. Considering the costs and environmental impacts, open-pit and underground mining are essentially impractical for these deposits characterized by low uranium content. Fortunately, in situ leaching can overcome this significant drawback. By operating within the ore body, in situ leaching reduces the excessive costs associated with waste processing and uranium milling while minimizing adverse environmental impacts. Consequently, these deposits can now be economically and efficiently mined, thereby expanding the scope of recoverable uranium resources and providing more robust support for the sustainable growth of the global nuclear energy industry.

3. In Situ Leaching Techniques

The schematic diagram of the in situ leaching process for uranium mining is shown in Figure 4. Injection and production wells are strategically positioned in the uranium field. The pre-configured leaching solution is injected into the target ore layer through injection wells to dissolve uranium. The uranium-bearing pregnant solution is then extracted to the surface through production wells. The connecting pipelines of the injection and production wells are equipped with header systems, which are linked to the processing plant via trunk lines. Following the extraction of uranium from the production wells, the pregnant solution undergoes specific processing [48,64,65], including uranium recovered by ion exchange, concentration, filtration, and drying. Ultimately, the qualified uranium concentrate, predominantly composed of triuranium octoxide (U_3O_8), known as yellowcake [66], is obtained. Simultaneously, the treated solution is reintroduced into the ore body for cyclic utilization as the leaching solution [48].

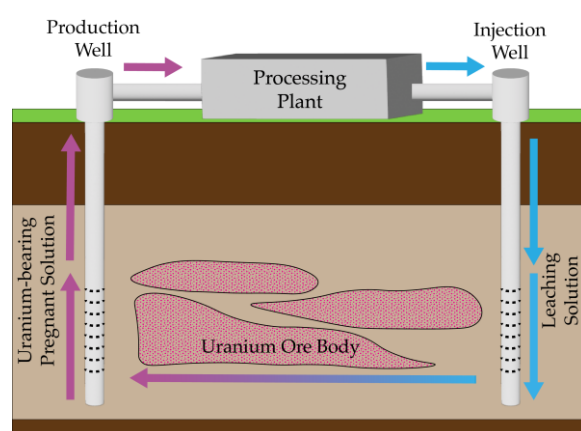


Figure 4. Schematic diagram of the in situ leaching process.

Uranium, classified as a redox-sensitive lithophile element [67], exhibits a strong affinity for oxygen [68]. Theoretically, uranium can exist in four oxidation states [69], including +3, +4, +5, and +6. However, due to the instability of uranium in the +3 and +5 states, uranium minerals typically manifest in nature in the +4 (U(IV)) and +6 (U(VI)) oxidation states [70–73]. Specifically, U(IV) typically appears in the solid forms of uraninite (UO_2) and coffinite ($U(SiO_4)_{1-x}(OH)_{4x}$) [37,74], representing common and stable uranium configurations. These compounds have low solubility and are extensively present in uranium ores under reducing conditions. U(VI) primarily exists as the solid form of uranium trioxide (UO_3) in the ore body and the soluble uranyl ion (UO_2^{2+}) in the aqueous systems of uranium deposits [75,76]. These configurations are prevalent under oxidizing or oxygen-rich conditions. The coexistence of U(IV) and U(VI) is also observed in some uranium deposits [77]. Typically, U(VI) demonstrates greater chemical reactivity in the high oxidation state than U(IV) in the lower oxidation state [78]. Additionally, these two valence states of uranium exhibit significant differences in crystallographic and geochemical properties [79,80]. Consequently, the thoughtful selection of a leaching solution tailored to the unique conditions of uranium deposits is crucial, as it significantly impacts key aspects of uranium mining [37,48,57,81], including uranium dissolution efficiency, cost-effectiveness, and environmental considerations. The choice of in situ leaching techniques aligns with the diverse geological conditions and mineral compositions of different uranium deposits. These techniques are systematically categorized based on the primary components of the leaching solution, encompassing acid leaching, alkaline leaching, neutral leaching, and bioleaching.

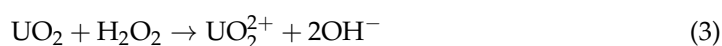
3.1. Acid Leaching

In situ acid leaching primarily employs strong acids as the main components of the leaching solution [37,39]. Upon contact with the ore, solid-state uranium is converted to a soluble form under conditions with $\text{pH} < 2$ [48,82], facilitating its extraction. In situations where uranium exists solely in the U(VI) form, characterized by its heightened chemical reactivity, it can directly react with the acid solution [76]. However, when uranium in the ore body predominantly exists in the U(IV) form or in a mixed form of both U(IV) and U(VI), the addition of an oxidizing agent to the acid solution becomes necessary [83]. This process oxidizes U(IV) to the hexavalent form, enhancing its reactivity and enabling subsequent reactions with the acid leaching solution to form soluble complexes. At present, sulfuric acid (H_2SO_4) is the most frequently utilized component in the acid leaching solution [64], while nitric acid (HNO_3) and hydrochloric acid (HCl) are occasionally employed [84]. Common oxidizing agents used in conjunction with acid solutions include oxygen (O_2) [82] and hydrogen peroxide (H_2O_2) [85,86].

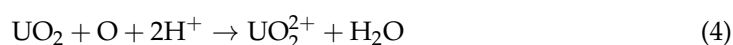
For solid U(VI) in the ore body, such as UO_3 , the fundamental reaction in the in situ acid leaching process is expressed by Reaction (1) [75,76]. Under the influence of H^+ , U(VI) transforms from a solid state to the most soluble uranyl ion (UO_2^{2+}) form. Depending on the composition of the acid solution, uranyl ion combines with sulfate, nitrate, and chloride ions, ultimately existing in the productive solution as complexes like UO_2SO_4 , $\text{UO}_2(\text{NO}_3)_2$, and UO_2Cl_2 .



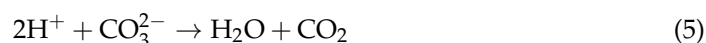
In the case of U(IV), such as UO_2 , it undergoes reactions with commonly used oxidizing agents [75,83,87]. The fundamental principle of the oxidation process relies on its ions acting as electron transfer mediators to facilitate the uranium transformation from the tetravalent form into the hexavalent form [88]. Reaction (2) describes the oxidation process in the presence of oxygen as the oxidizing agent [82], while Reaction (3) depicts the oxidation process when hydrogen peroxide is utilized as the oxidizing agent [85,86].



After undergoing Reaction (2) or Reaction (3), hexavalent uranium converted from UO_2 subsequently reacts with the acid solution. The oxidation of UO_2 and subsequent reaction with an acid can be combined and represented as Reaction (4) [87].



However, it is crucial to note that the in situ acid leaching technique has certain application limitations. This technique is not suitable for uranium deposits with high carbonate content, as it can lead to inefficiency and economic impracticality caused by the excessive consumption of the acid leaching solution. This is attributed to neutralization reactions [89] described in Reaction (5), where carbonate reacts with the acid leaching solution. Specifically, for optimal leaching results, the technique is applicable when the carbonate content in the ore body is less than 8% [37,90] and less than 2% in the aquifer [39,91].

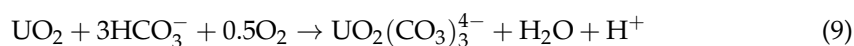
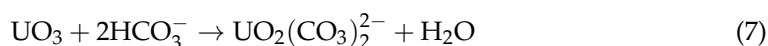
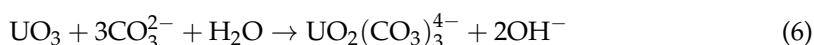


3.2. Alkaline Leaching

In situ alkaline leaching involves the use of an alkaline leaching solution to react with the solid uranium in the ore. Uranium becomes soluble at $\text{pH} > 9$ [90], facilitating subsequent extraction. While alkaline leaching exhibits lower extraction efficiency due to low kinetics and high energy consumption compared to acid leaching, its less corrosive nature and lower impurity content partially compensate for these drawbacks [28,90]. In

addition, alkaline leaching solutions can be employed for uranium deposits rich in alkaline accessory minerals, such as carbonates and some silicates [90,92]. These deposits, which are unsuitable for acid leaching due to their high acid consumption [75], find compatibility with the alkaline leaching technique.

An alkaline leaching solution is primarily composed of carbonate or bicarbonate [93,94], complemented by an oxidizing agent. The most utilized predominant constituents are sodium carbonate and sodium bicarbonate [95]. For alkaline leaching of U(VI), the reactions are delineated by Reaction (6) for carbonate ions and Reaction (7) for bicarbonate ions, respectively. In cases where the alkaline leaching solution reacts with U(IV), it is expressed through Reaction (8) for carbonate ions and Reaction (9) for bicarbonate ions, respectively. Both uranyl decarbonate ions ($\text{UO}_2(\text{CO}_3)_2^{2-}$) and uranyl tricarbonates ions ($\text{UO}_2(\text{CO}_3)_3^{4-}$) are soluble complexes that are eventually pumped to the surface for further processing.



Alkaline leaching is generally not recommended for uranium deposits with significant concentrations of pyrite (FeS_2) and other sulfides [75,96]. This is due to the ability of carbonate or bicarbonate ions in an alkaline environment to accelerate the oxidation reaction of pyrite, leading to the formation of various soluble iron–carbonate complex compounds. This complex situations includes coexistence of FeHCO_3^- , FeCO_3^0 , $\text{Fe}(\text{CO}_3)(\text{OH})^-$, and FeCO_3^{2-} [97]. Because of this, a considerable amount of alkali is consumed, making the extraction process ineffective and unfeasible from an economic standpoint.

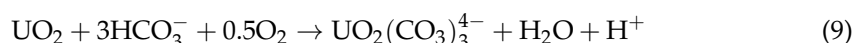
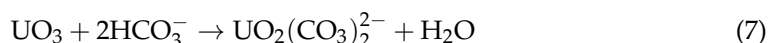
3.3. Neutral Leaching

In situ neutral leaching, a recently developed technology, is termed as such due to its ability to maintain a pH value within the range of 6.8–8.2 during application [98]. Compared to acid leaching and alkaline leaching, this approach employs a gentler leaching solution, resulting in reduced impact on comprehensive groundwater pollution and potentially a smaller environmental footprint [98]. Consequently, it is regarded as a promising green technology. The fundamental principle of this method involves utilizing bicarbonate ions (HCO_3^-) in the weakly acidic form in water to complex with uranium, forming uranyl ions. Depending on the source of bicarbonate ions, current neutral leaching methods are categorized into CO_2 - O_2 leaching and weak acid leaching.

3.3.1. CO_2 - O_2 Leaching

In neutral CO_2 - O_2 leaching, the leaching solution consists of native groundwater mixed with O_2 as an oxidizing agent and CO_2 as a complexing agent [74,98,99]. In this process, injected carbon dioxide dissolves to form carbonic acid (H_2CO_3) [100], as depicted in Reaction (10). Carbonic acid then dissociates into bicarbonate ions (HCO_3^-) in the solution, as illustrated in Reaction (11). Simultaneously, injected oxygen oxidizes a significant portion of U(IV) to the hexavalent form, following Reaction (2). Subsequently, U(VI) can form soluble uranyl decarbonate ions ($\text{UO}_2(\text{CO}_3)_2^{2-}$) through Reaction (7). Alternatively, some UO_2 may directly react with O_2 and HCO_3^- to generate uranyl tricarbonates ions ($\text{UO}_2(\text{CO}_3)_3^{4-}$) following Reaction (9). The chemical reactions involved in the fundamental principles of neutral CO_2 - O_2 leaching are listed below.





In addition to the fundamental reactions involving the dissolution of U(IV) and U(VI) mentioned above, the CO_2 - O_2 leaching solution also induces other water–rock interactions [98,101]. When carbon dioxide dissolves in water, it forms H_2CO_3 , HCO_3^- , and H^+ , leading to an increase in H^+ concentration and subsequently elevating groundwater acidity. This change facilitates the dissolution of carbonate minerals in uranium deposits, forming bicarbonate species that are readily complex with uranium minerals. Moreover, these reactions with carbonate minerals may enhance the porosity and permeability of the deposit pore media [102], favoring the flow of leaching solution and uranium-bearing pregnant solution.

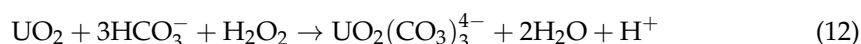
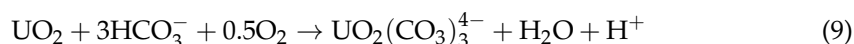
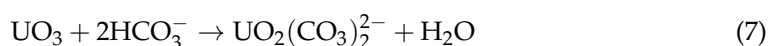
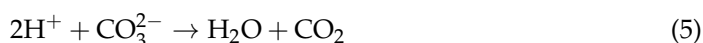
Furthermore, in addition to the formation of uranyl–carbonate complexes of U(VI), the CO_2 - O_2 leaching solution can also induce intricate reactions that lead to the generation of uranyl–carbonate ternary complexes of U(IV) [98]. This phenomenon arises from the propensity of U(IV) to engage in chemical reactions with ligands, including oxygen, nitrogen, and sulfur, under some specific conditions, thereby forming coordination bonds. In the presence of carbon dioxide, this process further evolves, giving rise to the generation of uranyl–carbonate ternary complexes, represented by entities such as $\text{MUO}_2(\text{CO}_3)_3^{2-}$ and $\text{M}_2\text{UO}_2(\text{CO}_3)_3^0$, wherein M^{2+} denotes divalent cations like Mg^{2+} , Ca^{2+} , Sr^{2+} , and Ba^{2+} [103]. The resultant uranyl–carbonate ternary complexes effectively mitigate the tendency of U(VI) complexes to adsorb onto the charged surfaces of iron (hydro)oxides and/or clay minerals in the presence of carbonate [98], thereby promoting the facilitated migration of uranium-bearing pregnant solution. In essence, the generation of U(IV) complexes is influenced by the presence of carbon dioxide and oxygen, and these complexes, in turn, intricately impact the migratory behavior of U(VI) complexes, ultimately leading to a favorable increase in uranium recovery rates.

In summary, neutral CO_2 - O_2 leaching involves a more intricate mechanism in comparison to acid leaching and alkaline leaching. These complex mechanisms collectively contribute to an enhancement in uranium recovery rates. Consequently, the application of CO_2 - O_2 in situ leaching is increasingly attracting attention and recognition. However, it is important to note that the physical conditions of the aquifer in uranium deposits can influence the status of carbon dioxide. Moreover, the transport of gaseous carbon dioxide within the porous structure of uranium deposits is subject to capillary action mechanisms [104–106]. Additionally, the dissolution of carbon dioxide may lead to a pH decrease, potentially causing the dissolution of surrounding rock minerals and triggering the secondary precipitation of carbonate minerals [107,108], posing a risk of blockages. Therefore, when implementing CO_2 - O_2 in situ leaching, comprehensive consideration must be given to the properties of gases, the characteristics of the aquifer, and the interactions with other constituents within the ore.

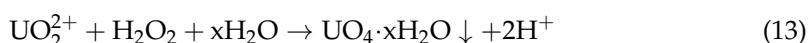
3.3.2. Weak Acid Leaching

Weak acid leaching [109] employs a low concentration of sulfuric acid, in conjunction with oxidizing agents such as oxygen or hydrogen peroxide, as the principal components of the leaching solution. The development of this technique primarily addresses the application restrictions associated with acid leaching in uranium deposits characterized by high carbonate content. Distinctively deviating from the conventional acid leaching

process, which involves the direct dissolution of U(IV) and U(VI) by H^+ , this approach allows the acid to engage in initial neutralization reactions with carbonates present in the ore, such as calcite and dolomite, as elucidated in Reaction (5). Despite the consumption of H^+ , the process gives rise to the formation of HCO_3^- , involving reactions detailed in Reactions (10) and (11). Subsequently, HCO_3^- , acting as a weak acidic ion, facilitates the dissolution of U(VI) in accordance with Reaction (7) and the dissolution of U(IV) following Reaction (9) with O_2 as the oxidizing agent or Reaction (12) with H_2O_2 as the oxidizing agent. The chemical reactions involved in the fundamental principles of weak acid leaching are delineated below.



However, careful consideration must be given to the quantity and concentration of H_2O_2 when it is chosen as the oxidizing agent during the weak acid leaching process. While oxidizing U(IV), excessive concentrations of high-concentration H_2O_2 may also participate in reactions described in Reaction (13), potentially causing the re-precipitation of soluble uranium from the solution [109]. Therefore, the judicious selection of the appropriate oxidizing agent and its dosage proves particularly crucial for the ultimate efficacy of uranium leaching when using this approach.

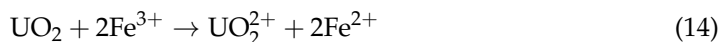


3.4. Bioleaching

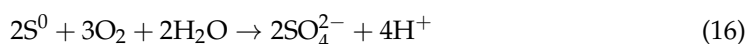
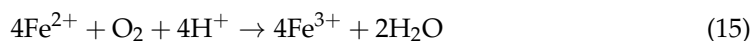
Bioleaching is regarded as a more environmentally sustainable and cost-effective method for uranium mining, positioning it as a superior alternative to other chemical in situ leaching techniques [75,110,111]. This approach is particularly well-suited for uranium deposits with elevated pyrite and sulfide contents [75,96]. Given the impact of microbial activities on the pH and redox conditions within the system, subsequently influencing uranium solubility, this method involves the introduction of leaching solutions containing specific types of microorganisms into the ore body. These microorganisms, typically dominated by acidophilic, autotrophic iron-, or autotrophic sulfur-oxidizing prokaryotes [75], can alter the environmental conditions in both the uranium deposit and aquifer system, thereby enhancing uranium dissolution and facilitating the recovery process.

The acidophilic Fe- and S-oxidizing microorganism consortia, comprising the principal constituents of the bioleaching solution, fulfill a dual purpose by not only establishing an acidic environment but also facilitating oxidation. Within the acidic milieu created by the microbial consortia, U(VI) transforms into soluble uranyl ions, aligning with the underlying principle of acid leaching for UO_3 , as delineated in Reaction (1) [75]. For U(IV), the trivalent iron ions within the microbial consortia act as oxidizing agents, driving Reaction (14) to convert solid UO_2 into soluble uranyl ions [35,75,112], facilitating subsequent extraction. These chemical reactions involved in the fundamental principles are delineated below.



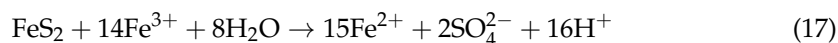


Moreover, in the application of bioleaching, a consistent provision of dissolved O_2 and CO_2 is required to sustain acidophilic Fe- and S-oxidizing microorganisms [75]. This highlights the synergistic impact of CO_2 - O_2 in situ leaching mechanisms in bioleaching, contributing to increased production yields. Meanwhile, the presence of oxygen initiates the production of soluble ferric iron from Fe^{2+} , as depicted in Reaction (15), and the generation of sulfuric acid from reduced sulfur compounds, including elemental S, as illustrated in Reaction (16) [75].



Reaction (15) signifies the biological oxidation of Fe^{2+} and the regeneration of Fe^{3+} in the sulfuric acid solution. This process consistently provides trivalent iron ions as oxidants for the oxidation reaction of UO_2 , facilitating its dissolution. Meanwhile, Reaction (16) underscores the inherent advantage of the bioleaching method in extracting uranium from deposits rich in sulfur compounds. The dissolution of sulfides releases additional H^+ , thereby sustaining the acidic environment conducive to the uranium dissolution.

This approach displays an additional benefit in the effective mining of uranium deposits rich in pyrite (FeS_2). Notably, the presence of pyrite, an inherent auxiliary mineral in this type of ore, undergoes Reaction (17) to release Fe^{2+} , SO_4^{2-} , and H^+ under the influence of microorganisms and acidic conditions [75,113]. Subsequently, the dissolved species repeatedly transform into Fe^{3+} following Reaction (15), thereby expediting the bioleaching process by providing additional iron ions for the oxidation of U(IV) [114].



In addition to achieving a more environmentally friendly and efficient in situ leaching, microorganisms have the potential to immobilize uranium from aqueous solutions and seawater, contributing to environmental remediation [115–118]. However, it is essential to highlight the impact of gangue minerals on the bioleaching process. For instance, the generation of H^+ and SO_4^{2-} during bioleaching may induce the dissolution of carbonate minerals, such as calcite and dolomite, leading to the subsequent precipitation of secondary minerals like anhydrite and gypsum, potentially causing plugging issues.

In summary, the four in situ leaching techniques for uranium mining have been elaborately discussed, and their fundamental principles are illustrated in Figure 5. Their applicable conditions and respective merits and drawbacks are summarized in Table 2. It is imperative to thoroughly consider the distinctive and variable characteristics of each uranium deposit when selecting an in situ leaching technique for uranium mining.

Table 2. Typic characteristics of in situ leaching techniques.

Technique	Applicable Condition	Advantage	Disadvantage	Reference
Acid Leaching	Applicable to uranium deposits with low carbonate content	Low risk of groundwater contamination outside the wellfield; High leaching efficiency and short leaching cycles	Obligatory use of corrosion-resistant instruments and pipelines; Significant impact on groundwater within the wellfield; Possible formation of sulfate precipitates, causing blockage and permeability deterioration in the ore body	[37,48,64,78,87,119]

Table 2. Cont.

Technique	Applicable Condition	Advantage	Disadvantage	Reference
Alkaline Leaching	Widely applicable to uranium deposits with high carbonate content; Not suitable for uranium deposits with high pyrite content	Utilization of common equipment and pipelines	Low leaching efficiency and long leaching cycles; High risk of groundwater contamination outside the wellfield; Formation of carbonate or sulfate precipitates, potentially causing deposit clogging	[90]
Neutral Leaching	Wide applicability with no apparent restrictions	Leaching solution with gentler components for enhanced environmental friendliness; Simultaneous uranium mining with CO ₂ utilization and storage for CO ₂ -O ₂ leaching	Possibility of gangue mineral dissolution and carbonate precipitation leading to deposit clogging due to pH drop	[2,99,109]
Bioleaching	Wide applicability, especially suitable for uranium deposits rich in pyrite and sulfides	High leaching rate and high overall leaching efficiency; Sustainable and environmentally friendly	Initial acid consumption must be considered until microbial oxidation of reducible sulfur compounds initiates acid production; Potential clogging due to gangue mineral dissolution and secondary precipitation resulting from the generation of H ⁺ and SO ₄ ²⁻	[75,96,111,120]

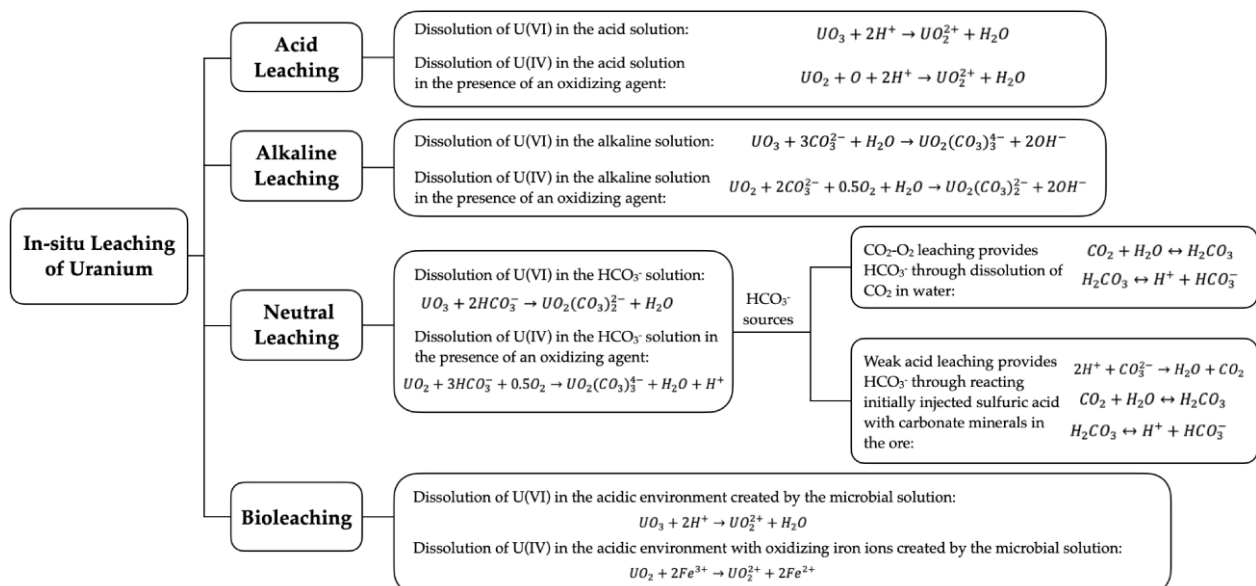


Figure 5. Classification and fundamental principles of in situ leaching techniques.

4. Technological Innovations in In Situ Leaching

Considering the distinct variations among different uranium deposits, it proves challenging to devise a universally applicable in situ leaching strategy for all scenarios. While experiences from similar deposits offer insights, personalized technological procedures and parameter adjustments tailored to the unique characteristics of each deposit are necessary

to achieve maximum leaching efficiency. Therefore, recent technological innovations in in situ leaching have predominantly focused on customized approaches designed based on the specific features of individual uranium deposits.

4.1. Permeability Modification Technique for In Situ Leaching

In situ leaching relies on seepage of leaching solution in the porous media of uranium deposits [121]. As a result, a key element determining the usability of this mining method and a major barrier to its widespread adoption is the permeability of the uranium deposit [122]. In situ leaching techniques are typically considered unsuitable for uranium deposits with low inherent permeability (<0.5 m/d) [123]. To address this challenge, many scholars have concentrated their studies on permeability modification techniques for low-permeability uranium deposits, thereby broadening the application of in situ leaching [123–126]. While hydraulic fracturing, a widely used approach for enhancing permeability in oil and gas reservoirs [127,128], has been proven ineffective for uranium deposits [124], blasting-enhanced permeability (BEP) has emerged as a promising and effective technique for this specific context [125]. The schematic diagram in Figure 6 illustrates the underlying principle of the BEP technique for enhancing the permeability of uranium deposits. Experimental and simulation methods have substantiated that blasting can initiate well-connected fracture networks. The creation of sustainable and large-scale seepage channels within the networks is a crucial factor in improving the permeability of low-permeability uranium deposits. This enhancement enables subsequent applications of in situ leaching and facilitates the flow of leaching solution [125]. This application of BEP in in situ leaching for uranium mining is also referred to as in situ blasting leaching [126] or in situ fragmentation leaching [129].

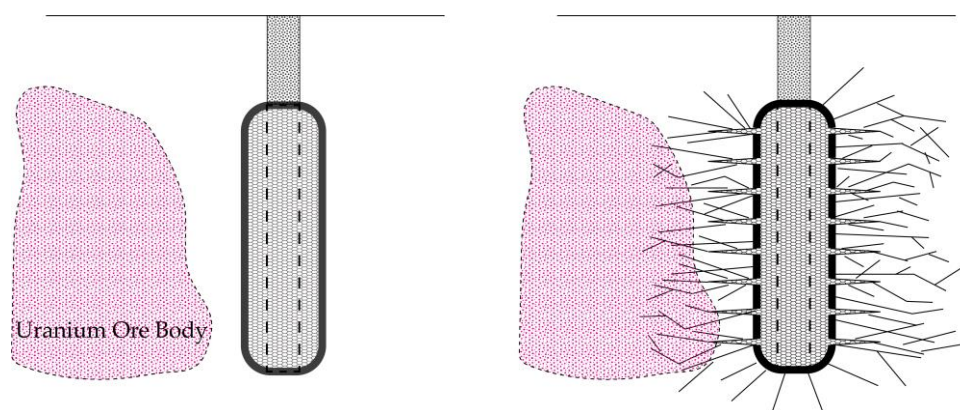


Figure 6. Principle of blasting-enhanced permeability (BEP) technique for uranium deposit.

When applying the BEP technique to low-permeability uranium deposits, a thorough assessment of the natural burial conditions of the uranium deposit is crucial. The appropriate blasting method should be selected based on the burial depth of the deposit [129]. For shallow deposits, either drilling-blasting [130] or chamber-blasting [131] methods can be employed. Usually, drilling blasting is preferable for shallow-buried thick deposits due to its more pronounced cost-effectiveness [132]. Conversely, deeper deposits often require chamber blasting to ensure the generation of a larger space for relieving underground pressure post-blasting. Subsequently, specific parameters for the blasting process are further determined based on the morphology, occurrence, and thickness of the ore body. Finally, the leaching solution is selected from the previously mentioned acid, alkaline, neutral, or bioleaching solutions, considering the actual mineral composition and properties of the ore rocks. The technique improves the permeability of uranium ore by pre-crushing the rock, allowing previously unsuitable deposits for in situ leaching to effectively utilize this method [123].

Significantly, the BEP technique enhances the permeability of the deposit and reduces the size of mineral particles [133], contributing to a notable improvement in subsequent in situ leaching effectiveness. Enhanced permeability in the deposit facilitates increased flow rates of the leaching solution through the pore spaces, enhancing uranium dissolution efficiency and leaching solution transfer efficiency [104,134–138]. Meanwhile, smaller mineral particles with larger surface areas favor the contact and reaction between the leaching solution and uranium minerals.

In addition to the intrinsic characteristics of the uranium deposit, the effectiveness of permeability modification by the BEP technique is influenced by blasting-related parameters such as shock wave [139,140], blasting stress [141,142], and water-decoupling coefficient [143,144]. Therefore, it is necessary to customize the blasting-related parameters according to the specific conditions of each uranium deposit. This entails conducting pre-simulation assessments of the in situ leaching effects of blasting using established numerical models [123,125] and making necessary adjustments to related parameters so as to achieve the optimal leaching effect.

4.2. Prediction Technique for Fluid Flow and Geochemical Reaction for In Situ Leaching

The in situ leaching process of uranium deposits involves intricate fluid flow and geochemical reactions. The fluid flow within the porous media of the ore body, as well as the reactions between the leaching solution and uranium minerals within the ore body, undergo dynamic changes that significantly impact in situ leaching efficiency. To comprehend these dynamic changes more effectively, some scholars have proposed utilizing reactive transport models (RTMs) tailored to the specific characteristics of different uranium deposits to predict these dynamic variations accurately [145,146].

The reactive transport model plays a crucial role in studying the behavior of solutes in the subsurface environment [147–149]. Its wide application extends to predicting fluid behavior in porous media during petroleum and natural gas production [146,150], as well as in the sequestration of carbon dioxide in saline aquifers [151]. In recent years, this technique has progressively been applied to the in situ leaching of uranium deposits. When studying fluid flow and geochemical reactions in uranium deposits using reactive transport models, it is convenient to choose mature commercial and open-source software such as PHREEQC (version 3) [152,153], MT3DMS (version 5) [154], TOUGHREACT (version 4) [155], and Geochemist's Workbench (version 6) [156] to directly establish and simulate research models. In cases where customized or advanced simulations are required, it is necessary to utilize programming languages such as Python (version 3), MATLAB (version 2010), and R (version 4) to write code for more flexible control over model implementation and simulation.

In laboratory research focused on in situ leaching for uranium mining, column experiments are commonly employed [157,158]. These experiments utilize tall column-like containers to hold uranium ore samples, simulating the actual in situ leaching process by injecting leaching solutions into the column. Such experiments help researchers assess the flow of leaching solutions and the migration of uranium-bearing pregnant solutions, providing valuable insights into the effectiveness of in situ leaching. In 2019, Laurent et al. proposed a one-dimensional reactive transport model for column experiments [111]. This approach thoroughly integrates the hydraulic properties of the leaching solution. Grounded in chemical reaction kinetics, this reactive transport model also considers the influence of grain size, providing nuanced insights into the dynamics of the leaching process. Although limited to 1D laboratory experiments, this methodology offers a deeper understanding of the hydrological and chemical processes occurring during in situ leaching. Afterward, Lagneau et al. exemplified the application of the reactive transport model in practical in situ leaching of uranium deposits [159]. By employing a reactive transport model, they precisely fitted historical data for 61 wells in one uranium block and subsequently assessed and predicted results for another block. This demonstration underscores the robustness of the model in real-world production scenarios. In 2022, Collet et al. developed a three-

dimensional reactive transport model to comprehensively simulate coupled hydrodynamic and geochemical processes during in situ leaching [35], aiming to predict production outcomes. This 3D reactive transport model is based on the HYTEC program code [160,161]. It employs actual data from uranium deposits, incorporating deposit hydrodynamic parameters and mineral descriptions as a 3D geological model for hydrological processes. The simulation integrates geochemical processes and relevant mineralogical databases (including kinetic and mineral databases, along with underlying chemical processes) as a geochemical model. Finally, specific parameters of operational conditions (such as well placement, leaching solution composition, injection and extraction rates, etc.) serve as input parameters for coupled simulations of hydrodynamic and geochemical processes. This comprehensive reactive transport model facilitates fitting historical data and predicting future production in actual uranium mining scenarios. It accurately considers the details of practical in situ leaching, including realistic mineral balances, dissolution rates, and recovery rates. It has been successfully applied in large-scale, real-world, in situ uranium mining production, demonstrating precise predictive capabilities. Furthermore, reactive transport models are beneficial in the context of CO₂-O₂ leaching, which entails more complex mechanisms. They can serve to quantitatively elucidate site-specific geochemical processes during leaching and also aid in comprehending the storage of CO₂ as a gas phase due to capillary mechanisms in the permeable pores of uranium deposits [98]. This dual function enhances insights into the effectiveness of CO₂-O₂ leaching and its long-term environmental impact in the context of CO₂ utilization and storage.

Reactive transport models, in addition to their capability to predict production based on uranium deposit characteristics, are also employed for evaluating downgradient transport at in situ leaching sites. This aids in optimizing management decisions and facilitating groundwater remediation post-in situ leaching [162,163], contributing to maximizing returns and ensuring the sustainable development of uranium mining through in situ leaching.

4.3. Information Technology for In Situ Leaching

In order to enhance the efficiency and sustainability of the entire in situ leaching process for uranium mining, a data-driven and intelligent information system with comprehensive analytical capabilities has become a notable innovation. The system offers thorough information on geological, technical, and economic elements to optimize the development and operation of mining sites. It is specifically developed to facilitate intelligent management and decision-making during the in situ leaching of uranium deposits.

The Seversk Technological Institute of the National Research Nuclear University (MEPhI) developed an informational support software package specifically designed to manage the in situ leaching process for uranium mining [164]. Operating on client-server technology, the software facilitates interaction between client programs and data storage through SQL queries, making it applicable at any stage of in situ leaching operations. There are seven interconnected information systems within the software package: (1) the mining-geological information system (MGIS) collects and processes raw geological data, generates 2D/3D mathematical models, calculates uranium reserves, and visually presents the production layer's information status; (2) the technological information system constructs a model for the geological-technical mining complex, coordinates technical data processing, evaluates relationships, and generates operational reports to ensure data integrity; (3) the geo-technological modeling system simulates in situ leaching and pollutant migration using geological mathematical models of the uranium deposit and numerical models of the mining complex; (4) the geo-information expert analytical system (GEAS) visualizes all information in the entire mining operation process, analyzes hydrodynamic flow in the production layer, optimizes solutions, and reduces reagent usage in the in situ leaching process; (5) the techno-economic system employs economic mathematical models to calculate the economic performance of uranium mining units, including fundamental costs and other economic indicators related to unit development; (6) the computer-aided design system

designs and optimizes mining development patterns based on initial data derived from geological and mathematical models of the deposit; and (7) the mining planning system predicts and formulates mining plans for operational units, ensuring planned uranium production levels based on multifactor statistical models of productivity. The software package offers advantages such as a modular architecture, scalability, and expandability. Its optimal database structure ensures both data integrity and consistency, complemented by seamless integration mechanisms with existing enterprise information systems. The collaborative utilization of the seven information systems within the package enhances the intelligence of geotechnical enterprise management through comprehensive analysis of geological and geotechnical data, multifaceted modeling of geotechnical processes, and intelligent decision support.

The collaboration between the Seversk Institute of Technology and ARMZ Uranium Holding Company has led to further enhancements of the software package, giving rise to the Smart ISL site digital mining system [24]. This system is currently capable of managing uranium production through informationization, utilizing automated data collection and remote control of wellfields. It comprehensively analyzes geological and operational data, as well as hydrogeological and technical simulations. In practical production scenarios, the system optimizes processes, enhances extraction efficiency, and reduces risks. This progression toward digitalization and intelligence in in situ leaching technology provides a sustainable and efficient intelligent solution for future uranium mining.

5. Application Status of In Situ Leaching

In the early 1960s, the in situ leaching technique for uranium mining was developed by the former USSR and the USA [39]. Notably, in situ acid leaching technology found widespread application in the former USSR, while in situ alkaline leaching technology achieved commercial success in the USA [165]. Over several decades of continuous development and refinement, this technique has progressively seen practical on-site implementation in numerous countries worldwide [24]. Figure 7 illustrates the recoverable uranium resources under various mining methods within a mining cost of less than \$40/kgU, based on statistical data from the OECD report for 2021 [24]. It is evident from the figure that the quantity of uranium produced through in situ leaching has significantly surpassed the total quantity produced through open-pit mining and underground mining. This establishes in situ leaching as the primary method for low-cost uranium production.

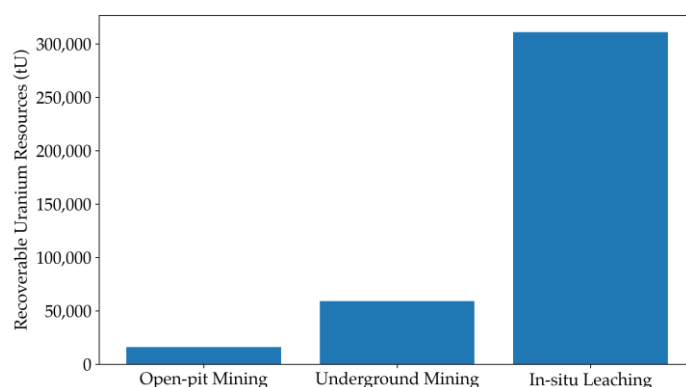


Figure 7. Recoverable uranium resources by different mining methods.

Based on data from OECD and other relevant sources, the basic details of representative uranium mines utilizing in situ leaching are summarized in Table 3. The additional information associated with the uranium resources of these countries employing in situ leaching for uranium mining, including identified recoverable uranium resources, current production capacity, and projected future production capacity, is provided in Figure 8.

Table 3. Representative in situ leaching uranium projects worldwide.

Country	Uranium Mine	Production Capacity (tU/Year)	Start Date	Technique	Reference
Australia	Beverley and Beverley North Uranium Deposit (Four Mile Uranium Mine)	Approximately 1200	2001/2014	Acid leaching/weak acid leaching	[24,38,78]
	Honeymoon Uranium Mine	Approximately 312 (average production for three years)	2019 (resumed production)	Acid leaching	
Kazakhstan	Katco Mine (Tortkuduk and Muyunkum Deposits)	3000–4000	2009	Acid leaching assisted by RTM simulation	[24,35]
	Zarechnoye Deposit	Approximately 1000	2020	Acid leaching with valuable by-product production	
Canada	Phoenix Uranium Deposit	Approximately 2300 (expected average production for ten years)	2023	Acid leaching	[166,167]
Russia	Dular Mine (Dobrovolnoye Deposit)	700	2020	Acid leaching assisted by Smart ISL site digital mining system	[24,168]
	Khiagda ISL Operation Plant	1000	2020	Acid leaching assisted by Smart ISL site digital mining system	
USA	Smith Ranch-Highland Operation Lost Creek project	Collectively 2900	2000	CO ₂ -O ₂ leaching	[24,74,169]
			2013	CO ₂ -O ₂ leaching	
China	Erdos Sandstone-hosted Uranium Deposit	Unknown	2020 (trial test)	CO ₂ -O ₂ leaching	[24]
	Songliao Sandstone-hosted Uranium Deposit	Unknown	2023 (trial test)	CO ₂ -O ₂ leaching assisted by RTM simulation	
India	Tummalapalle Mine	Unknown	2017	Alkaline leaching	[24,170]
Finland	Terrafame Mine (formerly Talvivaara Mine)	Unknown	2024 (trial test)	Bioleaching	[24,75,171]

Australia possesses the world's largest uranium reserves and has a history of utilizing open-cut and underground mining in regions like South Australia, Queensland, and the Northern Territory. The transition to in situ leaching began around 2000, primarily at the Beverley Uranium Deposit [38]. This deposit officially began operations in 2001, signifying Australia's first uranium mine using the in situ leaching technique with sulfuric acid as the leaching solution. In 2005, the significant discovery of the Four Mile Uranium Deposit [78], located a few kilometers northwest of Beverley, contributed substantially to the uranium

resources in the region, amassing reserves of 28,000 tons of uranium oxide. It has officially implemented weak acid leaching for uranium mining since 2014. Collectively, these two deposits are known as the Beverley and Beverley North Uranium Deposit. The Honey-moon Uranium Mine is another representative in situ leaching project for uranium mining currently operating in Australia [172]. It is a sandstone-hosted paleochannel uranium deposit, marking the second deposit in Australia to adopt in situ leaching technology. The mine officially commenced production in 2011 after two series of acid in situ leaching trials. Following a period of suspension for care and maintenance, it resumed production in 2019.

Kazakhstan, currently the world's leading uranium-producing country, achieved a production of 21,819 tU in 2021 [24]. The country hosts 13 uranium mining projects, with 6 in commercial operation [24]. Among them, the Katco Mine stands out as the largest in situ leaching uranium mine globally, boasting an annual production ranging from 3200 tU to 4000 tU since 2019 [35]. In an effort to maximize the extraction of remaining uranium resources in this deposit, a 3D reactive transport model simulation was implemented in 2019, covering 2394 wells across 39 production blocks. Remarkably, the simulation's predictions demonstrated less than a 10% deviation from the actual production results 16 months later [35], underscoring the feasibility of this method in large-scale industrial production and its promising prospects for broader future applications. The in situ acid leaching project at the Zarechnoye Deposit in Kazakhstan stands out as another significant venture [24]. Extensive exploration work conducted in 2020 extended the identified uranium reserves of this deposit, prolonging its feasible lifespan of in situ acid leaching. Kazatomprom [173], the national atomic company overseeing the project, implemented advancements in the acid leaching technique. They introduced nanofiltration technology to separate rare metals, including scandium, rhenium, and vanadium, from the uranium co-dissolving in the acid leaching solution. These rare metals are recovered as by-products in the form of scandium oxide, ammonium perrhenate, and vanadium during the processing of the pregnant solution. This enhancement substantially increases the value of the uranium deposit, contributing to heightened economic benefits for the overall uranium mining project.

Canada started operating its first in situ leaching project at the Phoenix Uranium Deposit in 2023. The deposit, characterized as a high-grade unconformity-type uranium deposit with proved reserves of 59.7 million pounds of uranium oxide, was discovered in the Athabasca Basin in 2008 [166]. Since 2021, comprehensive assessments of hydraulic conductivity, permeability, leachability, and containment parameters have been conducted for this deposit through commercial-scale in situ leaching tests. The acid leaching solution has been adopted with an additional neutralization step, introducing a mild alkaline solution to counteract residual acidity in the leaching zone [167]. During trial production in late 2022, the mine successfully recovered and processed 14,400 pounds of uranium oxide [166]. Upon full production, the Phoenix Uranium Deposit is expected to achieve an average annual production of 8.4 million pounds of uranium oxide for the initial five years, followed by an average annual production of 3.0 million pounds of uranium oxide [166], demonstrating substantial economic extraction benefits.

Russia has integrated its indigenously developed Smart ISL Site digital mining system [24] into the operational framework of the Dular Mine and Khiagda ISL operation plant [168]. The system is centrally managed from a control complex, facilitating the monitoring and administration of hydrodynamic processes. It conducts a comprehensive analysis of geological and production data through automated data collection, automatically optimizing extraction capacity. Furthermore, the system promptly detects wells in need of repair or restoration, ensuring a smooth production procedure. The implementation of this system has significantly enhanced the effectiveness of in situ leaching at both uranium mines. It has resulted in significant reductions in operating expenses by increasing extraction rates, shortening extraction times, and using fewer reagents [24].

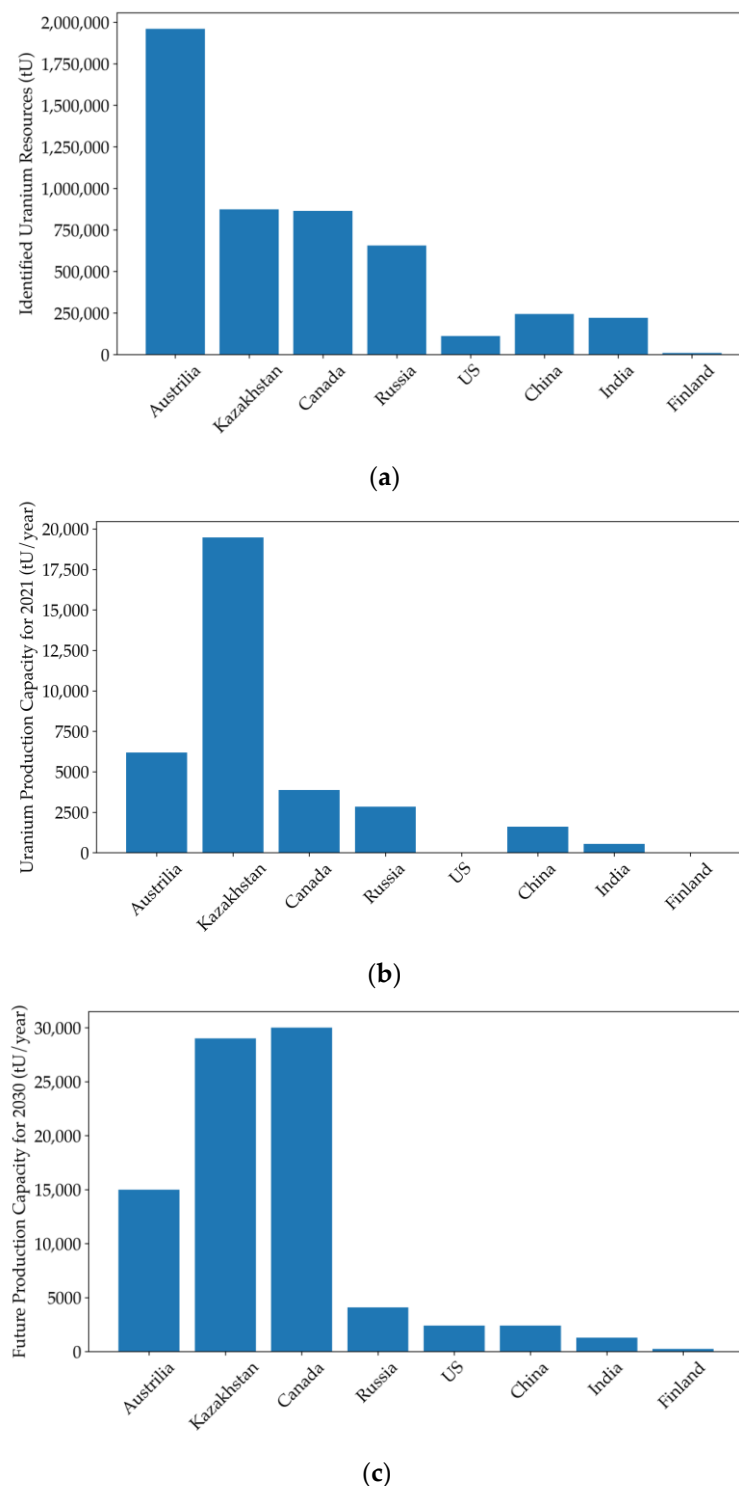


Figure 8. Overview of uranium resources and production capacities of countries utilizing in situ leaching. **(a)** Identified recoverable uranium resources of countries. **(b)** Uranium production capacities of countries for 2021. Note: The decline in uranium production in the United States was significant and attributed to the temporary suspension of mine operations at several facilities due to an unfavorable market. These data do not accurately reflect the actual production capacity of uranium mines in the United States. **(c)** Uranium production capacities of countries for 2030.

The United States' uranium resources generally contain a significant amount of carbonate. As a result, in situ alkaline leaching was the predominant method for early uranium mining. In recent years, the $\text{CO}_2\text{-O}_2$ leaching technique has replaced alkaline leaching as

the primary technology for in situ uranium mining in the country, offering new possibilities for efficient uranium extraction under specific geological characteristics. Currently, in situ leaching uranium mines in Nebraska and Wyoming significantly contribute to the United States' uranium production [24]. In the early 1960s, the Gas Hills and Shirley Basin uranium districts in Wyoming [169] pioneered in situ alkaline leaching technology and have now transitioned to CO₂-O₂ leaching [74]. Present-day operational in situ CO₂-O₂ leaching uranium projects in the district include the Smith Ranch-Highland operation, the Lost Creek project, and the Nichols Ranch project. Among these, the Smith Ranch-Highland operation, a sandstone-hosted uranium project, has maintained stable and relatively high annual uranium production since 2000. The combined annual uranium production of Smith Ranch-Highland and Lost Creek projects reaches as high as 2900 tU/year [24].

China's uranium resources exhibit characteristics such as low endowment, small deposit sizes, and low grades. Due to the sustained low uranium prices, Chinese uranium companies underwent reorganization in 2017 and 2018, emphasizing a domestic industry with a focus on in situ leaching in northern China to align with ecological goals [24]. Recent proactive exploration efforts have confirmed substantial uranium reserves in hydrocarbon-bearing basins [2,7,9,11], notably the Erdos Basin and Songliao Basin. Consequently, these sandstone-hosted uranium deposits have become the focal point of uranium mining in China. Given the high carbonate, high iron–aluminum content, and high mineralization level characteristics of these two sandstone-type uranium deposits, the CO₂-O₂ in situ leaching technique has been adopted and is currently in the trial test stage. In the test units of the Songliao Basin, a comprehensive understanding of the complex phenomena during CO₂-O₂ leaching under the conditions of the uranium deposit has been achieved. This involves practical sample collection, laboratory testing and analysis, and integration with a 3D multicomponent reactive transport model simulation. Neutral CO₂-O₂ leaching not only provides a more efficient approach for these low-permeability, low-grade, and high-carbonate-content uranium deposits but also contributes to achieving greenhouse gas emission reduction goals through the utilization and underground storage of CO₂ [2,98,101].

India's Tummalapalle uranium mine, which is situated within the South Cuddapah Basin, is a typical alkaline in situ leaching project [24,170]. This mine constitutes approximately 49% of the nation's uranium reserves. The uranium deposit is found in carbonate-hosted rock formations, predominantly composed of massive limestone, dolostone, and intra-formational conglomerate [170]. Consequently, in situ leaching at this mine employs an alkaline leaching solution primarily composed of sodium carbonate and sodium bicarbonate. In recent years, optimization endeavors within this in situ alkaline leaching project have predominantly concentrated on post-mining processing of the leaching solution, aiming to attain enhanced efficiency in the extraction of uranium resources [170].

Finland's Terrafame Mine serves as a typical example of a mine employing bioleaching technology [171]. The mine is regarded as an unconventional resource of uranium [24], characterized by metamorphosed black shale-hosted deposits containing uranium and accessory minerals such as Cu, Co, Ni, Zn, and Mn. Due to the high content of components like pyrite (FeS₂), sphalerite ((Fe,Zn)S), pentlandite ((Fe,Ni)₉S₈), and chalcopyrite (CuFeS₂) in its ore [75], it is particularly suitable for the application of bioleaching techniques in extraction. Currently, uranium bioleaching is undergoing testing using shake flasks containing samples of rock and ore deposits from four locations within this mine [75].

6. Challenges and Future Directions

Currently, approximately 63% of the world's natural uranium resources are mined through the in situ leaching technique [24,35]. Continuous advancements in in situ leaching techniques for uranium mining have been witnessed in recent years. These improvements have led to significant reductions in energy and material consumption, a substantial increase in productivity, and considerable decreases in direct mining costs. As a result, the uranium

mining industry has experienced noteworthy economic benefits. However, despite these advancements, in situ leaching still faces certain challenges.

For low-grade uranium deposits, larger amounts of leaching solution, extended leaching periods, and subsequent intricate concentration processes are typically required due to their lower uranium concentration, significantly impacting their economic benefits. To address this challenge, the research and development of pre-leaching beneficiation techniques for low-grade uranium deposits represent a potential avenue. Currently, Elevate Uranium Ltd is dedicated to developing a pre-leaching in situ uranium concentration enhancement process known as “U-pgrade” [24]. This initiative is specifically tailored for the low-grade uranium deposits inherent to the Namibian Marenica Uranium Deposit, primarily composed of a clay matrix, carbonate, black mica, feldspar, quartz, and other constituents. The ongoing research and development of analogous pre-leaching beneficiation processes, adaptable to various low-grade uranium deposits featuring diverse compositions, hold promise for enhancing the economic efficiency of in situ leaching mining in these deposits.

Reactive transport models have proven advantageous in the study of the in situ leaching process, providing profound insights into accurate predictions of fluid flow, liquid-rock geochemistry, and various aspects tailored to the characteristics of each reservoir. Nevertheless, it is crucial to recognize that the repeated use of reactive transport models may impose a substantial computational burden. Therefore, exploring alternative approaches, particularly iterative models based on machine learning (ML-based surrogate models), holds the promise to replace reactive transport models in predictive simulations for in situ leaching. This emerging direction represents a compelling research avenue, offering the potential for enhanced computational efficiency and predictive accuracy in the field of in situ leaching.

In the pursuit of sustainable development, a paramount goal in uranium resource mining is to maximize resource utilization while minimizing environmental impact during the in situ leaching process. This requires meticulous attention to issues such as pore plugging, waste generation, and post-mining ecological restoration associated with in situ leaching. Addressing the risk of pore plugging involves crucial steps, such as optimizing leaching solution formulations and refining the circulation injection system. Waste generation can be significantly reduced by researching and developing more advanced, efficient, economical, and environmentally friendly ion exchange resin materials for the concentration process of uranium-bearing pregnant solution. Post-mining ecological restoration of uranium deposits necessitates comprehensive actions in soil restoration, vegetation restoration, water resource restoration, and other aspects. Incorporating advanced ecological and environmental science techniques, along with sustained long-term monitoring and assessment, is indispensable to ensure the success of ecological restoration efforts [174].

Furthermore, it is noteworthy that the efficient extraction of uranium resources is impacted not only by the mining technologies explored in this study but also by related significant technologies, including uranium tailings enrichment [175,176], extraction of uranium and other valuable metal resources from enriched tailings [177,178], and techniques for reducing ore loss [179]. Through comprehensive research and enhancement of these technologies, further advancements can be achieved in addressing challenges associated with mineral resource wastage and environmental preservation.

The effectiveness of in situ leaching technology is closely associated with the selection of optimal schemes for the opening productive formations, the pattern of injection and production wells, the modes of pumping solutions, and the means of solution lifting [57]. When preparing uranium deposits for in situ leaching, the consideration of preparation parameters and methods in the mining plan is crucial. It is necessary to take into account the morphological characteristics of the deposits being mined, the hydrogeological conditions of the productive horizon, and the related geotechnical parameters to select appropriate preparation parameters, thereby achieving optimal mining results [57].

7. Conclusions

Uranium, as the cornerstone of nuclear energy, attracts significant attention for its pivotal role in clean and efficient energy conversion. In contrast to fossil fuels, nuclear energy generates no greenhouse gases like carbon dioxide during usage, making it a positive contributor to climate change mitigation. In the context of global clean energy initiatives, uranium resources emerge as a crucial component for achieving sustainability. Uranium mining techniques encompass open-pit mining, underground mining, and in situ leaching. Compared to the former two conventional approaches, in situ leaching technique stands out for its high extraction efficiency, environmental friendliness, and economic advantages.

The in situ leaching technique for uranium mining is classified into acid leaching, alkaline leaching, neutral leaching, and bioleaching based on the distinct properties of uranium deposits. Acid leaching is suitable for uranium deposits with low carbonate content, alkaline leaching is applicable to those with high carbonate but low pyrite content, and neutral leaching is widely applicable. Bioleaching, being a versatile method, is particularly effective for uranium deposits with high pyrite and other sulfide content.

In recent years, the in situ leaching technology for uranium mining has experienced multifaceted innovations. The blasting-enhanced permeability technique has been shown to effectively establish well-connected fracture networks with sustainable and large-scale seepage channels within low-permeability uranium deposits. This enables the utilization of in situ leaching in uranium deposits that were previously unsuitable for this method, thus facilitating the economically and environmentally sustainable extraction of uranium from such deposits. Reactive transport models showcase exceptional accuracy in predicting complex fluid flow and geochemical reactions, specifically tailored to the distinct characteristics of various uranium deposits. Furthermore, the integration of data-driven and intelligent information technologies offers intelligent optimization of the extraction process, holding promising potential for heightened production efficiency.

Globally, prominent uranium mines in Australia, Kazakhstan, Russia, Canada, the United States, China, India, and Finland serve as successful models for the effective application of in situ leaching technology. Australia, Kazakhstan, Canada, and Russia primarily rely on acid leaching with integrated technological advancements. Uranium deposits in the United States and China are characterized by high carbonate content, and they both emphasize the utilization of the neutral $\text{CO}_2\text{-O}_2$ leaching method. This allows for the economical extraction of uranium resources while effectively utilizing carbon dioxide, thereby contributing to clean energy projection and mitigating the negative environmental impact of greenhouse gas emissions. Uranium deposits with high carbonate content in India are mined using alkaline in situ leaching, while the bioleaching technique is employed in the uranium deposit characterized by high iron and sulfur content in Finland. The varied in situ leaching methods tailored to the primary composition of uranium deposits worldwide underscore the remarkable achievements of in situ leaching in improving extraction efficiency, reducing costs, and adapting to diverse geological conditions. These outcomes, serving as a robust foundation of experiences, can be applied to uranium deposits worldwide with similar characteristics, contributing to the sustainable and thriving development of the global uranium mining industry.

In situ leaching, while a promising technology for uranium extraction, confronts several challenges. To address the economic constraints of mining low-grade uranium deposits, research and development in pre-leaching beneficiation techniques represent a promising avenue. While reactive transport models are valuable for in situ leaching studies, their significant computational load poses challenges. Future directions involve exploring alternative methods, particularly iterative machine learning-based surrogate models, to enhance computational efficiency and predictive accuracy in in situ leaching simulations. Addressing environmental sustainability concerns, including pore plugging, waste generation, and post-mining ecological restoration, requires optimizing leaching solutions, employing advanced ion exchange resin materials, and applying ecological

methods with continuous monitoring to ensure the sustainability of in situ leaching for uranium mining. Moreover, advancements in tailings enrichment, strategies to minimize ore loss, and the careful consideration of preparation parameters when selecting optimal schemes are imperative for the efficient extraction of uranium resources.

Author Contributions: G.L.: original draft writing, resources, and visualization; J.Y.: conceptualization, original draft writing, and review and editing. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: No new data were created or analyzed in this study. Date sharing is not applicable to this article.

Acknowledgments: The authors are grateful to the Departments of Chemical Engineering and Petroleum Engineering at the University of Wyoming for the support.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Storrs, K.; Lyhne, I.; Drustrup, R. A Comprehensive Framework for Feasibility of CCUS Deployment: A Meta-Review of Literature on Factors Impacting CCUS Deployment. *Int. J. Greenh. Gas Control* **2023**, *125*, 103878. [\[CrossRef\]](#)
2. Yao, J.; Han, H.; Yang, Y.; Song, Y.; Li, G. A Review of Recent Progress of Carbon Capture, Utilization, and Storage (CCUS) in China. *Appl. Sci.* **2023**, *13*, 1169. [\[CrossRef\]](#)
3. Han, J.; Li, J.; Tang, X.; Wang, L.; Yang, X.; Ge, Z.; Yuan, F. Coal-Fired Power Plant CCUS Project Comprehensive Benefit Evaluation and Forecasting Model Study. *J. Clean. Prod.* **2023**, *385*, 135657. [\[CrossRef\]](#)
4. Bai, X.; Yan, G.; Kong, S.; Yao, J.; Wen, P.; Li, G.; Li, J.; Zhang, J. Suppression of Anthracite Dust by a Composite of Oppositely-Charged Ionic Surfactants with Ultra-High Surface Activity: Theoretical Calculation and Experiments. *Fuel* **2023**, *344*, 128075. [\[CrossRef\]](#)
5. Su, C.-W.; Pang, L.-D.; Qin, M.; Lobont, O.-R.; Umar, M. The Spillover Effects among Fossil Fuel, Renewables and Carbon Markets: Evidence under the Dual Dilemma of Climate Change and Energy Crises. *Energy* **2023**, *274*, 127304. [\[CrossRef\]](#)
6. Bai, X.; Yan, G.; Kong, S.; Yang, T.; Yao, J.; Wen, P.; Li, G. Study on the Mechanism of the Influence of Surfactant Alkyl Chain Length on the Wettability of Anthracite Dust Based on EDLVO Theory and Inverse Gas Chromatography. *Fuel* **2023**, *353*, 129187. [\[CrossRef\]](#)
7. Yao, J.; Li, G.; Wu, J. Application of In-Situ Combustion for Heavy Oil Production in China: A Review. *J. Oil Gas Petrochem. Sci.* **2018**, *1*, 69–72. [\[CrossRef\]](#)
8. Fetisov, V.; Gonopolsky, A.M.; Davardoost, H.; Ghanbari, A.R.; Mohammadi, A.H. Regulation and Impact of VOC and CO₂ Emissions on Low-carbon Energy Systems Resilient to Climate Change: A Case Study on an Environmental Issue in the Oil and Gas Industry. *Energy Sci. Eng.* **2023**, *11*, 1516–1535. [\[CrossRef\]](#)
9. Yao, J.; Song, Y. Dynamic Analysis Approach to Evaluate In-Situ Combustion Performance for Heavy Oil Production. *J. Oil Gas Petrochem. Sci.* **2019**, *2*, 42–47. [\[CrossRef\]](#)
10. Vieira, L.C.; Longo, M.; Mura, M. From Carbon Dependence to Renewables: The European Oil Majors' Strategies to Face Climate Change. *Bus. Strategy Environ.* **2023**, *32*, 1248–1259. [\[CrossRef\]](#)
11. Li, G.; Yao, J.; Song, Y.; Tang, J.; Han, H.; Cui, X. A Review of the Metallogenic Mechanisms of Sandstone-Type Uranium Deposits in Hydrocarbon-Bearing Basins in China. *Eng* **2023**, *4*, 1723–1741. [\[CrossRef\]](#)
12. Rehm, T.E. Advanced Nuclear Energy: The Safest and Most Renewable Clean Energy. *Curr. Opin. Chem. Eng.* **2023**, *39*, 100878. [\[CrossRef\]](#)
13. Wu, Y.; Xie, Y.; Liu, X.; Li, Y.; Wang, J.; Chen, Z.; Yang, H.; Hu, B.; Shen, C.; Tang, Z.; et al. Functional Nanomaterials for Selective Uranium Recovery from Seawater: Material Design, Extraction Properties and Mechanisms. *Coord. Chem. Rev.* **2023**, *483*, 215097. [\[CrossRef\]](#)
14. Degueldre, C. Uranium as a Renewable for Nuclear Energy. *Prog. Nucl. Energy* **2017**, *94*, 174–186. [\[CrossRef\]](#)
15. Costa Peluzo, B.M.T.; Kraka, E. Uranium: The Nuclear Fuel Cycle and Beyond. *Int. J. Mol. Sci.* **2022**, *23*, 4655. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Watkins, J.K.; Gonzales, A.; Wagner, A.R.; Sooby, E.S.; Jaques, B.J. Challenges and Opportunities to Alloyed and Composite Fuel Architectures to Mitigate High Uranium Density Fuel Oxidation: Uranium Mononitride. *J. Nucl. Mater.* **2021**, *553*, 153048. [\[CrossRef\]](#)
17. Muellner, N.; Arnold, N.; Gufler, K.; Kromp, W.; Renneberg, W.; Liebert, W. Nuclear Energy—The Solution to Climate Change? *Energy Policy* **2021**, *155*, 112363. [\[CrossRef\]](#)
18. Wu, R.; Xu, Z.; Gong, W.; Cai, J.; Ning, J. Genesis of Baixingtui Uranium Deposit in Songliao Basin. *Uranium Geol.* **2012**, *3*, 142–147.

19. Rong, H.; Jiao, Y.; Wu, L.; Ji, D.; Li, H.; Zhu, Q.; Cao, M.; Wang, X.; Li, Q.; Xie, H. Epigenetic Alteration and Its Constraints on Uranium Mineralization from the Qianjiadian Uranium Deposit, Southern Songliao Basin. *Earth Sci.-J. China Univ. Geosci.* **2016**, *41*, 2675–2696. [\[CrossRef\]](#)
20. Cuney, M. The Extreme Diversity of Uranium Deposits. *Minim. Depos.* **2009**, *44*, 3–9. [\[CrossRef\]](#)
21. Jiao, Y.; Wu, L.; Rong, H.; Zhang, F. Review of Basin Uranium Resources in China. *Earth Sci.-J. China Univ. Geosci.* **2021**, *46*, 2675. [\[CrossRef\]](#)
22. Jin, R.; Yu, R.; Miao, P. *Basin Uranium Mineralization Law*; Springer: Singapore, 2023; pp. 325–356.
23. World Nuclear Association. Available online: <https://world-nuclear.org/information-library/nuclear-fuel-cycle/mining-of-uranium/world-uranium-mining-production.aspx> (accessed on 21 August 2023).
24. OECD. Uranium 2022: Resources, Production and Demand. Available online: https://read.oecd-ilibrary.org/nuclear-energy/uranium-2022_2c4e111b-en (accessed on 11 May 2023).
25. Espinoza, D.; Goycoolea, M.; Moreno, E.; Newman, A. MineLib: A Library of Open Pit Mining Problems. *Ann. Oper. Res.* **2013**, *206*, 93–114. [\[CrossRef\]](#)
26. Ben-Awuah, E.; Richter, O.; Elkington, T.; Pourrahimian, Y. Strategic Mining Options Optimization: Open Pit Mining, Underground Mining or Both. *Int. J. Min. Sci. Technol.* **2016**, *26*, 1065–1071. [\[CrossRef\]](#)
27. Petersen, J. Heap Leaching as a Key Technology for Recovery of Values from Low-Grade Ores—A Brief Overview. *Hydrometallurgy* **2016**, *165*, 206–212. [\[CrossRef\]](#)
28. Abzalov, M.Z. Sandstone-Hosted Uranium Deposits Amenable for Exploitation by In Situ Leaching Technologies. *Appl. Earth Sci.* **2012**, *121*, 55–64. [\[CrossRef\]](#)
29. Abzalov, M.Z.; Drobov, S.R.; Gorbatenko, O.; Vershkov, A.F.; Bertoli, O.; Renard, D.; Beucher, H. Resource Estimation of In Situ Leach Uranium Projects. *Appl. Earth Sci.* **2014**, *123*, 71–85. [\[CrossRef\]](#)
30. Padilla, G.A.; Cisternas, L.A.; Cueto, J.Y. On the Optimization of Heap Leaching. *Miner. Eng.* **2008**, *21*, 673–678. [\[CrossRef\]](#)
31. Ghorbani, Y.; Becker, M.; Mainza, A.; Franzidis, J.-P.; Petersen, J. Large Particle Effects in Chemical/Biochemical Heap Leach Processes—A Review. *Miner. Eng.* **2011**, *24*, 1172–1184. [\[CrossRef\]](#)
32. Ghorbani, Y.; Franzidis, J.-P.; Petersen, J. Heap Leaching Technology—Current State, Innovations and Future Directions: A Review. *Miner. Process. Extr. Metall. Rev.* **2016**, *37*, 73–119. [\[CrossRef\]](#)
33. Robertson, S.W.; van Staden, P.J.; Cherkaev, A.; Petersen, J. Properties Governing the Flow of Solution through Crushed Ore for Heap Leaching. *Hydrometallurgy* **2022**, *208*, 105811. [\[CrossRef\]](#)
34. Van Lien, T.; Dinh, T.T.; Dung, N.T.K. Study on Leaching Systems and Recovery for PALUA–PARONG Low Grade Uranium Sandstone Ores. *Hydrometallurgy* **2020**, *191*, 105164. [\[CrossRef\]](#)
35. Collet, A.; Regnault, O.; Ozhogin, A.; Imantayeva, A.; Garnier, L. Three-Dimensional Reactive Transport Simulation of Uranium In Situ Recovery: Large-Scale well Field Applications in Shu Saryssu Bassin, Tortkuduk Deposit (Kazakhstan). *Hydrometallurgy* **2022**, *211*, 105873. [\[CrossRef\]](#)
36. Seredkin, M.; Zabolotsky, A.; Jeffress, G. In Situ Recovery, an Alternative to Conventional Methods of Mining: Exploration, Resource Estimation, Environmental Issues, Project Evaluation and Economics. *Ore Geol. Rev.* **2016**, *79*, 500–514. [\[CrossRef\]](#)
37. Bhargava, S.K.; Ram, R.; Pownceby, M.; Grocott, S.; Ring, B.; Tardio, J.; Jones, L. A Review of Acid Leaching of Uraninite. *Hydrometallurgy* **2015**, *151*, 10–24. [\[CrossRef\]](#)
38. Mudd, G.M. Acid In Situ Leach Uranium Mining—1. USA and Australia. In *Tailings and Mine Waste 2000*; CRC Press: Boca Raton, FL, USA, 2022; pp. 517–526.
39. Mudd, G. Critical Review of Acid In Situ Leach Uranium Mining: 2. Soviet Block and Asia. *Environ. Geol.* **2001**, *41*, 404–416. [\[CrossRef\]](#)
40. Zhao, L.; Deng, J.; Xu, Y.; Zhang, C. Mineral Alteration and Pore-Plugging Caused by Acid In Situ Leaching: A Case Study of the Wuyier Uranium Deposit, Xinjiang, NW China. *Arab. J. Geosci.* **2018**, *11*, 707. [\[CrossRef\]](#)
41. Su, X.; Liu, Z.; Yao, Y.; Du, Z. Petrology, Mineralogy, and Ore Leaching of Sandstone-Hosted Uranium Deposits in the Ordos Basin, North China. *Ore Geol. Rev.* **2020**, *127*, 103768. [\[CrossRef\]](#)
42. Zheng, F.; Teng, Y.; Zhai, Y.; Hu, J.; Dou, J.; Zuo, R. Geo-Environmental Models of In-Situ Leaching Sandstone-Type Uranium Deposits in North China: A Review and Perspective. *Water* **2023**, *15*, 1244. [\[CrossRef\]](#)
43. Mukherjee, S.; Goswami, S.; Zakaulla, S. Geological Relationship between Hydrocarbon and Uranium: Review on Two Different Sources of Energy and the Indian Scenario. *Geoenergy Sci. Eng.* **2023**, *221*, 111255. [\[CrossRef\]](#)
44. Herring, J.S. Uranium and Thorium Resources. In *Nuclear Energy*; Springer: New York, NY, USA, 2013; pp. 463–490.
45. Jia, J.; Rong, H.; Jiao, Y.; Wu, L.; Guo, X.; Cao, M.; Cui, Z.; Tao, Z. Occurrence of Carbonate Cements and Relationship between Carbonate Cementation and Uranium Mineralization of Qianjiadian Uranium Deposit. *Earth Sci.* **2018**, *2*, 149–161. [\[CrossRef\]](#)
46. Guthrie, V.A.; Kleeman, J.D. Changing Uranium Distributions during Weathering of Granite. *Chem. Geol.* **1986**, *54*, 113–126. [\[CrossRef\]](#)
47. Cuney, M.; Mercadier, J.; Bonnetti, C. Classification of Sandstone-Related Uranium Deposits. *J. Earth Sci.* **2022**, *33*, 236–256. [\[CrossRef\]](#)
48. Zhou, Y.; Li, G.; Xu, L.; Liu, J.; Sun, Z.; Shi, W. Uranium Recovery from Sandstone-Type Uranium Deposit by Acid In-Situ Leaching—An Example from the Kujiertai. *Hydrometallurgy* **2020**, *191*, 105209. [\[CrossRef\]](#)

49. Zhang, F.; Wang, S.; Jiao, Y.; Wu, L.; Rong, H. Trapping of Uranium by Organic Matter within Sandstones during Mineralization Process: A Case Study from the Shuanglong Uranium Deposit, China. *Ore Geol. Rev.* **2021**, *138*, 104296. [\[CrossRef\]](#)
50. Farjana, S.H.; Huda, N.; Mahmud, M.A.P.; Lang, C. Comparative Life-Cycle Assessment of Uranium Extraction Processes. *J. Clean. Prod.* **2018**, *202*, 666–683. [\[CrossRef\]](#)
51. Babaeian, M.; Sereshki, F.; Ataei, M.; Nehring, M.; Mohammadi, S. Application of Soft Computing, Statistical and Multi-Criteria Decision-Making Methods to Develop a Predictive Equation for Prediction of Flyrock Distance in Open-Pit Mining. *Mining* **2023**, *3*, 304–333. [\[CrossRef\]](#)
52. El Hiouile, L.; Errami, A.; Azami, N. Toward Automatic Monitoring for Anomaly Detection in Open-Pit Phosphate Mines Using Artificial Vision: A Case Study of the Screening Unit. *Mining* **2023**, *3*, 645–658. [\[CrossRef\]](#)
53. Brown, S.H.; Chambers, D.B. Uranium Mining and Norm in North America—Some Perspectives on Occupational Radiation Exposure. *Health Phys.* **2017**, *113*, 13–22. [\[CrossRef\]](#)
54. Woods, P.H. Uranium Mining (Open Cut and Underground) and Milling. In *Uranium for Nuclear Power*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 125–156.
55. Cardozo, F.A.C.; Campos, H.J.S.; Petter, C.O.; Ambrós, W.M. Application of Monte Carlo Analytic Hierarchy Process (MAHP) in Underground Mining Access Selection. *Mining* **2023**, *3*, 773–785. [\[CrossRef\]](#)
56. Ngwaku, S.R.; Pascoe, J.; Pelser, W.A.; Vosloo, J.C.; van Laar, J.H. A Data-Driven Framework to Reduce Diesel Spillages in Underground Mines. *Mining* **2023**, *3*, 683–695. [\[CrossRef\]](#)
57. Oryngozhin, E.S.; Fedorov, E.V.; Alisheva, Z.N.; Mitishova, N.A. In-Situ Leaching Technology for Uranium Deposits. *Eurasian Min.* **2021**, *2*, 31–35. [\[CrossRef\]](#)
58. Li, H.; Liu, M.; Jiao, T.; Xiang, D.; Yan, X.; Tang, Z.; Yang, J. Using Clustering, Geochemical Modeling, and a Decision Tree for the Hydrogeochemical Characterization of Groundwater in an In Situ Leaching Uranium Deposit in Bayan-Uul, Northern China. *Water* **2023**, *15*, 4234. [\[CrossRef\]](#)
59. Saunders, J.A.; Pivetz, B.E.; Voorhies, N.; Wilkin, R.T. Potential Aquifer Vulnerability in Regions Down-Gradient from Uranium In Situ Recovery (ISR) Sites. *J. Environ. Manag.* **2016**, *183*, 67–83. [\[CrossRef\]](#) [\[PubMed\]](#)
60. Sinclair, L.; Thompson, J. In Situ Leaching of Copper: Challenges and Future Prospects. *Hydrometallurgy* **2015**, *157*, 306–324. [\[CrossRef\]](#)
61. Alipour, A.; Khodaiari, A.A.; Jafari, A.; Tavakkoli-Moghaddam, R. An Integrated Approach to Open-Pit Mines Production Scheduling. *Resour. Policy* **2022**, *75*, 102459. [\[CrossRef\]](#)
62. Neiva, A.M.R.; Carvalho, P.C.S.; Antunes, I.M.H.R.; Albuquerque, M.T.D.; Santos, A.C.S.; Cunha, P.P.; Henriques, S.B.A. Assessment of Metal and Metalloid Contamination in the Waters and Stream Sediments around the Abandoned Uranium Mine Area from Mortórios, Central Portugal. *J. Geochem. Explor.* **2019**, *202*, 35–48. [\[CrossRef\]](#)
63. Zhang, Z. In-Situ Uranium Mining Technology and Its Application. *Resour. Surv. Environ.* **2002**, *23*, 200–204.
64. Skripchenko, S.Y.; Nalivaiko, K.A.; Titova, S.M.; Rychkov, V.N.; Semenishchev, V.S. Recovery of Uranium from Conversion Production Sludge by Leaching with Nitric Acid and Subsequent Ion-Exchange Concentration. *Hydrometallurgy* **2024**, *224*, 106255. [\[CrossRef\]](#)
65. Baigenzhenov, O.; Khabiyev, A.; Mishra, B.; Turan, M.D.; Akbarov, M.; Chepushtanova, T. Uranium (VI) Recovery from Black Shale Leaching Solutions Using Ion Exchange: Kinetics and Equilibrium Studies. *Minerals* **2020**, *10*, 689. [\[CrossRef\]](#)
66. Mudd, G.M. The Future of Yellowcake: A Global Assessment of Uranium Resources and Mining. *Sci. Total Environ.* **2014**, *472*, 590–607. [\[CrossRef\]](#)
67. Wohlers, A.; Wood, B.J. Uranium, Thorium and REE Partitioning into Sulfide Liquids: Implications for Reduced S-Rich Bodies. *Geochim. Cosmochim. Acta* **2017**, *205*, 226–244. [\[CrossRef\]](#)
68. Feng, L.; Wang, H.; Feng, T.; Yan, B.; Yu, Q.; Zhang, J.; Guo, Z.; Yuan, Y.; Ma, C.; Liu, T.; et al. In Situ Synthesis of Uranyl-Imprinted Nanocage for Selective Uranium Recovery from Seawater. *Angew. Chem.* **2022**, *134*, e202101015. [\[CrossRef\]](#)
69. Keener, M.; Shivaraam, R.A.K.; Rajeshkumar, T.; Tricoire, M.; Scopelliti, R.; Zivkovic, I.; Chauvin, A.-S.; Maron, L.; Mazzanti, M. Multielectron Redox Chemistry of Uranium by Accessing the +II Oxidation State and Enabling Reduction to a U(I) Synthon. *J. Am. Chem. Soc.* **2023**, *145*, 16271–16283. [\[CrossRef\]](#) [\[PubMed\]](#)
70. Burns, P.C.; Ewing, R.C.; Miller, M.L. Incorporation Mechanisms of Actinide Elements into the Structures of U6+ Phases Formed during the Oxidation of Spent Nuclear Fuel. *J. Nucl. Mater.* **1997**, *245*, 1–9. [\[CrossRef\]](#)
71. Schindler, M.; Hawthorne, F.C.; Freund, M.S.; Burns, P.C. XPS Spectra of Uranyl Minerals and Synthetic Uranyl Compounds. I: The U 4f Spectrum. *Geochim. Cosmochim. Acta* **2009**, *73*, 2471–2487. [\[CrossRef\]](#)
72. Li, T.; Wang, Q.; Zhu, C.; Huang, X.; Yang, G. Uranium(VI) Reduction at Mineral Surfaces by Fe(II): Periodic DFT Studies of Mechanistic Aspects and Combined Action of Fe(II) with Humic Acid. *Surf. Interfaces* **2021**, *26*, 101391. [\[CrossRef\]](#)
73. Xie, T.; Qian, T.; Lian, B.; Chen, C.; Liang, P.; Liu, X.; Li, T.; Wang, T.; Chen, K.; Zhang, A.; et al. Research on Leaching Behavior of Uranium from a Uranium Tailing and Its Adsorption Behavior in Geotechnical Media. *J. Environ. Manag.* **2024**, *353*, 120207. [\[CrossRef\]](#)
74. Gallegos, T.J.; Campbell, K.M.; Zielinski, R.A.; Reimus, P.W.; Clay, J.T.; Janot, N.; Bargar, J.R.; Benzel, W.M. Persistent U(IV) and U(VI) Following In-Situ Recovery (ISR) Mining of a Sandstone Uranium Deposit, Wyoming, USA. *Appl. Geochem.* **2015**, *63*, 222–234. [\[CrossRef\]](#)

75. Kaksonen, A.H.; Lakaniemi, A.-M.; Tuovinen, O.H. Acid and Ferric Sulfate Bioleaching of Uranium Ores: A Review. *J. Clean. Prod.* **2020**, *264*, 121586. [\[CrossRef\]](#)
76. Kurmanseiti, M.B.; Tungatarova, M.S.; Kaltayev, A.; Royer, J.-J. Reactive Transport Modeling during Uranium In Situ Leaching (ISL): The Effects of Ore Composition on Mining Recovery. *Minerals* **2022**, *12*, 1340. [\[CrossRef\]](#)
77. Avasarala, S.; Torres, C.; Ali, A.-M.S.; Thomson, B.M.; Spilde, M.N.; Peterson, E.J.; Artyushkova, K.; Dobrica, E.; Lezama-Pacheco, J.S.; Cerrato, J.M. Effect of Bicarbonate and Oxidizing Conditions on U(IV) and U(VI) Reactivity in Mineralized Deposits of New Mexico. *Chem. Geol.* **2019**, *524*, 345–355. [\[CrossRef\]](#)
78. Taylor, G.; Farrington, V.; Woods, P.; Ring, R.; Molloy, R. *Review of Environmental Impacts of the Acid In-Situ Leaching Uranium Mining Process*; CSIRO Clayton: Clayton, VIC, Australia, 2004.
79. Kvashnina, K.O.; Butorin, S.M.; Martin, P.; Glatzel, P. Chemical State of Complex Uranium Oxides. *Phys. Rev. Lett.* **2013**, *111*, 253002. [\[CrossRef\]](#)
80. Bank, T.L.; Kukkadapu, R.K.; Madden, A.S.; Ginder-Vogel, M.A.; Baldwin, M.E.; Jardine, P.M. Effects of Gamma-Sterilization on the Physico-Chemical Properties of Natural Sediments. *Chem. Geol.* **2008**, *251*, 1–7. [\[CrossRef\]](#)
81. Zakrzewska-Koltuniewicz, G.; Herdzyk-Koniecko, I.; Cojocar, C.; Chajduk, E. Experimental Design and Optimization of Leaching Process for Recovery of Valuable Chemical Elements (U, La, V, Mo, Yb and Th) from Low-Grade Uranium Ore. *J. Hazard. Mater.* **2014**, *275*, 136–145. [\[CrossRef\]](#) [\[PubMed\]](#)
82. Liao, W.; Tan, Y.; Wang, L.; Li, J. Oxygen Used as an Oxidizer in Acid In-Situ Leach Uranium: From Theory to Practice. In Proceedings of the International Conference on Nuclear Engineering, Charlotte, NC, USA, 26–30 June 2016; American Society of Mechanical Engineers: Charlotte, NC, USA, 2016.
83. Habashi, F. Dissolution of Uraninite. *Hydrometallurgy* **2020**, *194*, 105329. [\[CrossRef\]](#)
84. Abd El-Hamid, A.M.; Zahran, M.A.; Khalid, F.M.; Mahmoud, A.H. Leaching of Hafnium, Zirconium, Uranium and Other Nuclear Economic Elements from Petroleum Ash. *RSC Adv.* **2014**, *4*, 12506. [\[CrossRef\]](#)
85. Olsson, D.; Li, J.; Jonsson, M. Kinetic Effects of H₂O₂ Speciation on the Overall Peroxide Consumption at UO₂–Water Interfaces. *ACS Omega* **2022**, *7*, 15929–15935. [\[CrossRef\]](#) [\[PubMed\]](#)
86. Lasheen, T.A.; El-Ahmady, M.E.; Hassib, H.B.; Helal, A.S. Oxidative Leaching Kinetics of Molybdenum-Uranium Ore in H₂SO₄ Using H₂O₂ as an Oxidizing Agent. *Front. Chem. Sci. Eng.* **2013**, *7*, 95–102. [\[CrossRef\]](#)
87. Wang, P.; Tan, K.; Li, Y.; Liu, Z.; Li, C.; Tan, W.; Tian, Y.; Huang, W. Effect of Pyrite on the Leaching Kinetics of Pitchblende in the Process of Acid In Situ Leaching of Uranium. *Minerals* **2022**, *12*, 570. [\[CrossRef\]](#)
88. You, W.; Peng, W.; Tian, Z.; Zheng, M. Uranium Bioremediation with U(VI)-Reducing Bacteria. *Sci. Total Environ.* **2021**, *798*, 149107. [\[CrossRef\]](#)
89. Ali, H.N.; Atekwana, E.A. The Effect of Sulfuric Acid Neutralization on Carbonate and Stable Carbon Isotope Evolution of Shallow Groundwater. *Chem. Geol.* **2011**, *284*, 217–228. [\[CrossRef\]](#)
90. Gilligan, R.; Nikoloski, A.N. Alkaline Leaching of Brannerite. Part 1: Kinetics, Reaction Mechanisms and Mineralogical Transformations. *Hydrometallurgy* **2017**, *169*, 399–410. [\[CrossRef\]](#)
91. Shen, N.; Li, J.; Guo, Y.; Li, X. Thermodynamic Modeling of In Situ Leaching of Sandstone-Type Uranium Minerals. *J. Chem. Eng. Data* **2020**, *65*, 2017–2031. [\[CrossRef\]](#)
92. Lazo, D.E.; Dyer, L.G.; Alorro, R.D. Silicate, Phosphate and Carbonate Mineral Dissolution Behaviour in the Presence of Organic Acids: A Review. *Miner. Eng.* **2017**, *100*, 115–123. [\[CrossRef\]](#)
93. Ghorbani, Y.; Montenegro, M.R. Leaching Behaviour and the Solution Consumption of Uranium–Vanadium Ore in Alkali Carbonate–Bicarbonate Column Leaching. *Hydrometallurgy* **2016**, *161*, 127–137. [\[CrossRef\]](#)
94. Jana, A.; Unni, A.; Ravuru, S.S.; Das, A.; Das, D.; Biswas, S.; Sheshadri, H.; De, S. In-Situ Polymerization into the Basal Spacing of LDH for Selective and Enhanced Uranium Adsorption: A Case Study with Real Life Uranium Alkaline Leach Liquor. *Chem. Eng. J.* **2022**, *428*, 131180. [\[CrossRef\]](#)
95. Osiensky, J.L.; Williams, R.E. Factors Affecting Efficient Aquifer Restoration at In Situ Uranium Mine Sites. *Groundw. Monit. Remediat.* **1990**, *10*, 107–112. [\[CrossRef\]](#)
96. Cecal, A.; Humelnicu, D.; Popa, K.; Rudic, V.; Gulea, A.; Palamaru, I.; Nemtoi, G. Bioleaching of UO₂²⁺ Ions from Poor Uranium Ores by Means of Cyanobacteria. *J. Radioanal. Nucl. Chem.* **2000**, *245*, 427–429. [\[CrossRef\]](#)
97. Caldeira, C.L.; Ciminelli, V.S.T.; Osseo-Asare, K. The Role of Carbonate Ions in Pyrite Oxidation in Aqueous Systems. *Geochim. Cosmochim. Acta* **2010**, *74*, 1777–1789. [\[CrossRef\]](#)
98. Yang, Y.; Zuo, J.; Qiu, W.; Wu, J.; Que, W.; Zhou, G.; Liu, Z.; Wu, J. Assessment of the Greenhouse Gas Footprint and Environmental Impact of CO₂ and O₂ In Situ Uranium Leaching. *Acta Geol. Sin.-Engl. Ed.* **2023**, *97*, 986–994. [\[CrossRef\]](#)
99. Qiu, W.; Yang, Y.; Song, J.; Que, W.; Liu, Z.; Weng, H.; Wu, J.; Wu, J. What Chemical Reaction Dominates the CO₂ and O₂ In-Situ Uranium Leaching? Insights from a Three-Dimensional Multicomponent Reactive Transport Model at the Field Scale. *Appl. Geochem.* **2023**, *148*, 105522. [\[CrossRef\]](#)
100. Kim, S.; Yoon, H.; Min, T.; Han, B.; Lim, S.; Park, J. Carbon Dioxide Utilization in Lithium Carbonate Precipitation: A Short Review. *Environ. Eng. Res.* **2023**, *29*, 230553. [\[CrossRef\]](#)
101. Lu, C.; Xiu, W.; Guo, H.; Lian, G.; Yang, B.; Zhang, T.; Bi, E.; Shi, Z. Multi-Isotope Based Identification and Quantification of Oxygen Consuming Processes in Uranium Hosting Aquifers with CO₂ + O₂ In Situ Leaching. *Water Resour. Res.* **2023**, *59*, e2022WR033980. [\[CrossRef\]](#)

102. Wang, Q.; Liang, X.; Wang, W.; Niu, Q.; Zhuo, J.; Su, X.; Zhou, G.; Zhao, L.; Li, P.; Yuan, W.; et al. Mineral Composition and Full-Scale Pore Structure of Qianjiadian Sandstone-Type Uranium Deposits: Application for In Situ Leaching Mining. *Geofluids* **2022**, *2022*, 2860737. [[CrossRef](#)]
103. Dong, W.; Brooks, S.C. Determination of the Formation Constants of Ternary Complexes of Uranyl and Carbonate with Alkaline Earth Metals (Mg_{2+} , Ca_{2+} , Sr_{2+} , and Ba_{2+}) Using Anion Exchange Method. *Environ. Sci. Technol.* **2006**, *40*, 4689–4695. [[CrossRef](#)] [[PubMed](#)]
104. Liu, Y.; Iglauer, S.; Cai, J.; Amooie, M.A.; Qin, C. Local Instabilities during Capillary-Dominated Immiscible Displacement in Porous Media. *Capillarity* **2019**, *2*, 1–7. [[CrossRef](#)]
105. Yao, J.; Oakey, J. Geometrically-Mediated Snap-off of Water-in-Oil Emulsion Droplets in Microfluidic Flow Focusing Devices. *J. Oil Gas Petrochem. Sci.* **2018**, *1*, 42–46. [[CrossRef](#)] [[PubMed](#)]
106. Li, G.; Yao, J. Snap-Off during Imbibition in Porous Media: Mechanisms, Influencing Factors, and Impacts. *Eng* **2023**, *4*, 2896–2925. [[CrossRef](#)]
107. Kanakiya, S.; Adam, L.; Esteban, L.; Rowe, M.C.; Shane, P. Dissolution and Secondary Mineral Precipitation in Basalts Due to Reactions with Carbonic Acid. *J. Geophys. Res. Solid Earth* **2017**, *122*, 4312–4327. [[CrossRef](#)]
108. Kaszuba, J.; Yardley, B.; Andreani, M. Experimental Perspectives of Mineral Dissolution and Precipitation Due to Carbon Dioxide-Water-Rock Interactions. *Rev. Miner. Geochem.* **2013**, *77*, 153–188. [[CrossRef](#)]
109. Chen, S.; Wei, X.; Liu, J.; Sun, Z.; Chen, G.; Yang, M.; Liu, Y.; Wang, D.; Ma, C.; Kong, D. Weak Acid Leaching of Uranium Ore from a High Carbonate Uranium Deposit. *J. Radioanal. Nucl. Chem.* **2022**, *331*, 2583–2596. [[CrossRef](#)]
110. Rawlings, D.E.; Johnson, D.B. The Microbiology of Biomineralization: Development and Optimization of Mineral-Oxidizing Microbial Consortia. *Microbiology* **2007**, *153*, 315–324. [[CrossRef](#)]
111. Laurent, G.; Izart, C.; Lechenard, B.; Golfier, F.; Marion, P.; Collon, P.; Truche, L.; Royer, J.-J.; Filippov, L. Numerical Modelling of Column Experiments to Investigate In-Situ Bioleaching as an Alternative Mining Technology. *Hydrometallurgy* **2019**, *188*, 272–290. [[CrossRef](#)]
112. Ram, R.; Charalambous, F.; Tardio, J.; Bhargava, A.H.S. Investigation of the Dissolution Kinetics of Synthetic Uraninite (UO_2/UO_2^{2+}). In Proceedings of the Conference: Engineering Our Future: Are We up to the Challenge? (Chemeca 2009), Burswood, Australia, 27–30 September 2009; Engineers Australia: Barton, ACT, Australia, 2009.
113. Janzen, M.P.; Nicholson, R.V.; Scharer, J.M. Pyrrhotite Reaction Kinetics: Reaction Rates for Oxidation by Oxygen, Ferric Iron, and for Nonoxidative Dissolution. *Geochim. Cosmochim. Acta* **2000**, *64*, 1511–1522. [[CrossRef](#)]
114. Meruane, G.; Vargas, T. Bacterial Oxidation of Ferrous Iron by Acidithiobacillus Ferrooxidans in the PH Range 2.5–7.0. *Hydrometallurgy* **2003**, *71*, 149–158. [[CrossRef](#)]
115. Li, J.; Zhang, Y. Remediation Technology for the Uranium Contaminated Environment: A Review. *Procedia Environ. Sci.* **2012**, *13*, 1609–1615. [[CrossRef](#)]
116. Banala, U.K.; Das, N.P.I.; Toleti, S.R. Microbial Interactions with Uranium: Towards an Effective Bioremediation Approach. *Environ. Technol. Innov.* **2021**, *21*, 101254. [[CrossRef](#)]
117. Chung, A.P.; Sousa, T.; Pereira, A.; Morais, P.V. Microorganisms—Tools for Bioremediation of Uranium Contaminated Environments. *Procedia Earth Planet. Sci.* **2014**, *8*, 53–58. [[CrossRef](#)]
118. Yu, Q.; Cui, O. Enrichment and Remediation of Uranium by Microorganisms: A Review. *Open J. Environ. Biol.* **2023**, *8*, 20–38. [[CrossRef](#)]
119. Liu, Z.; Tan, K.; Li, C.; Li, Y.; Zhang, C.; Song, J.; Liu, L. Geochemical and S Isotopic Studies of Pollutant Evolution in Groundwater after Acid In Situ Leaching in A Uranium Mine Area in Xinjiang. *Nucl. Eng. Technol.* **2023**, *55*, 1476–1484. [[CrossRef](#)]
120. Yang, Y.; Ram, R.; McMaster, S.A.; Pownceby, M.I.; Chen, M. A Comparative Bio-Oxidative Leaching Study of Synthetic U-Bearing Minerals: Implications for Mobility and Retention. *J. Hazard. Mater.* **2021**, *403*, 123914. [[CrossRef](#)]
121. Zeng, S.; Song, J.; Sun, B.; Wang, F.; Ye, W.; Shen, Y.; Li, H. Seepage Characteristics of the Leaching Solution during In Situ Leaching of Uranium. *Nucl. Eng. Technol.* **2023**, *55*, 566–574. [[CrossRef](#)]
122. Yin, S.; Yang, X.; Chen, W.; Wang, L.; Chen, X. Permeability Characteristics of Sandstone-Type Uranium Deposits under Different Temperature and Confining Pressure. *J. Cent. South Univ.* **2023**, *30*, 2302–2312. [[CrossRef](#)]
123. Wang, W.; Liang, X.; Niu, Q.; Wang, Q.; Zhuo, J.; Su, X.; Zhou, G.; Zhao, L.; Yuan, W.; Chang, J.; et al. Reformability Evaluation of Blasting-Enhanced Permeability in In Situ Leaching Mining of Low-Permeability Sandstone-Type Uranium Deposits. *Nucl. Eng. Technol.* **2023**, *55*, 2773–2784. [[CrossRef](#)]
124. De Silva, V.R.S.; Ranjith, P.G.; Perera, M.S.A.; Wu, B.; Wanniarachchi, W.A.M. A Low Energy Rock Fragmentation Technique for In-Situ Leaching. *J. Clean. Prod.* **2018**, *204*, 586–606. [[CrossRef](#)]
125. Yuan, W.; Wang, W.; Su, X.; Wen, L.; Chang, J. Experimental and Numerical Study on the Effect of Water-Decoupling Charge Structure on the Attenuation of Blasting Stress. *Int. J. Rock Mech. Min. Sci.* **2019**, *124*, 104133. [[CrossRef](#)]
126. Liu, Y.; Huang, L.; He, G.; Hu, N.; Zhou, S.; Yu, Q.; Ding, D. Damage and Stability Analysis of Sandstone-Type Uranium Ore Body under Physical and Chemical Action of Leaching Solution. *Arch. Min. Sci.* **2023**, *68*, 409–423. [[CrossRef](#)]
127. Yuan, B.; Xu, C.; Wang, K.; Zhang, W.; Moghanloo, R.G.; Sun, X.; Wang, Y.; Zhou, T. Enhance Horizontal Well Performance by Optimising Multistage Hydraulic Fracture and Water Flooding. *Int. J. Oil Gas Coal Technol.* **2017**, *15*, 25–46. [[CrossRef](#)]
128. Yuan, B.; Wood, D.A.; Yu, W. Stimulation and Hydraulic Fracturing Technology in Natural Gas Reservoirs: Theory and Case Studies (2012–2015). *J. Nat. Gas Sci. Eng.* **2015**, *26*, 1414–1421. [[CrossRef](#)]

129. Yang, J.; Tan, K.; Huang, X. Evaluation and Analysis of Geological Condition of In-Situ Fragmentation Leaching Uranium. *China Nucl. Sci. Technol. Rep.* **2003**, *2*, 157–172.
130. Himanshu, V.K.; Mishra, A.K.; Roy, M.P.; Singh, P.K. Overview of Underground Metalliferous Mining. In *Blasting Technology for Underground Hard Rock Mining*; Springer Nature: Singapore, 2023; pp. 9–24.
131. Cai, Z.; Li, X.; Lei, B.; Yuan, J.; Hong, C.; Wang, H. Laboratory Experimental Laws for the Radon Exhalation of Similar Uranium Samples with Low-Frequency Vibrations. *Sustainability* **2018**, *10*, 2937. [\[CrossRef\]](#)
132. Debashish, M.; Rajesh, K. Advanced Vibration Management to Improve Productivity and Optimize Cost for Excavation of Iron Ore: A Case Study. In Proceedings of the Conference on Recent Advances in Rock Engineering (RARE 2016), Bengaluru, India, 16–18 November 2016; Atlantis Press: Paris, France, 2016.
133. Niu, Q.; Hu, M.; He, J.; Zhang, B.; Su, X.; Zhao, L.; Pan, J.; Wang, Z.; Du, Z.; Wei, Y. The Chemical Damage of Sandstone after Sulfuric Acid-Rock Reactions with Different Duration Times and Its Influence on the Impact Mechanical Behaviour. *Heliyon* **2023**, *9*, e22346. [\[CrossRef\]](#)
134. Yun, M.; Yu, B.; Cai, J. Analysis of Seepage Characters in Fractal Porous Media. *Int. J. Heat Mass Transf.* **2009**, *52*, 3272–3278. [\[CrossRef\]](#)
135. Qu, Z.; Yao, J.; Yang, Y.; Wang, B.; He, L. Laboratory Experiments of a Microfluidic Model for Imbibition. *J. Petrochem. Univ.* **2014**, *37*, 64–66.
136. Yao, J. Microfluidic Studies on Snap-Off during Imbibition Process. Master Thesis, China University of Petroleum (East China), Qingdao, China, 2014.
137. Yao, J. A Microfluidic Model for Visualizing Snap-Off During Imbibition. Ph.D. Dissertation, University of Wyoming, Laramie, WY, USA, 2017.
138. Yao, J. Microfluidic Studies of Geometrically-Mediated Snap-Off. Master Thesis, University of Wyoming, Laramie, WY, USA, 2014.
139. Roy, M.P.; Himanshu, V.K.; Kaushik, A.P.; Singh, P.K. Influence of Ring Blasting Pattern on the Safety of Nearby Underground Structures. *Sādhanā* **2022**, *47*, 192. [\[CrossRef\]](#)
140. Zhang, Z.-X.; Sanchidrián, J.A.; Ouchterlony, F.; Luukkanen, S. Reduction of Fragment Size from Mining to Mineral Processing: A Review. *Rock Mech. Rock. Eng.* **2023**, *56*, 747–778. [\[CrossRef\]](#)
141. Vennes, I.; Mitri, H.; Chinnasane, D.R.; Yao, M. Effect of Stress Anisotropy on the Efficiency of Large-Scale Destress Blasting. *Rock Mech. Rock. Eng.* **2021**, *54*, 31–46. [\[CrossRef\]](#)
142. Kan, J.; Dou, L.; Li, J.; Li, X.; Bai, J.; Wang, M. Characteristics of Microseismic Waveforms Induced by Underground Destress Blasting: Comparison with Those Induced by Ground Blasting and Coal Mining. *Front. Earth Sci.* **2022**, *10*, 797358. [\[CrossRef\]](#)
143. Ye, Z.; Chen, M. Characteristics of Peak Load on a Borehole Wall in Water-Coupling Blasting. *J. Eng. Mech.* **2023**, *149*, 04022087. [\[CrossRef\]](#)
144. Huo, X.; Qiu, X.; Shi, X.; Chen, H.; Gou, Y.; Yu, Z. Experimental and Numerical Investigation on the Peak Value and Loading Rate of Borehole Wall Pressure in Decoupled Charge Blasting. *Int. J. Rock Mech. Min. Sci.* **2023**, *170*, 105535. [\[CrossRef\]](#)
145. Johnson, R.H.; Paradis, C.J.; Kent, R.D.; Tigar, A.D.; Reimus, P.W. Single-Well Push–Pull Tracer Test Analyses to Determine Aquifer Reactive Transport Parameters at a Former Uranium Mill Site (Grand Junction, Colorado). *Minerals* **2023**, *13*, 228. [\[CrossRef\]](#)
146. Cheng, Y.; Arora, B.; Şengör, S.S.; Druhan, J.L.; Wanner, C.; van Breukelen, B.M.; Steefel, C.I. Microbially Mediated Kinetic Sulfur Isotope Fractionation: Reactive Transport Modeling Benchmark. *Comput. Geosci.* **2021**, *25*, 1379–1391. [\[CrossRef\]](#)
147. Deng, H.; Navarre-Sitchler, A.; Heil, E.; Peters, C. Addressing Water and Energy Challenges with Reactive Transport Modeling. *Environ. Eng. Sci.* **2021**, *38*, 109–114. [\[CrossRef\]](#)
148. Schabernack, J.; Fischer, C. Improved Kinetics for Mineral Dissolution Reactions in Pore-Scale Reactive Transport Modeling. *Geochim. Cosmochim. Acta* **2022**, *334*, 99–118. [\[CrossRef\]](#)
149. Chen, J.; Dai, Z.; Yang, Z.; Pan, Y.; Zhang, X.; Wu, J.; Reza Soltanian, M. An Improved Tandem Neural Network Architecture for Inverse Modeling of Multicomponent Reactive Transport in Porous Media. *Water Resour. Res.* **2021**, *57*, e2021WR030595. [\[CrossRef\]](#)
150. Xiong, Y.; Hou, Z.; Tan, X.; Luo, J.; Yue, Y.; Wu, K. Constraining Fluid-Rock Interactions during Eogenetic Karst and Their Impacts on Carbonate Reservoirs: Insights from Reactive Transport Modeling. *Appl. Geochem.* **2021**, *131*, 105050. [\[CrossRef\]](#)
151. Harrison, A.L.; Tutolo, B.M.; DePaolo, D.J. The Role of Reactive Transport Modeling in Geologic Carbon Storage. *Elements* **2019**, *15*, 93–98. [\[CrossRef\]](#)
152. Parkhurst, D.L.; Wissmeier, L. PhreeqcRM: A Reaction Module for Transport Simulators Based on the Geochemical Model PHREEQC. *Adv. Water Resour.* **2015**, *83*, 176–189. [\[CrossRef\]](#)
153. Kempka, T.; Steding, S.; Kühn, M. Verification of TRANSPORT Simulation Environment Coupling with PHREEQC for Reactive Transport Modelling. *Adv. Geosci.* **2022**, *58*, 19–29. [\[CrossRef\]](#)
154. Prommer, H.; Barry, D.A.; Zheng, C. MODFLOW/MT3DMS-Based Reactive Multicomponent Transport Modeling. *Groundwater* **2003**, *41*, 247–257. [\[CrossRef\]](#)
155. Xu, T.; Spycher, N.; Sonnenthal, E.; Zhang, G.; Zheng, L.; Pruess, K. TOUGHREACT Version 2.0: A Simulator for Subsurface Reactive Transport under Non-Isothermal Multiphase Flow Conditions. *Comput. Geosci.* **2011**, *37*, 763–774. [\[CrossRef\]](#)
156. Kim, B.-J.; Ko, M.-S. Two-Dimensional Reactive Transport Model as a New Approach for Identifying the Origins and Contribution of Arsenic in a Soil and Water System. *Sci. Total Environ.* **2023**, *898*, 165468. [\[CrossRef\]](#) [\[PubMed\]](#)

157. Ladeira, A.C.Q.; Morais, C.A. Uranium Recovery from Industrial Effluent by Ion Exchange—Column Experiments. *Miner. Eng.* **2005**, *18*, 1337–1340. [CrossRef]
158. Dangelmayr, M.A.; Reimus, P.W.; Wasserman, N.L.; Punsal, J.J.; Johnson, R.H.; Clay, J.T.; Stone, J.J. Laboratory Column Experiments and Transport Modeling to Evaluate Retardation of Uranium in an Aquifer Downgradient of a Uranium In-Situ Recovery Site. *Appl. Geochem.* **2017**, *80*, 1–13. [CrossRef]
159. Lagneau, V.; Regnault, O.; Descostes, M. Industrial Deployment of Reactive Transport Simulation: An Application to Uranium In Situ Recovery. *Rev. Miner. Geochem.* **2019**, *85*, 499–528. [CrossRef]
160. Lagneau, V.; van der Lee, J. HYTEC Results of the MoMas Reactive Transport Benchmark. *Comput. Geosci.* **2010**, *14*, 435–449. [CrossRef]
161. van der Lee, J.; De Windt, L.; Lagneau, V.; Goblet, P. Module-Oriented Modeling of Reactive Transport with HYTEC. *Comput. Geosci.* **2003**, *29*, 265–275. [CrossRef]
162. Chen, M.; Jiang, Z.; Feng, G.; Chen, M.; Du, Z. Improving the Efficiency of In Situ Uranium Leaching (Remediation) with Periodic Injection and Extraction: Insight from Reactive Transport Modeling and Field Test. *J. Hydrol.* **2024**, *630*, 130767. [CrossRef]
163. Sprocati, R.; Rolle, M. Integrating Process-Based Reactive Transport Modeling and Machine Learning for Electrokinetic Remediation of Contaminated Groundwater. *Water Resour. Res.* **2021**, *57*, e2021WR029959. [CrossRef]
164. Noskov, M.; Istomin, A.; Kesler, A.; Cheglov, A. Innovative Intellectual Management Technology of Uranium Mining by the ISL Method. In Proceedings of the International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (URAM-2018), Vienna, Austria, 25–29 June 2018; International Atomic Energy Agency: Vienna, Austria, 2018; p. 157.
165. Karami, E.; Kuhar, L.; Bona, A.; Nikoloski, A.N. A Review of Electrokinetic, Ultrasonic and Solution Pulsing Methods for Mass Transfer Enhancement in In-Situ Processing. *Miner. Eng.* **2021**, *170*, 107029. [CrossRef]
166. Denison Mines Corp. Denison Announces Successful Completion of Recovered Solution Management Phase of Phoenix ISR Feasibility Field Test. Available online: <https://www.prnewswire.com/news-releases/denison-announces-successful-completion-of-recovered-solution-management-phase-of-phoenix-isr-feasibility-field-test-301975387.html> (accessed on 2 November 2023).
167. World Nuclear News History-in-the-Making for Canadian Uranium Mining. Available online: <https://world-nuclear-news.org/Articles/History-in-the-making-for-Canadian-uranium-mining> (accessed on 18 October 2022).
168. Dolchinkov, N.T. Development of Uranium Mining and Uranium Processing in the Russian Federation. *Sci. Bus. Soc.* **2019**, *4*, 108–114.
169. Dooley, J.R.; Harshman, E.N.; Rosholt, J.N. Uranium-Lead Ages of the Uranium Deposits of the Gas Hills and Shirley Basin, Wyoming. *Econ. Geol.* **1974**, *69*, 527–531. [CrossRef]
170. Asnani, C.K. Development of Alkali Leaching Technology: Key to Self-Sufficiency in Uranium Production in India. In Proceedings of the URAM-2018: International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (1), Vienna, Austria, 25–29 June 2018; International Atomic Energy Agency (IAEA): Vienna, Austria, 2018; p. IAEACN261.
171. Roberto, F.F.; Schippers, A. Progress in Bioleaching: Part B, Applications of Microbial Processes by the Minerals Industries. *Appl. Microbiol. Biotechnol.* **2022**, *106*, 5913–5928. [CrossRef] [PubMed]
172. Bampton, K.F.; Haines, J.B.; Randell, M.H. Geology of the Honeymoon Uranium Project. *AusIMM Proc.* **2001**, *306*, 17–27.
173. Abiru, T. The Tokyo-Moscow-Astana Triangle: Strategic Partnership in Nuclear Energy Is Inevitable. *Secur. Index A Russ. J. Int. Secur.* **2008**, *14*, 117–122. [CrossRef]
174. Zine, H.; El Mansour, A.; Hakkou, R.; Papazoglou, E.G.; Benzaazoua, M. Advancements in Mine Closure and Ecological Reclamation: A Comprehensive Bibliometric Overview (1980–2023). *Mining* **2023**, *3*, 798–813. [CrossRef]
175. Yin, M.; Sun, J.; He, H.; Liu, J.; Zhong, Q.; Zeng, Q.; Huang, X.; Wang, J.; Wu, Y.; Chen, D. Uranium Re-Adsorption on Uranium Mill Tailings and Environmental Implications. *J. Hazard. Mater.* **2021**, *416*, 126153. [CrossRef]
176. Seigneur, N.; De Windt, L.; Déjeant, A.; Lagneau, V.; Descostes, M. Long-Term Evolution of Uranium Mobility within Sulfated Mill Tailings in Arid Regions: A Reactive Transport Study. *Minerals* **2021**, *11*, 1201. [CrossRef]
177. Hamza, M.F.; El-Aassy, I.E.; Guibal, E. Integrated Treatment of Tailing Material for the Selective Recovery of Uranium, Rare Earth Elements and Heavy Metals. *Miner. Eng.* **2019**, *133*, 138–148. [CrossRef]
178. Reynier, N.; Gagné-Turcotte, R.; Coudert, L.; Costis, S.; Cameron, R.; Blais, J.-F. Bioleaching of Uranium Tailings as Secondary Sources for Rare Earth Elements Production. *Minerals* **2021**, *11*, 302. [CrossRef]
179. Zhang, Z.-X.; Hou, D.-F.; Aladejare, A.; Ozoji, T.; Qiao, Y. World Mineral Loss and Possibility to Increase Ore Recovery Ratio in Mining Production. *Int. J. Min. Reclam. Environ.* **2021**, *35*, 670–691. [CrossRef]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.



The biogeochemistry and bioremediation of uranium and other priority radionuclides



Laura Newsome^{*}, Katherine Morris, Jonathan R. Lloyd

Research Centre for Radwaste and Decommissioning and Williamson Research Centre for Molecular Environmental Science, School of Earth, Atmospheric and Environmental Sciences, University of Manchester, Manchester M13 9PL, UK

ARTICLE INFO

Article history:

Received 20 June 2013

Received in revised form 29 October 2013

Accepted 29 October 2013

Available online 6 November 2013

Editor: J. Fein

Keywords:

Biostimulation

Microorganisms

Metal reduction

Electron transport

In situ

Nuclear

ABSTRACT

Microbial metabolism has the potential to alter the solubility of a broad range of priority radionuclides, including uranium, other actinides and fission products. Of notable interest has been the biostimulation of anaerobic microbial communities to remove redox-sensitive radionuclides such as uranium U(VI) from contaminated groundwaters at nuclear sites. Particularly promising are bioreduction processes, whereby bacteria enzymatically reduce aqueous U(VI) to insoluble U(IV) coupled to oxidation of an organic electron donor; and uranium phosphate biomineralisation, in which bacterial phosphatase activity cleaves organophosphates, liberating inorganic phosphate that precipitates with aqueous U(VI) as uranyl phosphate minerals. Here we review the mechanisms of uranium bioreduction and phosphate biomineralisation and their suitability to facilitate long-term precipitation of uranium from groundwater, with particular focus on in situ trials at the US Department of Energy field sites. Redox interactions of other priority radionuclides (technetium, neptunium, plutonium, americium, iodine, strontium and caesium) are also reviewed.

© 2013 The Authors. Published by Elsevier B.V. Open access under [CC BY license](https://creativecommons.org/licenses/by/4.0/).

Contents

1. Introduction	165
2. Microbe–radionuclide interactions	165
2.1. Bioreduction	166
2.2. Biomineralisation	167
2.3. Bioaccumulation	167
2.4. Biosorption	167
3. Uranium bioreduction	167
3.1. Early work & mechanisms	167
3.1.1. Cytochromes	168
3.1.2. Nanowires	168
3.1.3. Extracellular electron carriers	168
3.2. Mineralogical endpoints of bioreduction	168
3.3. Field studies	169
3.3.1. US DOE Rifle site, Colorado	170
3.3.2. US DOE Oak Ridge site, Tennessee	172
3.3.3. US DOE Hanford site, Washington	173
3.4. Stability of bioreduced U(IV) and reoxidation	173
3.4.1. Reoxidation by exposure to oxygen	173
3.4.2. Reoxidation by exposure to nitrate	174
4. Uranium phosphate biomineralisation	174
4.1. Early work & mechanisms	174
4.2. Mineralogical endpoints	175

^{*} Corresponding author.

E-mail address: laura.newsome@postgrad.manchester.ac.uk (L. Newsome).

4.3.	Demonstration at the US DOE Oak Ridge site, Tennessee	175
4.4.	Limitations	176
5.	Other priority radionuclides	176
5.1.	Technetium	176
5.1.1.	Early work & mechanisms	176
5.1.2.	Reduction and reoxidation studies	176
5.2.	Neptunium	177
5.3.	Plutonium	177
5.4.	Americium	177
5.5.	Iodine	178
5.6.	Strontium and caesium	178
6.	Conclusions and future directions	178
	Acknowledgements	178
	References	179

1. Introduction

Decades of nuclear activities have left a legacy of environmental contamination. Elevated concentrations of uranium and other radionuclides are present in mining and milling areas, at sites where uranium ore was processed, and where uranium was enriched. This contamination potentially represents an uncontrolled source of radiation, and therefore regulatory bodies may require it to be remediated to acceptable levels.

The mobility of uranium in the environment depends on its speciation and redox state (Fig. 1). It is present as mobile U(VI) in oxidising conditions, predominantly as the uranyl ion (UO_2^{2+}) or hydroxyl complexes below $\sim\text{pH}$ 6.5, or as uranyl carbonate complexes at higher pH

(Choppin et al., 2002). In the absence of carbonate, the uranyl ion and its complexes sorb strongly onto the surface of iron oxides and organics (Hsi and Langmuir, 1985; Andersson et al., 2001; Koch-Steindl and Pröhl, 2001) and onto the edge sites of clay minerals (Pabalan et al., 1998; Davis et al., 2004). Sorption decreases in the presence of complexing ligands such as humic and fulvic acids, and in the presence of competing cations such as Ca^{2+} and Mg^{2+} (Siegal and Bryan, 2003). Under reducing conditions, relatively insoluble and immobile U(IV) predominates, typically as the mineral uraninite, but recently a different, non-uraninite U(IV) phase has been reported (Bernier-Latmani et al., 2010; Bargar et al., 2013). U(V) is generally considered to be transient although evidence is emerging to suggest that it might be stable for periods of weeks under certain conditions (Docrat et al., 1999; Behrends et al., 2012; Ilton et al., 2012). Depleted uranium metal, used in anti-tank penetrators and present in the environment as a legacy of military activities, is relatively immobile, but may be oxidised to uraninite and consequently U(VI) depending on the redox conditions (UNEP, 2003; Parrish et al., 2008; Handley-Sidhu et al., 2010).

Biogeochemical interactions play a key role in controlling the speciation and mobility of uranium and other redox sensitive radionuclides (such as Tc, Np and Pu), through direct metabolic processes such as microbial respiration, or indirectly by changing ambient redox/pH conditions, producing ligands or new biominerals, or altering mineral surfaces. In addition to controlling radionuclide mobility via “natural attenuation”, these biogeochemical processes can be stimulated to accelerate clean-up of contaminated environments through bioremediation. This review focuses on microbe–radionuclide interactions, how they may control radionuclide (especially uranium) mobility in natural environments, and how they can be applied to bioremediate legacy metal and radionuclide contamination.

2. Microbe–radionuclide interactions

Microbial interactions with uranium and other radionuclides have been documented extensively e.g. Gorby and Lovley (1992), Lloyd and Gadd (2011), Lloyd and Macaskie (2000), Lloyd and Renshaw (2005), Lovley et al. (1991) and Merroun and Selenska-Pobell (2008). Most study the interactions between uranium and bacteria; these are the focus of this review. There is emerging interest in the use of microbial “bioleaching” mechanisms to extract uranium from low grade ores e.g. Choi et al. (2005) and Qiu et al. (2011), although these are not covered further in this review. Preventing uncontrolled dispersion and transport of radionuclides in groundwater is the overarching remediation goal at many nuclear sites. Stimulating bacterial interactions to fix aqueous uranium into insoluble minerals in situ may provide a relatively inexpensive and non-intrusive solution to remediating radionuclide contamination. The mechanisms of the different microbe–uranium interactions are illustrated in Fig. 2 and discussed below, along with their suitability to facilitate long-term uranium removal.

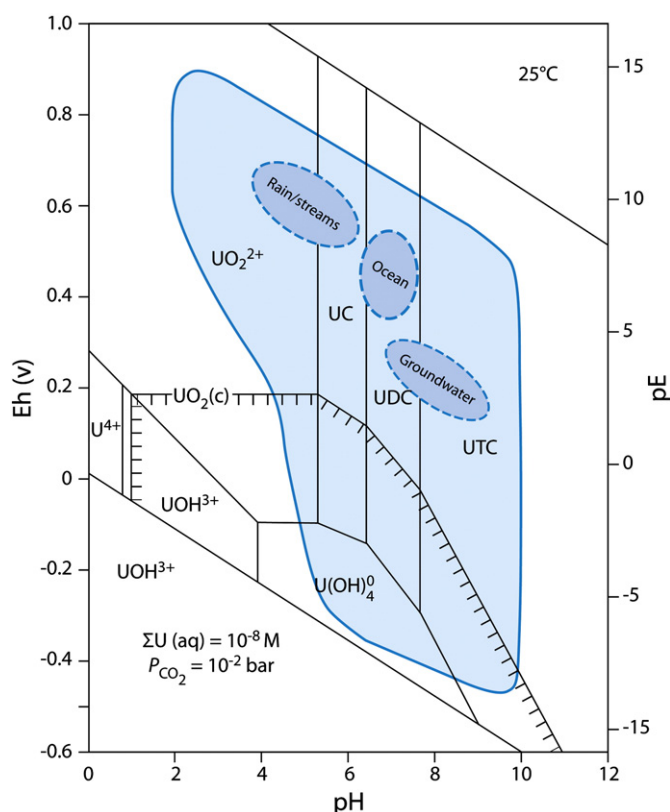


Fig. 1. Eh–pH diagram for aqueous species in the U–O₂–CO₂–H₂O system in pure water at 25 °C and 1 bar total pressure for $\Sigma\text{U} = 10^{-8}$ M and a typical groundwater CO₂ pressure of $\text{P}_{\text{CO}_2} = 10^{-2.0}$ bar, after Langmuir (1997). UC, UDC and UTC represent the aqueous complexes UO_2CO_3 , $\text{UO}_2(\text{CO}_3)_2^{2-}$ and $\text{UO}_2(\text{CO}_3)_3^{3-}$. The position of the $\text{UO}_2(\text{c})$ solid solution boundary for $\Sigma\text{U} = 10^{-8}$ M is stippled. The blue area represents the range of conditions of common natural waters, after Ewing (2010).

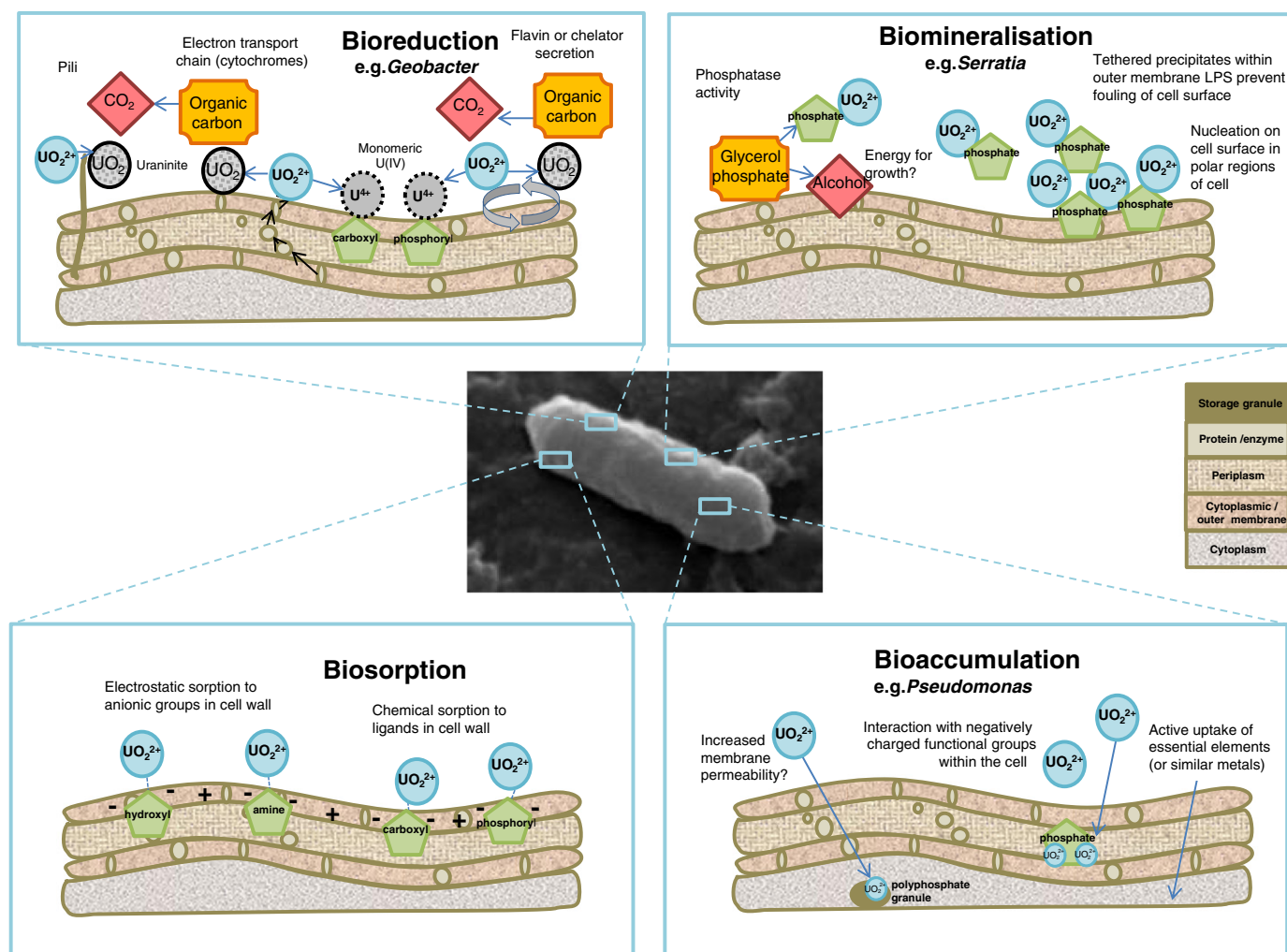


Fig. 2. Schematic illustrating the mechanisms of microbe–uranium interactions. Examples of recent or key references for these mechanisms include: bioreduction (Lovley et al., 1991; Bernier-Latmani et al., 2010; Brutinel and Gralnick, 2012; Williams et al., 2012), biom mineralisation (Macaskie et al., 1992, 2000; Beazley et al., 2011), biosorption (Beveridge and Murray, 1980; Gadd, 2009) and bioaccumulation (Choudhary and Sar, 2011).

2.1. Bioreduction

In the absence of oxygen, bacteria are able to respire different electron acceptors to gain energy for metabolism. As anoxia progresses, the most energetically favourable electron acceptors are used in sequence, starting with the reduction of nitrate, then proceeding through Mn(IV), Fe(III) and sulfate, and finally the reduction of carbon dioxide to produce methane. While this sequence is generally correct for the natural environment, it should be noted that under certain situations, such as when organic matter is in abundance, nitrate- and metal-reduction, or metal- and sulfate-reduction could potentially occur concurrently (Madden et al., 2007; Williams et al., 2011). At circumneutral pH, U(VI) has a similar redox couple to Fe(III), and Fe(III)-reducing bacteria are able to respire U(VI) as an alternative electron acceptor, reducing it to insoluble U(IV) (Lovley et al., 1991). Other groups capable of U(VI) reduction include sulfate-reducing bacteria (Lovley and Phillips, 1992a), fermentative bacteria (Francis et al., 1994), acid-tolerant bacteria (Shelobolina et al., 2004) and myxobacteria (Wu et al., 2006); some conserving energy for growth, others with no energy gain (Merroun and Selenska-Pobell, 2008).

Uranium bioreduction has been proposed as a bioremediation technique, stimulated by adding an electron donor to promote enzymatic reduction of aqueous U(VI) to insoluble U(IV). It has been demonstrated in laboratory experiments representative of UK conditions (Wilkins et al., 2007; Begg et al., 2011; Law et al., 2011) and also in situ in the

USA (Istok et al., 2004; Wu et al., 2007; Williams et al., 2011). The speciation of bioreduced uranium is often stated to be uraninite [UO_2] (Lovley and Phillips, 1992a; Suzuki et al., 2002) however; more recently other U(IV) forms have been identified as end-points (Kelly et al., 2008; Bernier-Latmani et al., 2010; Alessi et al., 2012). Most work has focussed on removal of aqueous U(VI) from solution, however, U(VI) may be present in the solid phase or sorbed to minerals. Microbial reduction of poorly soluble U(VI) as uramphite [$(\text{NH}_4)(\text{UO}_2)(\text{PO}_4) \cdot 3\text{H}_2\text{O}$], was demonstrated using *Thermoterrabacterium ferrireducens* (Khijniak et al., 2005) (since reclassified as *Carboxydotherrus ferrireducens* (Slobodkin et al., 2006)), and as metaschoepite [$\text{UO}_3 \cdot 2\text{H}_2\text{O}$] using *Shewanella putrefaciens* CN32 (Fredrickson et al., 2000), while bioreduction of sorbed U(VI) has been shown in natural soils (Begg et al., 2011; Law et al., 2011) and with synthetic and natural iron minerals (Jeon et al., 2004). Abiotic reduction of U(VI) is possible by Fe(II) minerals (Regenspurg et al., 2009; Hyun et al., 2012; Latta et al., 2012; Singer et al., 2012; Fox et al., 2013) and biominerals (O'Loughlin et al., 2010; Veeramani et al., 2011, 2013), however, the majority of studies have suggested that direct enzymatic reduction is the dominant mechanism mediating U(VI) reduction under ambient environmental conditions (Williams et al., 2012; Bargar et al., 2013). Potential concerns associated with the use of bioreduction as a remediation technique stem from whether reduced U(IV) will be stable over long time periods, particularly if the environmental conditions change, for example to oxidising conditions (Senko et al., 2002).

2.2. Biomineralisation

Biomineralisation refers to the process by which metals precipitate with microbially generated ligands such as sulfide or phosphate, or as carbonates or hydroxides in response to localised alkaline conditions at the cell surface. Uranium biomineralisation has been proven using a *Citrobacter* species (Macaskie et al., 1992), since reclassified as a *Serratia* species (Pattanapitpaisal et al., 2002). When supplied with glycerol phosphate, the cell phosphatase activity cleaved the organic phosphate to release inorganic phosphate, which precipitated with U(VI) as extra-cellular hydrogen uranyl phosphate minerals [H₂UO₂PO₄]. This has also been demonstrated using an environmental isolate from the US DOE Oak Ridge site (Beazley et al., 2007), and by a *Pseudomonas* species when supplied with a tributylphosphate donor (Thomas and Macaskie, 1996). Microbial cells that were entirely covered with uranium phosphate minerals have been observed in uraniferous soils, suggesting bacterial biomineralisation was occurring naturally in this system (Mondani et al., 2011).

A simpler approach would be to add inorganic phosphate directly to uranium contaminated groundwater, however, as phosphate is very reactive it is likely to precipitate rapidly with aqueous metals leading to clogging and limiting dispersion into the environment (Wellman et al., 2006). Stimulating bacterial phosphatase activity to liberate phosphate under controlled conditions limits the ingrowth of phosphate to the system to the rate of bacterial hydrolysis of organophosphate, thus avoiding clogging of the injection location with metal phosphate minerals. Furthermore, biomineralisation is often more efficient than chemical precipitation in dilute solutions because the ligands are concentrated near the cell surface, which provide nucleation foci for precipitation (Lloyd and Macaskie, 2000).

A potential problem with biomineralisation is that rapid precipitation of metals around the cell surface could in principle create a barrier to cell metabolism, although this has not been directly observed (Lloyd and Macaskie, 2000). A recent review highlighted the contradiction between some studies which suggest that biomineralisation is a toxicity resistance mechanism, and others in which it is assumed to be detrimental to the cells (Benzerara et al., 2011). From the sparse evidence available, it appears that encrustation does not necessarily limit metabolic activity. In the *Serratia* system, images of the precipitates appear to show uranyl phosphates were deposited on the cell wall on one side of the cell, or 'tethered' within the lipopolysaccharide preventing fouling of the cell surface (Macaskie et al., 2000). Bacteria may cause dissolution of uranyl phosphates such as autunite in phosphate limited systems (Smeaton et al., 2008). Other challenges may come from the cost of the organic phosphate donor, limiting the economic viability of biomineralisation as a bioremediation technique (Roig et al., 1995; Lloyd and Macaskie, 2000). Biominerals can act as nucleation foci for metal deposition; a process referred to as "microbially enhanced chemisorption of heavy metals" or MECHEM (Lloyd and Macaskie, 2000). For example, nickel can be removed from solution via intercalation into hydrogen uranyl phosphate (Bonthron et al., 1996).

2.3. Bioaccumulation

Microbial cells are also able to accumulate a broad range of metal ions via "bioaccumulation" mechanisms. With certain metals, adventitious uptake may occur because the transported metals are similar to essential elements needed for cell functioning, so are actively taken up into the cell. Uranium has no known biological function, and it has been suggested that uranium may be taken up into cells due to increased membrane permeability, caused for example by uranium toxicity (Suzuki and Banfield, 1999). Almost all published observations of intracellular uranium have been of uranyl phosphates in *Pseudomonas* species (Kazy et al., 2009; VanEngelen et al., 2010; Choudhary and Sar, 2011), although one study identified uranium bioaccumulation in an environmental isolate closely related to *Arthrobacter ilicis* (Suzuki and

Banfield, 2004). Although of academic interest, there is scant evidence suggesting bioaccumulation of uranium would be a viable technique for bioremediating contaminated land or water.

2.4. Biosorption

Biosorption describes the passive uptake of uranium to the surface of living or dead microbial cells. Both Gram-positive and Gram-negative bacterial cell envelopes possess an electronegative charge, so are able to attract metal cations which sorb to the surface. Ligands in the cell wall such as carboxyl, amine, hydroxyl, phosphate and sulfhydryl groups bind metals through chemical sorption (Beveridge and Murray, 1980; Lloyd and Macaskie, 2000). Biosorption is perhaps best suited to treating effluents with low to medium metal concentrations because binding to cell walls is faster than uptake into the cell, and it is easier to remove bound metals from a cell surface to regenerate the biosorbent (Schiewer and Volesky, 2000). Dead biomass is often a better biosorbent as the effects of metal toxicity are not important. A review of microbial biosorption capacity found uranium uptake in bacteria ranged from 45 to 615 mg g⁻¹ cell dry weight (Suzuki and Banfield, 1999).

Despite the potential for bacteria to biosorb uranium, it is unlikely to be useful in the context of bioremediation. Problems associated with biosorption are that desorption from cell surfaces can be as rapid as sorption, and other cations compete for binding sites (Schiewer and Volesky, 2000). Cell surfaces can also quickly become saturated, preventing further biosorption. Sorbed material could be re-released to solution when cells die and decompose, although in one study, simulated cell decomposition facilitated the precipitation of uranyl phosphate (Knopp et al., 2003). Furthermore, a critical review of biosorption noted that regardless of the significant amounts of research, there has been almost no industrial application of biosorption (Gadd, 2009). These challenges mean that it is not an adequate long-term solution for in situ bioremediation, although it could be potentially used for treating contaminated effluent in a "pump and treat" scenario.

3. Uranium bioreduction

3.1. Early work & mechanisms

Bacteria capable of completely oxidising organic matter coupled to the reduction of Fe(III) or Mn(IV) were first described by Lovley and Phillips (1988) and Myers and Nealson (1988). An environmental isolate from freshwater sediments (later designated *Geobacter metallireducens*) was able to enzymatically reduce Fe(III) as ferrihydrite gel to magnetite or vivianite while oxidising acetate to CO₂, obtaining energy for growth. When exposed to U(VI), the cells reduced it to a poorly soluble U(IV) phase, and were able to grow in an appropriate medium, until U(VI) became depleted (Lovley et al., 1991). In parallel, another bacterium isolated from freshwater sediments (*Alteromonas putrefaciens* strain MR1, later designated *Shewanella oneidensis* MR1 (Venkateswaran et al., 1999)) was also found to be able to couple growth to the reduction of Mn(IV) and Fe(III) (Myers and Nealson, 1988; Lovley et al., 1989) and U(VI) (Lovley et al., 1991).

A relatively wide diversity of prokaryotes has been shown to enzymatically reduce U(VI) (Williams et al., 2012). As well as *Geobacter* and *Shewanella* species, dissimilatory U(VI) reduction has been identified in the sulfate-reducers *Desulfovibrio desulfuricans* and *Desulfovibrio vulgaris*, which produced the U(IV) mineral uraninite via c-type cytochrome activity (Lovley and Phillips, 1992a, 1992b; Lovley et al., 1993a). Other species identified to enzymatically bioreduce U(VI) include the sulfate-reducer *Desulfosporosinus* (Suzuki et al., 2002, 2003), *Anaeromyxobacter* species (Sanford et al., 2007), *Paenibacillus* (Ahmed et al., 2012a), *C. ferrireducens* (Khijniak et al., 2005), and Gram-positive *Clostridium* species (Francis et al., 1994; Suzuki et al., 2003; Madden et al., 2007) and *Cellulomonas* species (Sani et al., 2002; Sivaswamy et al., 2011). Additional genera listed in a literature review on the subject

include *Deinococcus*, *Desulfomicrobium*, *Desulfotomaculum*, *Pseudomonas*, *Pyrobaculum*, *Salmonella*, *Veillonella*, *Thermoanaerobacter* and *Thermus* (Wall and Krumholz, 2006). Recently it has been recognised that as well as vegetative cells, spores are able to facilitate U(VI) reduction suggesting a microbial pathway for U(VI) reduction in more extreme environments (Junier et al., 2009; Dalla Vecchia et al., 2010). Not all these bacteria can gain sufficient energy for growth from U(VI) respiration. Those which are known to conserve energy using U(VI) as the sole electron acceptor include: *S. oneidensis*, *G. metallireducens*, *G. lovleyi*, *G. sulfurreducens*, *Desulfotomaculum reducens*, *C. ferrireducens* and *Anaeromyxobacter dehalogenans* (Lovley et al., 1991; Tebo and Obratsova, 1998; Khijniak et al., 2005; Wall and Krumholz, 2006; Sanford et al., 2007).

The mechanism by which cells transfer electrons from the electron donor to an electron acceptor such as U(VI) is debated, and it is thought that different mechanisms may exist for different species. For example, the consensus is *Shewanella* species do not necessarily require direct contact with the electron acceptor, while *Geobacter* species do. Although U(VI) can be significantly soluble in certain environmental conditions and therefore may diffuse into direct contact with a cell, bacteria are also capable of transferring electrons to solid electron acceptors such as Fe(III) or sorbed/precipitated U(VI). Therefore bacteria must have evolved mechanisms for transporting electrons from the central metabolism to the outside of the cytoplasmic membrane, the periplasm, the outer membrane (of Gram-negative cells), and potentially extracellularly. These include the use of electron-carriers such as cytochromes or flavins, or through the expression of conductive cell surface appendages such as pili. Indeed, extracellular electron transfer has been observed on the scale of centimetres in marine sediments, in addition to the usual nanometre scale (Nielsen et al., 2010; Pfeffer et al., 2012). The mechanisms of U(VI) bioreduction are not yet fully resolved, especially the significance of the role played by pili and electron shuttles. Reduction of U(VI) to U(IV) requires two electrons to be transferred, however, it has not yet been demonstrated whether bacteria are able to do this directly. One study using *Geobacter sulfurreducens* identified that U(VI) was reduced to the unstable intermediate U(V), which then disproportionated to the end product, U(IV) (Renshaw et al., 2005).

3.1.1. Cytochromes

The c-type cytochromes are essential proteins used by *Geobacter* and *Shewanella* to transfer electrons from the cytoplasmic membrane to the outer membrane (Lovley et al., 1993a; Richter et al., 2012). In *Shewanella*, the association of c-type cytochromes with extracellular polymeric substance containing biogenic uraninite has been demonstrated (Marshall et al., 2006). The cytochrome c_3 was identified as the U(VI) reductase in *Desulfovibrio vulgaris* (Lovley et al., 1993b).

Multiple lines of evidence suggest that c-type cytochromes contribute to U(VI) reduction in *Shewanella*, including observations of changes in cell cytochrome content, experiments with mutants lacking in certain cytochromes, and genomic sequencing (Wall and Krumholz, 2006). Mutant studies with *Shewanella* have found that while cytochromes, quinones and structural proteins are all needed for optimal U(VI) reduction, they are not essential, which indicates multiple pathways for electron transport.

c-Type cytochromes play an important role in U(VI) reduction by *Geobacter sulfurreducens*. Experiments with mutant strains suggest both periplasmic and outer membrane cytochromes are potentially involved. The periplasmic c-type cytochrome PpcA was identified to participate as an intermediary electron carrier during electron transfer from acetate to U(VI) (Lloyd et al., 2003). These results were not replicated by a later study, perhaps due to a modified methodology being used (Shelobolina et al., 2007). Instead, removing outer membrane cytochrome activity was found to have a greater effect on the rate of U(VI) reduction. One periplasmic cytochrome, MacA, was observed to be significant in reducing U(VI). As these outer membrane cytochromes were not able to reduce U(VI) directly, the authors proposed that U(VI)

reduction occurred at the cell surface. Another study with mutant strains of *Geobacter sulfurreducens* found that in order to substantially lower the rate of U(VI) reduction compared to wild type, the genes for the five most abundant c-type cytochromes had to be deleted (Orellana et al., 2013). This suggests that a diverse range of outer surface cytochromes can participate in U(VI) reduction, consistent with results for other extracellular electron acceptors.

Interestingly, recent work suggests that Gram-positive bacteria may use cytochromes to reduce Fe(III) (Carlson et al., 2012; Gavrilov et al., 2012), and this may have relevance to U(VI)- and radionuclide-reduction such as at alkaline pH where Gram-positive bacteria have also been implicated in metal reduction processes (Khijniak et al., 2005; Williamson et al., 2013).

The ability of particular proteins to reduce U(VI) is described as being fortuitous; the evolution of specific U(VI) respiratory pathways is considered unlikely given the low uranium content of natural groundwaters (Lovley, 2011; Cason et al., 2012; Williams et al., 2012). This non-specific protein activity is thought to be widespread in microbial U(VI) reduction, especially as in a similar way to with humic substances, a diverse range of c-type cytochromes are able to transfer electrons to U(VI) in *Geobacter* species.

3.1.2. Nanowires

The ability to express pili (nanowires) and flagella on one side of the cell has been observed in *Geobacter* species (Childers et al., 2002). Flagella are required for mobility, and are suggested to be a more energy efficient method of reaching an electron acceptor compared to, for example, the use of electron shuttles. *Geobacter* pili were found to be highly conductive, and so were proposed to act as a conduit for electrons from the cell to the surface of iron oxides (Reguera et al., 2005). A pili-deficient mutant was unable to reduce Fe(III)-oxides but was able to reduce soluble Fe(III) citrate, highlighting the potential importance of pili in extracellular electron transport in some systems. The c-type cytochrome OmcS, located on the pili of *Geobacter*, is thought to be required to transfer electrons between the cell and Fe(III)-oxides (Leang et al., 2010; Lovley, 2011; Mehta et al., 2005). Similar results occurred with U(VI) and furthermore, U(IV) was observed to precipitate along the pili, preventing periplasmic mineralisation and so preserving cell viability (Cologgi et al., 2011). The rate and extent of U(VI) reduction was greater when pili were expressed. However, these results were not replicated in a later study, with the pili-deficient mutant precipitating only slightly less U(IV) than the wild type strain (Orellana et al., 2013). Electron microscopy imaging of the wild type strains revealed U(IV) was not precipitated along the pili, instead it was mainly located at the outer membrane. Furthermore, a mutant with normal outer surface c-type cytochrome activity which produced low conductivity pili was able to reduce U(VI) at rates only slightly lower than wild type, challenging the importance of electron transfer through pili for U(VI) reduction. The precise mechanism of electron transfer to U(VI) in these systems, especially regarding the involvement of pili, remain hotly debated (Williams et al., 2012).

3.1.3. Extracellular electron carriers

To respire insoluble Fe(III) oxides, *Shewanella* can release chelators to solubilise Fe(III) and/or electron shuttles to mediate extracellular electron transfer (Lovley et al., 2004). Release of flavin mononucleotide and riboflavin by *S. oneidensis* MR-1 is an important process in transferring electrons to poorly soluble Fe(III) oxides (Marsili et al., 2008; von Canstein et al., 2008), with active secretion rather than release through cell lysis the dominant mechanism (Brutinel and Gralnick, 2012). Flavin mononucleotide has also been shown to mediate the reduction of U(VI) to U(IV) by *Shewanella* (Suzuki et al., 2010).

3.2. Mineralogical endpoints of bioreduction

Early uranium bioreduction experiments used X-ray diffraction (XRD) and transmission electron microscopy (TEM) to identify the

black mineral precipitate formed as uraninite $\text{UO}_{2(c)}$ (Lovley and Phillips, 1992a; Abdelouas et al., 1998). Nanometre sized particles of uraninite have been identified using high resolution TEM and X-ray Absorption Spectroscopy (XAS) (Suzuki et al., 2002, 2003; Burgos et al., 2008; Schofield et al., 2008; Jiang et al., 2011). More recently, another form of U(IV) has been identified using XAS (Kelly et al., 2008; Bernier-Latmani et al., 2010; Fletcher et al., 2010; Boyanov et al., 2011; Cologgi et al., 2011; Sharp et al., 2011; Latta et al., 2012). This non-crystalline disordered U(IV) phase, co-ordinated with carboxyl or phosphate ligands is commonly termed “monomeric” U(IV) (Bernier-Latmani et al., 2010). Determining whether U(VI) is reduced to uraninite or monomeric U(IV) is of interest to long-term remediation strategies; both are susceptible to reoxidation but uraninite has been suggested to be less prone to reoxidation due to its crystalline structure. However, a recent study comparing the susceptibility of bio-reduced U(IV) as biogenic uraninite and monomeric U(IV) found little difference in their oxidation rates under controlled experimental conditions (Cerrato et al., 2013). Other U(IV) minerals include coffinite $[\text{USiO}_4 \cdot n\text{H}_2\text{O}]$ and ningyosite $[\text{CaU}(\text{PO}_4)_2 \cdot 2\text{H}_2\text{O}]$; these are less susceptible than uraninite to remobilisation but coffinite has never been identified as the end-product of uranium bio-reduction although ningyosite has occasionally (Khijniak et al., 2005; Lee et al., 2010).

Review of this work indicates that uraninite is produced in experiments using bacterial pure cultures conducted in a simple medium and is precipitated within the periplasm, on the cell surface or extracellularly (Lloyd et al., 2002; Suzuki et al., 2002). Monomeric U(IV) tends to be produced in experiments using bacterial pure cultures in complex media (Bernier-Latmani et al., 2010; Alessi et al., 2012; Cerrato et al., 2013), when phosphate is added (Boyanov et al., 2011), or, under certain conditions, when natural sediments are included (Kelly et al., 2008, 2009; Sharp et al., 2011; Alessi et al., 2012). Ageing of U minerals to more crystalline forms has been observed, such as from monomeric U(IV) to uraninite (Kelly et al., 2009). However, a long-term study using *Thermoanaerobacter* to bio-reduce a mixture of U(VI) and FeOOH found nanocrystals of uraninite present after three months incubation persisted for three to four years suggesting no evidence for ageing and increasing crystallinity (Madden et al., 2012). Furthermore, analysis of in situ sediment columns found no evidence of transformation of monomeric U(IV) to uraninite; similar abundances of monomeric U(IV) and uraninite were observed post-U(VI) bio-reduction and after one year of in-well ageing (Bargar et al., 2013).

Cell wall architecture has been suggested to influence the form of bio-reduced U(IV) as under the same conditions (with no phosphate present), different U(IV) end products were generated by Gram-negative *Anaeromyxobacter* and Gram-positive *Desulfotobacterium* (Boyanov et al., 2011). The authors reason that uranyl carbonate complexes are reduced to U(IV) complexed to carbonate, and that neutral or positively charged uranyl complexes are reduced to free U(IV) which can form uraninite. It was proposed that outer membrane reductases in Gram-negative bacteria allow direct electron transfer to sorbed positive or neutral uranyl complexes, but as these are most likely lacking in Gram-positive bacteria, they perhaps rely on soluble mediators to reduce negatively charged aqueous uranyl carbonate complexes instead. However, in contrast to this theory, direct evidence for cell wall cytochrome participation in Fe(III) reduction was observed using Gram-positive *Thermincola potens* strain JR (Carlson et al., 2012). Furthermore, direct contact between Gram-positive *C. ferrireducens* and ferrihydrite was required for Fe(III)-reduction; no evidence was observed for electron shuttles or chelators, and the use of a cytochrome inhibitor indicated that cytochrome-bc1-complex was pivotal in ferrihydrite reduction (Gavrilov et al., 2012). Further work to elucidate the mechanism(s) of uranium reduction in Gram-positive bacteria is clearly warranted as they appear to be relevant to high pH conditions (Williamson et al., 2013).

3.3. Field studies

In situ bio-reduction of U(VI) in the field (Fig. 3) has been demonstrated successfully at pilot scale e.g. Anderson et al. (2003), Istok et al. (2004), Williams et al. (2011), although maintaining low U(VI) concentrations in groundwater over long periods of time may require a repeated supply of electron donor. Numerous factors determine whether bio-reduction will be successful or not, from the presence of a suitable electron donor, to competition from other processes such as nitrate and sulfate reduction. Environmental conditions will also control the composition of the microbial community and population dynamics (Williams et al., 2012). The long-term stability of the mineral phases formed is crucial to the success of in situ bio-remediation; the more insoluble a mineral is, the less likely it will be remobilised. It is also important to avoid clogging of the injection well and aquifer through biomass growth or excess mineral precipitation, and to consider dilution effects from pumping large volumes of water and electron donor.

While bacteria are generally thought of as being radiotolerant, too high concentrations of U(VI) will have an inhibitory effect, either through radiotoxicity or, more likely for normal isotopic compositions, chemotoxicity. Experiments with enrichment cultures from the Oak Ridge site found that the inhibition co-efficient for U(VI) was around 100 μM ; at this level the effective yield and growth rate were reduced by 50% (Nyman et al., 2007). Note that while this concentration of U(VI) far exceeds the concentrations reported in groundwater in the vicinity of the S3 ponds, of up to 11 μM (Spain and Krumholz, 2011), in other areas of the site concentrations greater than 100 μM have been reported, such as 250 μM in well FW113-47 (Cho et al., 2012).

Bacteria can use a wide range of organic carbon sources as electron donors. Determining which is most efficiently coupled to U(VI) reduction is an important step in tailoring bio-remediation strategies for different sites. Acetate is the most commonly used electron donor in laboratory and field experiments, followed by ethanol and lactate. An alternative approach is to use electrodes to donate electrons for U(VI) reduction (Lovley and Nevin, 2011). Studies comparing electron donors suggest that the most effective donor is specific to an individual site, for example, ethanol was recommended for the Oak Ridge site (Luo et al., 2007) while acetate was for the US DOE Shiprock site (Finneran et al., 2002a). Column experiments using alluvial Rifle sediments found that while a time lag was observed when hydrogen release compounds (HRC) and vegetable oil were used, the extent of U(VI) removal was greater with these donors compared to acetate (Barlett et al., 2012a). Rates of U(VI) reduction in Oak Ridge sediments using ethanol, glucose, methanol and methanol with added humic acids were nearly equivalent when donor concentrations were normalised for equivalent electron donor potential yield (Madden et al., 2009). A column study with Oak Ridge sediments found that acetate and lactate showed similar trends in U(VI) reduction, with comparable amounts removed over approximately one year (Tokunaga et al., 2008). An intermediate electron donor supply rate achieved optimal U(VI) reduction; too low rates were insufficient to stimulate bio-reduction, while soluble uranyl carbonate complexes formed from oxidation of the organic carbon at the lower and higher supply rates of organic carbon supply. Clearly the selection and application of an electron donor needs to be carefully considered on a site-specific basis. Genomic modelling has recently been developed to predict the response of microbial communities to bio-remediation (Williams et al., 2012). The Bottom-Up Genome Scale (BUGS) approach has been used to successfully to predict competition for electron donor between species capable of U(VI) reduction and those unable to reduce U(VI), but able to couple electron donor oxidation to Fe(III) or sulfate reduction (Barlett et al., 2012b; Zhuang et al., 2012). Further development of this model will allow application of bio-remediation to be customised to site-specific microbial communities (Williams et al., 2012).

As well as being able to drive the biotic reoxidation of biogenic U(IV), nitrate also acts as a competing electron acceptor. A number

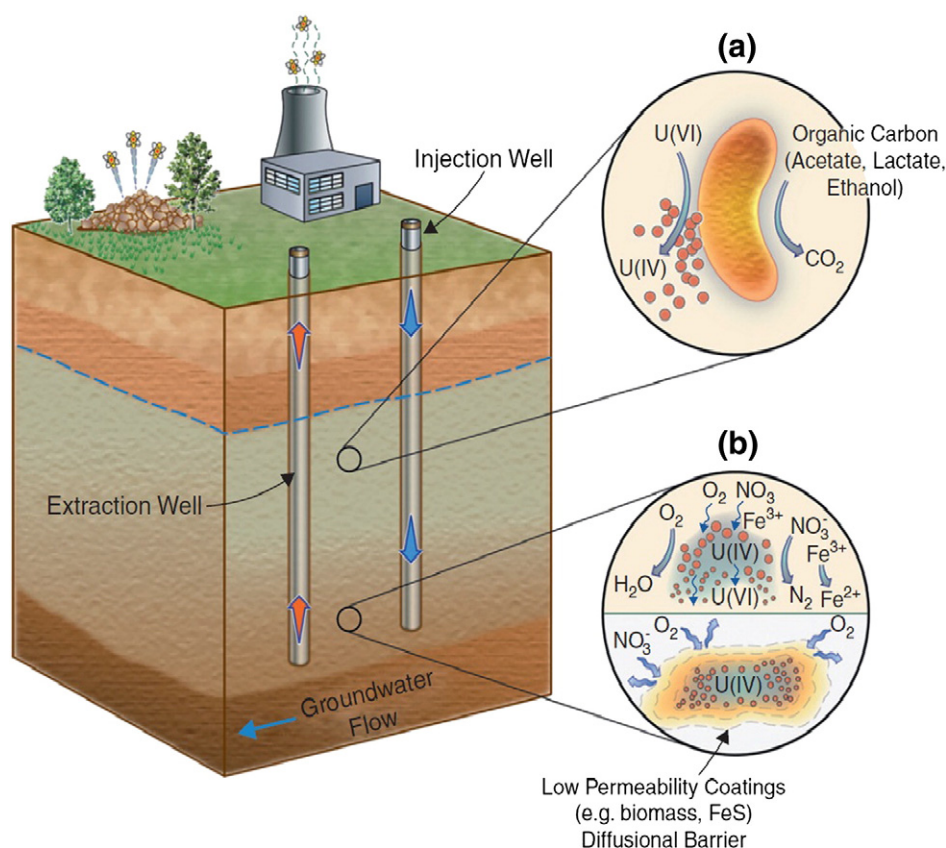


Fig. 3. Conceptual illustration of the process of uranium bioremediation after Williams et al. (2012). (a) Indigenous microorganisms present in soils, sediments, and groundwater contaminated by nuclear energy and weapons production activities are stimulated through introduction of organic carbon compounds via injection wells. Select organisms may couple the oxidation of organic carbon (and H₂) to the reduction of aqueous uranium, as U(VI), converting it from a soluble to an insoluble form, as U(IV). (b) Reduced U(IV) may be re-oxidized to U(VI) following cessation of organic carbon injection accompanying subsequent delivery of oxidants, such as O₂, NO₃⁻, and Fe³⁺; the presence of diffusional barriers (e.g., biomass or low permeability sediments) or preferential reductants (e.g., FeS) can suppress re-oxidation and maintain stability of immobilised U(IV).

of studies have shown that nitrate is preferentially used as an electron acceptor before U(VI) and Fe(III) due to it being more energetically favourable (DiChristina, 1992; Finneran et al., 2002b; Istok et al., 2004), although concomitant U(VI) and nitrate reduction has been demonstrated (Madden et al., 2007). As nitrate is a common co-contaminant with uranium at nuclear sites, this is a potential impediment to the application of bioreduction as a remediation strategy. An alternative theory is that the presence of nitrate is beneficial under low pH conditions, because consequent denitrification produces OH⁻ and HCO₃⁻, neutralising the pH and thus stimulating metal reduction (Law et al., 2010a; Thorpe et al., 2012a).

U(VI) forms stable complexes with carbonate in natural waters under oxic conditions and at pH > 6.5 (Langmuir, 1978). High concentrations of carbonate can stabilise U(VI) in solution therefore preventing it from being immobilised. Calcium-uranyl-carbonate complexes are very stable; in this form U(VI) is a much less favourable electron acceptor (Brooks et al., 2003). Indeed, higher concentrations of bicarbonate (40 mM) were found to lower the rate of U(VI) reduction in contaminated sediments (Luo et al., 2007) and the presence of 0.45–5 mM calcium significantly reduced the rate and extent of U(VI) bioreduction by *Shewanella*, *Desulfovibrio* and *Geobacter* (Brooks et al., 2003; Stewart et al., 2011). In contrast, results of bioreduction experiments with U(VI) sorbed to sediments representative of the Dounraey nuclear facility found reduction and immobilisation occurred even in the presence of micromolar quantities of bicarbonate and calcium (Begg et al., 2011). Similarly, experiments at the Rifle site with 5 mM Ca and abundant bicarbonate still show rapid rates of U(VI) bioreduction in situ (Williams et al., 2011).

3.3.1. US DOE Rifle site, Colorado

Groundwaters at this former uranium ore processing facility are contaminated with low levels of uranium, which leached from mill tailings into the unconfined aquifer (Anderson et al., 2003). The aquifer is an alluvial deposit of the nearby Colorado River, and groundwater flows from the site into the river at around 0.8 m per day. Vertical migration of uranium-contaminated groundwater is limited by the Wasatch formation; a silty shale which acts as an aquitard (Zachara et al., 2013). Evidence of deposition of uranium as U(IV) has been observed in naturally reducing zones of the aquifer; XAS analysis of one sample particularly high in natural uranium identified monomeric U(IV) complexed to organic matter, Fe(II) and sulfide (Campbell et al., 2012). Release of contaminant U(IV) from naturally reduced zones by oxidation, together with migration of up-gradient groundwater naturally high in U(VI) are responsible for the persistence of elevated concentrations of uranium in groundwater, despite the mill tailings being removed from site during the 1990s (Zachara et al., 2013).

Biostimulation with an injectate of 100 mM acetate was trialled at the site in 2002 (Anderson et al., 2003). Groundwater from an up-gradient well was collected and amended with the electron donor and 10 mM Br⁻ as a conservative tracer, before being injected into the treatment area over a three month period to generate 1 to 3 mM acetate in situ. Bromide detection demonstrated an average 2% volume addition to the aquifer per day. Within 50 days, U(VI) concentrations decreased from between 0.4 and 1.4 μM to below the maximum contaminant limit of 0.18 μM, with concurrent release of Fe(II). After 50 days, U(VI) concentrations began to increase and Fe(II) decreased. At the same time, sulfate decreased stoichiometrically with acetate consumption suggesting a release of U during early sulfate reduction.

Field trials also took place at the Rifle site during 2007 and 2008 (Williams et al., 2011). Even though more than 90% of U(VI) was present as recalcitrant uranyl-calcium-carbonate complexes, when acetate was supplied as an electron donor, concentrations of U decreased from 1–1.5 μM to 0.05–0.1 μM . These low concentrations were maintained over long periods (> 140 days) by ensuring the concentration of acetate remained greater than the 10 mM sulfate present. A shorter period of acetate amendment (at 5 mM) during the first trial caused a temporary increase in U(VI) at the onset of sulfate reduction. This was attributed to the increasing alkalinity and pH which promoted U(VI) desorption and complexation with carbonate. Another factor might be that sulfate-reducing bacteria were not able to couple U(VI) reduction to acetate oxidation at Rifle; perhaps unsurprisingly given most sulfate-reducing bacteria studied to date have used lactate as an electron donor for U(VI) reduction. However, when the system was not limited by acetate availability (supplied at 15 mM), concomitant Fe(III)- and sulfate-reduction occurred leading to accumulation of iron sulfides in soils and sustained U(VI) removal. Prolonged Fe(III)-reduction and sequestration in iron sulfides may prevent abiotic reoxidation of U(IV) by Fe(III) phases, while maintaining redox conditions under which U(IV) is stable. Once acetate amendment was stopped, U(VI) concentrations rebounded, although U(VI) levels remained 30–55% lower than pre-injection levels for more than 210 days in wells which had received prolonged acetate delivery. Stable isotope probing and gene expression analysis confirmed *Geobacter* were active and oxidising acetate, even during sulfate reduction, so are likely to be responsible for U(VI)-reduction and maintaining low concentrations of U(VI) in groundwater. During this trial the authors reported a decrease in hydraulic conductivity of four orders of magnitude at the injection well, possibly due to precipitation of carbonate and sulfide minerals and biomass accumulation, but this did not impede electron donor delivery and was not observed at any monitoring wells.

Monitoring of uranium isotope ratios during field trials found $^{238}\text{U}/^{235}\text{U}$ in groundwater decreased significantly during in situ bioreduction (Bopp et al., 2010). This is the opposite of what was expected, as generally lighter isotopes react faster than heavier, although it can be explained by an effect known as “nuclear field shift”. A bicarbonate injection designed to induce uranium desorption caused no change in the isotopic ratio, clarifying that adsorption and desorption do not impact $^{238}\text{U}/^{235}\text{U}$ and therefore uranium isotope ratios may be used to indicate the occurrence of in situ bioreduction (Shiel et al., 2013). A number of geophysical techniques have been used to monitor the effects of in situ biostimulation trials including measurement of: spectral ionisation potentials (Williams et al., 2009), self potentials (Williams et al., 2010a), current density (Williams et al., 2010b) and complex resistivity (Orozco et al., 2011). As geophysical techniques can cover larger areas and offer continuous time coverage compared to conventional geochemical analyses from borehole samples, they may considerably improve understanding of the changes occurring in the subsurface during biostimulation. Furthermore they could be used to provide real-time information to optimise biostimulation, such as allowing the acetate injection rate to be adjusted in order to maintain metal-reducing conditions (Orozco et al., 2011).

In situ sediment columns were deployed during a subsequent 2009 acetate-amendment field trial (Bargar et al., 2013). Most of the U(VI) was reduced during sulfate-reducing conditions and a close association was observed with U(IV) and Fe-sulfide (mackinawite) coatings on sediment grains, although this was heterogeneous at the micrometre and sub-micrometre scales. Mackinawite is known to be able to reduce U(VI) to uraninite abiotically (Hyun et al., 2012) when phosphate concentrations are low, such as in Rifle groundwater. Two forms of U(IV) were identified; uraninite and monomeric U(IV) associated with biomass-derived phosphoryl ligands. The authors proposed that the juxtaposition of biomass and mackinawite allows for the concurrent deposition of monomeric U(IV) and uraninite via a biotic–abiotic

transition pathway. Moreover, the simultaneous precipitation of U(IV) phases with sulfides creates physical and chemical barriers to U(IV) re-oxidation, potentially explaining how U(VI) removal is maintained post-acetate amendment.

The microbial communities stimulated at Rifle have been studied in detail using state-of-the-art molecular analyses. The PhyloChip microarray identified background Rifle sediments to contain diverse microbial communities (Handley et al., 2012). In general, *Geobacter* species have been found to dominate the microbial community during U(VI) bioreduction (Anderson et al., 2003; Chang et al., 2005; Chandler et al., 2010). Use of ^{13}C labelled acetate found a relatively diverse active microbial community prior to acetate addition, but *Geobacter*-like species dominated at the end of the trial (Kerkhof et al., 2011). Of the total *Geobacter* population, 90% of the cells were planktonic during the peak phase of Fe(III)-reduction, whereas 77% were attached to sediment surfaces during sulfate-reduction, as were 75% of sulfate-reducing bacteria (Dar et al., 2013). The authors suggest this is likely due to *Geobacter* having more energy to be motile and being able to seek out Fe(III) during periods of excess electron donor availability. Whole genome microarray analyses found the transcript abundance of *rpsC* (ribosomal proteins S3) correlated best with the growth rate of *Geobacter uraniireducens*, therefore monitoring expression of *rpsC* could be used to measure *Geobacter* metabolism during biostimulation (Holmes et al., 2013a). Phospholipid fatty acid analysis (PLFA) identified a large increase in biomarkers for *Geobacter* species and an unidentified Fe(III)-reducer during an acetate biostimulation field trial (Peacock et al., 2011). Proteomic analysis of planktonic biomass dominated by *Geobacter* detected an abundance of enzymes and peptides associated with acetate metabolism and energy generation (Wilkins et al., 2009). These data were used to validate an in silico genome-scale model of *G. metallireducens*, which may be used in future to manipulate geochemical conditions during uranium bioreduction, and so achieve cost effective bioremediation (Fang et al., 2012). The overall species diversity was lower in samples which had been biostimulated with acetate, but there was an increase in Fe(III)-reducing and sulfur redox cycling genera, especially organisms affiliated with the *Desulfuromonadales* and *Desulfobacterales* (Handley et al., 2012). A shift from Fe(III)-reducers to sulfate-reducers was observed as the trials progressed (N'Guessan et al., 2008). Analysis using the GeoChip microarray identified a change in microbial functional gene abundance, from genes predominantly used for metal reduction e.g. *c*-type cytochromes, to genes required for sulfate reduction and methane generation (Liang et al., 2012). A similar shift was detected using proteomic techniques (Callister et al., 2010). Post-trial, members of the *Firmicutes* group closely related to *Mollicutes* and *Clostridia* dominated, although these were thought to remove U(VI) via adsorption rather than bioreduction (N'Guessan et al., 2008). Proteomic analysis identified a legacy effect on the microbial community caused by field trials; a more diverse community remained following the 2007 trial which may have impacted the 2008 trial by decreasing the duration of Fe(III)-reduction (Callister et al., 2010). Finally, analysis of 18S rRNA gene sequences during an acetate amendment field trial revealed a predator–prey response between bacterivorous protozoa and metal- and sulfate-reducing bacteria (Holmes et al., 2013b). An initial bloom of *Geobacter* was followed by an increase in a species closely related to *Breviata anthemia*, an ameboid flagellate, while diplomonadid flagellates from *Hexamitidae* accompanied the bloom of sulfate-reducing *Peptococcaceae*. Although largely unexplored, predator–prey relationships may play an important role in subsurface microbial ecology, and may limit the rate of U(VI) reduction.

Finally, reactive transport modelling (RTM) has been used to simulate the in situ biostimulation trials at Rifle. In brief, RTM computes contaminant transport using:

- hydrogeological parameters to describe groundwater flow, obtained by monitoring transport of an inert tracer such as bromide; and

- geochemical parameters to estimate chemical reactions that may aid or hinder contaminant transport – this requires knowledge of, amongst other things, the microbial community and their metabolic pathways, and the likelihood of sorption.

The first application of RTM to Rifle was for the 2002 biostimulation trial (Yabusaki et al., 2007). Data on the injection tank composition and drawdown, together with field bromide tracer data were used to define groundwater transport. Equations governing the coupling of Fe(III) oxyhydroxides and U(VI) as electron acceptors to the consumption of acetate by *Geobacter* and sulfate-reducers, were used to represent the geochemical component of the model. These parameters were adjusted to reflect field geochemical data from the 2002 trial for both stimulated and background wells. Subsequently this RTM was successfully applied to a 2003 trial (in the same boreholes) without parameter modification, highlighting the usefulness of RTM to predict future contaminant transport. Additional development of the model to incorporate uranium adsorption and various mineral reactions, again benchmarked with the 2002 hydrogeological/geochemical parameters, was found to be applicable to a 2007 biostimulation trial in a different plot within the Rifle site (Fang et al., 2009). Recent developments in RTM of Rifle biostimulation trials include incorporation of microbial growth equations coupled to abiotic geochemical reactions (Istok et al., 2010), three-dimensional variably saturated flow (Yabusaki et al., 2011) and proteomic data (Fang et al., 2012). In parallel, RTM has been used to consider the effect of biomass growth and mineral precipitation during biostimulation on groundwater flow. Geochemical data from column experiments were used in a reactive transport model to predict accumulation of minerals and biomass for the 2002 and 2003 Rifle biostimulation trials; results suggested clogging of pore space may occur in the vicinity of electron donor injection wells (Li et al., 2009). Subsequent modelling confirmed this, and also emphasised the influence of physical and geochemical heterogeneities on the spatial distribution of pore clogging and its effect on hydraulic conductivity (Li et al., 2010, 2011).

In summary, a number of field trials at the US DOE Rifle site have demonstrated the potential for acetate application to stimulate bioreduction of U(VI) in groundwater and maintain low concentrations over long periods of time. It appears that *Geobacter* species play a major role in U(VI) reduction, and are active during Fe(III)- and sulfate-reducing conditions. Acetate amendment has a long-term effect on microbial community structure and diversity within the aquifer. State-of-the-art molecular analysis and modelling continue to improve understanding of subsurface processes occurring during in situ biostimulation.

3.3.2. US DOE Oak Ridge site, Tennessee

This site was contaminated with uranium through disposal of wastes in unlined ponds between 1951 and 1983, including those from the cleaning of uranium processing equipment using nitric acid (Green et al., 2012). The groundwater in some areas of the site is therefore characterised by low pH, high nitrate and U(VI) contamination, posing difficult challenges for in situ bioremediation. Multiple migration pathways are present, causing distinct plumes with different chemical compositions. For example, in the vicinity of the S3 ponds, concentrations of uranium range from 0.015 to 10.9 μM and nitrate from 0.47 to 37 mM (Spain and Krumholz, 2011). Over 95% of the uranium in the Oak Ridge subsurface is bound to sediments (Wu et al., 2010).

Push–pull tests were conducted using ethanol, acetate or glucose as electron donors to assess the potential for bioreduction of U(VI), Tc(VII) and nitrate (Istok et al., 2004). Background concentrations in groundwater from test wells were 0–5.8 μM U, 0.039–18 nM Tc and 1–168 mM nitrate. The injection solution comprised site groundwater amended with 80–130 mM sodium bicarbonate, 1.3 mM bromide tracer and 20–200 mM of electron donor, pH adjusted using 80% N_2 20% CO_2 . 200 l of injection solutions were pumped into each well over 0.5

to 2 days, and the wells monitored for up to approximately 40 days. In test wells, dilution-adjusted concentrations of Tc(VII) and nitrate decreased, nitrite was produced, but no reduction of Fe(III), U(VI) or sulfate was detected. The only changes observed in control wells were decreases in concentration due to dilution. A second identical injection generated Fe(III)-reducing conditions and increased the reduction rate of nitrate and Tc(VII) and stimulated limited reduction of U(VI).

A pilot field experiment was set up in which groundwater was firstly pre-treated to condition it prior to adding an electron donor to bioreduce uranium (Wu et al., 2006a, 2006b). The treatment area was selected for high hydraulic conductivity and relatively high uranium concentrations. Purged site groundwater was treated above ground by adjusting the pH to 4.3–4.5 to remove aluminium and calcium which otherwise might cause in situ clogging of the aquifer, and also to remove nitrate. This treated water was supplemented with tap water and returned to ground. Subsequently the pH of the treated water was increased to 6.0–6.3, in order to increase the subsurface pH to generate optimal conditions for microbial activity. Unsurprisingly these flushing phases drastically reduced the concentrations of contaminants in the groundwater, from an initial 48–158 μM U to 2.7–5.1 μM , and from 114–271 mM nitrate to 0.1–0.78 mM. Uranium in soils remained around 800 mg/kg. Following conditioning, ethanol was added intermittently to stimulate bioreduction. Nitrate reduction occurred for the first 47 days, followed by U(VI) reduction which decreased concentrations in groundwater to around 1 μM for the duration of the trial (350 days). Final uranium concentrations in soil ranged from 910 mg/kg to 4320 mg/kg, with 28–51% present as U(IV); the highest values were found closest to the injection well.

A field trial comprising single injection of the slow-release electron donor emulsified vegetable oil (EVO) caused the concentration of U(VI) in groundwater to decrease from between 3.8 and 9.1 μM to less than 1 μM in each monitoring well tested (Gihring et al., 2011). U(VI) concentrations remained lower than the initial values for at least four to eight months. Later trials demonstrated a single application of EVO substantially reduced the mass of uranium discharged from the site to Bear Creek for more than a year before concentrations rebounded (Tang et al., 2013a, 2013b). Aqueous U(VI) concentrations initially increased as rates of U desorption attributed to biogenic bicarbonate production and Fe(III)-reduction exceeded U(VI) reduction. A biogeochemical model developed from initial laboratory experiments was used to simulate the field trial, and predicted substantial bioreduction and U(IV) accumulation, although at the time of writing this does not appear to have been confirmed with sediment analysis.

Nitrate-reducing bacteria form a high proportion of the microbial community sequences from background Oak Ridge sediments (Akob et al., 2007). The denitrifying bacterium *Rhodanobacter* dominated the acidic, nitrate-rich contaminated sediments (Green et al., 2012). Compared to pristine groundwater, water from contaminated wells had lower gene diversity but the signal intensity was higher (Waldron et al., 2009). Metal-resistant and metal-reducing microbes were present in both contaminated and pristine water, highlighting the potential for bioremediation. Known U(VI)-reducers *Desulfovibrio*, *Geobacter*, *Anaeromyxobacter*, *Desulfosporosinus* and *Acidovarar* species were detected in wells which had been biostimulated for nearly two years (Cardenas et al., 2008). Indeed, the presence of *Desulfovibrio*, *Anaeromyxobacter*, and *Desulfosporosinus* species as well as the abundance of *Geobacter* species could be used to indicate areas where U(VI) reduction had occurred (Cardenas et al., 2010). A recent study linked the transcript level of key functional genes with geochemical data on rates of bioreduction of Fe(III) and sulfate (Akob et al., 2012). The response of *Geobacteraceae*-specific *gltA* (which codes for an enzyme associated with integrating acetate in the TCA cycle) transcript levels were found to correlate with Fe(III) reduction activity, as did expression of the *drsA* gene (codes for the rate-limiting sulfate reduction enzyme) with sulfate concentrations. The type of electron donor used

can have a significant influence on the microbial community. Adding EVO as a slow-release electron donor initially caused members of *Veillonellaceae* and *Desulfotomaculum* to dominate; these probably catalysed EVO decomposition and oxidised long-chain fatty acids to acetate (Gihring et al., 2011). An alternative approach to study the microbial community response is to use passive multilevel samplers deployed in situ into an electron donor injection well and down-gradient wells (Baldwin et al., 2008). Changes in community composition were observed to occur during biostimulation, with increases in cell density of denitrifying bacteria, delta-proteobacteria, *Geobacter* and methanogens.

In summary, most of the uranium in the Oak Ridge subsurface is bound to sediments. Multiple plumes of U(VI) in groundwater exist, some of which contain high concentrations of nitrate, which creates challenging conditions for U(VI) bioreduction. Application of EVO in situ to stimulate appears to be a promising bioremediation technique.

3.3.3. US DOE Hanford site, Washington

Uranium-containing liquid waste from fuel fabrication activity at the site was historically disposed of in trenches and ponds, which allowed leaching to groundwater (Peterson et al., 2008). A plume of uranium-contaminated groundwater is present with the unconfined aquifer of the alluvial Hanford formation; downward migration is limited by the consolidated fluvio-lacustrine Ringold formation (Zachara et al., 2013). Although the contaminant sources were removed in the 1990s, this plume persists with concentrations varying seasonally from 0.04 to 0.84 μM , in the form of very stable uranyl carbonate complexes (Peterson et al., 2008; Maher et al., 2012). The continued source of uranium is thought to be the release of adsorbed U(VI) from the vadose zone during spring groundwater rise driven by upstream snowmelt (Zachara et al., 2013). Under normal hydrological conditions, groundwater from the site discharges to the nearby Columbia River, while this reverses during periods of high river flow leading to a complex hydrodynamic regime and concentrations of uranium in river water between 2.1 and 7.1 nM.

The form of uranium in contaminated sediments has been investigated (Catalano et al., 2004, 2006). Sodium boltwoodite $[\text{Na}(\text{UO}_2)(\text{SiO}_3\text{OH}) \cdot 1.5\text{H}_2\text{O}]$ – a uranyl silicate from the uranophane group – predominated in the ground underlying a tank that was overfilled and leaked caustic aqueous sludge (of 2.5–5.0 M sodium carbonate with 0.5 M U(VI), 0.36 M phosphate and all fission products), presumably due to the high pH conditions in situ. Uranium was co-precipitated with calcite as micro-granules in the near surface underlying former process ponds, which had received wastes from the dissolution of nuclear fuel and cladding. Slightly deeper it was precipitated as metatorbernite $[\text{Cu}(\text{UO}_2\text{PO}_4)_2 \cdot 8\text{H}_2\text{O}]$, while at depth it was sorbed onto phyllosilicates. Phylogenetic analysis of DNA from 21 Hanford sediment samples identified 1233 and 120 unique bacterial and archaeal operational taxonomic units respectively (Lin et al., 2012). Microbial diversity was greater in the oxic Hanford formation and lower in the deeper anoxic Ringold formation.

Column experiments using sediments from the site have demonstrated the potential for bioreduction to remediate U(VI) from groundwater (Ahmed et al., 2012b). These were set up supplied with oxic synthetic groundwater with or without organic amendment (2 mM lactate, 2 mM malate, 2 mM succinate and 2 mM fumarate), or deionised water, each amended with 0.126 mM U(VI) and monitored over 7 months. When synthetic groundwater amended with electron donors was used, 80 to 85% of U(VI) was immobilised via microbial reduction to uraninite. In the other columns, 100% of the U(VI) was adsorbed. Subsequent exposure to oxic Columbia River water over a 50 day period failed to remobilise more than 7% of U in each column.

Chemical remediation was trialled at the site over a five day period in 2007, aiming to immobilise uranium from groundwater into autunite $[(\text{Ca},\text{Mg},\text{K},\text{H})(\text{UO}_2)(\text{PO}_4)]_{1-2}$ and apatite minerals $[\text{Ca}_5(\text{PO}_4)_3(\text{OH},\text{F},\text{Cl})]$ via phosphate injection (Vermeul et al., 2009). An earlier series of laboratory experiments identified a mixture of long-chain polyphosphates to be

the most suitable for injection into ground (Wellman et al., 2007a,b, 2008). Uranium concentrations were initially reduced to below the maximum contaminant limit, however, within six weeks they had rebounded significantly. Uranium removal might have been due to the formation of autunite but it could have been due to flushing and dilution effects from the large volumes of water injected. The capacity for apatite formation under site conditions was suggested to be limited. This work illustrates the challenges of applying remediation in situ, namely the large volumes of water required to introduce sufficient phosphate, and the high concentrations of phosphate (10.5 mM) needed to remove relatively low concentrations of uranium ($\sim 1 \mu\text{M}$). Furthermore, this trial reduced the hydraulic conductivity of the aquifer by on average a factor of six, over just five days. Moreover, despite demonstration in laboratory batch and column tests, the same results were not replicated under field conditions highlighting the complexities of scale-up.

In summary, despite the contaminant source being removed nearly 20 years ago, low concentrations of uranium persist in groundwater at Hanford. Column experiments demonstrated that uranium strongly sorbs to sediments under laboratory conditions; application of an electron donor did lead to bioreduction to uraninite but this was equivalent to sorbed U(VI) in terms of susceptibility to remobilisation. Developing a remediation strategy may be challenging given the difficulties in replicating site conditions in the laboratory, and the problems encountered during a trial of in situ chemical remediation.

3.4. Stability of bioreduced U(IV) and reoxidation

The resistance of poorly soluble U(IV) to reoxidation and consequent remobilisation as aqueous U(VI) is crucial for the success of remediation over the long term. Biogenic reduced nanoparticles have a large surface area so are more reactive (and potentially susceptible to reoxidation) than aggregates or crystals, although evidence suggests that biogenic uraninite nanoparticles aggregate, especially when formed by relatively slow rates of U(VI) reduction (Anderson et al., 2003; Senko et al., 2007). The presence of carbonate considerably increases the rate of uraninite reoxidation as it complexes with U(VI), removing it from the mineral surface and preventing a protective layer from accumulating (Ulrich et al., 2008; Campbell et al., 2011a). Thermodynamically, both oxygen and nitrate (via denitrification intermediates e.g. nitrite) should be able to reoxidise U(VI), but this may be limited by reaction kinetics. Here the focus is on reoxidation of U(IV) in sediments with natural microbial communities present, rather than on pure mineral forms. U(IV) may also be reoxidised by Fe(III) minerals (Sani et al., 2005; Ginder-Vogel et al., 2006; Spycher et al., 2011), manganese oxides (Fredrickson et al., 2002; Wang et al., 2013), organic ligands such as citrate and EDTA, even under anaerobic conditions (Luo and Gu, 2011), and microbially generated bicarbonate, even under bioreducing conditions (Wan et al., 2005, 2008).

3.4.1. Reoxidation by exposure to oxygen

The effects of reoxidation have been studied in terms of the long-term biocycling behaviour of radionuclides in natural and engineered environments. Laboratory microcosm experiments found near-complete reoxidation of U(IV) in sediment when gently agitated in air, within time periods as short as 24 h (Begg et al., 2011; Law et al., 2011). Around 60% of bioreduced Fe(II) was remobilised within 1 day (Burke et al., 2006) or 9 days (McBeth et al., 2007) after exposure to oxygen on an orbital shaker. Moderately fast reoxidation has been observed in column studies via purging the influent media with oxygen. For example, 61% of bioreduced U(IV) was remobilised within 21 days, and nearly all had been removed after 122 days (Komlos et al., 2008), while 88% of precipitated uranium was remobilised within 54 days of exposure to influent media containing 8.6 mg/l dissolved oxygen to represent the maximum concentration in groundwater at 15 °C (Moon et al., 2007). In contrast, negligible reoxidation of total bioreduced U(IV) was observed in a column supplied with oxygenated

influent for 64 days, although some modest localised reoxidation was observed (Sharp et al., 2011). The authors suggest this may be due to residual electron donor remaining in the sediments post-bioreduction.

Perhaps when trying to simulate the effects of oxic groundwater ingress a more environmentally-realistic oxidation method is to expose the sediments to naturally oxic water. A column study of this type used sediment and groundwater from the Rifle site, containing 1 to 2 mg/l dissolved oxygen (N'Guessan et al., 2010). Over the first month, 17% of the total U precipitated during the bioreduction phase was remobilised, after that no additional loss was detected. The microbial community became characterised by bacteria capable of oxidising complex organic matter from dead biomass, coupled to use of the low levels of dissolved oxygen present and this prevented reoxidation of biogenic U(IV). Experiments using sediments from the Hanford site found exposure to oxic river water over a 50 day period remobilised just 7% of bioreduced U(IV) in columns that had previously been supplied with an electron donor, and 7% of sorbed U(VI) in control columns (Ahmed et al., 2012b). The remaining 93% of U in the bioreduced column sediment was identified as nanoparticulate uraninite, suggesting it was recalcitrant to reoxidation under the conditions of study where, presumably, relatively low concentrations of dissolved oxygen were introduced to the column. Another environmentally relevant method used was to immerse biogenic uraninite into oxic groundwater within monitoring wells at the Rifle site (Campbell et al., 2011a, 2011b). After 104 days, approximately 50% had dissolved and no insoluble corrosion products were observed. This rate is 50 to 100 times slower than those measured in the laboratory, and this was attributed to the presence of biomass, molecular diffusion and surface passivation by groundwater solutes.

Reoxidation of bioreduced U(IV) has also been studied in situ at the Oak Ridge field site (Wu et al., 2007). Initial U(VI) concentrations in groundwater were up to 135 μM . Application of ethanol over a two year period stimulated immobilisation of uranium as U(IV). Subsequently sulfite was added to remove any remaining dissolved oxygen, which reduced concentrations of U(VI) in groundwater to <0.13 μM . Dissolved oxygen was introduced to the injection well over a 60 day period, causing a spatially variable increase in U in groundwaters of up to 2 μM . Concentrations of U in injection well sediment decreased from 10.3 g/kg to 4.64 g/kg; decreases were also observed in nearby monitoring wells, but concentrations of U in sediments actually increased in monitoring wells further away from the injection well. Ethanol additions were then resumed, restoring U(VI)-reduction and maintaining <0.1 μM U in groundwater. At the end of the trial, between 60 and 80% of U in monitoring well sediments was present as U(IV).

3.4.2. Reoxidation by exposure to nitrate

Proposed mechanisms of U(IV) reoxidation by nitrate include: abiotic oxidation by denitrification intermediates e.g. nitrite; direct oxidation by bacteria coupled to nitrate reduction; or oxidation by Fe(III) generated through oxidation by denitrification intermediates or by bacteria coupled to nitrate reduction (Senko et al., 2002). Nitrite alone was found to be a relatively poor oxidant of U(IV) compared to Fe(III) oxyhydroxides, but in combination with Fe(II) lead to complete reoxidation of U(IV), with the Fe(II) acting as an electron shuttle or catalyst between nitrate reduction and U(IV) oxidation (Senko et al., 2005). Amorphous biotic Fe(III) produced by biogenic nitrite oxidised U(IV) at a greater rate and extent, compared to the more crystalline biogenic Fe(III) with a lower surface area.

Nitrate-reducing bacteria appear to be particularly important in mediating the reoxidation of U(IV) by nitrate. A *Pseudomonas* species was isolated from a nitrate reoxidation system; total reoxidation of U(IV) occurred when *Pseudomonas* cells and nitrate were added to sterile pre-reduced sediment microcosms, but no reoxidation occurred when just nitrate was added to sterile systems (Wilkins et al., 2007). *Thiobacillus denitrificans* was observed to oxidise synthetic and biogenic uraninite under anaerobic conditions coupled to nitrate reduction (Beller, 2005). Reoxidation of U(IV) was investigated using two

enrichment cultures from the Oak Ridge site; an iron(III)-reducing culture dominated by *Clostridium* spp. and a sulfate-reducing culture dominated by *Desulfovibrio* spp. (Boonchayaanant et al., 2009). In these systems, 5 mM nitrate failed to reoxidise U(IV) in both enrichment cultures. The concentration of nitrate in the sulfate-reducing system remained constant; attributed to the lack of nitrate-reducing bacteria. In contrast in the Fe(III)-reducing system, the 5 mM nitrate had decreased to almost zero after 48 h, although no nitrite was detected nor increases in ammonium concentration were observed. Lack of U(IV) reoxidation is proposed to be due to the absence of nitrate-reducing bacteria or the redox buffering effect of Fe(II) and/or sulfide. Indeed, the authors highlight work showing that *Clostridium* species can bioreduce U(VI) in the presence of nitrate (Madden et al., 2007).

There does not appear to be an obvious trend between the amount of U(IV) remobilised compared to the amount of nitrate added. For example, adding an 80-fold stoichiometric excess of nitrate to the influent of columns containing bioreduced Rifle sediments remobilised 97% of uranium over 54 days (Moon et al., 2007). A later column study by the same authors found the addition of nitrate reoxidised more U(IV) than dissolved oxygen, due to the faster reaction kinetics of oxygen with iron sulfides causing slower advancement of the reaction front through the column compared to nitrate, therefore protecting more U(IV) from contact with the oxidant (Moon et al., 2009). Perhaps comparable are results demonstrating a high proportion of uranium (around 86%) being reoxidised 10 days after exposure to a 1000-fold stoichiometric excess of nitrate in microcosm experiments (Wilkins et al., 2007). In contrast, another microcosm study found minimal (3%) reoxidation of U(IV) had occurred 20 days after exposure to a 240-fold stoichiometric excess of nitrate (Law et al., 2011). The mechanism for U retention in this system was unidentified as more than 80% of Fe(II) was oxidised to Fe(III) and nitrate reduction was observed.

Nitrate (2 mM) was added in situ to sediments containing bioreduced U(IV) at the Oak Ridge field site (Wu et al., 2010). Initially Fe(II) and sulfate were released to solution, then Fe(II) concentrations decreased presumably as Fe(III) oxyhydroxides precipitated. Up to 1 μM U was remobilised, concurrent with nitrite formation (full denitrification processes were observed). Subsequent additions of ethanol caused a transient increase in U(VI) up to around 2.5 μM , probably due to desorption as Fe(III) oxyhydroxides were reduced, before concentrations decreased to less than 0.1 μM .

In summary, the potential for U(IV) reoxidation must be carefully considered when deciding whether bioreduction offers a long-term remediation strategy for removing U(VI) from groundwater. Maintaining reducing conditions and/or continual electron donor supply may be required for long-term success. The presence of iron sulfides appears to play an important role in protecting U(IV) from reoxidation. The method of assessing the susceptibility of U(IV) to reoxidation is crucial, with lower amounts of remobilisation observed during more realistic experiments (e.g. microcosms > columns > field trials) perhaps due to preferential flow pathways developing in larger scale trials. It is important to consider the likelihood of reoxidation scenarios actually occurring within the decision making process.

4. Uranium phosphate biomineralisation

Although less extensively studied compared to bioreduction, uranium sequestration as insoluble uranyl U(VI) phosphate biominerals is another promising technique for in situ bioremediation, particularly for sites where bioreduction might be unfeasible due to high nitrate concentrations or where there is a risk of reoxidation occurring.

4.1. Early work & mechanisms

The phosphatase activity of *Serratia* sp. strain N14 has been exploited to remove U(VI) from solution (Macaskie et al., 1992). When supplied with organic phosphate donors such as glycerol

phosphates, this *Serratia* sp. over-produced phosphatases which liberated orthophosphate (inorganic phosphate, P_i) and precipitated with U(VI) as uranyl phosphate at the cell surface. In a flow-through bioreactor with cells immobilised in polyacrylamide gel, 9 g of uranium was precipitated per gramme of bacterial dry weight after a three week period; indeed the experiment was so successful it had to be stopped because of blockage by accumulated metal (Macaskie, 1990). The precipitate was identified as hydrogen uranyl phosphate [HUO_2PO_4] (HUP). Analysis of peptide fragments identified the enzyme responsible as a class PhoN phosphatase, which is a non-specific acid phosphatase (NSAP) (Macaskie et al., 1994a). Detailed investigations noted phosphatase enzymes from the *Serratia* strain were mostly localised in the periplasm, with some associated with the outer membrane and some found extracellularly (Jeong et al., 1997). Higher concentrations of phosphatase were present in the polar regions of the cell, as was accumulated uranyl phosphate. The authors suggested that the architecture of the cell surface prevents fouling by the biominerals, allowing uranyl to access to the inner and outer cell membrane. Later work suggested that lipopolysaccharides produced by phosphatases provide the initial nucleation site for metal deposition, with further uranyl phosphates juxtaposed to create 'tethered' metal phosphates, so preventing fouling of the cell surface (Macaskie et al., 2000). The phosphatase activity of *Serratia* has been shown to be tolerant to gamma radiation at doses up to 1368 Gy, suggesting a potential for use at nuclear sites (Paterson-Beedle et al., 2012).

Phosphatase activity is a common feature of almost all microorganisms. P_i is the preferred source of the essential nutrient phosphorus for bacteria. If a surplus is present some organisms bioaccumulate P_i and store it intracellularly as polyphosphate granules; if it is in short-supply then a specific transport system can be used to ensure sufficient uptake (Hirota et al., 2010). Under anoxic conditions, some organisms such as *Acinetobacter* can then use the polyphosphate granules as an energy source via hydrolysis and efflux of phosphate (van Groenestijn et al., 1988). The impact of this process on metal cycling is currently poorly defined. In the absence of P_i , alternative sources of P can be transformed by bacteria to release P_i , including organophosphates (via hydrolytic cleavage catalysed by phosphatases), inorganic phosphite (via enzymatic oxidation) and phosphonates (via cleavage catalysed by C–P lyases). This action is an essential part of the phosphorus cycle. Some bacteria can transform organically bound phosphorus – that otherwise would not be used by other organisms – into an accessible form, for example from nucleic acids (Siuda and Chrost, 2001), phytate (Lim et al., 2007) or phospholipids (Ko and Hora, 1970). Up to 80% of the soil microbial population are able to accomplish hydrolytic cleavage of organophosphates through phosphatase activity, including *Bacillus*, *Serratia*, *Proteus*, *Arthrobacter* and *Streptomyces* species and various fungi (Ehrlich, 1990).

However, not all bacteria capable of phosphatase activity are able to remove uranium from solution; enterobacteria with acid-phosphatases were unable to do so (Macaskie et al., 1994a). This was suggested to indicate a *Serratia* strain-specific cell architecture may be necessary. More recently, uranium biomineralisation via phosphatase activity has been demonstrated using environmental isolates of *Rahnella*, *Bacillus*, and *Aeromonas* species; and the indigenous soil bacterial community from the US DOE Oak Ridge site (Beazley et al., 2007; Martinez et al., 2007; Shelobolina et al., 2009). Genetically altered strains of bacteria are also able to precipitate uranyl phosphates (Martinez et al., 2007), including engineered strains of *Deinococcus radiodurans* (Appukuttan et al., 2007), *Escherichia coli* with added acid-phosphatase genes (Basnakova et al., 1998), and strains of *Pseudomonas veronii* and *Pseudomonas rhodesiae* with added alkaline-phosphatase genes (Powers et al., 2002).

4.2. Mineralogical endpoints

The end-products are reported to be U(VI) phosphate minerals; these are insoluble and do not undergo redox changes. Experiments

with *Serratia* sp. strain N14 produced HUP (Macaskie et al., 1992). Adding ammonium acetate to the growth solution led to $NH_4UO_2PO_4$ being formed, which has a lower solubility product than HUP (Yong and Macaskie, 1995). Experiments using soils from the Oak Ridge site found autunite minerals were precipitated (Beazley et al., 2007), while when an environmental isolate was used the uranium was incorporated into hydroxyapatite [$Ca_5(PO_4)_3OH$] which is much less soluble at near-neutral pH compared to autunite (Shelobolina et al., 2009). Hydroxyapatite is argued to be a preferable end product because a large area of hydroxyapatite with dilute U(VI) concentrations should be more stable to dissolution over longer periods of times than a smaller area of autunite with higher concentrations of U(VI).

4.3. Demonstration at the US DOE Oak Ridge site, Tennessee

Uranium biomineralisation via phosphatase activity has been investigated for potential use at the Oak Ridge site, particularly due to the presence of acidic soils with high nitrate concentrations that may inhibit bioreduction (Beazley et al., 2007; Martinez et al., 2007). Screening of 135 environmental isolates identified 85 to be phosphatase-positive. Initial experiments with uranyl acetate and glycerol-3-phosphate (G3P) determined that a five-fold molar excess of phosphate would be sufficient to precipitate uranyl from solution. The ability of three representative strains to biomineralise 200 μM U was investigated, excluding carbonate to simulate site groundwater conditions. The *Bacillus* and *Rahnella* strains were able to liberate P_i in the presence of G3P which precipitated 73% (*Bacillus*) and 95% (*Rahnella*) of uranyl from solution. The phosphatase-negative *Arthrobacter* strain was unable to remove uranyl from solution; although the cells did not grow they remained culturable. The optimum pH was reported to be 5.0–5.5, suggesting non-specific acid phosphatases were responsible; this was confirmed by molecular genetic analysis. The culturability of the *Rahnella* cells decreased significantly on exposure to uranium, but recovered by the end of the experiment (after 3.5 days), while the *Bacillus* and *Arthrobacter* species were not affected. The U-phosphate precipitate was identified as calcium autunite [$Ca(UO_2)_2(PO_4)_2$].

Subsequent work determined that the *Rahnella* strain is able to biomineralise uranyl to chernikovite [$H_2(UO_2)_2(PO_4)_2$] under anaerobic conditions and in the presence of high nitrate (Beazley et al., 2009). The cells were able to respire nitrate in the absence of oxygen, although they grew more slowly and released less P_i compared to in aerobic conditions. A stress response was observed in both the aerobic and anaerobic experiments, but despite this 95% of uranium was removed from solution after 120 h incubation. Post uranium removal the cells in aerobic conditions recovered but those in anaerobic conditions did not. This was suggested to be due to the toxic effects of nitrite produced from nitrate respiration (the *Rahnella* sp. was unable to denitrify) in combination with the toxic effects of uranium. TEM images showed that uranium was initially associated with the cell surfaces, but over time it desorbed and precipitated extracellularly. This could be due to an initial reaction with the Gram-negative outer membrane/lipopolysaccharides before sufficient P_i generation, or due to the cells acting as a nucleation surface for biomineral precipitation.

Another experiment used pure cultures of bacteria isolated from sediments in an area with high levels of dissolved calcium (Shelobolina et al., 2009). Three strains, 99% similar to *Aeromonas hydrophila*, *Pantoea agglomerans* and *P. rhodesiae* were isolated which could remove uranium from solution under aerobic and nitrate-reducing conditions coupled to G3P hydrolysis. Analysis of the precipitate generated by the isolate closely related to *A. hydrophila* showed that uranium was incorporated within the mineral structure of hydroxyapatite. Approximately 16% of uranium was solubilised during five washing cycles meaning the majority was sequestered in the mineral phase. The authors explained that the combination of the high concentrations of Ca and circumneutral pH lead to hydroxyapatite precipitation rather than the Ca-autunite formed in previous experiments (Beazley et al., 2007).

Experiments with flow-through columns containing site sediment and synthetic groundwater amended with G3P demonstrated 97% removal of 200 μM U(VI) at pH 5.5 and 7.0 (Beazley et al., 2011). Most of the uranium was precipitated within 1 cm of the inlet. Control columns without glycerol phosphate removed 88–95% of the U(VI), presumably through sorption. Sequential extractions provided evidence for uranyl phosphate precipitation. XAS identified the uranium speciation as U(VI), which was mainly precipitated as uranyl phosphate minerals at pH 5.5, while at pH 7 it was mostly adsorbed to iron oxides with minor occurrences of uranyl phosphate precipitation. Similar results were obtained in anaerobic microcosm experiments (Salome et al., 2013). Almost all of the uranium and P_i released from G2P metabolism sorbed to sediments; XAS identified some U(VI)-phosphate but no evidence for U(VI) reduction was observed.

4.4. Limitations

All of the studies which demonstrate uranium biomineralisation via phosphatase activity have used glycerol phosphate as a carbon and phosphate source, either as glycerol-3-phosphate or glycerol-2-phosphate depending on commercial availability. Glycerol phosphate may not be cost effective for uranium biomineralisation (Roig et al., 1995; Lloyd and Macaskie, 2000). Alternative phosphate donors were tested for the *Serratia* system, but the enzyme in this organism was found to be substrate-specific (Michel et al., 1986). Bioreactors containing *E. coli* were able to liberate phosphate from phytic acid, which precipitated with uranyl nitrate as HUP, highlighting the potential for use of plant wastes as a source of P_i (Paterson-Beedle et al., 2010). Tributylphosphate (TBP), a solvent to extract actinides during nuclear fuel reprocessing, has been investigated as an alternative source of carbon and phosphorus in enrichment cultures (Thomas and Macaskie, 1996). A mixed culture containing *Pseudomonas* spp. was able to degrade TBP in the presence of U(VI), liberating 1-butanol for growth and releasing P_i which precipitated as uranyl phosphates. However, it is questionable whether introducing a solvent to groundwater would be considered a responsible remediation strategy.

Some evidence exists which indicates that if a system is phosphate-limited, bacteria can cause dissolution of uranyl phosphates such as autunite (Smeaton et al., 2008; Katsenovich et al., 2012). The ability of bacteria to reduce U(VI) in uranyl phosphate minerals has recently been assessed (Rui et al., 2013). Biogenic HUP associated with *Bacillus subtilis* and freely suspended abiotic HUP were incubated with dissimilatory metal-reducing bacteria in bicarbonate or HEPES buffer, with or without phosphate. U(IV) was produced, either in the form of adsorbed monomeric U(IV) or as an amorphous solid similar to ningyoite. The authors considered whether this was formed from solid phase U(VI) reduction, in which case the reduction rate should be proportional to HUP surface area, or dissolved phase U(VI) reduction where reduction rate would be proportional to the dissolution rate. A greater extent of reduction was observed with biogenic HUP, which had an effective surface area 27 times greater than abiotic HUP. More U(VI) reduction was observed in the presence of bicarbonate (which promotes HUP dissolution), while a lower extent of reduction was observed with phosphate. This suggests bacterial reduction of dissolved U(VI) rather than solid phase U(VI) in HUP, with precipitation of U(IV) driving further dissolution by disturbing the equilibrium between HUP and $\text{U(VI)}_{(\text{aq})}$. Similar dissolution controlled reduction of solid U(VI) has been observed using synthetic sodium boltwoodite (Liu et al., 2006) and intragrain sodium boltwoodite in contaminated Hanford sediments (Liu et al., 2009).

5. Other priority radionuclides

5.1. Technetium

Technetium ^{99}Tc is a long lived (half-life 212,000 years), high yield radioactive fission product produced as part of the nuclear fuel cycle.

Consequently it has contaminated groundwater at nuclear sites such as the US DOE Hanford site and Sellafield in the UK. Under oxic conditions in the natural environment, it is mobile as the highly soluble pertechnetate ion (Tc(VII)O_4^-) and is of concern both as a mobile radioactive contaminant and as a bioavailable analogue for sulfate (McBeth et al., 2007; Icenhower et al., 2010). Under reducing conditions it can form insoluble and strongly sorbing hydrous Tc(IV)O_2 phases. Therefore, bacterially-mediated reduction offers a promising strategy for removing soluble Tc(VII) from contaminated groundwater across a wide range of concentrations and has been demonstrated in laboratory experiments e.g. Law et al. (2010a) and Wilkins et al. (2007) and in the field (Istok et al., 2004).

5.1.1. Early work & mechanisms

Two mechanisms of Tc(VII) bioreduction have been identified; direct enzymatic reduction by microbial hydrogenases and indirect reduction by biogenic Fe(II) or sulfide (Lloyd et al., 2000a; Burke et al., 2005; McBeth et al., 2007). Given the low concentrations of Tc(VII) in the environment, indirect reduction by Fe(II) is likely to be the dominant mechanism (Lloyd et al., 1999a; McBeth et al., 2007), apart from in sediments with very low iron concentrations (Wildung et al., 2004). Indeed, novel gamma camera imaging techniques have shown Tc(VII) removal at picomolar concentrations (below the solubility limit for hydrous TcO_2 -like phase formation), and a direct link between biogenic Fe(II) and Tc(IV) (Lear et al., 2010; Vandehey et al., 2012). Much greater quantities of Tc(VII) were removed by *Geobacter*, *Anaeromyxobacter* and *Shewanella* in the presence of ferrihydrite compared to experiments with just cells, highlighting the importance of biogenic Fe(II) in Tc(VII) bioreduction (Plymale et al., 2011).

A number of bacteria have been identified that enzymatically reduce Tc(VII) coupled to the oxidation of H_2 or certain organic compounds (Fredrickson et al., 2004) including: the metal reducers *Geobacter* spp. (Lloyd and Macaskie, 1996; Lloyd et al., 2000a), *S. putrefaciens* (Wildung et al., 2000) and *A. dehalogenans* strain 2CP-C (Marshall et al., 2009); sulfate-reducing *Desulfovibrio* spp. (Lloyd et al., 1999b; De Luca et al., 2001); haloalkaliphilic *Halomonas* (Khijniak et al., 2003); acidophilic *Thiobacillus* spp. (Lyalikova and Khizhnyak, 1996); and *E. coli* (Lloyd et al., 1997). Electron transfer is mediated by periplasmic hydrogenase enzymes (Lloyd et al., 1997, 1999a,b; De Luca et al., 2001) although cytochromes may also facilitate electron transfer in *S. oneidensis* MR1 (Marshall et al., 2008).

Alternatively, abiotic reduction of Tc(VII) to Tc(IV) is possible, facilitated by Fe(II) biominerals generated from reduction of Fe(III) oxides (Lloyd et al., 2000a; Fredrickson et al., 2004). Biogenically produced magnetite was able to completely remove Tc(VII) from solution, while bio-vivianite and bio-siderite removed 68 and 84% respectively (McBeth et al., 2011). Abiotic reduction via Fe(II) minerals have now been documented in: the clay minerals nontronite (Jaisi et al., 2009; Yang et al., 2012) montmorillonite, nontronite, rectorite, mixed layered illite-smectite, illite, chlorite, and palygorskite (Bishop et al., 2011); amorphous iron sulfide (Liu et al., 2008); mackinawite (Wharton et al., 2000), Fe(II) sorbed to aluminium hydroxides (Peretyazhko et al., 2008); and in naturally reducing zones of aquifers containing Fe(II) minerals including Fe(II)-phylllosilicates, pyrite, magnetite and siderite (Peretyazhko et al., 2012). This is likely to be a dominant pathway for reduction in many environmental scenarios. Abiotic reduction of Tc(VII) by aqueous Fe(II) was found to be strongly pH dependent; complete and rapid removal of Tc(VII) was observed at pH 7 and 8, but not at pH 6 (Zachara et al., 2007).

5.1.2. Reduction and reoxidation studies

Sediment microcosms spiked with pertechnetate were able to completely remove Tc(VII) from solution during Fe(III)-reduction and precipitate hydrous TcO_2 (Burke et al., 2005). Removal of pertechnetate has been demonstrated in microcosm experiments using sediment from nuclear sites (McBeth et al., 2007; Wilkins et al., 2007; Begg et al., 2008;

Morris et al., 2008). The presence of nitrate and manganese is generally considered to inhibit the development of metal-reducing conditions. Tc(VII) removal was only observed after Fe(III)-reducing conditions had developed, and the presence of 100 mM nitrate prevented this from occurring (McBeth et al., 2007). Although acidic sediments failed to develop Fe(III)- and Tc(VII)-reducing conditions, denitrification of 10 mM nitrate caused the pH to rise from 5.5 to 7.2 which allowed progression to Fe(III)-reduction and Tc(VII) removal (Law et al., 2010a; Geissler et al., 2011). This change in pH did not occur with lower concentrations of nitrate. Tc removal has been reported under nitrate-reducing conditions in selected experiments (Fredrickson et al., 2004; Istok et al., 2004; Eagling et al., 2012).

Exposure of bioreduced sediments to air caused reoxidation of 40 to 80% Tc; the remaining amount was identified as a recalcitrant hydrous Tc(IV)O₂ solid phase and/or incorporated into new mineral phases formed on reoxidation (McBeth et al., 2007; Begg et al., 2008; Morris et al., 2008). The rate of Tc(VII) reduction and the susceptibility of bioreduced Tc(IV) to reoxidation via oxygen exposure have been investigated in sediments of different lithology (Fredrickson et al., 2009). Tc(VII) reduction was considerably faster in a fluvial sediment from Hanford compared to a saprolite from Oak Ridge, despite the saprolite containing a higher concentration of Fe(II). This may be because the saprolite contained Fe(II) associated with sheet silicate minerals, which is slower to react with pertechnetate compared to the Fe(II) sorbed to Fe(III) oxides in the fluvial sediment. Alternatively it could be due to mass transfer limitations in clayey sediments. Tc(IV) in the fluvial sediment was oxidised rapidly and completely on exposure to oxygen, but reoxidation was slow and incomplete in the clayey saprolite. These differences may be due to Tc(IV) forming reoxidation-resistant aggregates associated with Fe-containing mica (perhaps celadonite) in the saprolite. Biogenic TcO₂ has been shown to be susceptible to reoxidation by Mn(III/IV) oxides in anoxic but unreduced sediments (Fredrickson et al., 2004, 2009), although how this situation would arise in the natural environment is unclear. While humic acids increased the rate and extent of oxidative dissolution of TcO₂, the presence of EDTA decreased both (Gu et al., 2011). In contrast to oxygen exposure, addition of nitrate failed to remobilise Tc(IV) (McBeth et al., 2007; Wilkins et al., 2007; Begg et al., 2008; Morris et al., 2008). Failure of some Tc(IV) to be reoxidised may be due to it being protected by newly precipitated Fe(III) oxides (Zachara et al., 2007).

In summary, reduction of Tc(VII) facilitated by biogenic Fe(II) appears to be a promising bioremediation strategy for removing Tc from groundwater and fixing into insoluble minerals that are mostly resistant to oxidative remobilisation. Important factors to consider are: sediment mineralogy, with clayey sediments less susceptible to reoxidation; and sediment pH, as slightly acidic conditions appear to inhibit Tc removal.

5.2. Neptunium

Neptunium is an actinide produced by the decay of plutonium and americium. Although it is not a widespread groundwater contaminant at nuclear sites, it is of concern in nuclear wastes due to its high radiotoxicity and the long half-life (2.13×10^6 years) of its dominant isotope ²³⁷Np. Neptunium exists as the neptunyl cation Np(V)O₂⁺ in a wide range of environmental conditions; it sorbs relatively poorly to surfaces or microbial biomass and is therefore very mobile (Kaszuba and Runde, 1999). Np(IV) exists under reducing conditions, it is poorly soluble, has a strong tendency to form aqueous complexes and can be removed from solution by hydrolysis and reaction with surfaces.

Np(V) can be removed from solution via a combined bioreduction–biomineralisation system using anaerobic bacteria (Lloyd et al., 2000b). *S. putrefaciens* was able to reduce Np(V) to Np(IV), which then precipitated with phosphate liberated by phosphatase activity of a *Serratia* sp. Np(V) did not precipitate with *Serratia*-generated phosphate, or when solely reduced to Np(IV), hence a coupled system was required. Another study found that an anaerobic microbial consortium supplied with

hydrogen or pyruvate as an electron donor was able to reduce Np(V) and precipitate it as Np(IV) (Rittmann et al., 2002). *G. metallireducens* and *S. oneidensis* were both able to reduce aqueous Np(V)-citrate to aqueous Np(IV)-citrate, while only *S. oneidensis* was able to reduce unchelated Np(V) to insoluble Np(IV) (Icopini et al., 2007). This confirms earlier observations, that *G. sulfurreducens* was unable to reduce Np(V)O₂⁺ (Renshaw et al., 2005). As it reduced U(VI)O₂²⁺ by a single electron transfer to U(V), which rapidly disproportionated to U(IV), this suggests it is unable to transfer electrons to pentavalent actinides. This demonstrates the potentially important role played by organic ligands; they can make Np(V) less toxic to bacteria but allow Np(IV) complexes to remain in solution. Similar observations have been made for Cr(VI) in bioreducing systems (Mabbett et al., 2002). Microbially-active sediment systems were able to facilitate Np(V) reduction to Np(IV) when supplied with acetate as an electron donor (Law et al., 2010b). In a similar mechanism to that demonstrated for technetium, bioreduced Fe(II) in sterile sediments was shown to abiotically reduce Np(V) to poorly soluble Np(IV), suggesting abiotic reduction is possible for Np(V). Reoxidation experiments demonstrated the sediment-associated Np(IV) was somewhat resistant to remobilisation.

5.3. Plutonium

Plutonium is a long-lived toxic actinide produced by neutron activation of uranium. Kilogramme quantities of ²³⁹Pu (half-life 24,000 years) and ²⁴⁰Pu (half-life 6560 years) have been released into the environment (Morris et al., 2001). Plutonium has complex redox chemistry. The dominant oxidation state in most environments is Pu(IV), which forms a highly insoluble hydrous oxide Pu(OH)₄ and sorbs strongly to colloidal and suspended material (Banaszak et al., 1999; Choppin et al., 2002). In oxidising conditions, the most significant soluble state is the plutonyl cation Pu(V)O₂⁺, which has a lower tendency to be sorbed compared to Pu(IV) (Choppin, 2007). Under conditions relevant to natural waters, Pu can exist in multiple oxidation states simultaneously, meaning small changes in pH and redox can lead to changes in speciation and environmental mobility (Ewing, 2010).

Results from a study of porewaters indicated seasonal cycles in Fe, Mn and Pu may be influenced by non-redox driven microbial processes (Morris et al., 2001). Three laboratory studies have investigated the role played by Fe(III)-reducing bacteria *G. metallireducens* and *S. oneidensis* in Pu reduction (Boukhalfa et al., 2007; Icopini et al., 2009; Renshaw et al., 2009). Both bacteria could reduce aqueous Pu(V)/(VI) to insoluble nanocrystalline Pu(IV), while soluble Pu(III) was not produced. When supplied with amorphous Pu(IV)OH₄, *S. oneidensis* produced minor amounts of Pu(III) but *G. metallireducens* produced little (Boukhalfa et al., 2007). In contrast, both bacteria were able to rapidly reduce soluble Pu(IV)-EDTA to Pu(III)-EDTA, highlighting the importance of complexing ligands on Pu biogeochemistry. Other bacteria shown to reduce Pu(IV) to Pu(III) include *Clostridium* sp. (Francis et al., 2008), *Bacillus* sp. (Rusin et al., 1994), and *Bacillus mycoides* and *Serratia marcescens* (Luksiene et al., 2012). *Shewanella alga* reduced Pu(V)O₂⁺ to amorphous Pu(III)PO₄ (Reed et al., 2007; Deo et al., 2011). Finally, plutonium in contaminated sediments remained remarkably resistant to solubilisation throughout a cascade of anaerobic processes, including fermentation and Fe(III) reduction (Kimber et al., 2012).

5.4. Americium

Americium is an actinide produced by neutron activation of plutonium; ²⁴¹Am is the most common isotope with a half-life of 433 years. It exists as Am(III) under environmentally relevant conditions including in natural waters and is not subject to redox transformation (Choppin et al., 2002; Siegal and Bryan, 2003; Ewing, 2010). Americium readily sorbs to soils and sediments, consequently it has limited mobility in the environment and is not a target for in situ bioremediation. For completeness, documented biogeochemical interactions include biosorption

to marine algae (Fisher et al., 1983) and biomineralisation with biogenic phosphate produced by a *Serratia* sp. (Macaskie et al., 1994b).

5.5. Iodine

Radioactive iodine is produced as a fission product, with the isotope ^{129}I being of particular concern due to its long half-life (15.7×10^6 years), mobility in the environment and bioavailability. Iodine has a complex biogeochemistry with iodide (I^-), molecular iodine (I_2) and iodate (IO_3^-) all stable under environmental conditions, mobile in natural waters and forming a range of organic complexes (Gallard et al., 2009; Fox et al., 2010; Kaplan et al., 2011; Shetya et al., 2012). Mobile iodide predominates under reducing conditions, whereas in oxidising conditions iodate can be present and interact with organic matter and clays (Hu et al., 2007).

A wide range of soil organisms can convert iodide to volatile methyl iodide (CH_3I), and in some cases this activity is enhanced by the addition of organic carbon such as glucose (Amachi et al., 2003). Volatilisation of radioiodine from soils was confirmed using ^{125}I , while the role of microbes was confirmed as volatilisation was inhibited by the addition of bacterial-specific antibiotics. *D. desulfuricans* was able to enzymatically reduce iodate to iodide in bicarbonate and HEPES buffers, while *S. putrefaciens* was only able to perform this transformation in HEPES (Councell et al., 1997). As Fe(II), sulfide and FeS were shown to abiotically reduce iodate to iodide, it is inferred that Fe(III)- and sulfate-reducing bacteria are able to mediate iodate reduction both directly and indirectly.

Iodine speciation and transport was studied using representative surface soils and sediments collected at US nuclear facilities (Hu et al., 2007). Approximately 90% of iodine was present as organic species in soils, while inorganic iodine was important (up to 50%) only in sediments with low organic matter. An earlier study demonstrated the complex biogeochemical behaviour of iodine and emphasised the importance of structural Fe(II) in some clay minerals in mediating iodate reduction to iodide (Hu et al., 2005). The influence of iron minerals on iodine was further illustrated by data showing in situ bacteriogenic Fe(III) oxides at Chalk River, Canada were able to sorb 54% of iodine and 75% of ^{129}I from waters at near-neutral pH (Kennedy et al., 2011). Field tests demonstrated that iodide injected into the oxic zone of an aquifer was oxidised to iodine and iodate (Fox et al., 2010). Transport of iodate injected into an oxic aquifer zone was retarded, while iodate injected into an Fe(III)-reducing zone was rapidly reduced to iodide.

5.6. Strontium and caesium

Radioactive strontium and caesium are produced as fission products. Both have stable isotopes which are naturally occurring and ubiquitous in the natural environment. Neither strontium nor caesium are redox sensitive so their fate in the environment is mostly influenced sorption, although biotic interactions may play a role, for example by changing the pH or producing soluble ligands or new biomineral phases.

Several studies have demonstrated strontium biomineralisation via precipitation of strontium carbonate or calcite by actively metabolising microorganisms including *Pseudomonas fluorescens* (Anderson and Appanna, 1994), epilithic cyanobacteria (Ferris et al., 1995), *Halomonas* (Achal et al., 2012), *Sporosarcina pasteurii* (formerly *Bacillus pasteurii*) (Ferris et al., 2004; Fujita et al., 2004; Cuthbert et al., 2012), and indigenous groundwater bacteria (Fujita et al., 2010; Tobler et al., 2011). In most cases this occurs through carbonate generation linked to the hydrolysis of urea by ureolytic bacteria in the presence of calcium. Alternative bioremediation techniques proposed for strontium include sequestration as $(\text{Ba},\text{Sr})\text{SO}_4$ by desmid green algae (Krejci et al., 2011), incorporation into biogenic hydroxyapatite produced by a *Serratia* sp. (Handley-Sidhu et al., 2011a,b) and co-treatment with Tc(VII) and high nitrate levels via microbially induced increases in pH and alkalinity during bioreduction of Fe(III) and nitrate (Thorpe et al., 2012b).

Pure culture studies have shown that microbial biosorbents are inefficient for caesium uptake, but uptake by actively metabolising microorganisms is more efficient (Macaskie, 1991). Both K^+ and Cs^+ are taken up by the same metabolism-dependent transport systems due to the similarity of the cations. However in sediment systems, the mobility of Cs in the environment is dominated by cation-exchange processes at mineral surfaces, especially with phyllosilicates where Cs can form inner sphere complexes at edge sites. Indirect microbial impacts such as the release of competing ammonium ions or changes in mineral stability may play a role in controlling Cs mobility (Brookshaw et al., 2012).

6. Conclusions and future directions

Much research has been done on uranium biogeochemistry and bioremediation. Employment of bioreduction in particular appears promising, with state-of-the-art molecular techniques being developed to monitor progress and refine its application in the field. Indeed, field trials have shown sustained removal of U(VI) from groundwater. Questions do still remain however about the longevity of bioreduced U(IV). Although biomineralisation has been demonstrated to generate poorly soluble uranyl phosphates using pure bacterial cultures, results with soils from the Oak Ridge site have been dominated by sorption effects. Of the other priority radionuclides, technetium may be amenable to treatment by bioreduction and strontium amenable to biomineralisation.

Areas where research should continue include assessing which mechanisms of bacterial electron transport dominate, in both the natural environment and during biostimulation trials. There is still work to be done to determine the precise mechanism(s) of electron transfer to U(VI) in circumneutral aquifer sediments. The reduction of U(VI) at alkaline pH, especially the role played by Gram-positive bacteria should be explored in more detail, as should establishing conclusively whether bacteria are able to enzymatically reduce solid phase U(VI). Another area for future research is determining the longevity of bioreduced U(IV). This could be assessed by doing reoxidation experiments as part of field biostimulation trials, but crucial understanding is lacking in the factors which cause monomeric U(IV) or uraninite to precipitate. It is clear that precipitation of monomeric U(IV) is favoured under the conditions present at the Rifle site, however, as monomeric U(IV) is absent from the geological record and laboratory experiments have not demonstrated unequivocal evidence for an ageing mechanism, it is uncertain whether monomeric U(IV) is specific to that particular site or of wider significance. Field studies at alternative sites and/or in other countries could address this. In particular, uranium contamination in groundwater at mining or milling sites is an area which is yet to be examined. Application of uranium-phosphate biomineralisation in the field could be trialled, while if widespread use is indeed limited by the cost of glycerol phosphate, alternative organic phosphorus substrates should be investigated.

Overall it is clear that microbial cycling processes have a significant impact on radionuclide behaviour across a wide range of environments and will be important in managing contaminated land sites as well as in geological disposal scenarios where biogeochemical processes are likely to occur and should be considered in safety case development.

Acknowledgements

We acknowledge financial support from the Nuclear Decommissioning Authority via a PhD student bursary, managed by the National Nuclear Laboratory. JRL acknowledges the support of the Royal Society via an Industrial Fellowship. We also acknowledge financial support from NERC via the BIGRAD consortium (NE/H007768/1) and also via a BNFL Endowment which has supported the development of the Research Centre for Radwaste and Decommissioning.

References

- Abdelouas, A., Lu, Y., Lutz, W., Nuttall, H.E., 1998. Reduction of U(VI) to U(IV) by indigenous bacteria in contaminated ground water. *J. Contam. Hydrol.* 35, 217–233.
- Achal, V., Pan, X., Zhang, D., 2012. Bioremediation of strontium (Sr) contaminated aquifer quartz sand based on carbonate precipitation induced by Sr resistant *Halomonas* sp. *Chemosphere* 89 (6), 764–768.
- Ahmed, B., Cao, B., McLean, J.S., Ica, T., Dohnalkova, A., Istanbulu, O., Paksoy, A., Fredrickson, J.K., Beyenal, H., 2012a. Fe(III) Reduction and U(VI) immobilization by *Paenibacillus* sp. strain 300A, isolated from Hanford 300A subsurface sediments. *Appl. Environ. Microbiol.* 78, 8001–8009.
- Ahmed, B., Cao, B., Mishra, B., Boyanov, M.I., Kemner, K.M., Fredrickson, J.K., Beyenal, H., 2012b. Immobilization of U(VI) from oxic groundwater by Hanford 300 Area sediments and effects of Columbia River water. *Water Res.* 46, 3989–3998.
- Akob, D.M., Mills, H.J., Kostka, J.E., 2007. Metabolically active microbial communities in uranium-contaminated subsurface sediments. *FEMS Microbiol. Ecol.* 59, 95–107.
- Akob, D.M., Lee, S.H., Sheth, M., Kusel, K., Watson, D.B., Palumbo, A.V., Kostka, J.E., Chin, K.J., 2012. Gene expression correlates with process rates quantified for sulfate- and Fe(III)-reducing bacteria in U(VI)-contaminated sediments. *Front. Terr. Microbiol.* 3, 280.
- Alessi, D.S., Uster, B., Veeramani, H., Suvorova, E.I., Lezama-Pacheco, J.S., Stubbs, J.E., Bargar, J.R., Bernier-Latmani, R., 2012. Quantitative separation of monomeric U(IV) from UO₂ in products of U(VI) reduction. *Environ. Sci. Technol.* 46, 6150–6157.
- Amachi, S., Kasahara, M., Hanada, S., Kamagata, Y., Shinoyama, H., Fujii, T., Muramatsu, Y., 2003. Microbial participation in iodine volatilization from soils. *Environ. Sci. Technol.* 37, 3885–3890.
- Anderson, S., Appanna, V.D., 1994. Microbial formation of crystalline strontium carbonate. *FEMS Microbiol. Lett.* 116, 43–48.
- Anderson, R.T., Vronis, H.A., Ortiz-Bernad, I., Resch, C.T., Long, P.E., Dayvault, R., Karp, K., Marutzky, S., Metzler, D.R., Peacock, A., White, D.C., Lowe, M., Lovley, D.R., 2003. Stimulating the in situ activity of *Geobacter* species to remove uranium from the groundwater of a uranium-contaminated aquifer. *Appl. Environ. Microbiol.* 69, 5884–5891.
- Andersson, P.S., Porcelli, D., Gustafsson, Ö., Ingri, J., Wasserburg, G.J., 2001. The importance of colloids for the behavior of uranium isotopes in the low-salinity zone of a stable estuary. *Geochim. Cosmochim. Acta* 65, 13–25.
- Appukkuttan, D., Rao, A.S., Apte, S.K., 2007. Engineering of *Deinococcus radiodurans* R1 for bioprecipitation of uranium from dilute nuclear waste. *Appl. Environ. Microbiol.* 73, 1393.
- Baldwin, B.R., Peacock, A.D., Park, M., Ogles, D.M., Istok, J.D., McKinley, J.P., Resch, C.T., White, D.C., 2008. Multilevel samplers as microcosms to assess microbial response to biostimulation. *Ground Water* 46, 295–304.
- Banaszak, J.E., Rittmann, B.E., Reed, D.T., 1999. Subsurface interactions of actinide species and microorganisms: implications for the bioremediation of actinide-organic mixtures. *J. Radioanal. Nucl. Chem.* 241, 385–435.
- Bargar, J.R., Williams, K.H., Campbell, K.M., Long, P.E., Stubbs, J.E., Suvorova, E.I., Lezama-Pacheco, J.S., Alessi, D.S., Stylo, M., Webb, S.M., Davis, J.A., Giammar, D.E., Blue, L.Y., Bernier-Latmani, R., 2013. Uranium redox transition pathways in acetate-amended sediments. *Proc. Natl. Acad. Sci.* 110, 4506–4511.
- Barlett, M., Moon, H.S., Peacock, A.A., Hedrick, D.B., Williams, K.H., Long, P.E., Lovley, D., Jaffe, P.R., 2012a. Uranium reduction and microbial community development in response to stimulation with different electron donors. *Biodegradation* 23, 535–546.
- Barlett, M., Zhuang, K., Mahadevan, R., Lovley, D., 2012b. Integrative analysis of *Geobacter* spp. and sulfate-reducing bacteria during uranium bioremediation. *Biogeosciences* 9, 1033–1040.
- Basnakova, G., Stephens, E.R., Thaller, M.C., Rossolini, G.M., Macaskie, L.E., 1998. The use of *Escherichia coli* bearing a *phoN* gene for the removal of uranium and nickel from aqueous flows. *Appl. Microbiol. Biotechnol.* 50, 266–272.
- Beazley, M.J., Martinez, R.J., Sobecky, P.A., Webb, S.M., Taillefert, M., 2007. Uranium biomineralization as a result of bacterial phosphatase activity: insights from bacterial isolates from a contaminated subsurface. *Environ. Sci. Technol.* 41, 5701–5707.
- Beazley, M.J., Martinez, R.J., Sobecky, P.A., Webb, S.M., Taillefert, M., 2009. Nonreductive biomineralization of uranium(VI) phosphate via microbial phosphatase activity in anaerobic conditions. *Geomicrobiol. J.* 26, 431–441.
- Beazley, M.J., Martinez, R.J., Webb, S.M., Sobecky, P.A., Taillefert, M., 2011. The effect of pH and natural microbial phosphatase activity on the speciation of uranium in subsurface soils. *Geochim. Cosmochim. Acta* 75, 5648–5663.
- Begg, J.D.C., Burke, I.T., Charnock, J.M., Morris, K., 2008. Technetium reduction and reoxidation behaviour in Dounreay soils. *Radiochim. Acta* 96, 631–636.
- Begg, J.D.C., Burke, I.T., Lloyd, J.R., Boothman, C., Shaw, S., Charnock, J.M., Morris, K., 2011. Bioreduction behavior of U(VI) sorbed to sediments. *Geomicrobiol. J.* 28, 160–171.
- Behrends, T., Krawczyk-Barsch, E., Arnold, T., 2012. Implementation of microbial processes in the performance assessment of spent nuclear fuel repositories. *Appl. Geochem.* 27, 453–462.
- Beller, H.R., 2005. Anaerobic, nitrate-dependent oxidation of U(IV) oxide minerals by the chemolithoautotrophic bacterium *Thiobacillus denitrificans*. *Appl. Environ. Microbiol.* 71, 2170–2174.
- Benzerara, K., Miot, J., Morin, G., Ona-Nguema, G., Skouri-Panet, F., Féard, C., Féard, C., 2011. Significance, mechanisms and environmental implications of microbial biomineralization. *C. R. Geosci.* 343, 160–167.
- Bernier-Latmani, R., Veeramani, H., Vecchia, E.D., Junier, P., Lezama-Pacheco, J.S., Suvorova, E.I., Sharp, J.O., Wigginton, N.S., Bargar, J.R., 2010. Non-uraninite products of microbial U(IV) reduction. *Environ. Sci. Technol.* 44, 9456–9462.
- Beveridge, T.J., Murray, R.G., 1980. Sites of metal deposition in the cell wall of *Bacillus subtilis*. *J. Bacteriol.* 141, 876–887.
- Bishop, M.E., Dong, H.L., Kukkadapu, R.K., Liu, C.X., Edelman, R.E., 2011. Bioreduction of Fe-bearing clay minerals and their reactivity toward pertechnetate (Tc-99). *Geochim. Cosmochim. Acta* 75, 5229–5246.
- Bonthrone, K.M., Basnakova, G., Lin, F., Macaskie, L.E., 1996. Bioaccumulation of nickel by intercalation into polycrystalline hydrogen uranyl phosphate deposited via an enzymatic mechanism. *Nat. Biotechnol.* 14, 635–638.
- Boonchayaanant, B., Nayak, D., Du, X., Criddle, C.S., 2009. Uranium reduction and resistance to reoxidation under iron-reducing and sulfate-reducing conditions. *Water Res.* 43, 4652–4664.
- Bopp, C.J., Lundstrom, C.C., Johnson, T.M., Sanford, R.A., Long, P.E., Williams, K.H., 2010. Uranium ²³⁸U/²³⁵U isotope ratios as indicators of reduction: results from an in situ biostimulation experiment at Rifle, Colorado, U.S.A. *Environ. Sci. Technol.* 44, 5927–5933.
- Boukhalfa, H., Icopini, G.A., Reilly, S.D., Neu, M.P., 2007. Plutonium(IV) reduction by the metal-reducing bacteria *Geobacter metallireducens* GS15 and *Shewanella oneidensis* MR1. *Appl. Environ. Microbiol.* 73, 5897–5903.
- Boyanov, M.I., Fletcher, K.E., Kwon, M.J., Rui, X., O'Loughlin, E.J., Löffler, F.E., Kemner, K.M., 2011. Solution and microbial controls on the formation of reduced U(IV) species. *Environ. Sci. Technol.* 45, 8336–8344.
- Brooks, S.C., Fredrickson, J.K., Carroll, S.L., Kennedy, D.W., Zachara, J.M., Plymale, A.E., Kelly, S.D., Kemner, K.M., Fendorf, S., 2003. Inhibition of bacterial U(VI) reduction by calcium. *Environ. Sci. Technol.* 37, 1850–1858.
- Brookshaw, D.R., Patrick, R.A.D., Lloyd, J.R., Vaughan, D.J., 2012. Microbial effects on mineral-radiionuclide interactions and radionuclide solid-phase capture processes. *Mineral. Mag.* 76, 777–806.
- Brutinel, E., Gralnick, J., 2012. Shuttling happens: soluble flavin mediators of extracellular electron transfer in *Shewanella*. *Appl. Microbiol. Biotechnol.* 93, 41–48.
- Burgos, W.D., McDonough, J.T., Senko, J.M., Zhang, G., Dohnalkova, A.C., Kelly, S.D., Gorby, Y., Kemner, K.M., 2008. Characterization of uraninite nanoparticles produced by *Shewanella oneidensis* MR-1. *Geochim. Cosmochim. Acta* 72, 4901–4915.
- Burke, I.T., Boothman, C., Lloyd, J.R., Mortimer, R.J.G., Livens, F.R., Morris, K., 2005. Effects of progressive anoxia on the solubility of technetium in sediments. *Environ. Sci. Technol.* 39, 4109–4116.
- Burke, I.T., Boothman, C., Lloyd, J.R., Livens, F.R., Charnock, J.M., McBeth, J.M., Mortimer, R.J.G., Morris, K., 2006. Reoxidation behavior of technetium, iron, and sulfur in estuarine sediments. *Environ. Sci. Technol.* 40, 3529–3535.
- Callister, S.J., Wilkins, M.J., Nicora, C.D., Williams, K.H., Banfield, J.F., VerBerkmoes, N.C., Hettich, R.L., N'Guessan, L., Mouser, P.J., Elifantz, H., Smith, R.D., Loyley, D.R., Lipton, M.S., Long, P.E., 2010. Analysis of biostimulated microbial communities from two field experiments reveals temporal and spatial differences in proteome profiles. *Environ. Sci. Technol.* 44, 8897–8903.
- Campbell, K.M., Davis, J.A., Bargar, J., Giammar, D., Bernier-Latmani, R., Kukkadapu, R., Williams, K.H., Veramani, H., Ulrich, K.U., Stubbs, J., Yabusaki, S., Figueroa, L., Leshner, E., Wilkins, M.J., Peacock, A., Long, P.E., 2011a. Composition, stability, and measurement of reduced uranium phases for groundwater bioremediation at Old Rifle, CO. *Appl. Geochem.* 26, S167–S169.
- Campbell, K.M., Veeramani, H., Ulrich, K.U., Blue, L.Y., Giammar, D.E., Bernier-Latmani, R., Stubbs, J.E., Suvorova, E., Yabusaki, S., Lezama-Pacheco, J.S., Mehta, A., Long, P.E., Bargar, J.R., 2011b. Oxidative dissolution of biogenic uraninite in groundwater at Old Rifle, CO. *Environ. Sci. Technol.* 45, 8748–8754.
- Campbell, K.M., Kukkadapu, R.K., Qafoku, N.P., Peacock, A.D., Leshner, E., Williams, K.H., Bargar, J.R., Wilkins, M.J., Figueroa, L., Ranville, J., Davis, J.A., Long, P.E., 2012. Geochemical, mineralogical and microbiological characteristics of sediment from a naturally reduced zone in a uranium-contaminated aquifer. *Appl. Geochem.* 27, 1499–1511.
- Cardenas, E., Wu, W.M., Leigh, M.B., Carley, J., Carroll, S., Gentry, T., Luo, J., Watson, D., Gu, B., Ginder-Vogel, M., Kitanidis, P.K., Jardine, P.M., Zhou, J., Criddle, C.S., Marsh, T.L., Tiedje, J.A., 2008. Microbial communities in contaminated sediments, associated with bioremediation of uranium to submicromolar levels. *Appl. Environ. Microbiol.* 74, 3718–3729.
- Cardenas, E., Wu, W.M., Leigh, M.B., Carley, J., Carroll, S., Gentry, T., Luo, J., Watson, D., Gu, B.H., Ginder-Vogel, M., Kitanidis, P.K., Jardine, P.M., Zhou, J.Z., Criddle, C.S., Marsh, T.L., Tiedje, J.M., 2010. Significant association between sulfate-reducing bacteria and uranium-reducing microbial communities as revealed by a combined massively parallel sequencing-indicator species approach. *Appl. Environ. Microbiol.* 76, 6778–6786.
- Carlson, H.K., Iavarone, A.T., Gorur, A., Yeo, B.S., Tran, R., Melnyk, R.A., Mathies, R.A., Auer, M., Coates, J.D., 2012. Surface multiheme c-type cytochromes from *Thermincola potens* and implications for respiratory metal reduction by Gram-positive bacteria. *Proc. Natl. Acad. Sci.* 109, 1702–1707.
- Cason, E.D., Piater, L.A., van Heerden, E., 2012. Reduction of U(VI) by the deep subsurface bacterium *Thermoscutoductus* SA-01, and the involvement of the ABC transporter protein. *Chemosphere* 86, 572–577.
- Catalano, J.G., Heald, S.M., Zachara, J.M., Brown, G.E., 2004. Spectroscopic and diffraction study of uranium speciation in contaminated vadose zone sediments from the Hanford site, Washington state. *Environ. Sci. Technol.* 38, 2822–2828.
- Catalano, J.G., McKinley, J.P., Zachara, J.M., Heald, S.M., Smith, S.C., Brown, G.E., 2006. Changes in uranium speciation through a depth sequence of contaminated Hanford sediments. *Environ. Sci. Technol.* 40, 2517–2524.
- Cerrato, J.M., Ashner, M.N., Alessi, D.S., Lezama-Pacheco, J.S., Bernier-Latmani, R., Bargar, J.R., Giammar, D.E., 2013. Relative reactivity of biogenic and chemogenic uraninite and biogenic noncrystalline U(IV). *Environ. Sci. Technol.* 47, 9756–9763.
- Chandler, D.P., Kukhtin, A., Mokhiber, R., Knickerbocker, C., Ogles, D., Rudy, G., Golova, J., Long, P., Peacock, A., 2010. Monitoring microbial community structure and dynamics during in situ U(VI) bioremediation with a field-portable microarray analysis system. *Environ. Sci. Technol.* 44, 5516–5522.
- Chang, Y.-J., Long, P.E., Geyer, R., Peacock, A.D., Resch, C.T., Sublette, K., Pfiffner, S., Smithgall, A., Anderson, R.T., Vronis, H.A., Stephen, J.R., Dayvault, R., Ortiz-Bernad, I., Lovley, D.R., White, D.C., 2005. Microbial incorporation of ¹³C-labeled acetate at the field scale: detection of microbes responsible for reduction of U(VI). *Environ. Sci. Technol.* 39, 9039–9048.

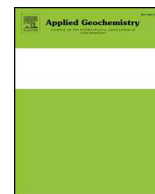
- Childers, S.E., Ciuffo, S., Lovley, D.R., 2002. *Geobacter metallireducens* accesses insoluble Fe(III) oxide by chemotaxis. *Nature* 416, 767–769.
- Cho, K., Zhou, A., Frabutt, D., Flood, M., Floyd, D., Tiquia, S.M., 2012. Linking bacterial diversity and geochemistry of uranium-contaminated groundwater. *Environ. Technol.* 33, 1629–1640.
- Choi, M.-S., Cho, K.-S., Kim, D.-S., Ryu, H.-W., 2005. Bioleaching of uranium from low grade black schists by *Acidithiobacillus ferrooxidans*. *World J. Microbiol. Biotechnol.* 21, 377–380.
- Choppin, G.R., 2007. Actinide speciation in the environment. *J. Radioanal. Nucl. Chem.* 273, 695–703.
- Choppin, G., Liljenzin, J.-O., Rydberg, J., 2002. Chapter 22. Behavior of radionuclides in the environment, Radiochemistry and Nuclear Chemistry, Third edition. Butterworth-Heinemann, London, pp. 653–685.
- Choudhary, S., Sar, P., 2011. Uranium biomineralization by a metal resistant *Pseudomonas aeruginosa* strain isolated from contaminated mine waste. *J. Hazard. Mater.* 186, 336–343.
- Cologgi, D.L., Lampa-Pastirk, S., Speers, A.M., Kelly, S.D., Reguera, G., 2011. Extracellular reduction of uranium via *Geobacter* conductive pili as a protective cellular mechanism. *Proc. Natl. Acad. Sci. U. S. A.* 108, 15248–15252.
- Council, T., Landa, E., Lovley, D., 1997. Microbial reduction of iodate. *Water Air Soil Pollut.* 100, 99–106.
- Cuthbert, M.O., Riley, M.S., Handley-Sidhu, S., Renshaw, J.C., Tobler, D.J., Phoenix, V.R., Mackay, R., 2012. Controls on the rate of ureolysis and the morphology of carbonate precipitated by *S. pasteurii* biofilms and limits due to bacterial encapsulation. *Ecol. Eng.* 41, 32–40.
- Dalla Vecchia, E.C., Veeramani, H., Suvorova, E.I., Wigginton, N.S., Bargar, J.R., Bernier-Latmani, R., 2010. U(VI) reduction by spores of *Clostridium acetobutylicum*. *Res. Microbiol.* 161, 765–771.
- Dar, S.A., Tan, H., Peacock, A.D., Jaffe, P., N'Guessan, L., Williams, K.H., Strycharz-Claven, S., 2013. Spatial distribution of *Geobacteraceae* and sulfate-reducing bacteria during in situ bioremediation of uranium-contaminated groundwater. *Remediat. J.* 23, 31–49.
- Davis, J.A., Meece, D.E., Kohler, M., Curtis, G.P., 2004. Approaches to surface complexation modeling of uranium(VI) adsorption on aquifer sediments. *Geochim. Cosmochim. Acta* 68, 3621–3641.
- De Luca, G., De Philip, P., Dermoun, Z., Rousset, M., Vermeglio, A., 2001. Reduction of technetium(VII) by *Desulfovibrio fructosovorans* is mediated by the nickel-iron hydrogenase. *Appl. Environ. Microbiol.* 67, 4583–4587.
- Deo, R.P., Rittmann, B.E., Reed, D.T., 2011. Bacterial Pu(V) reduction in the absence and presence of Fe(III)-NTA: modeling and experimental approach. *Biodegradation* 22, 921–929.
- DiChristina, T.J., 1992. Effects of nitrate and nitrite on dissimilatory iron reduction by *Shewanella putrefaciens* 200. *J. Bacteriol.* 174, 1891–1896.
- Docrat, T.I., Mosselmans, J.F.W., Charnock, J.M., Whiteley, M.W., Collison, D., Livens, F.R., Jones, C., Edmiston, M.J., 1999. X-ray absorption spectroscopy of tricarbonatodioxouranate(V), $[\text{UO}_2(\text{CO}_3)_3]^{5-}$, in aqueous solution. *Inorg. Chem.* 38, 1879–1882.
- Eagling, J., Worsfold, P.J., Blake, W.H., Keith-Roach, M.J., 2012. Mobilization of technetium from reduced sediments under seawater inundation and intrusion scenarios. *Environ. Sci. Technol.* 46, 11798–11803.
- Ehrlich, H.L., 1990. *Geomicrobiology*, 2nd edition. Marcel Dekker.
- Ewing, R.C., 2010. Environmental impact of the nuclear fuel cycle: fate of actinides. *MRS Bull.* 35, 859–866.
- Fang, Y.L., Yabusaki, S.B., Morrison, S.J., Amonette, J.P., Long, P.E., 2009. Multicomponent reactive transport modeling of uranium bioremediation field experiments. *Geochim. Cosmochim. Acta* 73, 6029–6051.
- Fang, Y., Wilkins, M.J., Yabusaki, S.B., Lipton, M.S., Long, P.E., 2012. Evaluation of a genome-scale *in silico* metabolic model for *Geobacter metallireducens* by using proteomic data from a field biostimulation experiment. *Appl. Environ. Microbiol.* 78, 8735–8742.
- Ferris, F.G., Frattol, C.M., Gerits, J.P., Schultze-Lam, S., Lollar, B.S., 1995. Microbial precipitation of a strontium calcite phase at a groundwater discharge zone near Rock Creek, British Columbia, Canada. *Geomicrobiol. J.* 13, 57–67.
- Ferris, F.G., Phoenix, V., Fujita, Y., Smith, R.W., 2004. Kinetics of calcite precipitation induced by ureolytic bacteria at 10 to 20 °C in artificial groundwater. *Geochim. Cosmochim. Acta* 68, 1701–1710.
- Finneran, K.T., Anderson, R.T., Nevin, K.P., Lovley, D.R., 2002a. Potential for bioremediation of uranium-contaminated aquifers with microbial U(VI) reduction. *Soil Sediment Contam.* 11, 339–357.
- Finneran, K.T., Housewright, M.E., Lovley, D.R., 2002b. Multiple influences of nitrate on uranium solubility during bioremediation of uranium-contaminated subsurface sediments. *Environ. Microbiol.* 4, 510–516.
- Fisher, N.S., Bjerregaard, P., Huynh-Ngoc, L., Harvey, G.R., 1983. Interactions of marine plankton with transuranic elements. II. Influence of dissolved organic compounds on americium and plutonium accumulation in a diatom. *Mar. Chem.* 13, 45–56.
- Fletcher, K.E., Boyanov, M.I., Thomas, S.H., Wu, Q., Kemner, K.M., Löffler, F.E., 2010. U(VI) reduction to mononuclear U(IV) by *Desulfotobacterium* species. *Environ. Sci. Technol.* 44, 4705–4709.
- Fox, P.M., Kent, D.B., Davis, J.A., 2010. Redox transformations and transport of cesium and iodine (−1, 0, +5) in oxidizing and reducing zones of a sand and gravel aquifer. *Environ. Sci. Technol.* 44, 1940–1946.
- Fox, P.M., Davis, J.A., Kukkadapu, R., Singer, D.M., Bargar, J., Williams, K.H., 2013. Abiotic U(VI) reduction by sorbed Fe(II) on natural sediments. *Geochim. Cosmochim. Acta* 117, 266–282.
- Francis, A.J., Dodge, C.J., Lu, F., Halada, G.P., Clayton, C.R., 1994. XPS and XANES studies of uranium reduction by *Clostridium* sp. *Environ. Sci. Technol.* 28, 636–639.
- Francis, A.J., Dodge, C.J., Gillow, J.B., 2008. Reductive dissolution of Pu(IV) by *Clostridium* sp. under anaerobic conditions. *Environ. Sci. Technol.* 42, 2355–2360.
- Fredrickson, J.K., Zachara, J.M., Kennedy, D.W., Duff, M.C., Gorby, Y.A., Li, S.W., Krupka, K.M., 2000. Reduction of U(VI) in goethite (α -FeOOH) suspensions by a dissimilatory metal-reducing bacterium. *Geochim. Cosmochim. Acta* 64, 3085–3098.
- Fredrickson, J.K., Zachara, J.M., Kennedy, D.W., Liu, C.X., Duff, M.C., Hunter, D.B., Dohnalkova, A., 2002. Influence of Mn oxides on the reduction of uranium(VI) by the metal-reducing bacterium *Shewanella putrefaciens*. *Geochim. Cosmochim. Acta* 66, 3247–3262.
- Fredrickson, J.K., Zachara, J.M., Kennedy, D.W., Kukkadapu, R.K., McKinley, J.P., Heald, S.M., Liu, C.X., Plymale, A.E., 2004. Reduction of TeO_4^{2-} by sediment-associated biogenic Fe(II). *Geochim. Cosmochim. Acta* 68, 3171–3187.
- Fredrickson, J.K., Zachara, J.M., Plymale, A.E., Heald, S.M., McKinley, J.P., Kennedy, D.W., Liu, C., Nachimuthu, P., 2009. Oxidative dissolution potential of biogenic and abiogenic TeO_2 in subsurface sediments. *Geochim. Cosmochim. Acta* 73, 2299–2313.
- Fujita, Y., Redden, G.D., Ingram, J.C., Cortez, M.M., Ferris, F.G., Smith, R.W., 2004. Strontium incorporation into calcite generated by bacterial ureolysis. *Geochim. Cosmochim. Acta* 68, 3261–3270.
- Fujita, Y., Taylor, J.L., Wendt, L.M., Reed, D.W., Smith, R.W., 2010. Evaluating the potential of native ureolytic microbes to remediate a ^{90}Sr contaminated environment. *Environ. Sci. Technol.* 44, 7652–7658.
- Gadd, G.M., 2009. Biosorption: critical review of scientific rationale, environmental importance and significance for pollution treatment. *J. Chem. Technol. Biotechnol.* 84, 13–28.
- Gallard, H., Allard, S., Nicolau, R., von Gunten, U., Croue, J.P., 2009. Formation of iodinated organic compounds by oxidation of iodide-containing waters with manganese dioxide. *Environ. Sci. Technol.* 43, 7003–7009.
- Gavrilov, S.N., Lloyd, J.R., Kostrikina, N.A., Slobodkin, A.I., 2012. Fe(III) oxide reduction by a Gram-positive thermophile: physiological mechanisms for dissimilatory reduction of poorly crystalline Fe(III) oxide by a thermophilic Gram-positive bacterium *Carboxydotherrmus ferrireducens*. *Geomicrobiol. J.* 29, 804–819.
- Geissler, A., Law, G.T.W., Boothman, C., Morris, K., Burke, I.T., Livens, F.R., Lloyd, J.R., 2011. Microbial communities associated with the oxidation of iron and technetium in bioreduced sediments. *Geomicrobiol. J.* 28, 507–518.
- Gibring, T.M., Zhang, G.X., Brandt, C.C., Brooks, S.C., Campbell, J.H., Carroll, S., Criddle, C.S., Green, S.J., Jardine, P., Kostka, J.E., Lowe, K., Mehlhorn, T.L., Overholt, W., Watson, D.B., Yang, Z.M., Wu, W.M., Schadt, C.W., 2011. A limited microbial consortium is responsible for extended bioreduction of uranium in a contaminated aquifer. *Appl. Environ. Microbiol.* 77, 5955–5965.
- Ginder-Vogel, M., Criddle, C.S., Fendorf, S., 2006. Thermodynamic constraints on the oxidation of biogenic UO_2 by Fe(III) (hydr)oxides. *Environ. Sci. Technol.* 40, 3544–3550.
- Gorby, Y.A., Lovley, D.R., 1992. Enzymatic uranium precipitation. *Environ. Sci. Technol.* 26, 205–207.
- Green, S.J., Prakash, O., Jasrotia, P., Overholt, W.A., Cardenas, E., Hubbard, D., Tiedje, J.M., Watson, D.B., Schadt, C.W., Brooks, S.C., Kostka, J.E., 2012. Denitrifying bacteria from the genus *Rhodanobacter* dominate bacterial communities in the highly contaminated subsurface of a nuclear legacy waste site. *Appl. Environ. Microbiol.* 78, 1039–1047.
- Gu, B.H., Dong, W.M., Liang, L.Y., Wall, N.A., 2011. Dissolution of technetium(IV) oxide by natural and synthetic organic ligands under both reducing and oxidizing conditions. *Environ. Sci. Technol.* 45, 4771–4777.
- Handley, K.M., Wrighton, K.C., Piceno, Y.M., Andersen, G.L., Desantis, T.Z., Williams, K.H., Wilkins, M.J., N'Guessan, A.L., Peacock, A., Bargar, J., Long, P.E., Banfield, J.F., 2012. High-density PhyloChip profiling of stimulated aquifer microbial communities reveals a complex response to acetate amendment. *FEMS Microbiol. Ecol.* 81 (1), 188–204.
- Handley-Sidhu, S., Keith-Roach, M.J., Lloyd, J.R., Vaughan, D.J., 2010. A review of the environmental corrosion, fate and bioavailability of munitions grade depleted uranium. *Sci. Total Environ.* 408, 5690–5700.
- Handley-Sidhu, S., Renshaw, J.C., Moriama, S., Stolpe, B., Mennan, C., Bagheriasl, S., Yong, P., Stamboulis, A., Paterson-Beedle, M., Sasaki, K., Patrick, R.A.D., Lead, J.R., Macaskie, L.E., 2011a. Uptake of Sr^{2+} and Co^{2+} into biogenic hydroxylapatite: implications for biomineral ion exchange synthesis. *Environ. Sci. Technol.* 45, 6985–6990.
- Handley-Sidhu, S., Renshaw, J.C., Yong, P., Kerley, R., Macaskie, L.E., 2011b. Nano-crystalline hydroxylapatite bio-mineral for the treatment of strontium from aqueous solutions. *Biotechnol. Lett.* 33, 79–87.
- Hirota, R., Kuroda, A., Kato, J., Ohtake, H., 2010. Bacterial phosphate metabolism and its application to phosphorus recovery and industrial bioprocesses. *J. Biosci. Bioeng.* 109, 423–432.
- Holmes, D.E., Giloteaux, L., Barlett, M., Chavan, M.A., Smith, J.A., Williams, K.H., Wilkins, M., Long, P., Lovley, D.R., 2013a. Molecular analysis of the in situ growth rates of subsurface *Geobacter* species. *Appl. Environ. Microbiol.* 79, 1646–1653.
- Holmes, D.E., Giloteaux, L., Williams, K.H., Wrighton, K.C., Wilkins, M.J., Thompson, C.A., Roper, T.J., Long, P.E., Lovley, D.R., 2013b. Enrichment of specific protozoan populations during in situ bioremediation of uranium-contaminated groundwater. *ISME J.* 7 (7), 1286–1298.
- Hsi, C.D., Langmuir, D., 1985. Adsorption of uranyl onto ferric oxyhydroxides: application of the surface complexation site-binding model. *Geochim. Cosmochim. Acta* 49, 1931–1941.
- Hu, Q., Zhao, P., Moran, J.E., Seaman, J.C., 2005. Sorption and transport of iodine species in sediments from the Savannah River and Hanford Sites. *J. Contam. Hydrol.* 78, 185–205.
- Hu, Q., Moran, J.E., Blackwood, V., 2007. Geochemical cycling of iodine species in soils. *Hyun, S.P., Davis, J.A., Sun, K., Hayes, K.F., 2012. Uranium(VI) reduction by iron(II) monosulfide mackinawite. Environ. Sci. Technol.* 46, 3369–3376.
- Icenhower, J.P., Qafoku, N.P., Zachara, J.M., Martin, W.J., 2010. The biogeochemistry of technetium: a review of the behavior of an artificial element in the natural environment. *Am. J. Sci.* 310, 721–752.
- Icopini, G.A., Boukhalfa, H., Neu, M.P., 2007. Biological reduction of Np(V) and Np(V) citrate by metal-reducing bacteria. *Environ. Sci. Technol.* 41, 2764–2769.

- Icopini, G.A., Lack, J.G., Hersman, L.E., Neu, M.P., Boukhalfa, H., 2009. Plutonium(V/VI) reduction by the metal-reducing bacteria *Geobacter metallireducens* GS-15 and *Shewanella oneidensis* MR-1. *Appl. Environ. Microbiol.* 75, 3641–3647.
- Ilton, E.S., Pacheco, J.S.L., Bargar, J.R., Shi, Z., Liu, J., Kovarik, L., Engelhard, M.H., Felmy, A.R., 2012. Reduction of U(VI) incorporated in the structure of hematite. *Environ. Sci. Technol.* 46, 9428–9436.
- Istok, J.D., Senko, J.M., Krumholz, L.R., Watson, D., Bogle, M.A., Peacock, A., Chang, Y.J., White, D.C., 2004. In situ bioreduction of technetium and uranium in a nitrate-contaminated aquifer. *Environ. Sci. Technol.* 38, 468–475.
- Istok, J.D., Park, M., Michalsen, M., Spain, A.M., Krumholz, L.R., Liu, C., McKinley, J., Long, P., Roden, E., Peacock, A.D., Baldwin, B., 2010. A thermodynamically-based model for predicting microbial growth and community composition coupled to system geochemistry: application to uranium bioreduction. *J. Contam. Hydrol.* 112, 1–14.
- Jaisi, D.P., Dong, H.L., Plymale, A.E., Fredrickson, J.K., Zachara, J.M., Heald, S., Liu, C.X., 2009. Reduction and long-term immobilization of technetium by Fe(II) associated with clay mineral nontronite. *Chem. Geol.* 264, 127–138.
- Jeon, B.H., Kelly, S.D., Kemner, K.M., Barnett, M.O., Burgos, W.D., Dempsey, B.A., Roden, E.E., 2004. Microbial reduction of U(VI) at the solid–water interface. *Environ. Sci. Technol.* 38, 5649–5655.
- Jeong, B.C., Hawes, C., Bonthron, K.M., Macaskie, L.E., 1997. Localization of enzymically enhanced heavy metal accumulation by *Citrobacter* sp. and metal accumulation in vitro by liposomes containing entrapped enzyme. *Microbiology* 143, 2497–2507.
- Jiang, S., Kim, M.-G., Kim, S.-J., Jung, H.S., Lee, S.W., Noh, D.Y., Sadowsky, M.J., Hur, H.-G., 2011. Bacterial formation of extracellular U(VI) nanowires. *Chem. Commun.* 47, 8076–8078.
- Junier, P., Fruttschi, M., Wigginton, N.S., Schofield, E.J., Bargar, J.R., Bernier-Latmani, R., 2009. Metal reduction by spores of *Desulfotomaculum reducens*. *Environ. Microbiol.* 11, 3007–3017.
- Kaplan, D.L., Roberts, K.A., Schwehr, K.A., Lilley, M.S., Brinkmeyer, R., Denham, M.E., Diprete, D., Li, H.P., Powell, B.A., Xu, C., Yeager, C.M., Zhang, S.J., Santschi, P.H., 2011. Evaluation of a radioiodine plume increasing in concentration at the Savannah River site. *Environ. Sci. Technol.* 45, 489–495.
- Kaszuba, J.P., Runde, W.H., 1999. The aqueous geochemistry of neptunium: dynamic control of soluble concentrations with applications to nuclear waste disposal. *Environ. Sci. Technol.* 33, 4427–4433.
- Katsenovich, Y.P., Carvajal, D.A., Wellman, D.M., Lagos, L.E., 2012. Enhanced U(VI) release from autinite mineral by aerobic *Arthrobacter* sp. in the presence of aqueous bicarbonate. *Chem. Geol.* 308–309, 1–9.
- Kazy, S.K., D'Souza, S.F., Sar, P., 2009. Uranium and thorium sequestration by a *Pseudomonas* sp.: mechanism and chemical characterization. *J. Hazard. Mater.* 163, 65–72.
- Kelly, S.D., Kemner, K.M., Carley, J., Criddle, C., Jardine, P.M., Marsh, T.L., Phillips, D., Watson, D., Wu, W.-M., 2008. Speciation of uranium in sediments before and after in situ biostimulation. *Environ. Sci. Technol.* 42, 1558–1564.
- Kelly, S.D., Wu, W.-M., Yang, F., Criddle, C.S., Marsh, T.L., O'Loughlin, E.J., Ravel, B., Watson, D., Jardine, P.M., Kemner, K.M., 2009. Uranium transformations in static microcosms. *Environ. Sci. Technol.* 44, 236–242.
- Kennedy, C.B., Gault, A.G., Fortin, D., Clark, I.D., Ferris, F.G., 2011. Retention of iodide by bacteriogenic iron oxides. *Geomicrobiol. J.* 28, 387–395.
- Kerkhof, L.J., Williams, K.H., Long, P.E., McGuinness, L.R., 2011. Phase preference by active, acetate-utilizing bacteria at the Rifle, CO Integrated Field Research Challenge site. *Environ. Sci. Technol.* 45, 1250–1256.
- Khijniak, T.V., Medvedeva-Lyalikova, N.N., Simonoff, M., 2003. Reduction of pertechnetate by haloalkaliphilic strains of *Halomonas*. *FEMS Microbiol. Ecol.* 44, 109–115.
- Khijniak, T.V., Slobodkin, A.L., Coker, V., Renshaw, J.C., Livens, F.R., Bonch-Osmolovskaya, E.A., Birkeland, N.K., Medvedeva-Lyalikova, N.N., Lloyd, J.R., 2005. Reduction of uranium(VI) phosphate during growth of the thermophilic bacterium *Thermoterrabacterium ferrireducens*. *Appl. Environ. Microbiol.* 71, 6423–6426.
- Kimber, R.L., Boothman, C., Purdie, P., Livens, F.R., Lloyd, J.R., 2012. Biogeochemical behaviour of plutonium during anoxic biostimulation of contaminated sediments. *Mineral. Mag.* 76, 567–578.
- Knopp, R., Panak, P.J., Wray, L.A., Renninger, N.S., Keasling, J.D., Nitsche, H., 2003. Laser spectroscopic studies of interactions of U(VI) with bacterial phosphate species. *Chem. Eur. J.* 9, 2812–2818.
- Ko, W.-H., Hora, F.K., 1970. Production of phospholipases by soil micro-organisms. *Soil Sci.* 110, 355–358.
- Koch-Steindl, H., Pröhl, G., 2001. Considerations on the behaviour of long-lived radionuclides in the soil. *Radiat. Environ. Biophys.* 40, 93–104.
- Komlos, J., Peacock, A., Kukkadapu, R.K., Jaffe, P.R., 2008. Long-term dynamics of uranium reduction/reoxidation under low sulfate conditions. *Geochim. Cosmochim. Acta* 72, 3603–3615.
- Krejci, M.R., Finney, L., Vogt, S., Joester, D., 2011. Selective sequestration of strontium in desmid green algae by biogenic co-precipitation with barite. *ChemSusChem* 4, 470–473.
- Langmuir, D., 1978. Uranium solution–mineral equilibria at low temperatures with applications to sedimentary ore deposits. *Geochim. Cosmochim. Acta* 42, 547–569.
- Langmuir, D., 1997. *Aqueous Environmental Geochemistry*. Prentice Hall, New Jersey, USA.
- Latta, D.E., Boyanov, M.I., Kemner, K.M., O'Loughlin, E.J., Scherer, M.M., 2012. Abiotic reduction of uranium by Fe(II) in soil. *Appl. Geochem.* 27, 1512–1524.
- Law, G.T.W., Geissler, A., Boothman, C., Burke, I.T., Livens, F.R., Lloyd, J.R., Morris, K., 2010a. Role of nitrate in conditioning aquifer sediments for technetium bioreduction. *Environ. Sci. Technol.* 44, 150–155.
- Law, G.T.W., Geissler, A., Lloyd, J.R., Livens, F.R., Boothman, C., Begg, J.D.C., Denecke, M.A., Rothe, J., Dardenne, K., Burke, I.T., Charnock, J.M., Morris, K., 2010b. Geomicrobiological redox cycling of the transuranic element neptunium. *Environ. Sci. Technol.* 44, 8924–8929.
- Law, G.T.W., Geissler, A., Burke, I.T., Livens, F.R., Lloyd, J.R., McBeth, J.M., Morris, K., 2011. Uranium redox cycling in sediment and biomineral systems. *Geomicrobiol. J.* 28, 497–506.
- Leang, C., Qian, X., Mester, T., Lovley, D.R., 2010. Alignment of the c-type cytochrome OmcS along pili of *Geobacter sulfurreducens*. *Appl. Environ. Microbiol.* 76, 4080–4084.
- Lear, G., McBeth, J.M., Boothman, C., Gunning, D.J., Ellis, B.L., Lawson, R.S., Morris, K., Burke, I.T., Bryan, N.D., Brown, A.P., Livens, F.R., Lloyd, J.R., 2010. Probing the biogeochemical behavior of technetium using a novel nuclear imaging approach. *Environ. Sci. Technol.* 44, 156–162.
- Lee, S.Y., Baik, M.H., Choi, J.W., 2010. Biogenic formation and growth of uraninite (UO₂). *Environ. Sci. Technol.* 44, 8409–8414.
- Li, L., Steefel, C.I., Williams, K.H., Wilkins, M.J., Hubbard, S.S., 2009. Mineral transformation and biomass accumulation associated with uranium bioremediation at Rifle, Colorado. *Environ. Sci. Technol.* 43, 5429–5435.
- Li, L., Steefel, C.I., Kowalsky, M.B., Englert, A., Hubbard, S.S., 2010. Effects of physical and geochemical heterogeneities on mineral transformation and biomass accumulation during biostimulation experiments at Rifle, Colorado. *J. Contam. Hydrol.* 112, 45–63.
- Li, L., Gawande, N., Kowalsky, M.B., Steefel, C.I., Hubbard, S.S., 2011. Physicochemical heterogeneity controls on uranium bioreduction rates at the field scale. *Environ. Sci. Technol.* 45, 9959–9966.
- Liang, Y.T., Van Nostrand, J.D., N'Guessan, A., Peacock, A.D., Deng, Y., Long, P.E., Resch, C.T., Wu, L.Y., He, Z.L., Li, G.H., Hazen, T.C., Lovley, D.R., Zhou, J.Z., 2012. Microbial functional gene diversity with a shift of subsurface redox conditions during in situ uranium reduction. *Appl. Environ. Microbiol.* 78, 2966–2972.
- Lim, B.L., Yeung, P., Cheng, C., Hill, J.E., 2007. Distribution and diversity of phytate-mineralizing bacteria. *ISME J.* 1, 321–330.
- Lin, X.J., Kennedy, D., Fredrickson, J., Bjornstad, B., Konopka, A., 2012. Vertical stratification of subsurface microbial community composition across geological formations at the Hanford Site. *Environ. Microbiol.* 14, 414–425.
- Liu, C.X., Jeon, B.-H.H., Zachara, J.M., Wang, Z.M., Dohnalkova, A., Fredrickson, J.K., 2006. Kinetics of microbial reduction of solid phase U(VI). *Environ. Sci. Technol.* 40, 6290–6296.
- Liu, Y., Terry, J., Jurisson, S., 2008. Pertechnetate immobilization with amorphous iron sulfide. *Radiochim. Acta* 96, 823–833.
- Liu, C.X., Zachara, J.M., Zhong, L.R., Heald, S.M., Wang, Z.M., Jeon, B.-H.H., Fredrickson, J.K., 2009. Microbial reduction of intragrain U(VI) in contaminated sediment. *Environ. Sci. Technol.* 43, 4928–4933.
- Lloyd, J.R., Gadd, G.M., 2011. The geomicrobiology of radionuclides. *Geomicrobiol. J.* 28, 383–386.
- Lloyd, J.R., Macaskie, L.E., 1996. A novel PhosphorImager-based technique for monitoring the microbial reduction of technetium. *Appl. Environ. Microbiol.* 62, 578–582.
- Lloyd, J.R., Macaskie, L.E., 2000. Bioremediation of radionuclide-containing wastewaters. In: Lovley, D.R. (Ed.), *Environmental Microbe–Metal Interactions*. ASM Press, Washington D. C., pp. 277–327.
- Lloyd, J.R., Renshaw, J.C., 2005. Microbial transformations of radionuclides: fundamental mechanisms and biogeochemical implications. In: Siegal, A., Siegal, H., Siegal, R.K.O. (Eds.), *Metal Ions in Biological Systems. Biogeochemistry, Availability and Transport of Metals in the Environment*, volume 44. M. Dekker, New York, pp. 205–240.
- Lloyd, J.R., Cole, J.A., Macaskie, L.E., 1997. Reduction and removal of heptavalent technetium from solution by *Escherichia coli*. *J. Bacteriol.* 179, 2014–2021.
- Lloyd, J.R., Ridley, J., Khizniak, T., Lyalikova, N.N., Macaskie, L.E., 1999a. Reduction of technetium by *Desulfovibrio desulfuricans*: biocatalyst characterization and use in a flowthrough bioreactor. *Appl. Environ. Microbiol.* 65, 2691–2696.
- Lloyd, J.R., Thomas, G.H., Finlay, J.A., Cole, J.A., Macaskie, L.E., 1999b. Microbial reduction of technetium by *Escherichia coli* and *Desulfovibrio desulfuricans*: enhancement via the use of high-activity strains and effect of process parameters. *Biotechnol. Bioeng.* 66, 122–130.
- Lloyd, J.R., Sole, V.A., Van Praagh, C.V.G., Lovley, D.R., 2000a. Direct and Fe(II)-mediated reduction of technetium by Fe(III)-reducing bacteria. *Appl. Environ. Microbiol.* 66, 3743–3749.
- Lloyd, J.R., Yong, P., Macaskie, L.E., 2000b. Biological reduction and removal of Np(V) by two microorganisms. *Environ. Sci. Technol.* 34, 1297–1301.
- Lloyd, J.R., Chesnes, J., Glasauer, S., Bunker, D.J., Livens, F.R., Lovley, D.R., 2002. Reduction of actinides and fission products by Fe(III)-reducing bacteria. *Geomicrobiol. J.* 19, 103–120.
- Lloyd, J.R., Leang, C., Myerson, A.L.H., Coppi, M.V., Cuifo, S., Methe, B., Sandler, S.J., Lovley, D.R., 2003. Biochemical and genetic characterization of PpcA, a periplasmic c-type cytochrome in *Geobacter sulfurreducens*. *Biochem. J.* 369, 153–161.
- Lovley, D.R., 2011. Live wires: direct extracellular electron exchange for bioenergy and the bioremediation of energy-related contamination. *Energy Environ. Sci.* 4, 4896–4906.
- Lovley, D.R., Nevin, K.P., 2011. A shift in the current: new applications and concepts for microbe–electrode electron exchange. *Curr. Opin. Biotechnol.* 22, 441–448.
- Lovley, D.R., Phillips, E.J.P., 1988. Novel mode of microbial energy metabolism: organic carbon oxidation coupled to dissimilatory reduction of iron or manganese. *Appl. Environ. Microbiol.* 54, 1472–1480.
- Lovley, D.R., Phillips, E.J., 1992a. Reduction of uranium by *Desulfovibrio desulfuricans*. *Appl. Environ. Microbiol.* 58, 850–856.
- Lovley, D.R., Phillips, E.J.P., 1992b. Bioremediation of uranium contamination with enzymatic uranium reduction. *Environ. Sci. Technol.* 26, 2228–2234.
- Lovley, D.R., Phillips, E.J.P., Lonergan, D.J., 1989. Hydrogen and formate oxidation coupled to dissimilatory reduction of iron or manganese by *Alteromonas putrefaciens*. *Appl. Environ. Microbiol.* 55, 700–706.
- Lovley, D.R., Phillips, E.J.P., Gorby, Y.A., Landa, E.R., 1991. Microbial reduction of uranium. *Nature* 350, 413–416.
- Lovley, D.R., Giovannoni, S.J., White, D.C., Champine, J.E., Phillips, E.J.P., Gorby, Y.A., Goodwin, S., 1993a. *Geobacter metallireducens* gen.-nov. sp.-nov., a microorganism

- capable of coupling the complete oxidation of organic-compounds to the reduction of iron and other metals. *Arch. Microbiol.* 159, 336–344.
- Lovley, D.R., Widman, P.K., Woodward, J.C., Phillips, E.J.P., 1993b. Reduction of uranium by cytochrome-*c*₃ of *Desulfovibrio vulgaris*. *Appl. Environ. Microbiol.* 59, 3572–3576.
- Lovley, D.R., Holmes, D.E., Nevin, K.P., 2004. Dissimilatory Fe(III) and Mn(IV) reduction. *Advances in Microbial Physiology*. Academic Press, pp. 219–286.
- Luksiene, B., Druteikiene, R., Peculyte, D., Baltrunas, D., Remeikis, V., Paskevicius, A., 2012. Effect of microorganisms on the plutonium oxidation states. *Appl. Radiat. Isot.* 70, 442–449.
- Luo, W., Gu, B., 2011. Dissolution of uranium-bearing minerals and mobilization of uranium by organic ligands in a biologically reduced sediment. *Environ. Sci. Technol.* 45, 2994–2999.
- Luo, W.S., Wu, W.M., Yan, T.F., Criddle, C.S., Jardine, P.M., Zhou, J.Z., Gu, B.H., 2007. Influence of bicarbonate, sulfate, and electron donors on biological reduction of uranium and microbial community composition. *Appl. Microbiol. Biotechnol.* 77, 713–721.
- Lyalikova, N.N., Khizhnyak, T.V., 1996. Reduction of heptavalent technetium by acidophilic bacteria of the genus *Thiobacillus*. *Microbiology* 65, 468–473.
- Mabbett, A.N., Lloyd, J.R., Macaskie, L.E., 2002. Effect of complexing agents on reduction of Cr(VI) by *Desulfovibrio vulgaris* ATCC 29579. *Biotechnol. Bioeng.* 79, 389–397.
- Macaskie, L.E., 1990. An immobilized cell bioprocess for the removal of heavy metals from aqueous flows. *J. Chem. Technol. Biotechnol.* 49, 357–379.
- Macaskie, L.E., 1991. The application of biotechnology to the treatment of wastes produced from the nuclear fuel cycle: biodegradation and bioaccumulation as a means of treating radionuclide-containing streams. *Crit. Rev. Biotechnol.* 11, 41–112.
- Macaskie, L.E., Empson, R.M., Cheetham, A.K., Grey, C.P., Skarnulis, A.J., 1992. Uranium bioaccumulation by a *Citrobacter* sp. as a result of enzymically mediated growth of polycrystalline HfO_2PO_4 . *Science* 257, 782–784.
- Macaskie, L.E., Bonthron, K.M., Rouch, D.A., 1994a. Phosphatase-mediated heavy metal accumulation by a *Citrobacter* sp. and related enterobacteria. *FEMS Microbiol. Lett.* 121, 141–146.
- Macaskie, L.E., Jeong, B.C., Tolley, M.R., 1994b. Enzymically accelerated biomineralization of heavy metals: application to the removal of americium and plutonium from aqueous flows. *FEMS Microbiol. Rev.* 14, 351–367.
- Macaskie, L.E., Bonthron, K.M., Yong, P., Goddard, D.T., 2000. Enzymically mediated bioprecipitation of uranium by a *Citrobacter* sp.: a concerted role for exocellular lipopolysaccharide and associated phosphatase in biomineral formation. *Microbiology* 146, 1855–1867.
- Madden, A.S., Smith, A.C., Balkwill, D.L., Fagan, L.A., Phelps, T.J., 2007. Microbial uranium immobilization independent of nitrate reduction. *Environ. Microbiol.* 9, 2321–2330.
- Madden, A.S., Palumbo, A.V., Ravel, B., Vishnivetskaya, T.A., Phelps, T.J., Schadt, C.W., Brandt, C.C., 2009. Donor-dependent extent of uranium reduction for bioremediation of contaminated sediment microcosms. *J. Environ. Qual.* 38, 53–60.
- Madden, A.S., Swindle, A.L., Beazley, M.J., Moon, J.W., Ravel, B., Phelps, T.J., 2012. Long-term solid-phase fate of co-precipitated U(VI)–Fe(III) following biological iron reduction by *Thermoanaerobacter*. *Am. Mineral.* 97, 1641–1652.
- Maher, K., Bargar, J.R., Brown, G.E., 2012. Environmental speciation of actinides. *Inorg. Chem.* 52, 3510–3532.
- Marshall, M.J., Beliaev, A.S., Dohnalkova, A.C., Kennedy, D.W., Shi, L., Wang, Z.M., Boyanov, M.I., Lai, B., Kemner, K.M., McLean, J.S., Reed, S.B., Culley, D.E., Bailey, V.L., Simonson, C.J., Saffarini, D.A., Romine, M.F., Zachara, J.M., Fredrickson, J.K., 2006. *c*-Type cytochrome-dependent formation of U(IV) nanoparticles by *Shewanella oneidensis*. *PLoS Biol.* 4, 1324–1333.
- Marshall, M.J., Plymale, A.E., Kennedy, D.W., Shi, L., Wang, Z.M., Reed, S.B., Dohnalkova, A.C., Simonson, C.J., Liu, C.X., Saffarini, D.A., Romine, M.F., Zachara, J.M., Beliaev, A.S., Fredrickson, J.K., 2008. Hydrogenase- and outer membrane *c*-type cytochrome-facilitated reduction of technetium(VII) by *Shewanella oneidensis* MR-1. *Environ. Microbiol.* 10, 125–136.
- Marshall, M.J., Dohnalkova, A.C., Kennedy, D.W., Plymale, A.E., Thomas, S.H., Löffler, F.E., Sanford, R.A., Zachara, J.M., Fredrickson, J.K., Beliaev, A.S., 2009. Electron donor-dependent radionuclide reduction and nanoparticle formation by *Anaeromyxobacter dehalogenans* strain 2CP-C. *Environ. Microbiol.* 11, 534–543.
- Marsili, E., Baron, D.B., Shikhar, I.D., Coursolle, D., Gralnick, J.A., Bond, D.R., 2008. *Shewanella* secretes flavins that mediate extracellular electron transfer. *Proc. Natl. Acad. Sci.* 105, 3968–3973.
- Martinez, R.J., Beazley, M.J., Taillefert, M., Arakaki, A.K., Skolnick, J., Sobecky, P.A., 2007. Aerobic uranium(VI) bioprecipitation by metal-resistant bacteria isolated from radionuclide- and metal-contaminated subsurface soils. *Environ. Microbiol.* 9, 3122–3133.
- McBeth, J.M., Lear, G., Lloyd, J.R., Livens, F.R., Morris, K., Burke, I.T., 2007. Technetium reduction and reoxidation in aquifer sediments. *Geomicrobiol. J.* 24, 189–197.
- McBeth, J.M., Lloyd, J.R., Law, G.T.W., Livens, F.R., Burke, I.T., Morris, K., 2011. Redox interactions of technetium with iron-bearing minerals. *Mineral. Mag.* 75, 2419–2430.
- Mehta, T., Coppi, M.V., Childers, S.E., Lovley, D.R., 2005. Outer membrane *c*-type cytochromes required for Fe(III) and Mn(IV) oxide reduction in *Geobacter sulfurreducens*. *Appl. Environ. Microbiol.* 71, 8634–8641.
- Merroun, M.L., Selenska-Pobell, S., 2008. Bacterial interactions with uranium: an environmental perspective. *J. Contam. Hydrol.* 102, 285–295.
- Michel, L.J., Macaskie, L.E., Dean, A.C.R., 1986. Cadmium accumulation by immobilized cells of a *Citrobacter* sp. using various phosphate donors. *Biotechnol. Bioeng.* 28, 1358–1365.
- Mondani, L., Benzerara, K., Carriere, M., Christen, R., Mamindy-Pajany, Y., Fevrier, L., Marmier, N., Achouak, W., Nardoux, P., Berthomieu, C., Chapon, V., 2011. Influence of uranium on bacterial communities: a comparison of natural uranium-rich soils with controls. *PLoS One* 6, 1–6.
- Moon, H.S., Komlos, J., Jaffe, P.R., 2007. Uranium reoxidation in previously bioreduced sediment by dissolved oxygen and nitrate. *Environ. Sci. Technol.* 41, 4587–4592.
- Moon, H.S., Komlos, J., Jaffe, P.R., 2009. Biogenic U(IV) oxidation by dissolved oxygen and nitrate in sediment after prolonged U(VI)/Fe(III)/ SO_4^{2-} reduction. *J. Contam. Hydrol.* 105, 18–27.
- Morris, K., Bryan, N.D., Livens, F.R., 2001. Plutonium solubility in sediment pore waters. *J. Environ. Radioact.* 56, 259–267.
- Morris, K., Livens, F.R., Charnock, J.M., Burke, I.T., McBeth, J.M., Begg, J.D.C., Boothman, C., Lloyd, J.R., 2008. An X-ray absorption study of the fate of technetium in reduced and reoxidised sediments and mineral phases. *Appl. Geochem.* 23, 603–617.
- Myers, C.R., Nealson, K.H., 1988. Bacterial manganese reduction and growth with manganese oxide as the sole electron acceptor. *Science* 240, 1319–1321.
- N'Guessan, A.L., Vrionis, H.A., Resch, C.T., Long, P.E., Lovley, D.R., 2008. Sustained removal of uranium from contaminated groundwater following stimulation of dissimilatory metal reduction. *Environ. Sci. Technol.* 42, 2999–3004.
- N'Guessan, A.L., Moon, H.S., Peacock, A.D., Tan, H., Sinha, M., Long, P.E., Jaffe, P.R., 2010. Postbiostimulation microbial community structure changes that control the reoxidation of uranium. *FEMS Microbiol. Ecol.* 74, 184–195.
- Nielsen, L.P., Risgaard-Petersen, N., Fossing, H., Christensen, P.B., Sayama, M., 2010. Electric currents couple spatially separated biogeochemical processes in marine sediment. *Nature* 463, 1071–1074.
- Nyman, J.L., Wu, H.I., Gentile, M.E., Kitanidis, P.K., Criddle, C.S., 2007. Inhibition of a U(VI)- and sulfate-reducing consortia by U(VI). *Environ. Sci. Technol.* 41, 6528–6533.
- O'Loughlin, E.J., Kelly, S.D., Kemner, K.M., 2010. XAFS investigation of the interactions of U(VI) with secondary mineralization products from the bioreduction of Fe(III) oxides. *Environ. Sci. Technol.* 44, 1656–1661.
- Orellana, R., Leavitt, J.J., Comolli, L.R., Csencsits, R., Janot, N., Flanagan, K.A., Gray, A.S., Leang, C., Izallalen, M., Mester, T., Lovley, D.R., 2013. U(VI) reduction by diverse outer surface *c*-type cytochromes of *Geobacter sulfurreducens*. *Appl. Environ. Microbiol.* 79, 6369–6374.
- Orozco, A.F., Williams, K.H., Long, P.E., Hubbard, S.S., Kemna, A., 2011. Using complex resistivity imaging to infer biogeochemical processes associated with bioremediation of an uranium-contaminated aquifer. *J. Geophys. Res.* 116, 1–17.
- Pabalan, R.T., Turner, D.R., Paul Bertetti, F., Prikrýl, J.D., 1998. Uranium(VI) sorption onto selected mineral surfaces: key geochemical parameters. *Adsorption of Metals by Geomedia*. Academic P, pp. 99–130.
- Parrish, R.R., Horstwood, M., Arnason, J.G., Chenery, S., Brewer, T., Lloyd, N.S., Carpenter, D.O., 2008. Depleted uranium contamination by inhalation exposure and its detection after approximately 20 years: implications for human health assessment. *Sci. Total Environ.* 390, 58–68.
- Paterson-Beedle, M., Readman, J.E., Hriljac, J.A., Macaskie, L.E., 2010. Biorecovery of uranium from aqueous solutions at the expense of phytic acid. *Hydrometallurgy* 104, 524–528.
- Paterson-Beedle, M., Jeong, B.C., Lee, C.H., Jee, K.Y., Kim, W.H., Renshaw, J.C., Macaskie, L.E., 2012. Radiotolerance of phosphatases of a *Serratia* sp.: potential for the use of this organism in the biomineralization of wastes containing radionuclides. *Biotechnol. Bioeng.* 109, 1937–1946.
- Pattanaipitpaisal, P., Mabbett, A.N., Finlay, J.A., Beswick, A.J., Paterson-Beedle, M., Essa, A., Wright, J., Tolley, M.R., Badar, U., Ahmed, N., Hobman, J.L., Brown, N.L., Macaskie, L.E., 2002. Reduction of Cr(VI) and bioaccumulation of chromium by Gram-positive and Gram-negative microorganisms not previously exposed to Cr-stress. *Environ. Technol.* 23, 731–745.
- Peacock, A.D., Hedrick, D.B., Long, P.E., Nevin, K.P., Resch, C.T., Lovley, D.R., White, D.C., 2011. Field-scale uranium (VI) bioimmobilization monitored by lipid biomarkers and ^{13}C -acetate incorporation. *Remediat. J.* 21, 85–106.
- Peretyazhko, T., Zachara, J.M., Heald, S.M., Kukkadapu, R.K., Liu, C., Plymale, A.E., Resch, C.T., 2008. Reduction of Tc(VII) by Fe(II) sorbed on Al (hydr)oxides. *Environ. Sci. Technol.* 42, 5499–5506.
- Peretyazhko, T.S., Zachara, J.M., Kukkadapu, R.K., Heald, S.M., Kutnyakov, I.V., Resch, C.T., Arey, B.W., Wang, C.M., Kovarik, L., Phillips, J.L., Moore, D.A., 2012. Pertechnetate (TcO_4^-) reduction by reactive ferrous iron forms in naturally anoxic, redox transition zone sediments from the Hanford Site, USA. *Geochim. Cosmochim. Acta* 92, 48–66.
- Peterson, R.E., Rockhold, M.L., Serne, R.J., Thorne, P.D., Williams, M.D., 2008. Uranium contamination in the subsurface beneath the 300 Area, Hanford Site, Washington. Pacific Northwest National Laboratory, Washington.
- Pfeffer, C., Larsen, S., Song, J., Dong, M., Besenbacher, F., Meyer, R.L., Kjeldsen, K.U., Schreiber, L., Gorbey, Y.A., El-Naggar, M.Y., Leung, K.M., Schramm, A., Risgaard-Petersen, N., Nielsen, L.P., 2012. Filamentous bacteria transport electrons over centimetre distances. *Nature* 491, 218–221.
- Plymale, A.E., Fredrickson, J.K., Zachara, J.M., Dohnalkova, A.C., Heald, S.M., Moore, D.A., Kennedy, D.W., Marshall, M.J., Wang, C.M., Resch, C.T., Nachimuthu, P., 2011. Competitive reduction of pertechnetate (TcO_4^-)–Tc-99 by dissimilatory metal reducing bacteria and biogenic Fe(II). *Environ. Sci. Technol.* 45, 951–957.
- Powers, L.G., Mills, H.J., Palumbo, A.V., Zhang, C.L., Delaney, K., Sobecky, P.A., 2002. Introduction of a plasmid-encoded *phoA* gene for constitutive overproduction of alkaline phosphatase in three subsurface *Pseudomonas* isolates. *FEMS Microbiol. Ecol.* 41, 115–123.
- Qiu, G., Li, Q., Yu, R., Sun, Z., Liu, Y., Chen, M., Yin, H., Zhang, Y., Liang, Y., Xu, L., Sun, L., Liu, X., 2011. Column bioleaching of uranium embedded in granite porphyry by a mesophilic acidophilic consortium. *Bioresour. Technol.* 102, 4697–4702.
- Reed, D.T., Pepper, S.E., Richmann, M.K., Smith, G., Deo, R., Rittmann, B.E., 2007. Subsurface bio-mediated reduction of higher-valent uranium and plutonium. *J. Alloys Compd.* 444–445, 376–382.
- Regenspurg, S., Schild, D., Schafer, T., Huber, F., Malmstrom, M.E., 2009. Removal of uranium(VI) from the aqueous phase by iron(II) minerals in presence of bicarbonate. *Appl. Geochem.* 24, 1617–1625.

- Reguera, G., McCarthy, K.D., Mehta, T., Nicoll, J.S., Tuominen, M.T., Lovley, D.R., 2005. Extracellular electron transfer via microbial nanowires. *Nature* 435, 1098–1101.
- Renshaw, J.C., Butchins, L.J.C., Livens, F.R., May, I., Charnock, J.M., Lloyd, J.R., 2005. Bioreduction of uranium: environmental implications of a pentavalent intermediate. *Environ. Sci. Technol.* 39, 5657–5660.
- Renshaw, J.C., Law, N., Geissler, A., Livens, F.R., Lloyd, J.R., 2009. Impact of the Fe(III)-reducing bacteria *Geobacter sulfurreducens* and *Shewanella oneidensis* on the speciation of plutonium. *Biogeochemistry* 94, 191–196.
- Richter, K., Schickelberger, M., Gescher, J., 2012. Dissimilatory reduction of extracellular electron acceptors in anaerobic respiration. *Appl. Environ. Microbiol.* 78, 913–921.
- Rittmann, B., Banaszak, J., Reed, D., 2002. Reduction of Np(V) and precipitation of Np(IV) by an anaerobic microbial consortium. *Biodegradation* 13, 329–342.
- Roig, M.G., Kennedy, J.F., Macaskie, L.E., 1995. Biological rehabilitation of metal bearing wastewaters. Final Report. European Commission, Brussels (EC contract EV5V-CT93-0251).
- Rui, X., Kwon, M.J., O'Loughlin, E.J., Dunham-Cheatham, S., Fein, J.B., Bunker, B.A., Kemner, K.M., Boyanov, M.I., 2013. Bioreduction of hydrogen uranyl phosphate: mechanisms and U(IV) products. *Environ. Sci. Technol.* 47 (11), 5668–5678.
- Rusin, P.A., Quintana, L., Brainard, J.R., Strietelmeier, B.A., Tait, C.D., Ekberg, S.A., Palmer, P.D., Newton, T.W., Clark, D.L., 1994. Solubilization of plutonium hydrous oxide by iron-reducing bacteria. *Environ. Sci. Technol.* 28, 1686–1690.
- Salome, K.R., Green, S.J., Beazley, M.J., Webb, S.M., Kostka, J.E., Taillefert, M., 2013. The role of anaerobic respiration in the immobilization of uranium through biomineralization of phosphate minerals. *Geochim. Cosmochim. Acta* 106, 344–363.
- Sanford, R.A., Wu, Q., Sung, Y., Thomas, S.H., Amos, B.K., Prince, E.K., Löffler, F.E., 2007. Hexavalent uranium supports growth of *Anaeromyxobacter dehalogenans* and *Geobacter* spp. with lower than predicted biomass yields. *Environ. Microbiol.* 9, 2885–2893.
- Sani, R.S., Peyton, B.P., Smith, W.S., Apel, W.A., Petersen, J.P., 2002. Dissimilatory reduction of Cr(VI), Fe(III), and U(VI) by *Cellulomonas* isolates. *Appl. Microbiol. Biotechnol.* 60, 192–199.
- Sani, R.K., Peyton, B.M., Dohnalkova, A., Amonette, J.E., 2005. Reoxidation of reduced uranium with iron(III) (hydr)oxides under sulfate-reducing conditions. *Environ. Sci. Technol.* 39, 2059–2066.
- Schiewer, S., Volesky, B., 2000. Biosorption processes for heavy metal removal. In: Lovley, D.R. (Ed.), *Environmental Microbe–Metal Interactions*. ASM Press, Washington D. C., pp. 329–362.
- Schofield, E.J., Veeramani, H., Sharp, J.O., Suvorova, E., Bernier-Latmani, R., Mehta, A., Stahlman, J., Webb, S.M., Clark, D.L., Conradson, S.D., Ilton, E.S., Bargar, J.R., 2008. Structure of biogenic uraninite produced by *Shewanella oneidensis* strain MR-1. *Environ. Sci. Technol.* 42, 7898–7904.
- Senko, J.M., Istok, J.D., Suflita, J.M., Krumholz, L.R., 2002. In situ evidence for uranium immobilization and remobilization. *Environ. Sci. Technol.* 36, 1491–1496.
- Senko, J.M., Mohamed, Y., Dewers, T.A., Krumholz, L.R., 2005. Role for Fe(III) minerals in nitrate-dependent microbial U(IV) oxidation. *Environ. Sci. Technol.* 39, 2529–2536.
- Senko, J.M., Kelly, S.D., Dohnalkova, A.C., McDonough, J.T., Kemner, K.M., Burgos, W.D., 2007. The effect of U(VI) bioreduction kinetics on subsequent reoxidation of biogenic U(IV). *Geochim. Cosmochim. Acta* 71, 4644–4654.
- Sharp, J.O., Lezama-Pacheco, J.S., Schofield, E.J., Junier, P., Ulrich, K.-U., Chinni, S., Veeramani, H., Margot-Roquier, C., Webb, S.M., Tebo, B.M., Giammar, D.E., Bargar, J.R., Bernier-Latmani, R., 2011. Uranium speciation and stability after reductive immobilization in aquifer sediments. *Geochim. Cosmochim. Acta* 75, 6497–6510.
- Shelobolina, E.S., Sullivan, S.A., O'Neill, K.R., Nevin, K.P., Lovley, D.R., 2004. Isolation, characterization, and U(VI)-reducing potential of a facultatively anaerobic, acid-resistant bacterium from low-pH, nitrate- and U(VI)-contaminated subsurface sediment and description of *Salmonella subterranea* sp. nov. *Appl. Environ. Microbiol.* 70, 2959–2965.
- Shelobolina, E.S., Coppi, M.V., Korenevsky, A.A., DiDonato, L.N., Sullivan, S.A., Konishi, H., Xu, H.F., Leang, C., Butler, J.E., Kim, B.C., Lovley, D.R., 2007. Importance of c-type cytochromes for U(VI) reduction by *Geobacter sulfurreducens*. *BMC Microbiol.* 7, 15.
- Shelobolina, E.S., Konishi, H., Xu, H.F., Roden, E.E., 2009. U(VI) sequestration in hydroxyapatite produced by microbial glycerol 3-phosphate metabolism. *Appl. Environ. Microbiol.* 75, 5773–5778.
- Shetaya, W.H., Young, S.D., Watts, M.J., Ander, E.L., Bailey, E.H., 2012. Iodine dynamics in soils. *Geochim. Cosmochim. Acta* 77, 457–473.
- Shiel, A.E., Laubach, P.G., Johnson, T.M., Lundstrom, C.C., Long, P.E., Williams, K.H., 2013. No measurable changes in $^{238}\text{U}/^{235}\text{U}$ due to desorption–adsorption of U(VI) from groundwater at the Rifle, Colorado, Integrated Field Research Challenge site. *Environ. Sci. Technol.* 47, 2535–2541.
- Siegal, M.D., Bryan, C.R., 2003. *Environmental Geochemistry of Radioactive Contamination*. Sandia National Laboratories.
- Singer, D.M., Chatman, S.M., Ilton, E.S., Rosso, K.M., Banfield, J.F., Waychunas, G.A., 2012. U(VI) sorption and reduction kinetics on the magnetite (111) surface. *Environ. Sci. Technol.* 46, 3821–3830.
- Siuda, W., Chrost, R.J., 2001. Utilisation of selected dissolved organic phosphorus compounds by bacteria in lake water under non-limiting orthophosphate conditions. *Pol. J. Environ. Stud.* 10, 475–483.
- Sivaswamy, V., Boyanov, M.I., Peyton, B.M., Viamajala, S., Gerlach, R., Apel, W.A., Sani, R.K., Dohnalkova, A., Kemner, K.M., Borch, T., 2011. Multiple mechanisms of uranium immobilization by *Cellulomonas* sp. strain ES6. *Biotechnol. Bioeng.* 108, 264–276.
- Slobodkin, A.I., Sokolova, T.G., Lysenko, A.M., Wiegell, J., 2006. Reclassification of *Thermoterracoccus ferrireducens* as *Carboxydotherrmus ferrireducens* comb. nov., and emended description of the genus *Carboxydotherrmus*. *Int. J. Syst. Evol. Microbiol.* 56, 2349–2351.
- Smeaton, C.M., Weisener, C.G., Burns, P.C., Fryer, B.J., Fowle, D.A., 2008. Bacterially enhanced dissolution of meta-autunite. *Am. Mineral.* 93, 1858–1864.
- Spain, A.M., Krumholz, L.R., 2011. Nitrate-reducing bacteria at the nitrate and radionuclide contaminated Oak Ridge Integrated Field Research Challenge site: a review. *Geomicrobiol. J.* 28, 418–429.
- Spycher, N.F., Issarangkun, M., Stewart, B.D., Sevinç Şengör, S., Belding, E., Ginn, T.R., Peyton, B.M., Sani, R.K., 2011. Biogenic uraninite precipitation and its reoxidation by iron(III) (hydr)oxides: a reaction modeling approach. *Geochim. Cosmochim. Acta* 75, 4426–4440.
- Stewart, B.D., Amos, R.T., Nico, P.S., Fendorf, S., 2011. Influence of uranyl speciation and iron oxides on uranium biogeochemical redox reactions. *Geomicrobiol. J.* 28, 444–456.
- Suzuki, Y., Banfield, J.F., 1999. Geomicrobiology of uranium. *Rev. Mineral. Geochem.* 38, 393–432.
- Suzuki, Y., Banfield, J.F., 2004. Resistance to, and accumulation of, uranium by bacteria from a uranium-contaminated site. *Geomicrobiol. J.* 21, 113–121.
- Suzuki, Y., Kelly, S.D., Kemner, K.M., Banfield, J.F., 2002. Radionuclide contamination: nanometre-size products of uranium bioreduction. *Nature* 419, 134.
- Suzuki, Y., Kelly, S.D., Kemner, K.A., Banfield, J.F., 2003. Microbial populations stimulated for hexavalent uranium reduction in uranium mine sediment. *Appl. Environ. Microbiol.* 69, 1337–1346.
- Suzuki, Y., Kitatsujii, Y., Ohnuki, T., Tsujimura, S., 2010. Flavin mononucleotide mediated electron pathway for microbial U(VI) reduction. *Phys. Chem. Chem. Phys.* 12, 10081–10087.
- Tang, G., Watson, D.B., Wu, W.-M., Schadt, C.W., Parker, J.C., Brooks, S.C., 2013a. U(VI) bioreduction with emulsified vegetable oil as the electron donor – model application to a field test. *Environ. Sci. Technol.* 47, 3218–3225.
- Tang, G., Wu, W.-M., Watson, D.B., Parker, J.C., Schadt, C.W., Shi, X., Brooks, S.C., 2013b. U(VI) bioreduction with emulsified vegetable oil as the electron donor – microcosm tests and model development. *Environ. Sci. Technol.* 47, 3209–3217.
- Tebo, B.M., Obraztsova, A.Y., 1998. Sulfate-reducing bacterium grows with Cr(VI), U(VI), Mn(IV), and Fe(III) as electron acceptors. *FEMS Microbiol. Lett.* 162, 193–198.
- Thomas, R.A.P., Macaskie, L.E., 1996. Biodegradation of tributyl phosphate by naturally occurring microbial isolates and coupling to the removal of uranium from aqueous solution. *Environ. Sci. Technol.* 30, 2371–2375.
- Thorpe, C.L., Law, G.T.W., Boothman, C., Lloyd, J.R., Burke, I.T., Morris, K., 2012a. The synergistic effects of high nitrate concentrations on sediment bioreduction. *Geomicrobiol. J.* 29, 484–493.
- Thorpe, C.L., Lloyd, J.R., Law, G.T.W., Burke, I.T., Shaw, S., Bryan, N.D., Morris, K., 2012b. Strontium sorption and precipitation behaviour during bioreduction in nitrate impacted sediments. *Chem. Geol.* 306–307, 114–122.
- Tobler, D.J., Cuthbert, M.O., Greswell, R.B., Riley, M.S., Renshaw, J.C., Handley-Sidhu, S., Phoenix, V.R., 2011. Comparison of rates of ureolysis between *Sporosarcina pasteurii* and an indigenous groundwater community under conditions required to precipitate large volumes of calcite. *Geochim. Cosmochim. Acta* 75, 3290–3301.
- Tokunaga, T.K., Wan, J., Kim, Y., Daly, R.A., Brodie, E.L., Hazen, T.C., Herman, D., Firestone, M.K., 2008. Influences of organic carbon supply rate on uranium bioreduction in initially oxidizing, contaminated sediment. *Environ. Sci. Technol.* 42, 8901–8907.
- Ulrich, K.U., Singh, A., Schofield, E.J., Bargar, J.R., Veeramani, H., Sharp, J.O., Bernier-Latmani, R., Giammar, D.E., 2008. Dissolution of biogenic and synthetic UO_2 under varied reducing conditions. *Environ. Sci. Technol.* 42, 5600–5606.
- UNEP, 2003. Depleted Uranium in Bosnia and Herzegovina: Post-conflict Environmental Assessment, March 2003.
- Van Groenestijn, J.W., Vlekke, G.J.F.M., Anink, D.M.E., Deinema, M.H., Zehnder, A.J.B., 1988. Role of cations in accumulation and release of phosphate by *Acinetobacter* strain 210A. *Appl. Environ. Microbiol.* 54, 2894–2901.
- Vandeyne, N.T., O'Neil, J.P., Slowey, A.J., Bouchko, R., Druhan, J.L., Moses, W.W., Nico, P.S., 2012. Monitoring Tc dynamics in a bioreduced sediment: an investigation with gamma camera imaging of ^{99m}Tc -pertechnetate and ^{99m}Tc -DTPA. *Environ. Sci. Technol.* 46, 12583–12590.
- VanEngelen, M.R., Field, E.K., Gerlach, R., Lee, B.D., Apel, W.A., Peyton, B.M., 2010. UO_2^{2+} speciation determines uranium toxicity and bioaccumulation in an environmental *Pseudomonas* sp. isolate. *Environ. Toxicol. Chem.* 29, 763–769.
- Veeramani, H., Alessi, D.S., Suvorova, E.I., Lezama-Pacheco, J.S., Stubbs, J.E., Sharp, J.O., Dippon, U., Kappler, A., Bargar, J.R., Bernier-Latmani, R., 2011. Products of abiotic U(VI) reduction by biogenic magnetite and vivianite. *Geochim. Cosmochim. Acta* 75, 2512–2528.
- Veeramani, H., Scheinost, A.C., Monsegue, N., Qafoku, N.P., Kukkadapu, R., Newville, M., Lanzirrotti, A., Pruden, A., Murayama, M., Hochella, M.F., 2013. Abiotic reductive immobilization of U(VI) by biogenic mackinawite. *Environ. Sci. Technol.* 47, 2361–2369.
- Venkateswaran, K., Moser, D.P., Dollhopf, M.E., Lies, D.P., Saffarini, D.A., MacGregor, B.J., Ringelberg, D.B., White, D.C., Nishijima, M., Sano, H., Burghardt, J., Stackebrandt, E., Nealson, K.H., 1999. Polyphasic taxonomy of the genus *Shewanella* and description of *Shewanella oneidensis* sp. nov. *Int. J. Syst. Bacteriol.* 49, 705–724.
- Vermeil, V.R., Bjornstad, B.N., Fritz, B.G., Fruchter, J.S., Mackley, R.D., Mendoza, D.P., Newcomer, D.R., Rockhold, M.L., Wellman, D.M., Williams, M.D., 2009. 300 Area Uranium Stabilisation Through Polyphosphate Injection: Final Report. Pacific Northwest National Laboratory, Richland, Washington.
- Von Canstein, H., Ogawa, J., Shimizu, S., Lloyd, J.R., 2008. Secretion of flavins by *Shewanella* species and their role in extracellular electron transfer. *Appl. Environ. Microbiol.* 74, 615–623.
- Waldron, P.J., Wu, L.Y., Van Nostrand, J.D., Schadt, C.W., He, Z.L., Watson, D.B., Jardine, P.M., Palumbo, A.V., Hazen, T.C., Zhou, J.Z., 2009. Functional gene array-based analysis of microbial community structure in groundwaters with a gradient of contaminant levels. *Environ. Sci. Technol.* 43, 3529–3534.

- Wall, J.D., Krumholz, L.R., 2006. Uranium reduction. *Annual Review of Microbiology*, pp. 149–166.
- Wan, J., Tokunaga, T.K., Brodie, E., Wang, Z., Zheng, Z., Herman, D., Hazen, T.C., Firestone, M.K., Sutton, S.R., 2005. Reoxidation of bioreduced uranium under reducing conditions. *Environ. Sci. Technol.* 39, 6162–6169.
- Wan, J., Tokunaga, T.K., Kim, Y., Brodie, E., Daly, R., Hazen, T.C., Firestone, M.K., 2008. Effects of organic carbon supply rates on uranium mobility in a previously bioreduced contaminated sediment. *Environ. Sci. Technol.* 42, 7573–7579.
- Wang, Z.M., Lee, S.-W.W., Kapoor, P., Tebo, B.M., Giammar, D.E., 2013. Uraninite oxidation and dissolution induced by manganese oxide: a redox reaction between two insoluble minerals. *Geochim. Cosmochim. Acta* 100, 24–40.
- Wellman, D.M., Icenhower, J.P., Owen, A.T., 2006. Comparative analysis of soluble phosphate amendments for the remediation of heavy metal contaminants: effect on sediment hydraulic conductivity. *Environ. Chem.* 3, 219–224.
- Wellman, D.M., Pierce, E.M., Oostrom, M., Fruchter, J.S., 2007a. Experimental Plan: 300 Area Treatability Test: In Situ Treatment of the Vadose Zone and Smear Zone Uranium Contamination by Polyphosphate Infiltration. Pacific Northwest National Laboratory, Richland, Washington.
- Wellman, D.M., Pierce, E.M., Richards, E.L., Butler, B.C., Parker, K.E., Glovack, J.N., Burton, S.D., Baum, S.R., Clayton, E.T., Rodriguez, E.A., 2007b. Interim Report: Uranium Stabilisation Through Polyphosphate Injection. Pacific Northwest National Laboratory, Richland, Washington.
- Wellman, D.M., Pierce, E.M., Bacon, D.H., Oostrom, M., Gunderson, K.M., Bovaird, C.C., Cordova, E.A., Clayton, E.T., Parker, K.E., Ermi, R.M., Baum, S.R., Vermeul, V.R., Fruchter, J.S., 2008. 300 Area Treatability Test: Laboratory Development of Polyphosphate Remediation Technology for In Situ Treatment of Uranium Contamination in the Vadose Zone and Capillary Fringe. Pacific Northwest National Laboratory, Richland, Washington.
- Wharton, M.J., Atkins, B., Charnockab, J.M., Livens, F.R., Patrick, R.A.D., Collison, D., 2000. An X-ray absorption spectroscopy study of the coprecipitation of Tc and Re with mackinawite (FeS). *Appl. Geochem.* 15, 347–354.
- Wildung, R.E., Gorby, Y.A., Krupka, K.M., Hess, N.J., Li, S.W., Plymale, A.E., McKinley, J.P., Fredrickson, J.K., 2000. Effect of electron donor and solution chemistry on products of dissimilatory reduction of technetium by *Shewanella putrefaciens*. *Appl. Environ. Microbiol.* 66, 2451–2460.
- Wildung, R.E., Li, S.W., Murray, C.J., Krupka, K.M., Xie, Y., Hess, N.J., Roden, E.E., 2004. Technetium reduction in sediments of a shallow aquifer exhibiting dissimilatory iron reduction potential. *FEMS Microbiol. Ecol.* 49, 151–162.
- Wilkins, M.J., Livens, F.R., Vaughan, D.J., Beadle, I., Lloyd, J.R., 2007. The influence of microbial redox cycling on radionuclide mobility in the subsurface at a low-level radioactive waste storage site. *Geobiology* 5, 293–301.
- Wilkins, M.J., VerBerkmoes, N.C., Williams, K.H., Callister, S.J., Mouser, P.J., Elifantz, H., N'Guessan, A.L., Thomas, B.C., Nicora, C.D., Shah, M.B., Abraham, P., Lipton, M.S., Lovley, D.R., Hettich, R.L., Long, P.E., Banfield, J.F., 2009. Proteogenomic monitoring of *Geobacter* physiology during stimulated uranium bioremediation. *Appl. Environ. Microbiol.* 75, 6591–6599.
- Williams, K.H., Kemna, A., Wilkins, M.J., Druhan, J., Arntzen, E., N'Guessan, A.L., Long, P.E., Hubbard, S.S., Banfield, J.F., 2009. Geophysical monitoring of coupled microbial and geochemical processes during stimulated subsurface bioremediation. *Environ. Sci. Technol.* 43, 6717–6723.
- Williams, K.H., N'Guessan, A.L., Druhan, J., Long, P.E., Hubbard, S.S., Lovley, D.R., Banfield, J.F., 2010a. Electrode voltages accompanying stimulated bioremediation of a uranium-contaminated aquifer. *J. Geophys. Res.* 115.
- Williams, K.H., Nevin, K.P., Franks, A., Englert, A., Long, P.E., Lovley, D.R., 2010b. Electrode-based approach for monitoring in situ microbial activity during subsurface bioremediation. *Environ. Sci. Technol.* 44, 47–54.
- Williams, K.H., Long, P.E., Davis, J.A., Wilkins, M.J., N'Guessan, A.L., Steefel, C.I., Yang, L., Newcomer, D., Spane, F.A., Kerkhof, L.J., McGuinness, L., Dayvault, R., Lovley, D.R., 2011. Acetate availability and its influence on sustainable bioremediation of uranium-contaminated groundwater. *Geomicrobiol. J.* 28, 519–539.
- Williams, K.H., Bargar, J.R., Lloyd, J.R., Lovley, D.R., 2012. Bioremediation of uranium-contaminated groundwater: a systems approach to subsurface biogeochemistry. *Curr. Opin. Biotechnol.* 24 (3), 489–497.
- Williamson, A.J., Morris, K., Shaw, S., Byrne, J.M., Boothman, C., Lloyd, J.R., 2013. Microbial reduction of Fe(III) under alkaline conditions relevant to geological disposal. *Appl. Environ. Microbiol.* 79, 3320–3326.
- Wu, Q., Sanford, R.A., Löffler, F.E., 2006a. Uranium(VI) reduction by *Anaeromyxobacter dehalogenans* strain 2CP-C. *Appl. Environ. Microbiol.* 72, 3608–3614.
- Wu, W.M., Carley, J., Fienen, M., Mehlhorn, T., Lowe, K., Nyman, J., Luo, J., Gentile, M.E., Rajan, R., Wagner, D., Hickey, R.F., Gu, B.H., Watson, D., Cirpka, O.A., Kitanidis, P.K., Jardine, P.M., Criddle, C.S., 2006b. Pilot-scale in situ bioremediation of uranium in a highly contaminated aquifer. 1. Conditioning of a treatment zone. *Environ. Sci. Technol.* 40, 3978–3985.
- Wu, W.M., Carley, J., Gentry, T., Ginder-Vogel, M.A., Fienen, M., Mehlhorn, T., Yan, H., Carroll, S., Pace, M.N., Nyman, J., Luo, J., Gentile, M.E., Fields, M.W., Hickey, R.F., Gu, B.H., Watson, D., Cirpka, O.A., Zhou, J.Z., Fendorf, S., Kitanidis, P.K., Jardine, P.M., Criddle, C.S., 2006c. Pilot-scale in situ bioremediation of uranium in a highly contaminated aquifer. 2. Reduction of U(VI) and geochemical control of U(VI) bioavailability. *Environ. Sci. Technol.* 40, 3986–3995.
- Wu, W.M., Carley, J., Luo, J., Ginder-Vogel, M.A., Cardenas, E., Leigh, M.B., Hwang, C., Kelly, S.D., Ruan, C., Wu, L., Van Nostrand, J., Gentry, T., Lowe, K., Carroll, S., Luo, W., Fields, M.W., Gu, B., Watson, D., Kemner, K.M., Marsh, T., Tiedje, J., Zhou, J., Fendorf, S., Kitanidis, P.K., Jardine, P.M., Criddle, C.S., 2007. In situ bioreduction of uranium (VI) to submicromolar levels and reoxidation by dissolved oxygen. *Environ. Sci. Technol.* 41, 5716–5723.
- Wu, W.M., Carley, J., Green, S.J., Luo, J., Kelly, S.D., Van Nostrand, J., Lowe, K., Mehlhorn, T., Carroll, S., Boonchayanant, B., Löffler, F.E., Watson, D., Kemner, K.M., Zhou, J.Z., Kitanidis, P.K., Kostka, J.E., Jardine, P.M., Criddle, C.S., 2010. Effects of nitrate on the stability of uranium in a bioreduced region of the subsurface. *Environ. Sci. Technol.* 44, 5104–5111.
- Yabusaki, S.B., Fang, Y., Long, P.E., Resch, C.T., Peacock, A.D., Komlos, J., Jaffe, P.R., Morrison, S.J., Dayvault, R.D., White, D.C., Anderson, R.T., 2007. Uranium removal from groundwater via in situ biostimulation: field-scale modeling of transport and biological processes. *J. Contam. Hydrol.* 93, 216–235.
- Yabusaki, S.B., Fang, Y.L., Williams, K.H., Murray, C.J., Ward, A.L., Dayvault, R.D., Waichler, S.R., Newcomer, D.R., Spane, F.A., Long, P.E., 2011. Variably saturated flow and multi-component biogeochemical reactive transport modeling of a uranium bioremediation field experiment. *J. Contam. Hydrol.* 126, 271–290.
- Yang, J.J., Kukkadapu, R.K., Dong, H.L., Shelobolina, E.S., Zhang, J., Kim, J., 2012. Effects of redox cycling of iron in nontronite on reduction of technetium. *Chem. Geol.* 291, 206–216.
- Yong, P., Macaskie, L.E., 1995. Enhancement of uranium bioaccumulation by a *Citrobacter* sp. via enzymically-mediated growth of polycrystalline $\text{NH}_4\text{UO}_2\text{PO}_4$. *J. Chem. Technol. Biotechnol.* 63, 101–108.
- Zachara, J.M., Heald, S.M., Jeon, B.H., Kukkadapu, R.K., Liu, C.X., McKinley, J.P., Dohnalkova, A.C., Moore, D.A., 2007. Reduction of pertechnetate Tc(VII) by aqueous Fe(II) and the nature of solid phase redox products. *Geochim. Cosmochim. Acta* 71, 2137–2157.
- Zachara, J.M., Long, P.E., Bargar, J., Davis, J.A., Fox, P., Fredrickson, J.K., Freshley, M.D., Konopka, A.E., Liu, C., McKinley, J.P., Rockhold, M.L., Williams, K.H., Yabusaki, S.B., 2013. Persistence of uranium groundwater plumes: contrasting mechanisms at two DOE sites in the groundwater–river interaction zone. *J. Contam. Hydrol.* 147, 45–72.
- Zhuang, K., Ma, E., Lovley, D.R., Mahadevan, R., 2012. The design of long-term effective uranium bioremediation strategy using a community metabolic model. *Biotechnol. Bioeng.* 109, 2475–2483.



Groundwater restoration following in-situ recovery (ISR) mining of uranium

Omar Ruiz^a, Bruce Thomson^{b,*}, José M. Cerrato^b, Lucia Rodriguez-Freire^c^a Geo-Logic Associates, Albuquerque, NM, USA^b Civil Engineering, University of New Mexico, Albuquerque, NM, USA^c Civil & Environmental Engineering, New Jersey Institute of Technology, Newark, NJ, USA

ARTICLE INFO

Editorial handling by J. Mirecki

Keywords:

Uranium
In-situ recovery
In-situ leach mining
Ground water restoration
Aquifer stabilization

ABSTRACT

From 1950 through the early 1980's New Mexico accounted for roughly half of domestic uranium (U) production for the nuclear power industry and the nation's weapon programs. Increased interest in nuclear energy has led to proposals for renewed development using both underground mining and uranium in situ recovery (ISR). When feasible, ISR greatly reduces waste generated by the mining and milling processes, however, the ability to restore ground water to acceptable quality after ISR ends is uncertain. This research investigated two methods of stabilizing an aquifer following ISR. Batch and column studies were performed to evaluate chemical and biological methods of stabilization. Columns packed with ore were first leached with an aerated NaHCO_3 ground water solution to simulate ISR. Constituents present at elevated concentrations after leaching included molybdenum (Mo), selenium (Se), U, and vanadium (V). Chemical stabilization was studied by passing a phosphate (PO_4^{3-}) amended solution through the ore to achieve passivation of mineral surfaces by P precipitates. Microbial stabilization was studied by passing a lactate solution through the ore to stimulate growth of anaerobic metal- and sulfate-reducing organisms to reduce U and other elements to less soluble phases. Analyses of the solids from the columns after completion of these experiments by X-ray photo electron spectroscopy (XPS) identified phosphate on samples near the column inlet of the chemically stabilized columns. Microbial populations were characterized by Illumina DNA sequencing and confirmed the presence of metal- and sulfate-reducing organisms. Neither chemical nor microbial stabilization method achieved contaminant immobilization, which is believed due to limited mixing of the stabilization solutions with the contaminated leach solutions. These results emphasize that ground water hydrodynamics, especially mixing, must be considered in aquifer restoration of soluble constituents.

1. Introduction

New Mexico has a long history of producing uranium (U) for the nation's nuclear power industry and nuclear weapons programs. The first U mines in the U.S. opened in the late 1940's and by the mid-1960's were responsible for the 35% of global U production measured as U_3O_8 and known as yellowcake (Roskill, 1991). Between 1947 and 2002, more than 200 recorded mines and 8 mills in the state produced more than 340 million pounds of yellowcake (U_3O_8) and generated \$4.7B in revenue (McLemore et al., 2013; McLemore and Chenoweth, 2017). All of this production was from conventional surface and underground mining.

Although U mining and milling in New Mexico is inactive at present, increased interest in nuclear energy as a carbon-free power source has led to renewed interest in development of U resources. It is estimated that NM reserves contain nearly 390 million pounds of yellowcake at a price of \$100/lb (McLemore and Chenoweth, 2017). Several projects to

reopen inactive mines or construct new ones are in the advanced permitting stage, although actual resumption of mining or initiation of mine construction most likely depends on increased demand for U as reflected by improved U markets (Zemlick et al., 2017).

Currently, nearly all domestic U production is from in-situ recovery (ISR), also referred to as in-situ leach (ISL) mining. In 2015, total U.S. production was 3.3 M lbs of U_3O_8 from one underground mine and six ISL mines (EIA, 2018). Uranium ISR in the US is conducted by circulating an oxidizing solution containing high bicarbonate concentrations through the ore body to oxidize, complex, and mobilize U (NRC, 2009). If U mining resumes in NM it is likely that it will be done by a combination of ISR and conventional underground methods, as geologic, geochemical, and hydrologic conditions are not favorable to ISR at all sites. McLemore et al. (2016) have recently described opportunities for ISR in NM. Several obstacles to ISR were identified including hydro-geochemical considerations (i.e. the ability to circulate leach solutions

* Corresponding author. Civil Engineering MSC01-1070, University of New Mexico, Albuquerque, NM, 87131, USA.

E-mail addresses: ruiz9.omar@gmail.com (O. Ruiz), bthomson@unm.edu (B. Thomson), jcerrato@unm.edu (J.M. Cerrato), lucia.rodriguezfreire@njit.edu (L. Rodriguez-Freire).

<https://doi.org/10.1016/j.apgeochem.2019.104418>

Received 5 February 2019; Received in revised form 29 August 2019; Accepted 1 September 2019

Available online 03 September 2019

0883-2927/ © 2019 Elsevier Ltd. All rights reserved.

through the ore body, extract U from the ore, and not impact nearby aquifers), policy and economic challenges, and the difficulty of reclaiming the aquifer and subsurface environment after mining is completed. McLemore et al. (2016) identified eight small scale or pilot scale ISR projects that were done in New Mexico. All were conducted in the 1970's.

Conventional aquifer restoration following ISR is done by circulating uncontaminated water through the mined formation (NRC, 2009). This may simply involve pumping water from the mine to allow surrounding uncontaminated water to replace mining lixiviants (ground water transfer), or pumping water from the mine, treating it at the surface to remove contaminants, then recirculating it back through formation (ground water sweep). Current practice at some ISR mines involves ground water sweep through the mined out ore body using reverse osmosis (RO) at the surface to treat the recovered water prior to recirculating it back through the ore body (Borch et al., 2012). Incorporation of chemical methods to improve ground water restoration has been described (Catchpole and Kuchelka, 1993; Davis and Curtis, 2007) in which the subsurface environment is modified to achieve precipitation through chemical methods such as addition of phosphates (PO_4^{3-}) or addition of a strong reducing agent such as sodium sulfide (Na_2S).

In the past decade, there have been numerous investigations of chemical and biological methods of achieving in-situ aquifer restoration following ISR. Most of the recent field research has been done in co-operation with ISR in WY (Borch et al., 2012; Gallegos et al., 2015; Reimus et al., 2015). Gallegos et al. (2015) described a wide ranging study in which geochemical, mineralogical, and microbiological techniques were used to investigate the persistent post-mining leachability of U and other constituents and identify solid phases and microbial populations that might influence remediation activities. In particular, the investigators considered whether reducing minerals or organic carbon in the mined out formation might be capable of re-establishing reducing conditions with consequent immobilization of U and other oxyanions. A study by Troyer et al. (2014) considered whether U and As immobilization could be achieved by iron sulfide minerals such as mackinawite (FeS).

Two variations on chemical addition to stabilize an aquifer following ISR besides addition of a reducing agent such as Na_2S include addition of a precipitating agent and addition of organic substrates to stimulate microbial growth and achieve biological reduction of U and co-contaminants. Addition of phosphate in batch studies has been shown to immobilize U by precipitating a Ca-U- PO_4 phase such as autunite ($\text{Ca}(\text{UO}_2)_2(\text{PO}_4)_2$) or by adsorption onto P minerals (Arey et al., 1999; Mehta et al., 2016; Moore, 2003; Moore et al., 2015; Pan et al., 2016; Mehta, 2017; Wellman et al., 2008; Wen et al., 2018). Mehta et al. (2015) injected phosphate to immobilize U in contaminated ground water underneath the Rifle, CO mill tailings site. A column study using sediments from the Hanford 300 Area in Washington State found that more U(VI) was retained in U(VI)-bearing sediments reacted with groundwater containing P compared to columns reacted with groundwater that did not contain P (Pan et al., 2016). The processes described by Szecsody et al. (2010) and Moore et al. (2015) consisted of injecting a Ca-phosphate solution that included a biodegradable chelating agent such as citrate. The purpose of the chelating agent is to delay phosphate precipitation to allow migration of the solution farther into the aquifer. Wen et al. (2018) used reactive transport modeling to suggest that U(VI) immobilization was achieved through a combination of U(VI)-P surface complexes and Ca-P precipitation which reduced the concentration of the highly-mobile U-calcium-carbonate (U-Ca- CO_3) complexes.

An alternative to chemical restoration methods is to achieve reduction of U and other constituents by stimulating the growth of naturally occurring nitrate, sulfate, and metal reducing microorganisms through addition of an organic substrate. While there is an extensive body of literature on microbial reduction of U and other metals (Lovley and Phillips, 1992; Anderson et al., 2003), there are several recent reviews of research that are especially relevant to in-situ remediation of U

contaminated aquifers (Converse et al., 2013; Williams et al., 2013; Gallegos et al., 2015; and Newsome et al., 2014). Stabilization may occur through microbial reduction, biomineralization, biosorption or bioaccumulation; multiple mechanisms are likely to occur in most subsurface environments. Newsome et al. (2014), in an extensive review, summarized the results of field studies in which in-situ bioremediation of U was investigated at the Rifle, CO mill tailings site, and ground water contamination at sites in Oak Ridge, TN and Hanford, WA. The studies have found that while in-place immobilization of U can be achieved through microbial reduction, this effect may be temporary with subsequent release of U and other constituents after organic feed is discontinued or after re-oxidation. Note however, that deep ore formations may be less susceptible to re-oxidation because of their isolation from the atmosphere and because reducing conditions are present throughout the rest of the formation so that reducing conditions will quickly be re-establishing once mining has been completed. The studies highlight the importance of subsurface aqueous and solid phase geochemistry to the success of bioremediation in addition to microbiological considerations such as nature of the organic substrate, availability of nutrients, and the microbial population present.

While most ISR studies in NM solely focused on extracting U, a study done by Mobil Oil near Crownpoint, NM also performed extensive work between 1980 and 1986 to restore ground water quality to meet state ground water standards (HRI Inc, 2012). Restoration activities started with ground water transfer then used ground water sweep methods incorporating ion exchange (IX) and then RO desalination at the surface to remove contaminants from the water before recirculating it. Finally, chemical reduction was attempted by adding sodium sulfide (Na_2S) to the circulating water. Over the course of six years ground water quality improved to the point that it met all state standards except those for molybdenum and U. At the conclusion of the study the average concentrations of Mo and U in ground water was 1.1 mg/L and 0.32 mg/L respectively. This water would not meet the current state ground water standard for U of 0.03 mg/L. Reliable remediation must be assured if future ISR is to occur.

The objective of the study described here was to determine the effectiveness of in-situ restoration processes to stabilize U and co-constituents following ISL U mining in NM. The study, done in the laboratory, consisted of three tasks. The first was to determine the chemical characteristics of lixiviants that would result from ISR of NM ores. Ore samples of varying grades from three different mines were collected for the study. The second task evaluated in-situ aquifer remediation by addition of a phosphate (PO_4^{3-}) solution to stabilize U species by precipitation and/or adsorption reactions. The third task evaluated in-situ bioremediation achieved by addition of an organic substrate to the columns. Contaminant elution curves were conducted to determine the effectiveness of the remediation processes. At the end of the studies, the columns were disassembled and subjected to chemical and microbiological analyses to assist in interpreting the results. The results of this study help understand the chemistry, transport and remediation of U and related constituents that would occur if ISR occurs in the future in NM.

2. Materials and methods

2.1. Sample collection

Undisturbed samples from New Mexico ore deposits were not available, hence U containing rock samples from three different sources were used (see Fig. 1): (1) stockpiled low grade ore and waste rock from the Section 11/12 mine near Ambrosia lake, (2) exposed beds from a mineralized zone at the Jackpile open pit mine on the Laguna Pueblo, and (3) stockpiled ore samples from the Mt. Taylor mine near San Mateo, NM. Several kilograms of samples were collected at each site. All of the samples were uniformly black, consolidated sandstones except that collected from the Jackpile mine. The sample collected from the face of the ore body at the Jackpile mine had three distinctly different mineralized zones characterized as yellow, black and gray (see



Fig. 1. Map showing locations from which samples were collected.

Figure SI-1 of Supplemental Information). All work described in this paper was done with ore samples from the Mt. Taylor mine. The ore produced from this mine was present in a sandstone deposit that resembled roll front deposits of the Wyoming Tertiary basins (Riese and Brookins, 1980). The samples were not pulverized in order to avoid fracturing the fine-grained minerals and unnecessarily exposing internal surfaces to leaching solutions so instead were broken using a stainless steel weight. Particles between 0.425 mm and 0.075 mm were used in subsequent laboratory experiments.

2.2. Analytical methods

The acid extractable elemental composition was determined by leaching samples with *aqua regia* (three parts HCl and one part HNO₃) for 12 h, heating at 90 °C for 3 h, then analyzing the extract for major and trace elements. A PerkinElmer Optima 5300 DV inductively coupled plasma-optical emission spectrometer (ICP-OES) was used for general metal analyses and a PerkinElmer Optima NexION 300D inductively coupled plasma-mass spectrometer (ICP-MS) was used to measure U and other trace constituents. For samples leached with water, anions were measured by ion chromatography using a Dionex ICS-1100 ion chromatograph equipped with a Dionex Ion Pac AS9-HC column. The organic fraction of the samples was estimated by measuring Loss on Ignition (LOI). This involved drying the samples at 105 °C for 1 h, weighing to determine moisture content, then ashing the dried samples at 550 °C for 1 h and re-weighing. The difference in weight is assumed to be the loss of the organic matter as a result of oxidation to CO_{2(g)}.

X-ray Photoelectron Spectroscopy (XPS, Kratos AXIS-UltraDLD) was used to characterize the near-surface (outermost 10 nm of the sample) oxidation state of U and the binding of phosphorus in unreacted ore and samples from near the column inlet (bottom) and outlet (top) after reaction for remediation experiments with P. We used similar methods as described elsewhere (Blake et al., 2015; Rodriguez-Freire et al., 2016). Briefly, monochromatic Al K α source operating at 225W was used to acquire survey spectra at 80 eV and high resolution U 4f and P 2p spectra at 20 eV pass energy. The CasaXPS software was used to process all data. All spectra were charge referenced to Au 4f at 84 eV and a 70% Gaussian/30% Lorentzian line shape was used for the curve-fits.

2.3. Batch & column leach tests

Leaching tests were done in order to simulate conditions that would occur during the ISL process. Batch leaching experiments were conducted under oxic conditions to determine appropriate leach solution chemistry which would then be used in column tests to simulate the ISL leach process. In particular, these tests were done to determine an appropriate bicarbonate concentration for use in subsequent column tests. A solid:solution ratio of 1:20 on a mass basis was used in the batch leach tests. Following the batch tests, column leach tests were performed to generate leachate solutions similar to those expected to occur in an ISL mine. These columns were subsequently subjected to chemical and biological treatments to evaluate possible remediation strategies.

For the batch leaching tests, sodium bicarbonate (NaHCO₃) was mixed with 18 M Ω water to prepare 1, 10, 100 and 500 mM solution

concentrations. This was done in order to promote the formation of mobile carbonate complexes and to determine the release of U and co-constituents in the samples as a function of HCO_3^- concentrations. The initial pH of the slurry consisting of ore and leach solution was adjusted to 8.3. Leach tests were conducted in shaken, loosely capped Erlenmeyer flasks. Aerobic conditions in the leach tests were consistent with those that occur in an ISL mine in which an oxidizing carbonate solution is circulated through the mine to oxidize and complex U to facilitate dissolution of U minerals and subsequent ground water transport. Aliquots were taken at 0, 40 min, and 6, 12, 24 and 120 h. Duplicate samples were leached for all of the materials except the Section 11 mine samples, which were leached in triplicate. All samples were filtered through 0.45 μm membrane filters prior to analysis by ICP-OES, ICP-MS and ion chromatography.

Column leach experiments were performed in 5 cm \times 25 cm Plexiglas® columns packed with broken and sieved Mt. Taylor mine ore samples with particle diameters between 0.075 mm and 0.425 mm. Five columns were loosely packed with broken and sieved Mt. Taylor Mine ore samples with particle sizes between 0.075 mm and 0.425 mm. Two columns were used for chemical stabilization experiments, two for microbial stabilization experiments, and the last served as a control column and was simply fed simulated ground water. The columns were saturated with leachate to simulate conditions in an ISL mine. The columns were fed a simulated ground water (SGW) solution (Table 1) augmented with 50 mM NaHCO_3 that was similar to the field-scale pilot tests done at the Crownpoint ISL Pilot Plant (UPA, 2015). The solution was prepared using NaHCO_3 , Na_2SO_4 , and CaCl_2 salts. Note that other common ions (Mg, K, NO_3 , Fe, etc.) were present at concentrations of 1.0 mg/L or lower and were not included in the ground water recipe.

The initial pH of the leach solution in the column tests was 8.3. The columns were allowed to equilibrate with the leach solution for 11 days. Stabilization experiments were started after 11 d equilibration period. The feed solutions were aerated to simulate ISL mine operation. However, the columns were sealed and were operated in upflow mode to prevent introduction of air. The solution used to simulate restoration consisted of SGW to which either phosphate or lactate were added. The restoration feed water did not contain the 50 mM NaHCO_3 complexant used to simulate leaching. Two types of stabilization methods were evaluated: (1) chemical stabilization using a phosphate solution and (2) microbial stabilization by stimulating growth of naturally occurring reducing organisms.

Chemical stabilization with phosphate was simulated using a 100 μM solution of Na_2HPO_4 (9.5 mg/L as PO_4^{3-}), a concentration similar to that used in previous studies (Arey et al., 1999; Mehta et al., 2016). After the columns were leached with a 50 mM NaHCO_3 solution for 11 days to simulate U ISR, introduction of the phosphate amended SGW was initiated.

Microbial stabilization was simulated through stimulation of the growth of naturally occurring microorganisms already present in the ore through addition of sodium lactate ($\text{C}_3\text{H}_5\text{NaO}_3$), a readily biodegradable carboxylic acid widely used in work with anaerobic microbial cultures (see for example Lovley and Phillips, 1992; Wall and Krumholz, 2006). 60% sodium lactate solution was added to SGW to

prepare a 3 mM feed solution for the columns. After the columns were leached with a 50 mM NaHCO_3 solution for 11 days to simulate U ISR, introduction of the lactate amended SGW was initiated. Samples of column feed water and column effluent were collected at each pore volume of solution fed to the columns.

Groundwater-flow velocities in an ISL mine are low, though seldom reported in the literature. Information on an ISR mine in Wyoming showed that four pore volumes or less would be circulated through the formation per month (Hunter, 1991). It was not feasible to pump water continuously through the columns at such a slow velocity so instead they were fed discontinuously by slowly passing one pore volume of leach solution every two days for the chemical restoration experiments, and one pore volume every seven days for the microbial restoration experiments. The slower feed rate for the lactate solution was used in recognition that microbial processes are generally slower than chemical precipitation reactions. Eight pore volumes of restoration fluid were passed through chemical and microbial stabilization columns, followed by an additional 10 pore volumes of simulated ground water to determine whether remobilization of contaminants might occur after restoration efforts stopped. The pore volume in each column was approximately 153 mL. This results in a solid:solution ratio of approximately 4:1 in the columns compared to 1:20 in the batch leach system. The procedures for operating the columns are summarized in Table 2. Samples of column feed water and column effluent were collected at each pore volume of solution fed to the columns. The samples were filtered and acidified for metals analysis or filtered and refrigerated for analysis of anions.

Forty mL of effluent from each column were collected each time the columns were fed. Samples were filtered with a 0.45 μm syringe filter. Twenty mL were preserved by adding HNO_3 to pH < 2 for metals analysis and the other 20 mL were refrigerated for analysis of anions. All samples were analyzed within three days of collection. At the conclusion of the runs, the columns were taken apart and the sediments were subjected to chemical and biological analyses. Soil samples from the phosphate amended columns were dried and then analyzed by XPS to detect the presence of phosphate on the solid surfaces.

All geochemical modeling referred to in this research was done with the PHREEQC code using the WATEQF thermodynamic database (Parkhurst and Appelo, 2013). Data on U-Ca- CO_3 ternary species as reported by Wen et al. (2018) were included in the database.

2.4. Microbial analyses

The microbial population in the unaltered ore samples and in each of the lactate amended columns at the end of the experiment were analyzed using MiSeq Illumina DNA Sequencing. The column samples were collected from approximately the middle point of the column using a sterile 60 mL-syringe and polypropylene tubing after the column operation was finished, and transferred into a sterile PCR workstation with the ore samples for further processing. DNA extraction was done using FastDNA™ SPIN Kit for Soil (MP Biomedicals, Santa Ana, CA, USA). Approximately one gram of soil was used for the extraction. Upon extraction the DNA was frozen and shipped to the MR DNA laboratory for MiSeq Illumina DNA Sequencing. Sequencing was performed at MR DNA (www.mrdnalab.com, Shallowater, TX, USA) on a MiSeq following the manufacturer's guidelines. The 16S rRNA gene V4 variable region PCR primers 515/806 with barcode on the forward primer were used in a 28 cycle PCR (5 cycle used on PCR products) using the HotStarTaq Plus Master Mix Kit (Qiagen, USA) under the following conditions: 94 °C for 3 min, followed by 28 cycles of 94 °C for 30 s, 53 °C for 40 s and 72 °C for 1 min, after which a final elongation step at 72 °C for 5 min was performed. After amplification, PCR products were checked in 2% agarose gel to determine the success of amplification and the relative intensity of bands. Pooled samples are purified using calibrated Ampure XP beads. Then the pooled and purified PCR product is used to prepare Illumina DNA library. Sequencing

Table 1

Simulated ground water (SGW) chemistry used in column tests based on average 1986 baseline water quality of the Crownpoint ISL Pilot Plant (UPA, 2015).

Constituent	Concentration (mM)
Calcium	0.5
Sodium	4.8
Bicarbonate	3.2
Sulfate	0.7
Chloride	1.1
pH	7.5

Table 2
Summary of column operation procedures for restoration experiments.

Method	Control Column	Chemical Restoration	Biological Restoration
Solution	SGW	SGW + Phosphate	SGW + Lactate
Conc. of Restoration Chemical	–	0.10 mM PO_4^{3-}	3 mM Lactate
Feed Rate	1 PV every 2 days	1 PV every 2 days	1 PV every 7 days
Approximate Flow (mL/day)	70	70	20
Duration	64 days	68 days	91 days

Notes: SGW = simulated ground water.

PV = pore volume.

was performed at MR DNA (www.mrdnalab.com, Shallowater, TX, USA) on a MiSeq following the manufacturer's guidelines. Sequence data were processed using MR DNA analysis pipeline (MR DNA, Shallowater, TX, USA).

In summary, sequences were aligned and depleted of barcode indexes, then sequences with less than 150bp and with ambiguous base calls removed. Sequences were denoised, chimeras removed and the operational taxonomic units (OTUs) generated. OTUs were defined by clustering at 3% divergence (97% similarity). Final OTUs were taxonomically classified using BLASTn against a curated database derived from Ribosomal Database Project II (RDPII) and the National Center for Biotechnology Information (NCBI) (www.ncbi.nlm.nih.gov, <http://rdp.cme.msu.edu>).

3. Results and discussion

3.1. Characterization of ore samples

The principal elements of concern associated with ground water contamination in the Grants Mineral Belt include Mo, Se, U, and V. The acid extractable concentration of these elements in the ore samples used in this study is summarized in Table 3. This table includes values for the mass of organics in each sample estimated by loss on ignition (LOI). The U concentration in the ore sample from the Mt. Taylor Mine was just over 1%. This was a high concentration as historically the cutoff grade for U content was about 0.2% (McLemore and Chenoweth, 2017). Data for metal and organic concentrations in other ore samples collected in this project are presented in Table SI-1 in the Supplemental Information.

The oxidation state of U in each sample was determined by fitting U 4f high resolution XPS spectra to library samples. These measurements showed that 75.2% of the U in the Mt. Taylor Mine ore sample is present in the oxidized U(VI) form. The Mt. Taylor mine sample was stored in capped drums in a warehouse but these were not air tight so were considered to be exposed to atmospheric oxygen. The Mt. Taylor mine samples were dry with moisture contents less than 3.34%, which will limit chemical and biological oxidation reactions.

3.2. Results of batch leach tests

The purpose of the batch tests was to determine an appropriate leaching solution for use in subsequent column leach tests to simulate U ISR.

Table 3

Total concentration of molybdenum, selenium, uranium, and vanadium on Mt. Taylor Mine ore sample as determined by acid extraction and fraction of total metal leached from the ore sample after 5 d of leaching with 100 mM NaHCO_3 .

Constituent	Acid Extractable Concentration (mg/kg)	Fraction of Total Metal Leached (%)
Mo	90.5	40.7
Se	8.44	88.9
U	1	29.2
V	512.	8.7
LOI ^a	3.99%	–

^a LOI = Loss on Ignition.

Additionally, these batch experiments were useful to assess leaching of metals from the ore samples. Batch leach experiments were conducted using ore samples in open shake flasks buffered with NaHCO_3 . Initial pH of the leach solutions was 8.3. The samples were broken but not pulverized to be more representative of ore in an ISR mine. The results of duplicate leach tests of the Mt. Taylor Mine samples using a 100 mM NaHCO_3 solution after five days are presented in Table 3 for the four elements of interest (Mo, Se, U and V). All experimental results reported in this study are from Mt. Taylor Mine ore samples. Results of bicarbonate batch leach experiments for other ore samples are presented in Tables SI–2 Supplemental Information.

The time dependence of leaching is shown in Fig. 2. This figure shows the mass fraction of each element leached from the ore sample. The concentration and fraction of the total acid leachable mass fraction of each element leached from the ore sample in five days is presented in Table 3. Rapid leaching of U occurred during the first 24 h followed by much slower release over the next four days. Similar results were obtained for the other constituents and for the other ore samples (data not presented here). These results suggest that little oxidation of the ore sample occurred during the five day test. It is interesting to note that a small fraction, less than 10%, of the other elements of concern in each sample was released during the batch leaching studies.

According to the XPS analyses, approximately 75% of the U in the Mt. Taylor Mine ore samples was U(VI) whereas the data in Table 3 show that 30% of the total U was leached by 100 mM NaHCO_3 . Geochemical modeling suggests that all U(VI) mineral phases are under saturated in the batch leach tests and that at pH 7.5 55% of U is present as a U-phosphate complex ($\text{UO}_2(\text{HPO}_4)_2^{2-}$), 25% of the soluble U is present as anionic uranyl-calcium-tricarbonate ($\text{UO}_2\text{Ca}(\text{CO}_3)_3^{2-}$)

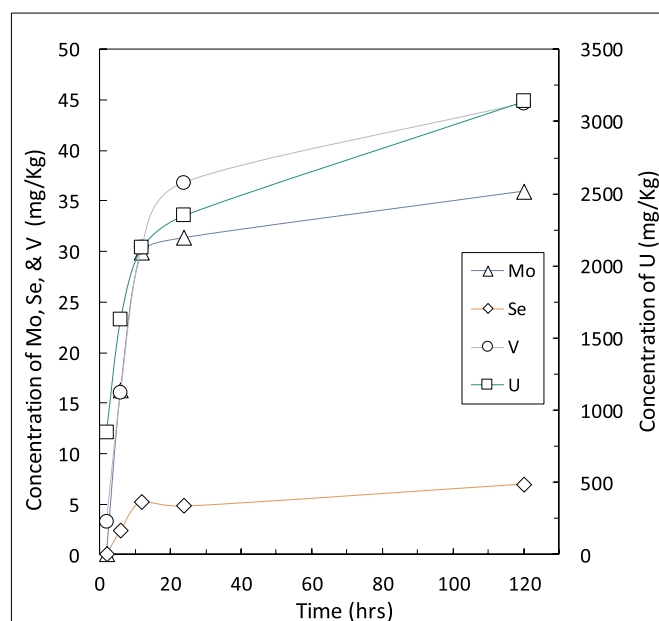


Fig. 2. Time dependence of U leaching from Mt. Taylor ore samples by 100 mM NaHCO_3 solutions.

complex, and 15% is present as neutral uranyl-di-calcium-tricarbonate ($\text{UO}_2\text{Ca}_2(\text{CO}_3)_3$) and 20% present as uranyl-dicarbonate ($\text{UO}_2(\text{CO}_3)_2^{2-}$). These anionic and neutral complexes will have little interaction with soil minerals in the ore. During the 5 day leach period, the batch leach tests found that approximately half of the leachable U(VI) in the Mt. Taylor Mine ore sample was leached by the 100 mM NaHCO_3 solution.

3.3. Results of column leach tests

The column tests were performed to simulate aqueous geochemical conditions that might be encountered in an ISL mine. The average concentrations of all major ions and the four trace metals of concern after 11 days of equilibrating with the leach solution are presented in Table 4. Note that although the initial solution pH was 8.3 and initial alkalinity was 50 mM (2500 mg CaCO_3/L), the pH and alkalinity dropped substantially during the 11 day equilibration period. This is believed to be due to acid produced by partial oxidation of sulfide minerals such as pyrite (FeS_2) as a result of weathering reactions that occurred in the stockpiled ore. The very high U concentration in the leachate was due to the high U concentration in the ore (> 1%), however, less than 15% of the bicarbonate leachable U was present in the leachate.

The stabilization experiments began after the 11 days equilibration period. After the equilibration period the columns were fed simulated ground water with the same chemistry as shown in Table 1 except that the NaHCO_3 concentration was lowered to 5 mM to approximate the alkalinity of the native ground water.

3.4. Chemical stabilization experiments

Chemical stabilization was studied by addition of a phosphate solution as described in studies by Arey et al. (1999), Mehta et al. (2016), and Pan et al. (2016). For the column experiments, 0.1 mM Na_2HPO_4 was added to the SGW and passed the solution through the saturated column at a rate of one pore volume every two days. The control column was simply fed simulated ground water at the same rate.

The results of the chemical stabilization study using the PO_4^{3-} addition (referred to as P-amended ground water) are summarized in Fig. 3, which plots U concentration and pH in the column effluent versus pore volumes of simulated ground water fed to each column. The figure presents data for two replicate columns (C1 & C2) and a control column (CC) leached only with simulated ground water (SGW) to simulate restoration by ground water sweeping. During the leaching tests, the U concentration decayed asymptotically to below 20 mg/L while the pH climbed from an initial pH of 6.4 to about 7.5. Note that there is no discernible difference between the U concentrations and pH in the effluent of columns fed P-amended ground water and the concentrations and pH in the effluent of the control column.

The final concentrations of the trace elements of interest after 8 pore volumes of P-amended ground water had been passed through columns followed by 10 pore volumes of SGW are summarized in Table 5.

The average anion concentrations in the effluent from the two columns fed P-amended ground water is presented in Fig. 4. The plots

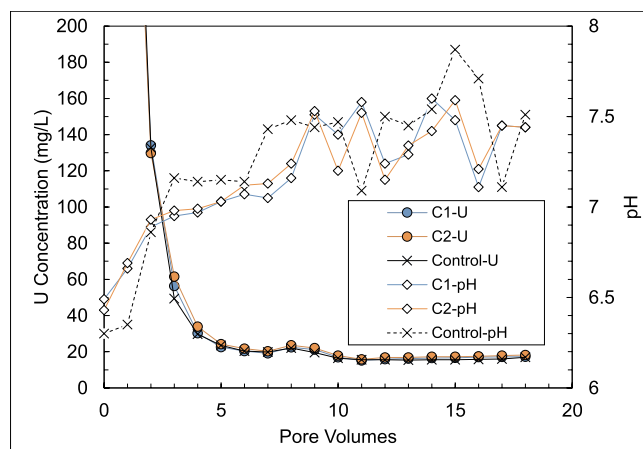


Fig. 3. Uranium concentration and pH plotted against pore volumes of solution for columns containing Mt. Taylor ore samples fed simulated ground water containing 0.1 mM PO_4^{3-} (columns C1 and C2) and simulated ground water only (Control) (Modified from Ruiz et al., 2016.).

show that the anions all stabilized at close to their influent concentrations by the time approximately three pore volumes had passed through the columns. Phosphate was not detected in the column effluent which suggests that it was removed by precipitation or adsorption reactions. Nitrate and fluoride were also not present at detectable concentrations. Chloride and SO_4^{2-} are usually considered to be non-reactive constituents in this system and therefore served as conservative tracers. Their concentrations stabilized at three pore volumes in contrast to the six pore volumes required to reach a steady state U concentration. The slight difference between the U profile in Fig. 3 and the anion profile in Fig. 4, and the fact that U stabilized at between 16 and 18 mg/L is believed to be due to continuing dissolution of U minerals from the Mt. Taylor Mine ore. Based on the chemistry of the column effluent, geochemical modeling suggests that the secondary U-carbonate mineral Rutherfordine ($\text{UO}_2\text{CO}_3(\text{s})$) was initially supersaturated in the columns. Thus, it is plausible that this secondary mineral formed during the equilibration period with the high concentration NaHCO_3 solution then subsequently dissolved as the stabilization fluid was introduced. In addition, electron microscopy has shown that much of the U in the Mt. Taylor ore samples is embedded within a matrix of soil materials (Avasarala et al., 2019; Blake et al., 2017). Furthermore, the ore materials used in the column leach tests were not finely ground so that mass transfer within the particles must be considered. These factors suggest that dissolution and diffusion of embedded minerals within the ore particles to the bulk leach fluid are at least partly responsible for the long tail of elevated U concentrations in the column leach tests.

Geochemical modeling using the solution chemistry listed in Table 1 with U(VI) present at 50 μM confirms that all mineral phases in the WATEQF data base were under saturated at pH 7.5 (Parkhurst and

Table 4

Average concentration of major cations and anions and selected trace elements in column tests after 11 d of leaching with 50 mM NaHCO_3 .

Major Cations		Major Anions		Trace Metals	
Constituent	Conc. (mg/L)	Constituent	Conc. (mg/L)	Constituent	Conc. (mg/L)
Ca^{2+}	198.0	Cl^-	17.3	Mo	8.87
K^+	9.9	SO_4^{2-}	257.0	Se	0.03
Mg^{2+}	12.8	Alkalinity ^a	1085.0	U	1627.0
Na^+	376.0	pH ^b	6.3	V	0.69

^a Units of alkalinity are mg CaCO_3/L .

^b pH units.

Table 5

Final concentrations of trace elements in the effluent of columns fed phosphate-amended and lactate-amended simulated ground water and a control column fed simulated ground water. All concentrations in mg/L except pH.

Constituent	Phosphate-Amended Columns	Lactate-Amended Columns	Control Column
	Final Average Conc. (Range)	Final Average Conc. (Range)	Final Conc.
Mo	0.56 (0.55–0.57)	0.42 (0.40–0.44)	0.75
Se	0.022 (0.021–0.022)	0.0024 (0.023–0.024)	0.0024
U	17.7 (17.3–18.2)	16.0 (15.8–16.2)	16.0
V	0.0038 (0.0037–0.0038)	0.0036 (0.0034–0.0037)	0.0055
pH	7.4 (7.4–7.4)	7.5 (7.5–7.6)	7.5

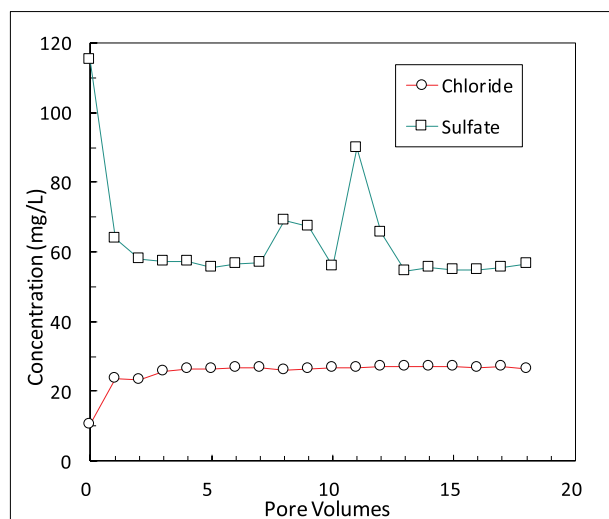


Fig. 4. Average anion concentrations plotted against pore volumes of solution for the two columns containing Mt. Taylor ore samples fed simulated ground water amended with 0.1 mM PO_4^{3-} .

Appelo, 2013). Addition of ortho-phosphate (o-PO_4) at 100 μM to the leachate results in a solution that is super saturated with respect to hydroxyapatite ($\text{Ca}_5(\text{PO}_4)_3\text{OH}$ abbreviated as HA here), however, Ca-U- PO_4 phases such as autunite are predicted to be under saturated.

Precipitate formation in the feed solution was not observed and measurements of influent phosphate concentrations were from filtered samples which confirmed the presence of soluble phosphate. At pH 7.5 and with the solution chemistry in our experiments the reaction rate for HA precipitation is calculated to be 2×10^{-6} mol/L-s using the rate expression presented by Gebrehiwet et al. (2014). The reaction is strongly pH dependent and increases by 4 orders of magnitude for each incremental rise in pH. In addition to the slow rate of reaction, there are numerous reports that supersaturated solutions of Ca- PO_4 are often metastable and that HA does not normally precipitate directly from solution but requires nucleation sites (Tomson and Nancollas, 1978). Other studies report a very long induction period for the homogeneous precipitation reaction, on the order of many hundreds of minutes for the conditions in our system (Feenstra and De Bruyn, 1979). Soil particles such as those in our system greatly accelerate the precipitation reaction by providing nucleation sites to facilitate heterogeneous precipitation.

Regardless of whether phosphate precipitation occurred in the feed solution or the column, use of solid phosphate materials such as HA, tricalcium phosphates, and bone char has been widely investigated for removal of U and other metals from contaminated ground water, most often by placing them in permeable reactive barriers (see for example Thomson et al., 2003; Conca and Wright, 2006; Fuller et al., 2002; Rigali et al., 2016). The review paper by Rigali (et al., 2016) provides a recent discussion of contaminant removal mechanisms by these materials.

3.5. Microbial stabilization experiments

The microbial stabilization experiments were performed by introducing a 3 mM sodium lactate-SGW solution to duplicate columns using procedures summarized in Table 2. One pore volume (PV) of lactate solution was passed through the columns (C3 and C4) every seven days for a total of 8 pore volumes followed by 10 pore volumes of simulated ground water.

Fig. 5 presents average effluent U concentrations for samples from replicate columns (C3 & C4) and from a control column (CC) leached only with SGW to simulate restoration by ground water sweeping. During the leaching tests, the U concentration decayed asymptotically to below 20 mg/L while the pH climbed from an initial pH of 6.4 to about 7.5, with no discernible difference between the leach profile of U or pH in the

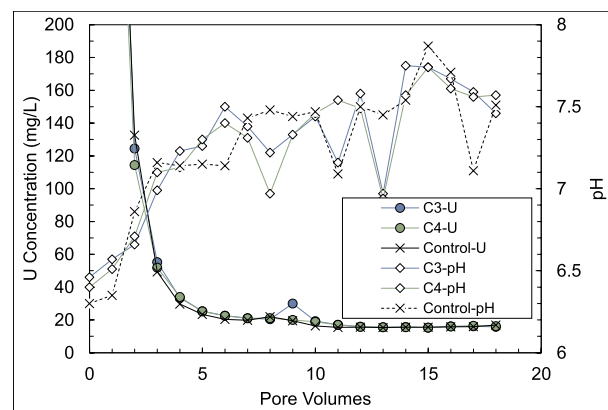


Fig. 5. Uranium concentration and pH plotted against pore volumes of solution for columns containing Mt. Taylor ore samples fed simulated ground water and 3 mM Na-lactate solution (columns C3 and C4) and simulated ground water only Control (Modified from Ruiz et al., 2016.).

effluent of columns fed lactate-amended SGW (C3 and C4) and that for the control column (CC). The final concentrations of the trace elements of interest after 8 pore volumes of lactate-amended SGW and 10 pore volumes of non-amended SGW had been passed through columns C3 and C4 and 18 pore volumes of SGW passed through the control column are summarized in Table 5. The fraction of the total mass of U leached from the control column and the U concentration in the leachate is plotted in Fig. 6. It shows that at the end of the experiment approximately 90% of the total acid extractable U in the ore was still present in the sample.

The average anion concentrations in the effluent from the two columns fed lactate-amended SGW are presented in Fig. 7. The plots show that the anions all stabilized at close to their influent concentrations after approximately five pore volumes of stabilization solution had passed through the columns. Chloride and SO_4^{2-} are considered to be non-reactive compounds in this system and therefore serve as effective tracers. As with the results of the P-amended column, the slight difference between the U profile and the anion profile is believed to be due to continued dissolution of U phases from the Mt. Taylor ore described in Section 3.4. The effluent concentrations of Ca, Mg, K, and Na are plotted in Figures SI-4 through SI-7 of the Supplemental Information and show a similar drop to near influent concentrations within five pore volumes.

3.6. Groundwater mixing considerations

The results of both the chemical and microbial column tests show that neither strategy provided measurable stabilization of U in the

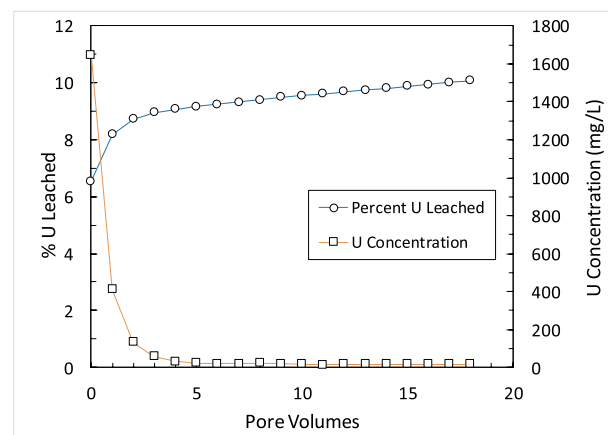


Fig. 6. Mass of U leached from Mt. Taylor ore and U concentration in control column experiment.

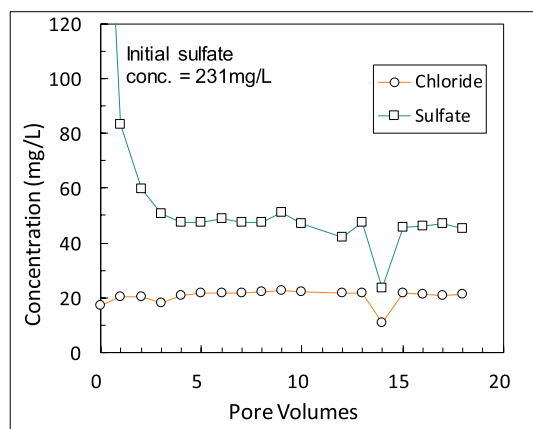


Fig. 7. Average anion concentrations plotted against pore volumes of solution for columns containing Mt. Taylor ore samples fed simulated ground water amended with 3 mM Na-lactate.

experiments under the conditions used for this study. The elution concentration profiles in all columns were virtually identical to that in the control column (CC) which received no stabilization treatment. In essence, U was only removed by flushing. This appears to be inconsistent with previous studies for both chemical stabilization using phosphate (Arey et al., 1999; Mehta et al., 2016; Pan et al., 2016) and microbial reduction (Gallegos et al., 2015; Newsome et al., 2014; Williams et al., 2013). One obvious shortcoming of the study described here is that it occurred over a relatively short period of time, approximately two months for chemical stabilization and three months for microbial stabilization. However, other studies have evaluated stabilization strategies over even shorter time frames or in batch experiments. The principal explanation for the lack of stabilization observed in this study is due to limited mixing of contaminated ground water and the solutions introduced to achieve restoration.

In a one-dimensional flow through column packed with granular media reactions will occur primarily in a mixing zone where the reactants from the leachate mix with those from the restoration fluid (see Figure SI-2 in the Supplemental Information). The length of the mixing zone can be calculated using an analytical solution to the one-dimensional advection-dispersion equation (Charbeneau, 2000):

$$\frac{C}{C_0} = \frac{1}{2} \left[\operatorname{erfc} \left(\frac{L - v_x t}{2\sqrt{D_L t}} \right) + \exp \left(\frac{v_x L}{D_L} \right) \operatorname{erfc} \left(\frac{L + v_x t}{2\sqrt{D_L t}} \right) \right] \quad (1)$$

In this model C/C_0 is dimensionless concentration in the media, L is distance along the column (L), v_x is the interstitial water velocity (L/t), D_L is longitudinal dispersion (L^2/t), and t is time (t). The dispersion coefficient depends on velocity, molecular diffusivity (D_d units of L^2/t) and dispersivity (α in units of L):

$$D_L = D_d + \alpha v_x \quad (2)$$

It can be shown that the dispersivity has the greatest effect on the length of the mixing zone except for very slow interstitial velocities. Charbeneau (2000) states that in lab columns the value of dispersivity is usually about the same as the mean particle diameter which was 0.03 cm in this study. The Peclet number is a dimensionless parameter representing the ratio of advective transport to dispersive transport and is defined as:

$$Pe = \frac{v_x L}{D_L} \quad (3)$$

Combining equations (2) and (3) and assuming that molecular diffusion (D_d) is much less than hydrodynamic mixing, shows that the Peclet number is independent of velocity:

$$Pe = \frac{L}{\alpha} \quad (4)$$

For the column conditions described here the Peclet number was approximately 700. Charbeneau (2000, p. 374) notes that the amount of spreading is independent of velocity but is a function of column length.

The mixing zone can be defined as the distance between where the upstream dimensionless concentration is $C/C_0 = 0.95$ and the downstream dimensionless concentration is $C/C_0 = 0.05$. Using the flow rate of 1 pore volume every two days (59 mL/d) and a dispersivity of 0.03 cm, the length of the mixing zone at the mid-point in the 20 cm column can be calculated to be 6.6 cm or roughly one-third the column length. The actual length of the mixing zone is not especially important for this experiment but its small value confirms that there is limited mixing in the column and gives some validation to the suggestion that flow through the column exhibits characteristics of plug flow. Recognition of limited mixing in the subsurface environment is important when evaluating potential subsurface remediation strategies, especially if the contaminants of concern are soluble and have high mobility.

3.7. Analyses of columns after completion of tests

At the conclusion of the tests the columns were sampled to help interpret the stabilization experiments. Solid material from the phosphate stabilized columns were analyzed by XPS to detect phosphate precipitates while the soils from the microbially stabilized columns were analyzed by Illumina next generation genetic sequencing to characterize the microbial population.

High resolution XPS P 2p spectra detect a low phosphorus signal for un-leached Mt. Taylor ore which served as a control. However, fitting of high resolution XPS P 2p spectra suggest that phosphate is present near both the column entrance and exit (Fig. 8). The XPS data show that a higher phosphate concentration was present near the column entrance compared to samples near the exit. It was not possible to determine from XPS whether phosphate is precipitating or adsorbing to the solids in the column. Neither was it possible to determine if phosphate accumulation near the column exit was due to transport of colloidal phosphate solids formed near the column entrance or the result of precipitation of phosphate solids from solution near the exit. The amount of phosphate accumulated on the surface of the ore particles was too small to permit identification of mineral phases by X-ray diffraction.

Subsurface introduction of phosphate solutions to achieve immobilization of U has been widely studied (see for example Wellman et al., 2008; Szecsody et al., 2010; Moore, 2003; Moore et al., 2015). Mehta et al. (2015) injected phosphate to immobilize U in contaminated ground water underneath the Rifle, CO mill tailings site. Similarly, Wellman et al. (2008) describe injection of ortho- pyro- and tripolyphosphates in a lab study to achieve immobilization of U in ground water at the Hanford sites. The processes described by Szecsody et al. (2010) and Moore et al. (2015) consisted of injecting a Ca-phosphate solution that included a biodegradable chelating agent such as citrate. The purpose of the chelating agent is to delay phosphate precipitation to allow migration of the solution farther into the aquifer. Due to the small scale of our columns and comparatively rapid ground water velocity through them this strategy was not needed. The absence of phosphate in the column effluent and the presence of phosphate phases identified by the XPS data confirm retention of phosphate in the columns, most likely as a phosphate precipitate.

It is informative to compare the results of this study with other studies in which phosphate addition was investigated as a strategy to immobilize U in contaminated aquifers. Perhaps the most relevant work is that which has been done to remediate contaminated ground water at the Hanford Site in southeast Washington State. Pan et al. (2016) and Wen et al. (2018) conducted laboratory studies in which the chemistry and transport of U through Hanford soils was studied. Uranium contaminated

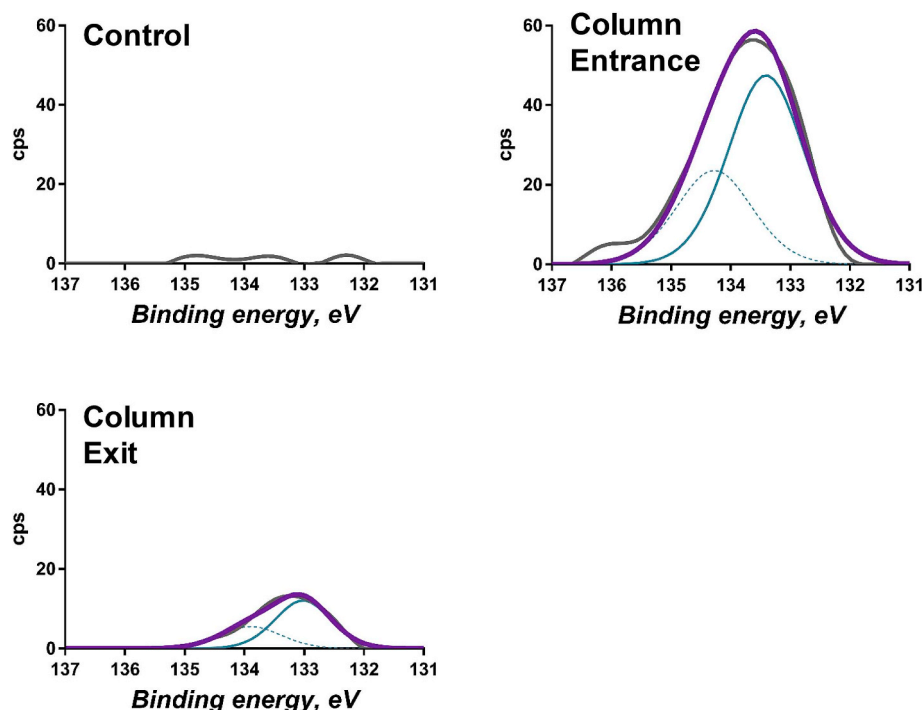


Fig. 8. Phosphorous 2p XPS spectra for: (a) unreacted Mt. Taylor ore sample (control), (b) ore sample from near column entrance and (c) ore sample from near column exit.

ground water was passed through small columns followed by stabilization using phosphate solutions. Immobilization was achieved through a combination of adsorption and precipitation reactions onto Ca-U-P phases. Mehta (2017) described results of field studies on phosphate stabilization of U contaminated soils also at Hanford Site.

In these studies U was introduced to the soil by infiltration of contaminated solutions and therefore was present on soil particle surfaces as adsorbed or possibly precipitated phases. An important difference between these investigations and ours is that we used U ore samples that had been leached with an HCO_3^- solution instead of underlying soil with very low U content. We believe that this difference is important and discuss it in the results section.

There is a fairly important distinction between the research done on Hanford sediments (Pan et al., 2016; Mehta, 2017; Wen et al., 2018), contaminated sediments at the Rifle, CO mill tailings site, and the leached ore samples reported in this paper. The Hanford sediments were contaminated by U solutions leaking from process ponds so that immobilized U is present on the surface of soil particles as adsorbed or precipitated U(VI) species (Singer et al., 2009; Arai et al., 2007). The laboratory research reported by Pan et al. (2016) and Wen et al. (2018) used uncontaminated sediments which were “conditioned” by contacting them with synthetic ground water to which U(VI) was added. Mehta (2017) described the results of a field study in which 7 million liters of a polyphosphate solution were added to a U contaminated vadose zone and aquifer. In contrast, the study described in this paper focused on U present in ore samples which is mainly present as U(IV) and U(VI) minerals or associated with amorphous organic detritus. Characterization of similar ore materials by Avasarala et al. (2019) and Blake et al. (2017) showed that much of the U is present as occluded U minerals that are embedded within a matrix of other soil minerals. The U immobilization mechanisms may be different in these two systems. Specifically, U present on the surface of soil particles may be more amenable to stabilization by phosphate precipitation reactions whereas U present inside soil minerals or within soil organics is less available to form insoluble Ca-U-P phases. In addition, the U present in interstitial pore water within an ore sample following ISL leaching by a carbonate solution will likely be more soluble and mobile than U in contaminated soil.

While it is possible that there was insufficient phosphate added to stabilize U in ore materials along the entire length of the column, the fact that there was no discernible difference in the leach profiles for the phosphate amended columns, the control columns, and the lactate columns suggest that stabilization of U on ore materials near the column entrance was not significant.

3.8. Microbial diversity and population changes in the lactate amended columns

Microbial stabilization of ground water following U ISR is based on aqueous geochemical behavior exhibited by some metals and metalloids which are less soluble in their reduced forms than in their oxidized state. This is true for the four elements of interest in this study, Mo, Se, U, and V. Stimulating growth of naturally occurring microorganisms in subsurface formations can provide strongly reducing conditions to reduce these constituents to less soluble phases through either biological (i.e. metabolic or enzymatic processes) or abiotic mechanisms (i.e. chemical reduction). Representative investigations of microbial stabilization of U contaminated aquifers have been presented by Wu et al. (2006), Williams et al. (2013), and Newsome et al. (2014).

In this work, lactate amendment did not enhance U immobilization in the microbial stabilization treatments. The microbial community in the ore, control column (CC), and lactate-amended columns (C3 and C4) was investigated to assess the potential reason behind the negligible difference between the control and amended reactors. The microbial population in the Mt. Taylor ore and the control column (labeled CC) and lactate-amended columns (labeled C3 and C4) was evaluated using MiSeq Illumina Sequencing. The most abundant populations in the samples are typical of soil environments, such as *Collimonas*, *Bradyrhizobium*, and *Herbaspirillum*, and *Herminiimonas*, a strict aerobic organotroph. Their relative abundances are presented in Table 6. The percentage of these common soil organisms increased in the lactate-amended columns compare to the ore sample, from 56.90% to 84.44% in C3 and 82.52% in C4, while it drastically decreased in the control column to 1.75%, suggesting an increase in heterotrophic microorganisms in the sediments following the addition of lactate. A

Table 6

Abundance of common soil microorganisms, sulfate reducing, iron reducing and uranium reducing bacteria in undisturbed ore samples, lactate amended leach columns, and a control leach column as determined by Illumina Sequencing.

			Lactate Amended Columns	
Organism	Ore Sample (%)	Control Column (%)	Column C3 (%)	Column C4 (%)
Common Soil Organisms				
<i>Collimonas</i>	18.99	0.30	3.87	30.66
<i>Bradyrhizobium</i>	17.53	0.58	9.71	9.43
<i>Herbaspirillum</i>	16.53	0.30	3.23	25.84
<i>Herminiimonas</i>	3.85	0.57	67.63	16.59
Total	56.90	1.75	84.44	82.52
Sulfate Reducers	0.19	0.42	0.14	0.26
Iron Reducers	0.79	2.69	0.47	0.59
Uranium Reducers	5.01	3.12	0.76	0.49

complete list of organisms identified is included in [Tables SI-4, SI-5 and SI-6](#) of the Supplemental Information.

The abundance of metal reducers in the samples was also investigated ([Table 6](#)). Information generated by the Illumina sequencing process identified the major organisms and the presence of organisms known to reduce U, sulfate and iron in the samples from the microbial stabilization columns, (presented separately as Supplemental Information). Contrary to the soil organisms, the abundance of U reducers in the samples greatly decreased in the lactate amended columns (C3 0.76% and C4 0.49%), and just slightly in the control column (CC 3.12%) compared to the organisms in the undisturbed Mt. Taylor ore sample (ore 5.01%). In addition, the abundance of sulfate and iron reducers increased in the control column without lactate addition (sulfate: ore 0.19% and CC 0.42%; iron: ore 0.79% and CC 2.69%), and it was maintained almost constant in the biological columns (sulfate: C3 0.14% and C4 0.26%; C3 0.47% and C4 0.59%).

The microbial diversity of the columns was assessed by calculating the Simpson Diversity Index using the following equation:

$$D = 1 - \frac{\sum n(n-1)}{N(N-1)} \quad (5)$$

where: n = number of total individuals of the same population, I; N = total number of individual species per sample; and, when D approaches 1, the diversity of the sample tends to infinite. [Table 7](#) shows the Simpson Diversity Index for the four samples. This showed that the microbial diversity decreased in the lactate-amended columns, most likely to the enrichment of organic-utilizing microorganism in the samples, such as *Herminiimonas* and other common soil organisms; but the microbial diversity increased in the control.

The abundance of the microorganisms present in the four samples was evaluated using an agglomerative hierarchical clustering (AHC) (a dendrogram which displays these results graphically is presented in [Figure SI-8](#) of the Supplemental Information). The analysis shows that the ore differs from the reacted samples but the microbial communities in all the columns, both lactate-amended and control, cluster together, with greater similarity between C4 and CC. The data suggest that the lactate concentration was not sufficient to promote changes in the overall microbial communities, which are dominated by soil microorganisms, in the active columns (C3 and C4).

When considering the difference between the samples for the different microbial families (i.e. U, sulfate, and Fe reducers) we see different trends as shown in the Principal Component Analysis (PCA) presented in [Fig. 9](#). The population of U-reducers in the samples are more similar in the lactate amended columns (C3 and C4) and in the ore sample than in the control column (CC), which might suggest that the absence of lactate from the SGW contributed to a decrease in the relative abundance of U-utilizers in the CC, instead of the columns fed

Table 7

Simpson Diversity Index for microbial analyses of ore, control column (CC), and two columns fed lactate amended ground water (C3 and C4).

Sample ID	N	Simpson Diversity Index (D)
Ore	36611	0.876
CC	20725	0.920
C3	41289	0.529
C4	31293	0.801

lactate thereby promoting the enrichment of U-reducers. The relative abundance of sulfate reducers in the samples is similar, which is in agreement with the observation that the columns were not operated under sulfate-reducing conditions. Finally, the abundance of Fe-utilizing microorganisms in the columns aligns with the overall microbial abundance trend is consistent with the hypothesis that Fe-utilizer microorganisms were dominant in the samples, and the addition of SGW stimulated their growth.

In conclusion, the analyses of the microbial community after completion of the column tests shows that the amendment of lactate promoted the enrichment of heterotroph microorganisms in the columns. The increase in heterotrophs is linked to a decrease in the diversity of microbial populations and in the abundance of U reducers, which hinder the role of lactate in promoting U microbial stabilization in the treatments. Furthermore, when the sediments were exposed to simulated groundwater only, the microbial diversity and the abundance of sulfate and iron utilizers increased (as in the control column), while the abundance of soil organisms decreased. Hydrogen sulfide was not measured in the column effluent because its odor was not detected. The detection limit for the human nose is in the range of 10–100 ng/L, much lower than detectable by most analytical methods ([Pomeroy and Cruse, 1969](#)).

The absence of hydrogen sulfide suggested that-sulfate reducing conditions were not present. Air was not permitted to enter the columns and they were filled with leach solution by pulling a vacuum to draw the solution into the columns and to remove air from interstitial pores. However, the actual redox conditions in the columns was not known. This is important because there is evidence that sulfate reduction under some conditions may increase the solubility of biologically reduced U ([Anderson et al., 2003](#)).

4. Conclusions

This study investigated stabilization of contaminated ground water and aquifer materials following ISL U mining. Ore samples representative of those which occur in the Grants Mineral Belt of western New Mexico were packed in columns then subjected to leaching by oxidized NaHCO_3 solutions to simulate U ISR. Stabilization solutions were then passed through the columns to simulate in-situ chemical and microbial stabilization. Chemical stabilization was simulated by passing a phosphate amended simulated groundwater through the column to precipitate phosphate phases that would immobilize U and other constituents. Microbial stabilization was simulated by passing a lactated-amended simulated groundwater through the column to stimulate growth of heterotrophic organisms with subsequent reduction and subsequent precipitation of U and other constituents.

Both the chemical and microbial column stabilization tests showed little or no stabilization of U or other constituents when compared to a control column fed only simulated ground water. This is believed to be due to limited interaction between the stabilization solutions and the contaminated pore water solutions within the columns from simulated ISL leaching. The results suggest that the stabilization fluids simply flushed the contaminated leach solutions from the columns similar to that which would occur in a ground water sweep remediation strategy because there was little or no mixing between the reactants. This

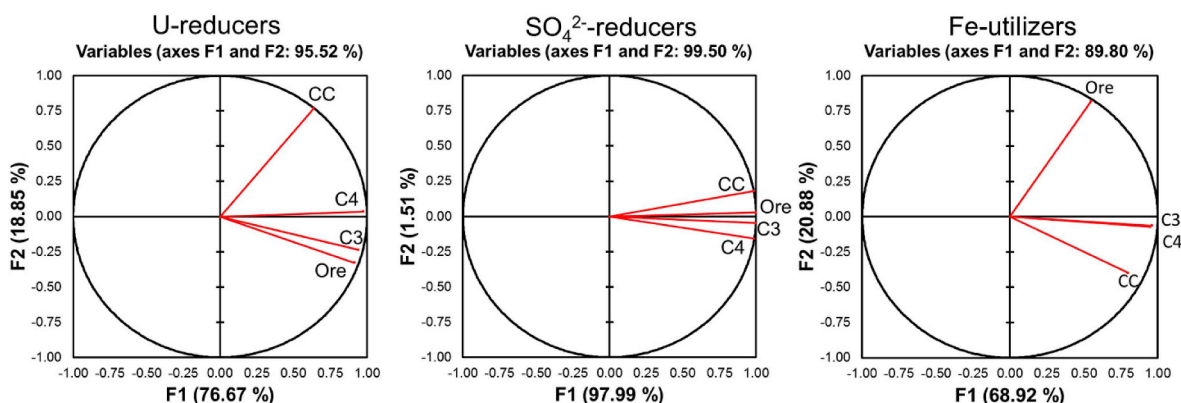


Fig. 9. Principal component analysis for the abundance of the U-reducing, SO_4^{2-} -reducing, and Fe-utilizing microorganisms present in the ore, active columns (C3 and C4) fed with lactate amended-SGW, and control column (CC) fed with SGW without lactate.

interpretation is supported by calculations that show the presence of a short mixing zone relative to the length of the columns used in this study.

In retrospect the results of this study suggest two modifications that might have been worthwhile. First, the column studies simulated the initial conditions that would be produced by an ISR leach process, not those that would be present at the end of mining. The initial leachate had very high U concentrations (1640 mg/L) and relatively low pH (6.5). At the conclusion of ISR mining the leach solution would have low U concentration and the solution chemistry would more closely resemble the leach solution summarized in Table 1 with addition of 50 mM NaHCO_3 . This change would have consequences for both the phosphate amended and lactate amended stabilization methods. The second modification might be to increase the phosphate concentration in the phosphate amended columns. Other investigators have used phosphate concentrations of 1 mM or higher whereas the study described here introduced a solution containing 0.1 mM. We have noted a recent report of a field study to stabilize U in leachate beneath a U mill tailings pile in which phosphate concentrations ranging from 6.8 mM to 25.8 mM were used (Arcadis, 2016). However, even a phosphate concentration of 6.8 mM generates a solution supersaturated with respect to hydroxyapatite but undersaturated with respect to autunite.

The most important conclusion of this study is that ground water hydrodynamic considerations are as important as biogeochemical factors for achieving successful in-situ remediation of a subsurface environment containing soluble and mobile contaminants. In particular, our data indicate that attempting in-situ remediation of a mobile contaminant by injecting mobile reactants into the formation may not be successful because of the limited mixing between the reactants and the contaminants in the subsurface environment. This study was conducted in short (20 cm) columns with an estimated mixing zone of a third of the column length. In a field scale system in which ground water path lengths of tens or hundreds of meters exist the length of the mixing zone will be longer but it will constitute an even smaller fraction of the total length of the flow path. The consequence of limited mixing is that in-situ remediation for subsurface environments containing mobile contaminants will require injection strategies that are more sophisticated than simple steady state recirculation of remediation fluids in order to provide mixing of reactants needed to achieve stabilization.

It is important to recognize the limitations of this study. The major limitation of this study was its short duration compared to what would be used in a field scale remediation. There are two scenarios where a longer duration study might produce different results. First, this study used short hydraulic residence times of two days in the chemical stabilization experiments and seven days in the microbial experiments. It is conceivable that a very slow reaction might have affected the results, especially for processes that rely upon microbial growth which can be very slow under anaerobic conditions. Second, it is possible that though the stabilization experiments did not immobilize the dissolved

contaminants, a longer study might show that leaching of U from the ore was reduced as a result of deposition of mineral phases in the column or possible coating of the mineral phases themselves. For example, the XPS results showed that a phosphate phase accumulated on sediment surfaces in the chemical stabilization column. This might act either as a U sorbent as has been reported by others or form a phosphate mineral on soil particles that prevents dissolution of U minerals. Similarly, a longer duration study might produce sufficient biological growth resulting in reduction of soluble U(VI) to insoluble U(IV) and/or coating of soil particles with organic material to prevent further U dissolution. Nevertheless, the results demonstrate that it is important to evaluate hydrodynamic phenomena when considering in-situ aquifer remediation strategies following in-situ recovery of uranium.

Declaration of interest

None.

Acknowledgements

This research was sponsored by a grant from the NSF Center for Research Excellence in Science and Technology (CREST), NSF Award #1345169. The paper benefited significantly from the technical assistance of Dr. Mehdi Ali, Department of Earth and Planetary Sciences, University of New Mexico. The paper also benefited from the thoughtful comments of two anonymous reviewers.

Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.apgeochem.2019.104418>.

References

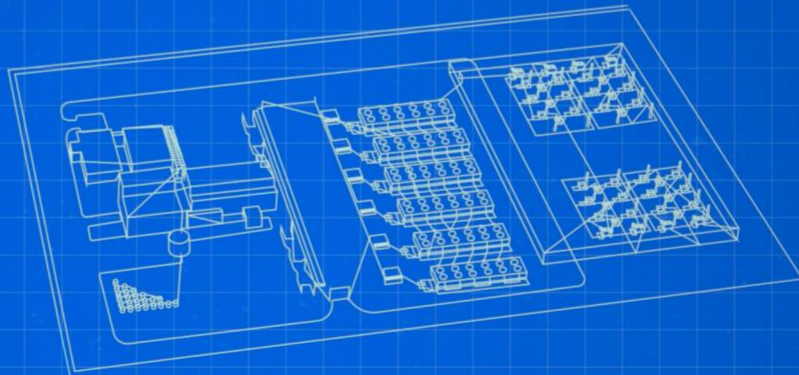
- Anderson, R.T., Vrionis, H.A., Ortiz-Bernad, I., Resch, C.T., Long, P.E., Dayvault, R., Lovley, D.R., 2003. Stimulating the in situ activity of geobacter species to remove uranium from the groundwater of a uranium-contaminated aquifer. *Appl. Environ. Microbiol.* 69 (10), 5884–5891. <https://doi.org/10.1128/AEM.69.10.5884-5891.2003>.
- Arai, Y., Marcus, M.A., Tamura, N., Davis, J.A., Zachara, J.M., 2007. Spectroscopic evidence for uranium bearing precipitates in vadose zone sediments at the Hanford 300-area site. *Environ. Sci. Technol.* 41 (13), 4633–4639. <https://doi.org/10.1021/es062196u>.
- Arcadis, 2016. Expanded TPP Pilot Test in the Alluvial Aquifer, Summary Report, Grants Reclamation Project, Grants, New Mexico. Arcadis U.S., Inc., Highlands Ranch, CO, pp. 101. <https://adamswebsearch2.nrc.gov/webSearch2/main.jsp?AccessionNumber=ML17171A392>.
- Arey, J.S., Seaman, J.C., Bertsch, P.M., 1999. Immobilization of uranium in contaminated sediments by hydroxyapatite addition. *Environ. Sci. Technol.* 33 (2), 337–342. <https://doi.org/10.1021/es980425+>.
- Avasarala, S., Torres, C., Ali, A.-M., Thomson, B.M., Spilde, M.N., Peterson, E.J., Artyushkova, K., Dobrica, E., Lezama-Pacheco, J.S., Cerrato, J.M., 2019. Effect of

- bicarbonate and oxidizing conditions on U(IV) and U(VI) reactivity in mineralized deposits of New Mexico. *Chem. Geol. CHEMGEI2202R1*. <https://doi.org/10.1016/j.chemgeo.2019.07.007>.
- Blake, J.M., Avasarala, S., Artyushkova, K., Ali, A.-M.S., Brearley, A.J., Shuey, C., Cerrato, J.M., 2015. Elevated concentrations of U and Co-occurring metals in abandoned mine wastes in a Northeastern Arizona native American community. *Environ. Sci. Technol.* 49 (14), 8506–8514. <https://doi.org/10.1021/acs.est.5b01408>.
- Blake, J.M., Vore, C.L.D., Avasarala, S., Ali, A.-M., Roldan, C., Bowers, F., Cerrato, J.M., 2017. Uranium mobility and accumulation along the rio paguate, jackpile mine in Laguna Pueblo, NM. *Environ. Sci.: Process. Impacts* 19 (4), 605–621. <https://doi.org/10.1039/C6EM00612D>.
- Borch, T., Roche, N., Johnson, T.E., 2012. Determination of contaminant levels and remediation efficacy in groundwater at a former in situ recovery uranium mine. *J. Environ. Monit.* 14 (7), 1814–1823. <https://doi.org/10.1039/C2EM30077J>.
- Catchpole, G., Kuchelka, R., 1993. Groundwater restoration of uranium ISL mines in the United States. In: *Proceedings of Workshop on Uranium Production Environmental Restoration: an Exchange between the United States and Germany*, Sponsored by Jacobs Engineering Group, vol. 9 Retrieved from. http://inis.iaea.org/Search/search.aspx?orig_q=RN:26025786.
- Charbeneau, R.J., 2000. *Groundwater Hydraulics and Pollutant Transport*. Prentice-Hall, upper Saddle River, NJ.
- Conca, J.L., Wright, J., 2006. An Apatite II permeable reactive barrier to remediate groundwater containing Zn, Pb and Cd. *Appl. Geochem.* 21 (8), 1288–1300. <https://doi.org/10.1016/j.apgeochem.2006.06.008>.
- Converse, B.J., Wu, T., Findlay, R.H., Roden, E.E., 2013. U(VI) reduction in sulfate-reducing subsurface sediments amended with ethanol or acetate. *Appl. Environ. Microbiol.* 79 (13), 4173–4177. <https://doi.org/10.1128/AEM.00420-13>.
- Davis, J.A., Curtis, G.P., 2007. Consideration of geochemical issues in groundwater Restoration at uranium in-situ leach mining facilities (No. NUREG/CR-6870). pp. 150. Retrieved from U.S. Nuclear Regulatory Commission website. <https://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr6870/>.
- EIA, 2018. 2017 Domestic Uranium Production Report. U.S. Energy Information Administration, pp. 20. Retrieved from U.S. Energy Information Administration website. <https://www.eia.gov/uranium/production/annual/pdf/dupr.pdf>.
- Feenstra, T.P., De Bruyn, P.L., 1979. Formation of calcium phosphates in moderately supersaturated solutions. *J. Phys. Chem.* 83 (4), 475–479. <https://doi.org/10.1021/j100467a010>.
- Fuller, C.C., Bargar, J.R., Davis, J.A., Piana, M.J., 2002. Mechanisms of uranium interactions with hydroxyapatite: implications for groundwater remediation. *Environ. Sci. Technol.* 36 (2), 158–165. <https://doi.org/10.1021/es0108483>.
- Gallegos, T.J., Campbell, K.M., Zielinski, R.A., Reimus, P.W., Clay, J.T., Janot, N., et al., 2015. Persistent U(IV) and U(VI) following in-situ recovery (ISR) mining of a sandstone uranium deposit, Wyoming, USA. *Appl. Geochem.* 63, 222–234. <https://doi.org/10.1016/j.apgeochem.2015.08.017>.
- Gebrehiwet, T., Guo, L., Fox, D., Huang, H., Fujita, Y., Smith, R., et al., 2014. Precipitation of calcium carbonate and calcium phosphate under diffusion controlled mixing. *Appl. Geochem.* 46, 43–56. <https://doi.org/10.1016/j.apgeochem.2014.04.005>.
- HRI Inc, 2012. The Section 9 Pilot Restoration Results, Summary Report and Applicability to the Section 8 Site. report submitted to the New Mexico Environment Department, Santa Fe, NM, pp. 15.
- Hunter, J., 1991. Highland in-situ leach mine. *Min. Mag.* 165 (2), 58–63.
- Lovley, D.R., Phillips, E.J.P., 1992. Bioremediation of uranium contamination with enzymatic uranium reduction. *Environ. Sci. Technol.* 26 (11), 2228–2234. <https://doi.org/10.1021/es00035a023>.
- McLemore, Virginia T., Wilton, T., Pelizza, M.S., 2016. In situ recovery of sandstone-hosted uranium deposits in New Mexico: past, present, and future issues and potential. *N. M. Geol.* 38 (4), 68–76.
- McLemore, V.T., Chenoweth, W.L., 2017. Energy And Mineral Resources Of New Mexico: Uranium Resources (No). *Memoir 50C*, Special Publication 13C, pp. 67. Retrieved from NM Bureau of Geology & Mineral Resources website. https://geoinfo.nmt.edu/staff/mclemore/projects/uranium/documents/50C_URANIUM_inprog_013ginger.pdf.
- McLemore, V.T., Hill, B., Khalsa, N., Lucas Kamat, S.A., 2013. Uranium Resources in the Grants Uranium District, New Mexico: an Update. *Geology of Route 66 Region: Flagstaff to Grants*. NM Bureau of Geology & Mineral Resources, Socorro, NM, pp. 117–126.
- Mehta, S., 2017. Geochemical evaluation of uranium sequestration from field-scale infiltration and injection of polyphosphate solutions in contaminated Hanford sediments. *Appl. Geochem.* 84, 133–153. <https://doi.org/10.1016/j.apgeochem.2017.06.009>.
- Mehta, V.S., Maillot, F., Wang, Z., Catalano, J.G., Giammar, D.E., 2015. Transport of U (VI) through sediments amended with phosphate to induce in situ uranium immobilization. *Water Res.* 69, 307–317. <https://doi.org/10.1016/j.watres.2014.11.044>.
- Mehta, V.S., Maillot, F., Wang, Z., Catalano, J.G., Giammar, D.E., 2016. Effect of reaction pathway on the extent and mechanism of uranium(VI) immobilization with calcium and phosphate. *Environ. Sci. Technol.* 50 (6), 3128–3136. <https://doi.org/10.1021/acs.est.5b06212>.
- Moore, R.C., 2003. Patent No. U.S. patent No. 6592294. Retrieved from. <http://patft.uspto.gov/netaqi/nph-Parser?Sect1=PTO1&Sect2=HITOFF&d=PALL&p=1&u=%2Fnetahml%2FPTO%2Fsrchnum.htm&r=1&f=G&l=50&s1=6592294.PN.&OS=PN/6592294&RS=PN/6592294>.
- Moore, R.C., Rigali, M.J., Szecsody, J., Vermeul, V., Leullen, J., 2015. In Situ Formation of Apatite in Sediment for Construction of Permeable Reactive Barriers for Immobilization of Radionuclides. Presented at the DOE Legacy Management Project Meeting, Grand Junction, CO SAND201-3933PE.
- Newsome, L., Morris, K., Lloyd, J.R., 2014. The biogeochemistry and bioremediation of uranium and other priority radionuclides. *Chem. Geol.* 363, 164–184. <https://doi.org/10.1016/j.chemgeo.2013.10.034>.
- NRC, 2009. Generic environmental impact statement for in-situ leach uranium milling facilities, US nuclear regulator y ommission. (No. NUREG-1910). Retrieved from U.S. Nuclear Regulatory Commission website. <https://www.nrc.gov/materials/uranium-recovery/geis.html>.
- Pan, Z., Giammar, D.E., Mehta, V., Troyer, L.D., Catalano, J.G., Wang, Z., 2016. Phosphate-induced immobilization of uranium in Hanford sediments. *Environ. Sci. Technol.* 50 (24), 13486–13494. <https://doi.org/10.1021/acs.est.6b02928>.
- Parkhurst, D.L., Appelo, C.A.J., 2013. Description of Input and Examples for PHREEQC version 3—a computer Program for speciation, batch-reaction, one-dimensional transport, and inverse geochemical calculations (No. Techniques and methods 6-A43, chapter 43, section A: groundwater, in book 6, modeling techniques). pp. 519. Retrieved from U.S. Geological Survey website. <https://pubs.usgs.gov/tm/06/a43/>.
- Pomeroy, R.D., Cruse, H., 1969. Notes and comment: hydrogen sulfide odor threshold. *J. Am. Water Work. Assoc.* 61 (12), 677.
- Reimus, P., Rearick, M., Perkins, G., Marina, O., Punsal, J., Wasserman, N., Clay, J., 2015. Field Evaluation of the restoration Capacity of the aquifer Downgradient of a uranium in-situ recovery mining site (No. Report LA-UR-1522858). pp. 63. Retrieved from Los Alamos national Laboratory website. <https://www.osti.gov/biblio/1178314>.
- Riese, W.C., Brookins, D.G., 1980. Mount taylor uranium deposit, san Mateo, New Mexico. In: *Geology and Mineral Technology of the Grants Uranium Region, 1979*, Compiled by C.A. Rautman. N.M. Bureau of Mines & Mineral Resources, Socorro, NM, pp. 397.
- Rigali, M.J., Brady, P.V., Moore, R.C., 2016. Radionuclide removal by apatite: American Mineralogist. *Am. Mineral.* 101 (12), 2611–2619.
- Rodriguez-Freire, L., Avasarala, S., Ali, A.-M.S., Agnew, D., Hoover, J.H., Artyushkova, K., Cerrato, J.M., 2016. Post gold king mine spill investigation of metal stability in water and sediments of the animas river watershed. *Environ. Sci. Technol.* 50 (21), 11539–11548. <https://doi.org/10.1021/acs.est.6b03092>.
- Roskill, 1991. The economics of uranium, third ed. pp. 178. Retrieved from Roskill Information Services, Ltd. website. <https://roskill.com/>.
- Ruiz, O., Thomson, B.M., Cerrato, J.M., 2016. Investigation of In Situ Leach (ISL) Mining of Uranium in New Mexico and Post-mining Reclamation. *New Mexico Geology* 38, 79–85 NM Bureau of Geology, Socorro, NM, 4.
- Singer, D.M., Zachara, J.M., Brown Jr., G.S., 2009. Uranium speciation as a function of depth in contaminated Hanford sediments - a micro-XRF, micro-XRD, and micro- and bulk-XAFS study. *Environ. Sci. Technol.* 43 (3), 630–636. <https://doi.org/10.1021/es8021045>.
- Szecsody, J.E., Vermeul, V.R., Fruchter, J.S., Williams, M.D., Rockhold, M.L., Qafoku, N., Phillips, J.L., 2010. Hanford 100-N Area in situ Apatite and phosphate Emplacement by Groundwater and jet injection: Geochemical and physical core analysis (No. PNNL-19524). <https://doi.org/10.2172/985586>.
- Thomson, B.M., Smith, C.L., Busch, R.D., Siegel, M.D., Baldwin, C., 2003. Removal of metals and radionuclides using apatite and other natural sorbents. *J. Environ. Eng.* 129 (6), 492–499. [https://doi.org/10.1061/\(ASCE\)0733-9372\(2003\)129:6\(492\)](https://doi.org/10.1061/(ASCE)0733-9372(2003)129:6(492)).
- Tomson, M.B., Nancollas, G.H., 1978. Mineralization kinetics: a constant composition approach | science. *Science* 200 (4345), 1059–1060. <https://doi.org/10.1126/science.200.4345.105>.
- Troyer, L.D., Tang, Y., Borch, T., 2014. Simultaneous reduction of arsenic(V) and uranium (VI) by macinawite: role of uranyl arsenate precipitate formation. *Environ. Sci. Technol.* 48 (24), 14326–14334. <https://doi.org/10.1021/es5037496>.
- UPA, 2015. The Section 9 Pilot Restoration Results Summary Report and Applicability to the Section 8 Site, Comments on the Environmental Protection Agency's Proposed Revisions to 40 CFR Part 192.80 Federal Register 4156, Jan. 26, 2015 (P. 16) [Report Submitted by Uranium Producers of America]. NM Environment Department, Santa Fe, NM.
- Wall, J.D., Krumholz, L.R., 2006. Uranium reduction. *Annu. Rev. Microbiol.* 60 (1), 149–166. <https://doi.org/10.1146/annurev.micro.59.030804.121357>.
- Wellman, D.M., Glovack, J.N., Parker, K., Richards, E.L., Pierce, E.M., 2008. Sequestration and retention of uranium(VI) in the presence of hydroxylapatite under dynamic geochemical conditions. *Environ. Chem.* 5 (1), 40–50. <https://doi.org/10.1071/EN07060>.
- Wen, H., Pan, Z., Giammar, D., Li, L., 2018. Enhanced uranium immobilization by phosphate amendment under variable geochemical and flow conditions: insights from reactive transport modeling. *Environ. Sci. Technol.* 52 (10), 5841–5850. <https://doi.org/10.1021/acs.est.7b05662>.
- Williams, K.H., Bargar, J.R., Lloyd, J.R., Lovley, D.R., 2013. Bioremediation of uranium-contaminated groundwater: a systems approach to subsurface biogeochemistry. *Curr. Opin. Biotechnol.* 24 (3), 489–497. <https://doi.org/10.1016/j.copbio.2012.10.008>.
- Wu, W.-M., Carley, J., Gentry, T., Ginder-Vogel, M.A., Fienen, M., Mehlhorn, T., Criddle, C.S., 2006. Pilot-scale in situ bioremediation of uranium in a highly contaminated aquifer. 2. Reduction of U(VI) and geochemical control of U(VI) bioavailability. *Environ. Sci. Technol.* 40 (12), 3986–3995. <https://doi.org/10.1021/es051960u>.
- Zemlick, K., Thomson, B.M., Chermak, J., Tidwell, V.C., 2017. Modeled Impacts of Economics and Policy on Historic Uranium Mining Operations in New Mexico, vol.39. pp. 11–24. 1. <https://par.nsf.gov/servlets/purl/10082843>.



Small Modular Reactors Still Too Expensive, Too Slow and Too Risky

David Schlissel, Director of Resource Planning Analysis
Dennis Wamsted, Energy Analyst



Expensive to build
Delays in construction
Financially risky
Not a good fit

Contents

Key Findings.....	3
Executive Summary.....	4
Too Expensive.....	6
Too Slow.....	12
Too Risky.....	16
A Bad Fit.....	19
The Boeing Problem.....	20
Conclusion	22
About IEEFA.....	23
About the Authors.....	23

Figures

Figure ES 1: SMR Construction Cost Estimates Keep Rising	5
Figure 1: Cost Escalation Experienced by SMRs in Operation or Under Construction	6
Figure 2: Projected Cost Increases for Proposed U.S. SMRs	8
Figure 3: Projected vs. Actual SMR Construction Schedules	12
Figure 4: Nuclear Construction Reality vs. Rhetoric	14
Figure 5: SMR Power Costs Will Be Much Higher Than Renewables, Storage	16
Figure 6: SMR Power Costs Rise as Capacity Factor Falls	20

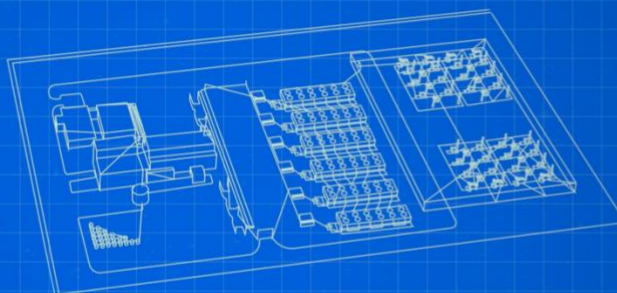
Key Findings

Small modular reactors still look to be too expensive, too slow to build, and too risky to play a significant role in transitioning from fossil fuels in the coming 10-15 years.

Investment in SMRs will take resources away from carbon-free and lower-cost renewable technologies that are available today and can push the transition from fossil fuels forward significantly in the coming 10 years.

Experience with operating and proposed SMRs shows that the reactors will continue to cost far more and take much longer to build than promised by proponents.

Regulators, utilities, investors and government officials should embrace the reality that renewables, not SMRs, are the near-term solution to the energy transition.



Executive Summary

The rhetoric from small modular reactor (SMR) advocates is loud and persistent: This time will be different because the cost overruns and schedule delays that have plagued large reactor construction projects will not be repeated with the new designs. But the few SMRs that have been built (or have been started) paint a different picture—one that looks startlingly similar to the past. Significant construction delays are still the norm and costs have continued to climb.

Factbox: Small Modular Reactors

- Generally defined as reactors that are no more than 300 megawatts (MW)¹, although several so-called SMRs are larger.
- The International Atomic Energy Agency says there are more than 80 SMR concepts at some phase of development worldwide.
- SMR proposals span the technology gamut, from scaled-down conventional boiling and pressurized water reactors (BWRs and PWRs) to first-of-a-kind technologies, as well as designs that have been tried previously and have failed.

¹ All megawatt numbers in this paper are megawatts-electric (MW) unless otherwise noted.

IEEFA has taken a close look at the data available from the four SMRs currently in operation or under construction, as well as new information about projected costs from some of the leading SMR developers in the U.S. The results of the analysis show little has changed from our previous work. SMRs still are too expensive, too slow to build, and too risky to play a significant role in transitioning from fossil fuels in the coming 10 to 15 years.

We believe these findings should serve as a cautionary flag for all energy industry participants. In particular, we recommend that:

- Regulators who will be asked to approve utility or developer-backed SMR proposals should craft restrictions to prevent delays and cost increases from being pushed onto ratepayers.
- Utilities that are considering SMRs should be required to compare the technology's uncertain costs and completion dates with the known costs and construction timetables of renewable alternatives. Utilities that still opt for the SMR option should be required to put shareholder funds at risk if costs and construction times exceed utility estimates.
- Investors and bankers weighing any SMR proposal should carefully conduct their due diligence. Things will go wrong, imperiling the chances for full recovery of any invested funds.
- State and federal governments should require that estimated SMR construction costs and schedules be publicly available so that utility ratepayers, taxpayers and investors are better

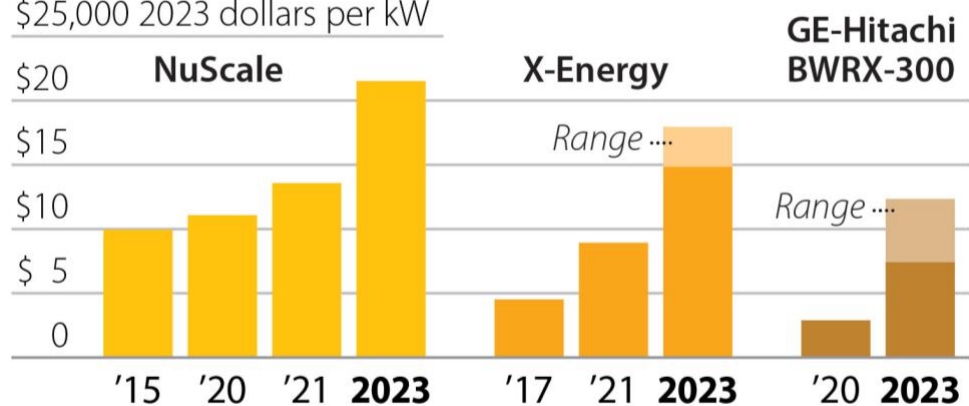
able to assess the magnitude of the SMR-related financial risks that they may be forced to bear.

- Finally, it is vital that this debate consider the opportunity costs associated with the SMR push. The dollars invested in SMRs will not be available for use in building out a wind, solar and battery storage resource base. These carbon-free and lower-cost technologies are available today and can push the transition from fossil fuels forward significantly in the coming 10 years—years when SMRs will still be looking for licensing approval and construction funding.

Figure ES 1: SMR Construction Cost Estimates Keep Rising

Cost projections for small modular reactors, by year

\$25,000 2023 dollars per kW



Source: IEEFA calculations based on public data

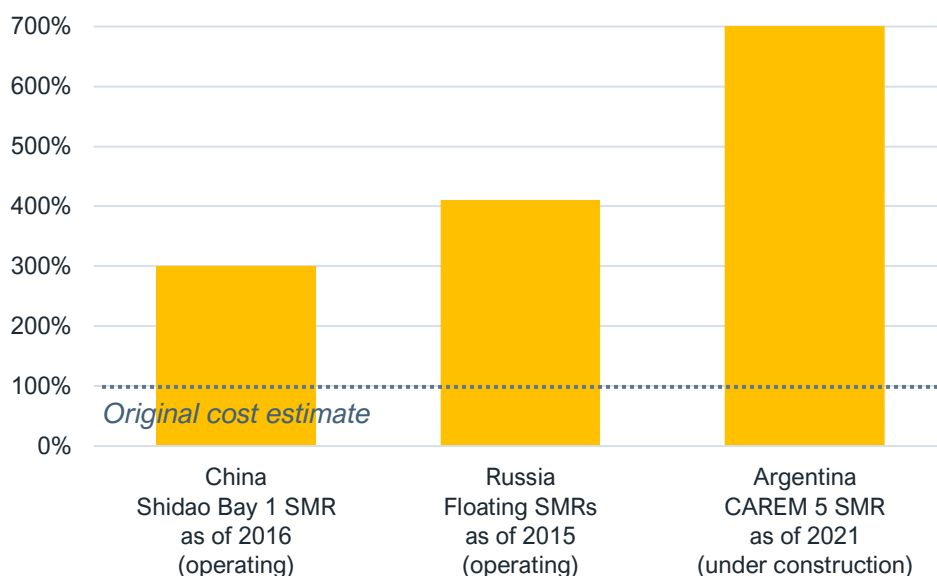
IEEFA

Too Expensive

A key tenet for SMR proponents is that the new reactors will be economically competitive. But the on-the-ground experience with the initial SMRs that have been built or that are currently under construction shows that this simply is not true.

There currently are three operating SMRs worldwide—two in Russia and one in China, plus a fourth under construction in Argentina. Costs for all four have been significantly higher than originally forecast (see below).

Figure 1: Cost Escalation Experienced by SMRs in Operation or Under Construction



Source: IEEFA calculations from data in the 2023 World Nuclear Industry Status Report and Bellona Environmental Foundation.

The takeaway is that the projected costs significantly understated actual construction expenditures. Projected costs for the Russian SMRs climbed more than 300% from initial estimates, according to the last available information.¹ Since the estimate is from 2015, it is likely the final costs were even higher since the two units did not enter commercial service until 2019. Likewise, it has been reported that the cost for China's Shidao Bay 1 SMR, a 150MW high-temperature gas-cooled reactor (HTGR), was triple initial cost projections.²

The example from Argentina is even more extreme. Projected costs for the CAREM 25 (*Central Argentina de Elementos Modulares*), a 25MW research reactor designed to serve as the prototype for 100MW models, have climbed 600% since initial work began on the project in 2013.³ According

¹ Bellona Environmental Foundation. [New documents show cost of Russian floating nuclear power plant skyrockets](#). May 25, 2015.

² World Nuclear Association. [Nuclear Power in China](#). Accessed May 12, 2024. Nuclear Engineering and Design. [Current status and technical description of Chinese 2 × 250 MWth HTR-PM demonstration plant](#). 2009.

³ IEEFA calculations based on data in [2023 World Nuclear Industry Status Report](#), pp. 438-439.

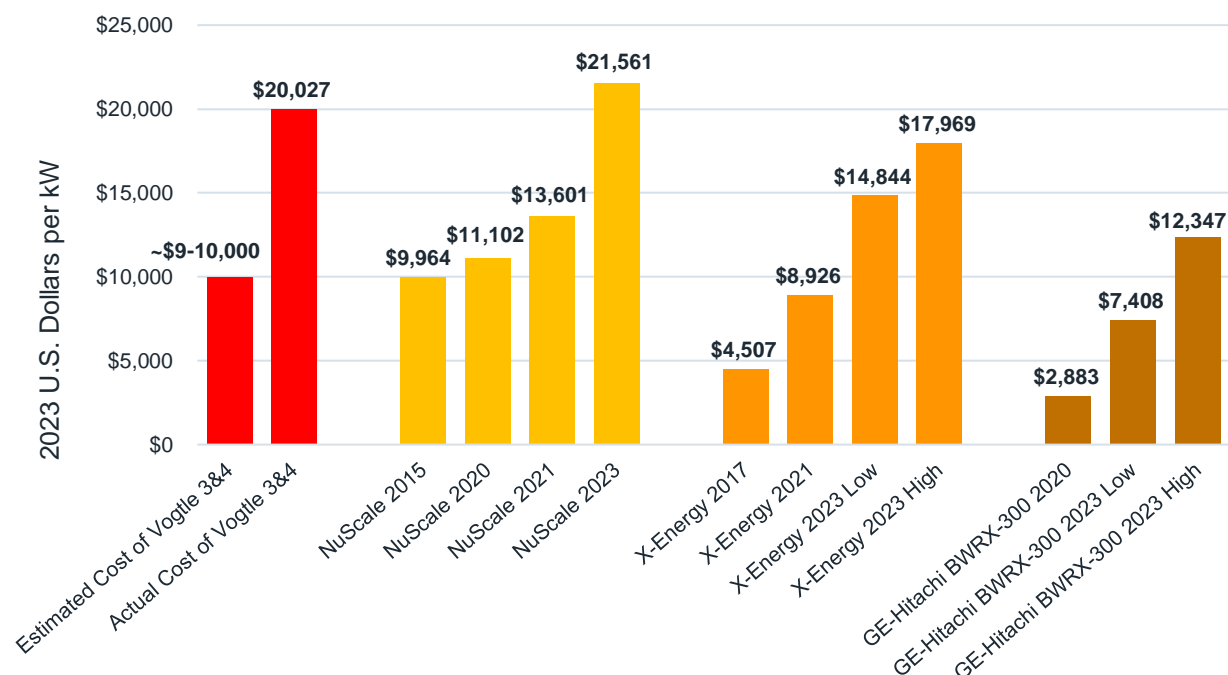
to the World Nuclear Association, the plant will not begin operation until 2027,⁴ which makes additional cost increases a real possibility.

Similar significant cost increases have occurred at proposed projects in the U.S. IEEFA has previously documented the problems at NuScale.⁵ Costs for that company's SMR more than doubled from 2015-2023, rising from \$9,964 per kilowatt (kW) to \$21,561 per kW, prompting the cancellation of the company's signature project, a planned six-reactor, 462MW facility to be built in Idaho in cooperation with the Utah Associated Municipal Power Systems (UAMPS).

NuScale's problems are not unique. U.S. SMR developers have consistently sought to shield their construction cost estimates, but information about two other prominent projects shows that the estimated costs for these projects also have skyrocketed. The cost increases for the X-Energy and GE-Hitachi SMR projects (see graphic below) occurred well before either had secured licensing approval from NRC, let alone begun construction. IEEFA believes this should be a red flag for utilities, regulators and investors. The costs, already high, are likely to climb even higher.

⁴ World Nuclear Association. [Nuclear Power in Argentina](#). April 17, 2024.

⁵ See IEEFA, [NuScale's small modular reactor](#) and [Eye-popping new cost estimates release for NuScale small modular reactor](#).

Figure 2: Projected Cost Increases for Proposed U.S. SMRs

Source: IEEFA calculations based on public data for each of the projects converted to 2023-year U.S. dollars. For example, see the [GE Hitachi website](#), [Four reactors could cost Saskatchewan \\$12 to \\$20 billion](#), [X-Energy and ARES Acquisition Corporation Announce Strategic Update](#), [Georgia Power Company's monthly and Quarterly Reports to the Georgia Public Service Commission on construction of the Vogtle Nuclear Project](#) and [IEEFA reports on NuScale](#).

This chart illustrates two key important points.

First, when NuScale's proposed SMR project with UAMPS was cancelled in November 2023, years before it even would have had a license from the NRC, its estimated construction cost was already higher (on a per-kW basis using 2023 dollars) than the actual cost of the two new reactors at Georgia Power's Vogtle nuclear plant.

Second, evidence is now starting to come out showing that the estimated construction costs of other leading SMR developers are also rising significantly, even before companies have secured licenses from the Nuclear Regulatory Commission and well ahead of any actual construction activity.

It is also important to note that these price increases aren't design-specific. For example, when X-Energy raised the projected all-in price of its SMR in July 2023 (effectively doubling the cost from \$2.5 billion to \$4.75 billion to \$5.75 billion), the company cited the following factors: Inflationary

pressures for construction materials, higher labor costs, increased interest rates and supply chain constraints for equipment, among others.⁶

NuScale attributed the significant cost increases at its UAMPS project to similar factors including rising interest rates and higher prices for steel and other construction commodities.⁷

These types of generic increases almost certainly have been felt by all SMR developers, pushing up the projected prices of their projects as well.

Harder to forecast, but certainly an issue that should concern regulators and potential customers, is the likelihood of future price increases as proposed projects inch closer to construction. At that point, developers will be competing against one another for skilled labor, design resources and reactor-related construction materials. This competition, with many developers chasing scarce labor and material in a still-nascent market, is bound to lead to significant upward pressure on project costs.

The cost debate inevitably includes Westinghouse, the developer of the two AP1000 reactors recently brought online at Georgia Power's Vogtle nuclear facility. That project, which led to Westinghouse's bankruptcy, was more than \$20 billion over budget and took more than six years longer to complete than forecast.⁸ Undaunted by that debacle, Westinghouse has now jumped into the SMR market, introducing a 300MW unit (the AP300) that it says it can build for \$3,333 per kW—even though the final cost of the Vogtle reactors was more than \$20,000 per kW in 2023-year dollars. Even if Westinghouse's projected AP300 cost is just an overnight estimate that excludes escalation and financing costs, that is a spectacular projected cost reduction for a facility that is still not licensed and far from breaking ground for construction.

The BWRX-300

The BWRX-300 is a planned 300MW boiling water reactor that is being developed by GE-Hitachi Nuclear Energy. It is based on the companies' 1,600MW economic simplified boiling water reactor (ESBWR); the ESBWR has been licensed by the U.S. Nuclear Regulatory Commission (NRC) but not built.

The BWRX-300 still has not been licensed in the U.S., but the company signed a contract with Ontario Power Generation (OPG) in 2023 to build the first unit at OPG's Darlington nuclear facility in Canada.¹ The companies have begun work and say they plan to have the first unit online by the end of 2028.

The Tennessee Valley Authority is also considering building one or more of the reactors in its service territory and has invested in a joint effort to help fund licensing activities at the NRC.

¹ Utility Dive. [GE Hitachi and 3 partners announce first commercial contract for grid-scale SMR in North America](#). January 30, 2023.

⁶ EE Power. [Inflation-Ridden Supply Chains, Interest Rates Dampen SMR Development](#). July 13, 2023.

⁷ UAMPS Talking Points. January 2, 2023.

⁸ For more details, see IEEFA, [Southern Company's Troubled Vogtle Nuclear Project](#).

Westinghouse's cost projections for the AP300 are notable given two framing points—one recent and the other from the early 2000s. In the first data point, from 2002, Westinghouse executives were discussing the company's decision to stop development of its AP600 reactor and pursue commercialization of the AP1000.⁹

"Industry executives indicate that any new nuclear plant must be able to compete in the deregulated generation wholesale marketplace and provide a return to the shareholders," they wrote.¹⁰ "Against this standard, the costs of advanced nuclear power plants currently are still too high. This includes the AP600, Westinghouse's 600 MWe advanced passive plant ... Although the AP600 is the most cost-effective nuclear power plant ready for deployment, it is still more expensive than other new generation options in the U.S."

That was 20 years ago, and the situation has become even more tenuous since with the significant decline in the costs of wind, solar and battery storage.

The other development, from February, was the announcement by the Czech utility CEZ that Westinghouse had been eliminated from a bidding process to build four large nuclear reactors in the country because it refused to offer a fixed bid proposal for the project.¹¹ A fixed bid process resulted in Westinghouse's bankruptcy in 2017 due to the rising costs of the Vogtle and Summer projects, so maybe the company, now owned by private equity firm Brookfield Energy Partners and the

The Xe-100

X-Energy is planning to build an 80MW high temperature gas reactor that will be capable of delivering electricity or steam to customers. The company says the modules usually will be bundled in fours as a 320MW facility.

The two previous HTGRs in the U.S. were the 40MW Peach Bottom 1 reactor in Pennsylvania, which operated from 1966-74, and the 330MW Fort St. Vrain facility in Colorado, which operated from 1976-89.¹ Fort St. Vrain had significant operating issues, recording a lifetime capacity factor of only roughly 17% before its closure years ahead of schedule.²

X-Energy's planned SMR will use a different fueling system than Fort St. Vrain, a so-called pebble bed process in which the fuel is fed continuously into the reactor in the form of small spheres, or pebbles.³ The only currently operating reactor using this system is China's Shidao SMR, mentioned previously.⁴

The company announced plans in 2023 to build four of the reactors at a Dow Chemical manufacturing facility in Seadrift, Texas.

¹ [High Temperature Gas Reactors: Assessment of Applicable Codes and Standards](#), Pacific Northwest National Laboratory. October 2015.

² Ibid. PNNL data with IEEFA calculations.

³ [Pebble Bed – The Nuclear Gumball Machine](#), Dec. 14, 2022.

⁴ [World's first HTR-PM nuclear power plant connected to grid](#), Dec. 20, 2021.

⁹ As its name suggests, the AP600 reactor was 600 MW in size. While not literally an SMR, the AP600 was Westinghouse's first effort to market a reactor smaller than those the nuclear industry had generally built in the U.S.

¹⁰ International Atomic Energy Agency. [AP1000: Meeting economic goals in a competitive world](#). May 2002.

¹¹ Neutron Bytes. [Westinghouse Eliminated from Czech Nuclear Project](#). February 10, 2024.

uranium miner Cameco, has learned its lesson. But what does that say about its cost estimates, either for the AP1000 or the AP300?

IEEFA also does not believe these will be the last cost increases, either for the SMRs referenced here or the many other designs under development. All the proposed SMRs still need additional design work, licensing by the U.S. Nuclear Regulatory Commission, the scaling up of SMR designs to commercial-size projects during construction and pre-operational testing. The experience of other reactor projects has repeatedly shown that further significant cost increases and substantial schedule delays should be anticipated at future stages of project development.

Finally, IEEFA questions the assertion by SMR advocates that costs will decline as more reactors of a given design are brought online, leading to what is known as a positive learning curve. The U.S. nuclear industry has never shown a positive learning curve. Instead, it has repeatedly shown a negative learning curve where the cost of new reactors continued to rise, even as more were built.

Even the French nuclear program, which relied on a high degree of standardization in the design of its 58 reactors built between 1970 and 2000, failed to achieve a positive learning curve. Rather, costs continued to increase over time despite the program's design standardization.¹²

And any positive learning curve achieved in building SMRs will depend heavily on how many of each design are built. The International Atomic Energy Agency (IAEA) estimates that there are about 80 SMR designs currently being proposed and marketed worldwide,¹³ making it highly uncertain how many of each design will be constructed. Too few, and there may not be any cost savings over time, and there may also be no economic justification for modular construction in a factory.

With these concerns in mind, IEEFA believes companies considering the Westinghouse AP300 (or any other SMR) should insist on a fixed price contract in any development agreements. A developer's willingness to sign one would say volumes about their confidence in their own estimates, and keep risks down for the buyer.

¹² Energy Policy. [The Costs of the French nuclear scale-up: a case of negative learning by doing](#). September 2010.

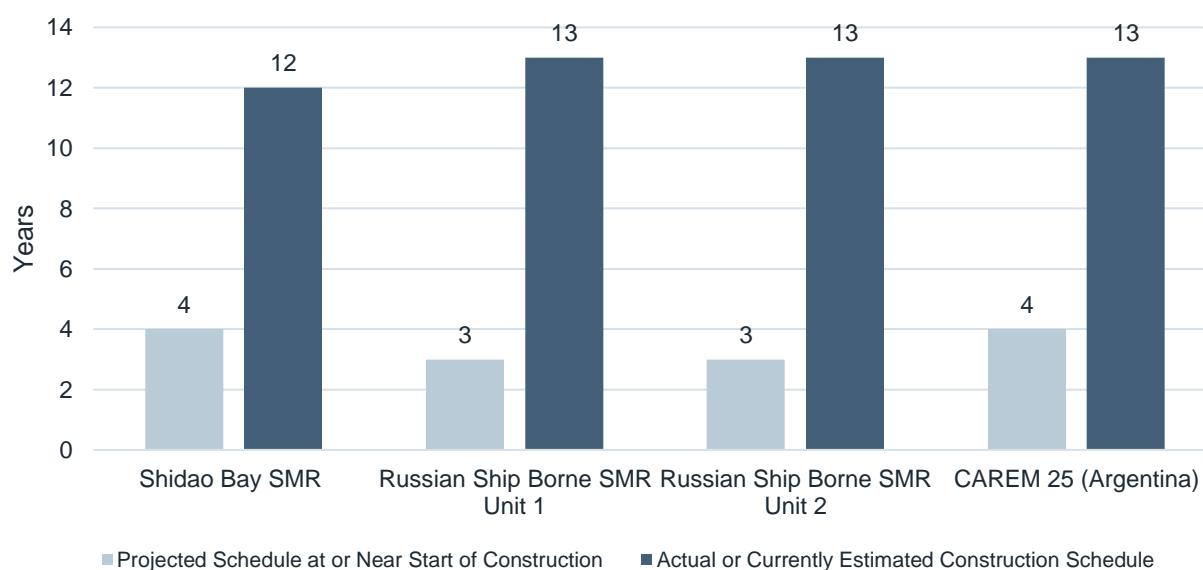
¹³ IAEA. [Small modular reactors](#). Accessed May 14, 2024.

Too Slow

A second tenet for SMR backers is that the reactors can be built quickly—in sharp contrast to recent history with larger units. But just as with the cost claims, the rhetoric here does not match reality.

Turning again to the results in Russia, China and Argentina, long construction delays have been the norm, not the exception. As the graphic below shows, not one of these SMRs has come close to meeting its projected three- to four-year construction schedule.

Figure 3: Projected vs. Actual SMR Construction Schedules



Source: IEEFA calculations based on data in the 2023 World Nuclear Industry Status Report and IAEA's Power Reactor Information System.

Two other SMRs currently under construction in China and Russia are also years behind schedule. Russia's BREST-300 lead-cooled reactor is now scheduled for completion in 2026, even though announcements in the early 2010s had indicated it would be operational by 2018.¹⁴ Similarly, China's ACP100, a 125MW pressurized water SMR that has been under development since the early 2010s, is now not scheduled to begin commercial operation until 2026.¹⁵

Similarly optimistic construction estimates have consistently shown up in U.S. SMR project development presentations.

One of the first planned SMRs in the U.S., the 195MW mPower PWR design backed by Babcock & Wilcox and Bechtel, was launched in 2009 with plans to have the first two units operational by

¹⁴ Mycle Schneider Consulting. [World Nuclear Industry Status Report 2023](#). December 2023, p. 325.

¹⁵ *Ibid.*, p. 322.

2022.¹⁶ The development effort was shelved in 2017 after the companies and the U.S. Department of Energy had spent almost \$500 million on the reactor design. In announcing the cancellation, Bechtel's Fred deSousa hit on one of the key issues facing all SMR developers—cost. “However, bringing a new reactor program through the design, engineering and regulatory process is a very complex and expensive proposition. It needed a plant owner with an identified location and **an investor willing to wait a significant period of time for a return, and these were not available**” [emphasis added].¹⁷

NuScale, another U.S. SMR developer, has also consistently been overly optimistic about costs and construction time frames. In 2016, for example, John Hopkins, NuScale's CEO, told the Senate Energy and Natural Resources Committee that the company's SMR project with UAMPS would be commercially operational by 2024. “We expect to deliver our first project of twelve power modules in a 600MWe (gross) plant to UAMPS for an overnight price of approximately \$3 billion, with commercial operation commencing in 2024.”¹⁸ By the time the project was cancelled in November 2023, full commercial operation had been pushed back to 2030 and the cost had jumped to \$9.3 billion.¹⁹

Despite this real-world experience, Westinghouse, X-Energy and NuScale, among others, continue to claim they will be able to construct their SMRs in 36 to 48 months, perhaps quickly enough to have them online by 2030. GE-Hitachi even claims it ultimately will be able to construct its 300MW facility in as little as 24 months.²⁰ Admittedly, there is a not-zero chance this is possible, but it flies in the face of nuclear industry experience, both in terms of past SMR development and construction efforts and the larger universe of full-size reactors, all of which have taken significantly longer than projected to begin commercial operation.

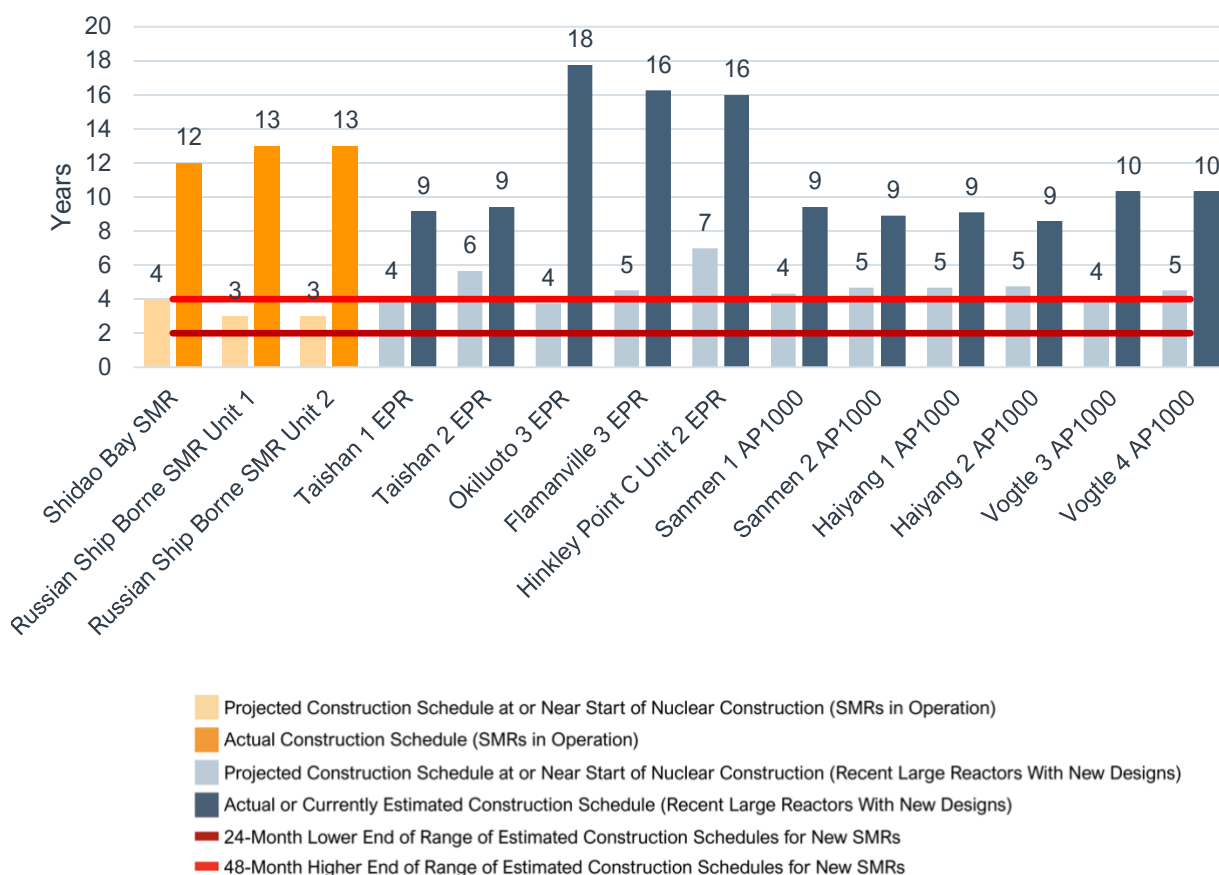
¹⁶ Wise International. [Nuclear Monitor](#). March 21, 2017.

¹⁷ American Nuclear Society. [mPower Consortium Halts Project](#). March 16, 2017.

¹⁸ Senate Energy and Natural Resources Committee. [John Hopkins testimony](#). May 17, 2016.

¹⁹ E&E News. [NuScale cancels first-of-a-kind nuclear project as costs surge](#). November 9, 2023.

²⁰ Hitachi. [BWRX-300 Small Modular Reactor](#). Accessed May 6, 2024.

Figure 4: Nuclear Construction Reality vs. Rhetoric

Source: IAEA Power Reactor Information System, EDF, 2023 World Nuclear Industry Status Report.

Much of the developer optimism regarding rapid completion schedules is tied to the supposed benefits of modular construction—the factory construction of reactor parts that are then shipped to the reactor site and essentially put together like a puzzle. Here, it is worth noting that Vogtle reactors 3 and 4, Georgia Power’s just-completed but vastly over-budget and long-delayed project, were built using modular techniques, a feature that Westinghouse touted when marketing its AP1000 reactors, the model built at Vogtle and the one it still touts today.

The same modular construction techniques were also used by Westinghouse at the V.C. Summer project in South Carolina. This project was planned as a two-unit expansion at the existing site, using the same Westinghouse AP1000 design used at Vogtle. The project was cancelled in 2017 after \$9 billion had been spent.²¹

²¹ The New York Times. [U.S. Nuclear Comeback Stalls as Two Reactors Are Abandoned](#). July 31, 2017.

It is safe to say that modular construction didn't keep costs down or speed construction at either site. Yet SMR advocates, including the U.S. Department of Energy, keep promoting its unproven benefits.²²

While SMR developers struggle to get just one reactor into commercial operation, the buildout of U.S. renewable resources is rapidly picking up speed. The U.S. Energy Information Administration (EIA) projects that installed solar capacity will jump to 158,000 MW by the end of 2025, a 75% increase from the 90,000 MW installed by the end of 2023.²³

And this is likely just the beginning. In NextEra Energy's first-quarter earnings call in April, John Ketchum, the company's chairman, CEO and president, stressed the key role renewables will play in meeting the expected strong increase in electricity demand across the U.S. "In fact," Ketchum said, "we believe the U.S. renewables and storage market opportunity has the potential to be three times bigger over the next seven years compared to the last seven, growing from roughly 140 gigawatts of additions to approximately 375 to 450 gigawatts."²⁴

The seven-year forecast period is interesting. It is highly unlikely that even one SMR will be commercially operational in the U.S. within seven years.

Focusing just on the company's own growth plans, NextEra reported that it expects to build at least 32,000 MW of new renewable capacity, and perhaps as much as 42,000 MW, in the U.S. through 2026—in addition to the ongoing renewable expansion at its utility, Florida Power & Light. There certainly will be no operational SMRs by that date.

NextEra's optimism is not unique. The American Clean Power Association said in May that it expects 260,000 MW of renewable energy generation, mostly solar, to be added to the U.S. grid just through 2028.²⁵

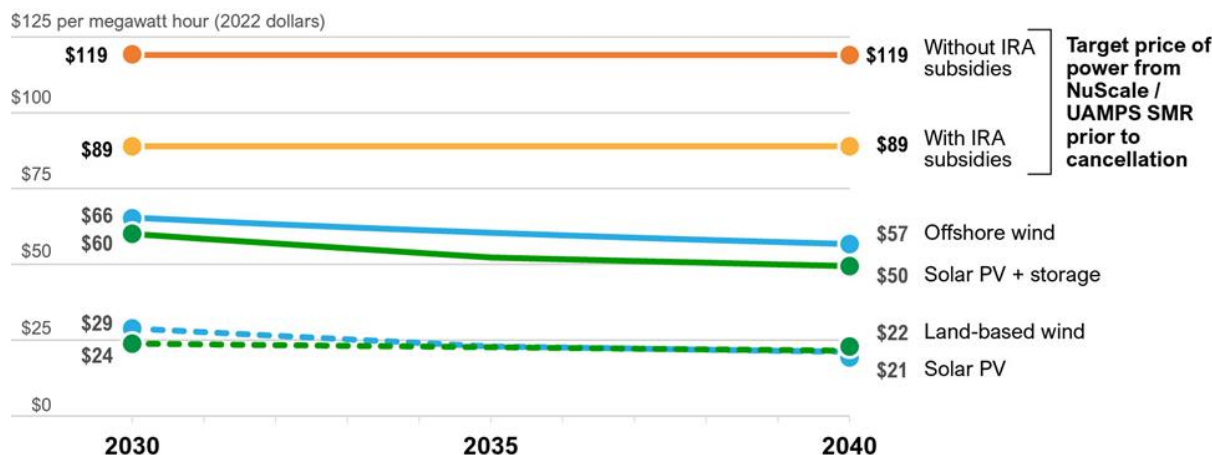
It is becoming increasingly clear that the cost of power from SMRs will be far more expensive than that from renewable energy and battery storage. This is illustrated in the figure below, which highlights the substantial gap between the estimated cost of power from the now-cancelled NuScale UAMPS project and projected renewable power costs from the DOE's National Renewable Energy Laboratory.

²² DOE Office of Nuclear Energy. [Benefits of Small Modular Reactors](#). Accessed May 13, 2024.

²³ Energy Information Administration. [Short-Term Energy Outlook Data Browser](#). Accessed May 7, 2024.

²⁴ [NextEra Energy Q1 Earnings Call Prepared Remarks](#). April 23, 2024.

²⁵ S&P. [Solar will do 'heavy lifting' during influx of renewables to US grid – analysts](#). May 10, 2024.

Figure 5: SMR Power Costs Will Be Much Higher Than Renewables, Storage

Source: IEEFA analysis based on data from NuScale, UAMPS and NREL.

Too Risky

Southern Company, Georgia Power's parent, just wrapped up what even its executives acknowledged was an "arduous journey" to complete construction at the two-unit expansion of its Vogtle nuclear plant, with commercial operation at Unit 4 beginning in April (Unit 3 began operations in July 2023). Still, it is safe to say that no utility in the U.S. has a better understanding of the risks of nuclear power than Southern does. And, judging by CEO Chris Womack's comments during the company's first-quarter earnings call, at this time Southern wants no part of any future nuclear construction.

Womack endorsed nuclear power in the abstract, saying "the country is going to need more nuclear. I mean there's clearly no technology better suited to support demands of this increasingly digital economy and society."²⁶

But the kicker tells the story. "I'd also say we're going to celebrate what we've done at Vogtle for a very long time before we give any consideration to any more [nuclear]."²⁷

Womack is not alone in his risk aversion.

In a 2022 conference presentation, NextEra's Ketchum voiced significant skepticism regarding SMRs.

²⁶ Southern Company Q1 earnings call transcript. May 2, 2024.

²⁷ *Ibid.*

"... I'm very skeptical with regard to SMRs," Ketchum said. "They are going to be very expensive and then you're going to be taking a bet on the technology. Right now, I look at SMRs as an opportunity to lose money in smaller batches."²⁸



Right now, I look at SMRs as an opportunity to lose money in smaller batches.

John Ketchum

Chairman, CEO and President of NextEra Energy

Instead, Ketchum reiterated that NextEra will continue with its rapid buildout of wind, solar and battery storage. In the company's first-quarter 2024 quarterly earnings call, NextEra projected that its Florida Power & Light (FPL) subsidiary will add 21,000 MW of solar capacity and 4,000 MW of battery storage capacity in its service territory in the next 10 years, pushing solar's share of its generation from 6% to 38%.

"FPL's annual Ten-Year Site Plan continues to indicate that solar and storage are the most cost-effective answer for customers to add reliable grid capacity over the next decade," Kirk Crews, the company's newly appointed chief risk officer, told analysts. Even though FPL operates the two-unit, 1,747MW Turkey Point nuclear plant and has an existing site license from NRC to build two additional reactors at the site, there was no mention of new nuclear.

That risk aversion is even shared by Constellation, the U.S.'s largest nuclear power company. In its first-quarter earnings call this month, company executives talked extensively about their nuclear operations and plans for growth, particularly to serve the strong forecasted growth in electricity demand from data centers and the burgeoning artificial intelligence (AI) industry. But Joseph Dominguez, the company's president and CEO, made it clear that the financial risks for any new builds would be borne by customers, not the company.

The current thinking, Dominguez explained, is to negotiate power purchase agreements (PPAs) to supply companies looking for carbon-free power with electricity from Constellation's existing nuclear facilities, and then in the future to consider the construction of one or more SMRs to provide new capacity. "...[T]he customer, through increases in the PPA, would begin to fund site development work construction," Dominguez said, "ultimately scaling up to the point where the PPA absorbs the full cost of an operating new unit."²⁹

The structure may work for Constellation, but given the cost increases and construction delays that have plagued the SMR sector already, this will push enormous financial and time risks onto customers, potentially undercutting their interest and ability in pursuing such projects.

²⁸ S&P Global. NextEra CEO sees US climate law catalyzing decades of clean energy growth. Oct. 3, 2022.

²⁹ Constellation Q1 earnings call transcript. May 9, 2024.

Aware of these risk-related problems, the Department of Energy has floated several ideas to get the government involved in the buildout of the SMR sector. These include providing “cost overrun insurance,” other undefined financial assistance, becoming an owner or serving as a buyer for the power.³⁰ None of these options would reduce the development risk—they would simply transfer those risks and the associated costs to U.S. taxpayers.

Other Cost and Risk Considerations

A 2023 study for the U.S. Air Force underscored the concerns raised by Ketchum, highlighting the virtually complete lack of publicly available data about construction costs and future performance. It also raised other concerns that have not yet been considered in the discussions about building SMRs: “Since SMR technology is still developing and is not deployed in the U.S., information is scarce concerning the various costs for [operations & maintenance], decommissioning and end-of-life dissolution, property restoration and site clean-up and waste management.”¹

In other words, it is not just the construction costs that matter. All other potential costs need to be factored into the decision-making process before moving forward with plans for an unproven SMR.

¹ Pacific Northwest National Laboratory. Emerging Technologies Review: Small Modular Reactors. April 2023.

³⁰ U.S. Department of Energy. [Pathways to Commercial Liftoff: Advanced Nuclear](#). March 2023, p. 4.

A Bad Fit

Another tenet for SMR developers is that their reactors will be complementary resources for renewable-dominated electric grids.

In 2020, for example, Jay Wileman, president and CEO of GE Hitachi Nuclear, told a panel hosted by the World Nuclear Association that SMRs can be more than just baseload generation.

“However, as we start to see the increase in penetration of renewables, you will need to acknowledge the ability for nuclear not to just be baseload, but to load-follow: something that is not typically thought of with a nuclear reactor. I think that, looking forward, small modular reactors are excellently fit for that purpose, and the ability to follow the output of renewables and load-follow on the grid,” he said.³¹

Similarly, TerraPower says its planned Natrium SMR, a 345MW reactor with accompanying storage, will be able “to operate as a baseload power source or as a flexible, load-following system to support grids with variable-output renewables.”³²

Finally, NuScale consistently touts the flexibility of its planned SMR, which it says can help integrate renewables into the grid.³³

But here too, the reality and the rhetoric don’t mesh.

NuScale has based its reactor cost estimates on the assumption that its SMR will operate with a capacity factor of 95%. If built, that is possible, although probably optimistic, since the average for the operating reactors in the U.S. has never been that high. Duke Energy, for example, one of the largest nuclear plant operators in the U.S., says its fleet average has hit 95% during a couple of years, but not consistently.³⁴ Still, the key point is that if NuScale did consistently post a 95% capacity factor it would be impossible by definition for it also to be a flexible, load-following resource. Both things cannot be true.

The reality is that developers bringing multibillion-dollar SMRs onto the electric grid would have every incentive to run them as much as possible to recover their costs through electricity sales. Instead of working with renewables, they would effectively be blocking renewables from the grid.

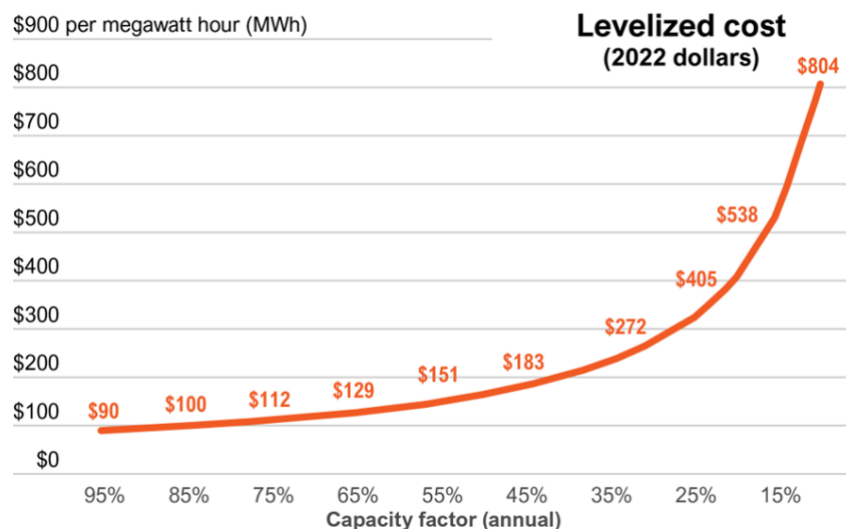
The graphic below illustrates the problem for SMR developers. The less they run, the more their per megawatt-hour costs rise and the harder it will be for them to compete in the market. Having invested billions, it is unlikely developers will willingly cycle their plants to accommodate renewables.

³¹ World Nuclear News. [Cost-competitive SMRs will find place in electricity ecosystem](#). September 16, 2020.

³² [Natrium Power website](#). Accessed May 7, 2024.

³³ [NuScale Power 2023 Earnings Release](#). March 14, 2024.

³⁴ Duke Energy. [Nuclear Generation - On track to a cleaner energy future](#). October 18, 2022.

Figure 6: SMR Power Costs Rise as Capacity Factor Falls

Source: IEEFA analysis using data in the November 2020 Development Cost Reimbursement Agreement between UAMPS and NuScale.

The Boeing Problem

One key issue that has received too little attention in the discussion of SMR commercialization is the potential for systemic flaws in reactors with the same standardized design.

This has been referred to as the “Boeing Problem” by Arjun Makhijani of the Institute for Energy and Environmental Research because of problems that affected the company’s fleet of 787 Dreamliners.³⁵ But it could also apply to Boeing’s more recent experience with a poorly designed feature in its 737 MAX aircraft that led to two critical crashes, and several years of the 737 MAX air fleet needing to be grounded until the problem was identified and fully corrected. Similarly, an unexpected and unidentified design flaw discovered in a key component of a highly standardized SMR could lead to extended and expensive outages, repairs and design changes. But taking an airplane back to Boeing for those repairs and design changes is relatively easy. Taking an SMR back to the factory would be extremely difficult, if not impossible.

The potential risk that a problem identified in one SMR will affect the costs, and maybe the operation, of other SMRs with the exact or similar standardized design, is not merely hypothetical. The same problems have cropped up at many existing reactors around the world due to materials choices and design decisions made by the industry before these plants were even being built.

For example, according to the World Nuclear Association, operators have been forced to replace steam generators at more than 110 pressurized water reactors (PWRs)—more than half of which

³⁵ [Light Water Designs of Small Modular Reactors: Facts and Analysis](#). Revised September 2013.

have been in the U.S.—since 1980.³⁶ These replacements were the result of the denting and wall thinning of large numbers of steam generator tubes that had been made from a material called heat-treated Alloy 600. Five additional U.S. PWRs were shut down early due to steam generator tube cracking.

Similarly, a decision on the material to be used in key safety-related piping in boiling water reactors (BWRs) led to significant pipe cracking from intergranular stress corrosion cracking (IGSCC). As a result, nine U.S. BWRs completely replaced their full recirculation system piping with pipes made from lower carbon steel. Another three BWRs replaced the heavily cracked sections of their recirculation system piping.³⁷ Detailed inspections of key piping systems and changes to the water chemistry used in the plants were made at essentially all BWRs in the U.S.

The efforts required to fix these systemic problems were both time-consuming and expensive.

We're not arguing that new SMRs will have these same issues. We expect that the design and material decisions made for SMRs will reflect remedial measures taken at existing reactors. Our concern is broader in that a problem at one SMR might have serious repercussions at many other SMRs with the same standardized design.

³⁶ [World Nuclear Associate website](#). Accessed May 13, 2024.

³⁷ U.S. Nuclear Regulatory Commission. [Pipe Cracking in U.S. BWRs: A Regulatory History](#).

Conclusion

The pro-SMR rhetoric in the U.S. is loud and persistent. But it does not mesh with reality.

IEEFA released its first analysis of the SMR sector more than two years ago, concluding that the much-hyped resource would be too slow, too expensive and too risky to help in the transition away from fossil fuels. We stand by that conclusion.

Experience with the few existing SMRs that have been built or are under construction shows a repetition of the nuclear industry's longstanding history: The facilities have been both significantly over budget and have taken much longer to complete than forecast.

New data from proposed SMR projects in the U.S. also shows a worrying upward trend in cost estimates, undercutting the repeated rhetoric that the plants can be built economically without the dizzying construction price increases that pushed Vogtle's total costs to more than \$36 billion—more than two and a half times the original estimate—and resulted in the cancellation of the V.C. Summer project.

Perhaps most concerning is the risk factor, especially when compared to the known costs and construction timelines for readily available wind, solar and battery storage resources. On this issue, the new estimate for renewable capacity additions recently offered by NextEra's Ketchum is worth repeating: At least 375,000 MW of new renewable energy generating capacity is likely to be added to the U.S. grid in the next seven years. By contrast, IEEFA believes it is highly unlikely any SMRs will be brought online in that same time frame.

The comparison couldn't be clearer. Regulators, utilities, investors and government officials should acknowledge this and embrace the available reality: Renewables are the near-term solution.

About IEEFA

The Institute for Energy Economics and Financial Analysis (IEEFA) examines issues related to energy markets, trends and policies. The Institute's mission is to accelerate the transition to a diverse, sustainable and profitable energy economy. www.ieefa.org

About the Authors

David Schlissel

David Schlissel is an IEEFA analyst with 50 years of experience as an economic and technical consultant on energy and environmental issues. He has testified as an expert witness before regulatory commissions in more than 35 states and before the U.S. Federal Energy Regulatory Commission and the Nuclear Regulatory Commission.

Schlissel's work has included researching, writing and testifying about the U.S. nuclear industry and the cost overruns, construction delays and other challenges associated with many nuclear projects. He has engineering degrees from MIT and Stanford University as well as a Juris Doctor from Stanford Law School. He also has studied nuclear engineering at MIT in a non-degree program.

Dennis Wamsted

Dennis Wamsted concentrates on the ongoing transition away from fossil fuels to green generation resources, focusing particularly on the electric power sector. He has 30 years of experience tracking utility transitions and technology developments, beginning with a long stint as executive editor of The Energy Daily, a leading trade publication based in Washington, D.C. He has consulted for numerous utilities and industry organizations, focusing on the technology and policy trends reshaping the power sector.

This report is for information and educational purposes only. The Institute for Energy Economics and Financial Analysis ("IEEFA") does not provide tax, legal, investment, financial product or accounting advice. This report is not intended to provide, and should not be relied on for, tax, legal, investment, financial product or accounting advice. Nothing in this report is intended as investment or financial product advice, as an offer or solicitation of an offer to buy or sell, or as a recommendation, opinion, endorsement, or sponsorship of any financial product, class of financial products, security, company, or fund. IEEFA is not responsible for any investment or other decision made by you. You are responsible for your own investment research and investment decisions. This report is not meant as a general guide to investing, nor as a source of any specific or general recommendation or opinion in relation to any financial products. Unless attributed to others, any opinions expressed are our current opinions only. Certain information presented may have been provided by third parties. IEEFA believes that such third-party information is reliable, and has checked public records to verify it where possible, but does not guarantee its accuracy, timeliness or completeness; and it is subject to change without notice.



Impacts of Uranium In-Situ Leaching

(not really updated since the 1990s - sorry...)



Contents:

- [Existing and Proposed Sites](#)
- [Environmental Impacts](#)
- [Reclamation Concepts](#)
- [Reclamation Projects](#)
- [References](#)
- [Further Information](#)

In the case of *in-situ leaching* (ISL) - also called *in-situ recovery* (ISR), or *solution mining* - the uranium-bearing ore is not removed from its geological deposit, but a leaching liquid is injected through wells into the ore deposit, and the uranium-bearing liquid is pumped to the surface from other wells.

In-situ leaching gains importance for the exploitation of low grade ore deposits, for its low production cost. Many new projects for uranium in-situ leaching are being planned at present.

Existing and Proposed Uranium In-Situ Leaching Sites

The USA produced 1684 t U from in-situ leaching in 1996, this corresponds to 93% of all uranium produced in that year. The ISL operations are mainly located in Wyoming, Texas and Nebraska. For current U.S. ISL operations, see [Operating Status of Nonconventional Uranium Plants](#)  and [U.S. Uranium Mine Production](#)  (US DOE). [New ISL projects](#) are being proposed for Texas, Wyoming, and New Mexico.

In Eastern *Germany*, an underground mine converted to an in-situ leaching facility was in operation at Königstein near Dresden until the end of 1990. It produced a total of 18,000 t U, 30% of which were from ISL with sulfuric acid.

In the *Czech Republic*, in-situ leaching with sulfuric acid was used on a large scale at Stráz pod Ralskem in North Bohemia: The ore deposit is located in Cretaceous sandstones with grades of 0.08 - 0.15% uranium. In an area of 5.6 km², 9340 wells were drilled from the surface into the deposit. The total production to 1994 was 13,835 t U.

In *Bulgaria*, in-situ leaching was in use at many locations. The first uranium mines in Bulgaria were underground mines. From 1979, in-situ leaching was also applied, using wells, drilled from the surface. The leaching agent used in most cases was sulfuric acid. From 1981, in-situ leaching was also used to increase the yield from mined out conventional underground mines [Tabakov1993]. From 1981, 23 ore deposits were mined by conventional underground mining techniques, 17 by in-situ leaching from the surface, and 11 by in-situ leaching in combination with conventional mining techniques. In 1990, 70% of the uranium produced was from in-situ leaching of ore deposits with very low grades of 0.02 - 0.07% of uranium [Kuzmanov1993]. In the years 1991 - 1992, 14,000 wells in 15 in-situ leaching fields were in operation [OECD1994]. The total area used for in-situ leaching comprised 6 km² [Vapirev1996]. The total production from in-situ leaching to 1994 was 5,175 t U [OECD1996].

In *Ukraine*, ISL has been used at the Devladove, Bratske, and Safonovskoye sites from 1966 - 1983.

In *Russia*, a new ISL project is being proposed for [Dalmatovkoye](#) in Western Siberia.

In *Kazakhstan*, in-situ leaching is being used at the Kandjungan, Uvanas, Mynkuduk, Karamurun sites. In 1994, the production from ISL was 1580 t U, a 70% share in the country's uranium production; the total production from ISL

to 1994 was 19,961 t U [OECD1996]. The [new projects](#) of Muyunkum and Inkay are also planned for exploitation by ISL.

In *Uzbekistan*, in-situ leaching (with sulfuric acid) is being used at the Uchkuduk, Zarafabad, and Nurabad deposits, covering a total area of 13 km². Since 1995, all production is from ISL (3050 t U annually) [OECD1996].

In *China*, ISL is being used at Tengchong and Yining.

In *Australia*, new ISL projects are being proposed for [Beverley](#) and [Honeymoon](#) in South Australia.

Environmental Impacts

The leaching liquid used for in-situ leaching contains the leaching agent ammonium carbonate for example, or - particularly in Europe - sulfuric acid. This method can only be applied if the uranium deposit is located in porous rock, confined in impermeable rock layers.

The advantages of this technology are:

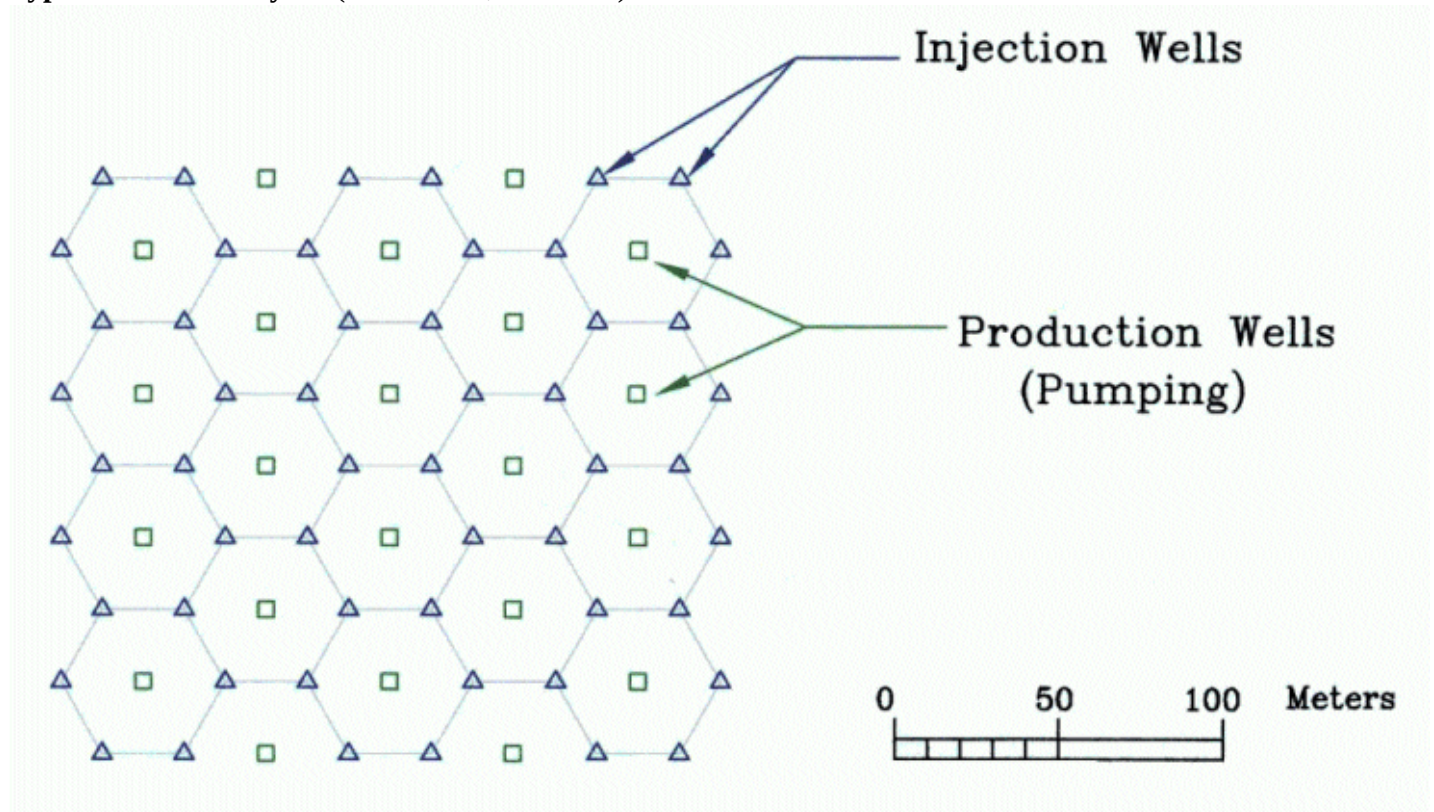
- the reduced hazards for the employees from accidents, dust, and radiation,
- the low cost;
- no need for large uranium mill tailings deposits.

The disadvantages of the in-situ leaching technology are:

- the risk of spreading of leaching liquid outside of the uranium deposit, involving subsequent groundwater contamination,
- the unpredictable impact of the leaching liquid on the rock of the deposit,
- the impossibility of restoring natural groundwater conditions after completion of the leaching operations.

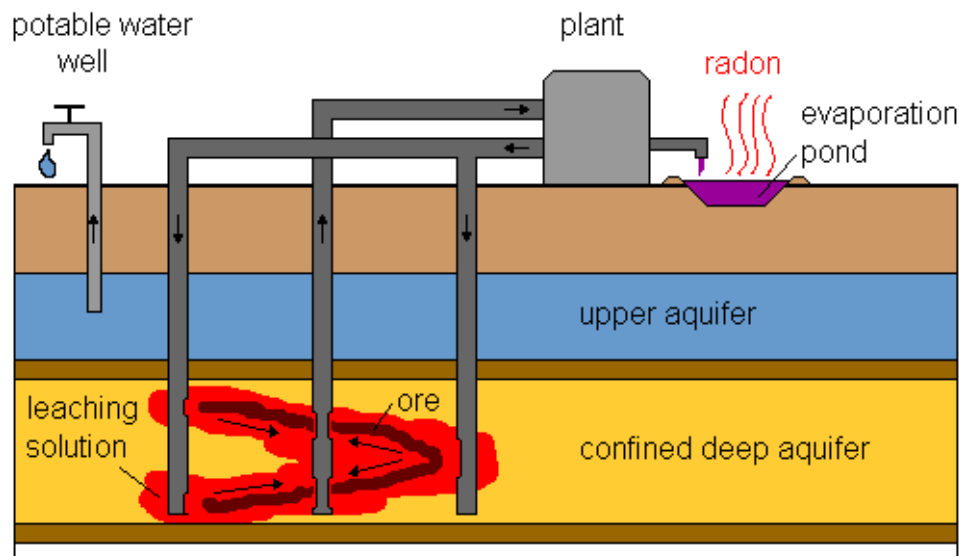
Moreover, in-situ leaching releases considerable amounts of radon, and produces certain amounts of waste slurries and waste water during recovery of the uranium from the liquid.

Typical Wellfield Layout (Crow Butte, Nebraska)



(excerpt without monitor wells from: [Technical Report - North Trend Expansion Area, Crow Butte Resources, Inc. 2007](#) p.3.1-13)

Scheme of normal ISL operation



> View [Typical failure modes during ISL operation \(animation - 58k\)](#)

In the case of Königstein (Germany), a total of 100,000 tonnes of sulfuric acid was injected with the leaching liquid into the ore deposit. At present, 1.9 million m³ of leaching liquid are still locked in the pores of the rock leached so far; a further 0.85 million m³ are circulating between the leaching zone and the recovery plant. The liquid contains high contaminant concentrations, for example, expressed as multiples of the drinking water standards: cadmium 400x, arsenic 280x, nickel 130x, uranium 83x, etc. This liquid presents a hazard to an aquifer that is of importance for the drinking water supply of the region.

Groundwater impact is much larger at the Czech in-situ leaching site of Stráz pod Ralskem: 28.7 million m³ of contaminated liquid is contained in the leaching zone, covering an area of 5.74 km². This zone contains a total of 1.5 million tonnes of sulphate, 37,500 tonnes of ammonium, and others. In addition to the chemicals needed for the leaching operation (including 3.7 million tonnes of sulfuric acid, among others), 100,000 tonnes of ammonium were injected; they were a waste product resulting from the recovery of uranium from the leaching liquid. Moreover, the contaminated liquid has spread out beyond the leaching zone horizontally and vertically, thus contaminating another area of 28 km² and a further 235 million m³ of groundwater. To the southwest, the groundwater contamination has already reached the second zone of groundwater protection of the potable water supply of the town of Mimon. In southeastern direction, the contaminated groundwater is still at a distance of 1.2 - 1.5 km from the second zone of groundwater protection of the Dolánky potable water wells, which supply 200 l/s for the city of Liberec [Andel1996]. The migration of the contaminated liquids in an easterly direction towards the Hamr I underground mine is at present intercepted by a hydraulic barrier: decontaminated water is injected into a chain of wells to prevent further migration of the contaminated groundwater.

In Bulgaria, a total of 2.5 million tonnes of sulfuric acid was injected into the ore deposits exploited by in-situ leaching. It is estimated that about 10% of the surface area used for ISL could be contaminated from solution spills. This is of concern, since the area is to be returned to its previous owners for agricultural use.

After termination of the ISL operations, the contaminated groundwater spreads offsite. Some in-situ leaching facilities (for example Bolyarovo, Tenevo/Okop) are located close to drinking water wells. [Vapirev1996]

The impacts of ISL on surface and groundwater are catastrophic:

"Very high concentrations of sulfate ions are measured in surface water and even in wells of private owners as a result of accidental spilling of solutions in sites of in-situ leaching. At the site "Cheshmata" (Haskovo), in the valley downstream from the sorption station, the measured content of sulfates is 1400 mg/l, free H₂SO₄ is 392 mg/l and pH is 2.2 (5.5 - 8.5 for 3-rd category water). A similar case has been recorded in Navusen where in a valley the sulfate concentration is 13362 mg/l and almost 5 g/l H₂SO₄, which means that actually the water is leaching solution.

In the underground water of such sites the salt content is >20 g/l, from which the sulfates are 12-15 g/l." [Dimitrov1996]

The Devladovo site in Ukraine was leached with sulfuric and nitric acid. The surface of the site was heavily contaminated from spills of leaching solutions. Groundwater contamination is spreading downstream from the site at a speed of 53 m/year. It has traveled a distance of 1.7 km already and will reach the village of Devladovo after 24.5 years. [Molchanov1995]

Typical examples for the incidents occurring during *business as usual* at in-situ operations, including surface spills and underground solution excursions, can be found here: [Christensen Ranch \(Wyoming\)](#), [Highland \(Wyoming\)](#), [Smith Ranch \(Wyoming\)](#), [Crow Butte \(Nebraska\)](#), [Kingsville Dome \(Texas\)](#), [Rosita \(Texas\)](#), [Bruni \(Texas\)](#), [Beverley \(South Australia\)](#)

Reclamation Concepts After In-Situ Leaching

After termination of an in-situ leaching operation, the waste slurries produced must be safely disposed, and the aquifer, contaminated from the leaching activities, must be restored. Groundwater restoration is a very tedious process that is not yet fully understood. So far, it is not possible to restore groundwater quality to previous conditions.

The best results have been obtained with the following treatment scheme, consisting of a series of different steps [Schmidt1989], [Catchpole1995]:

- Phase 1: Pumping of contaminated water: the injection of the leaching solution is stopped and the contaminated liquid is pumped from the leaching zone. Subsequently, clean groundwater flows in from outside of the leaching zone.

- Phase 2: as 1, but with treatment of the pumped liquid (by reverse osmosis) and re-injection into the former leaching zone. This scheme results in circulation of the liquid.
- Phase 3: as 2, with the addition of a reducing chemical (for example hydrogen sulfide H_2S or sodium sulfide Na_2S). This causes the chemical precipitation and thus immobilization of major contaminants.
- Phase 4: Circulation of the liquid by pumping and re- injection, to obtain uniform conditions in the whole former leaching zone.

But, even with this treatment scheme, various problems remain unresolved:

- Contaminants, that are mobile under chemically reducing conditions, such as radium, cannot be controlled,
- if the chemically reducing conditions are later disturbed for any reasons, the precipitated contaminants are re-mobilized,
- the restoration process takes very long periods of time,
- not all parameters can be lowered appropriately.

Most restoration experiments reported refer to the alkaline leaching scheme, since this scheme is the only one used in Western world commercial in-situ operations. Therefore, nearly no experience exists with groundwater restoration after acid in- situ leaching, the scheme that was applied in most instances in Eastern Europe. The only Western in-situ leaching site restored after sulfuric acid leaching so far, is the small pilot scale facility Nine Mile Lake near Casper, Wyoming (USA). The results can therefore not simply be transferred to production scale facilities. The restoration scheme applied included the first two steps mentioned above. It turned out that a water volume of more than 20 times the porevolume of the leaching zone had to be pumped, and still several parameters did not reach background levels. Moreover, the restoration required about the same time as used for the leaching period [Nigbor1982] [Engelmann1982].

Reclamation Projects

In USA, the Pawnee, Lamprecht, and Zamzow ISL Sites in Texas were restored using steps 1 and 2 of the above listed treatment scheme [Mays1993]. Relaxed groundwater restoration standards have been granted at these and other sites, since the restoration criteria could not be met (see [details](#)).

A study published by the U.S. Geological Survey in 2009 found that *"To date, no remediation of an ISR operation in the United States has successfully returned the aquifer to baseline conditions."* [Otton 2009] (see [details](#))

For the Königstein (Germany) in-situ leaching mine, there are still no large-scale proven methods to remove the remaining leaching liquid from the deposit and to inhibit continued leaching of uranium and other contaminants. The impact is rather severe, as the mining activities damaged an aquifer used for the drinking water supply in the Dresden area.

At present, it is planned to flood the Königstein mine (which is an underground mine converted to in-situ leaching in some areas), up to a certain groundwater level, to wash the leaching blocs. The flooding should be halted and the flooding waters be contained and treated, until their contaminant concentrations would only be marginal. It must be anticipated, though, that this procedure might take long periods of time, as the leaching zone is no longer washed under pressure, unlike during the leaching action.

The situation is even more difficult in the Czech in-situ leaching facility of Stráz pod Ralskem: the goal of restoring groundwater quality in the leaching zone to background has been abandoned as unrealistic.

The restoration goal for the upper aquifer above the leaching zone (used for potable water supply), however, is the drinking water standard, to be achieved by pumping of contaminated waters. The goal seems to be attainable for this aquifer, although some contaminants, as aluminium, exceed the standard up to 1000-fold.

But, for the leaching zone and its surroundings, the goal of reaching the potable water standard is regarded as absolutely unrealistic. For this aquifer, the goal is defined that anticipated contaminant migration to the upper aquifer shall not worsen the water quality in this aquifer beyond potable water standards. But it is still unclear, which contaminant level in the lower aquifer is sufficient to achieve this goal. According to modeling results, a level of total dissolved solids of 10 g/l will be reached in the year 2014, and a level of 1 g/l in 2032, after continuous

pumping.

> View details on [Stráz groundwater restoration project](#).

In Bulgaria, a restoration attempt using recirculation of the solution without addition of acid failed: the tubes and filters of the sorption columns plugged, and all restoration attempts were stopped [Vapirev1996]. In some cases, heavy metals and rare earth elements (V, W, Mo, La) were detected in groundwater due to the recycling of solution [Dimitrov1996]. At present, the installations at the surface of the ISL sites are being decommissioned, and all pipes are being removed. But, there is no groundwater restoration: the ISL wells are being plugged; and the groundwater is submitted to "natural restoration".

The restoration of the Devladovo ISL site in Ukraine was limited to soil cleanup at the surface. Some heavily contaminated soil was replaced, while deep ploughing was the only remedy used at the major part of the site. Cleanup was finished in 1975. Subsequently, the site has been used for agriculture. Surveys performed in 1991 have shown that the radionuclide concentrations in the soil had not decreased at all, and that the anticipated self-cleaning of the soil had not taken place. Effective dose equivalents of up to 0.2 mSv/year were calculated for the members of the local population consuming the wheat grown on this soil. [Molchanov1995]

References

- [Andel1996] Andel,P; Pribán,V: Environmental restoration of uranium mines and mills in the Czech Republic. In: Planning for environmental restoration of radioactively contaminated sites in central and eastern Europe, Vol.1: Identification and characterization of contaminated sites, IAEA- TECDOC-865, Vienna 1996, p.113-135
- [Catchpole1995] Catchpole,Glenn; Kirchner,Gerhard: Restoration of Groundwater Contaminated by Alkaline In-Situ Leach of Uranium Mining. In: Merkel,B et al. (Ed.): Uranium Mining and Hydrogeology, GeoCongress 1, Köln 1995, p.81-89
- [Dimitrov1996] Dimitrov,M; Vapirev,E I: Uranium Industry in Bulgaria and Environment: Problems and Specific Features of the Period of the Technical Close-Out and Remediation of the Negative Consequences. In: Planning for environmental restoration of radioactively contaminated sites in central and eastern Europe, Vol.2: Planning for environmental restoration of contaminated sites, IAEA-TECDOC-865, Vienna 1996,p.43-52
- [Engelmann1982] Engelmann,W H; Phillips,P E; Tweeton,D R; Loest,K W; Nigbor,M T: Restoration of Groundwater Quality Following Pilot-Scale Acidic In-Situ Uranium Leaching at Nine- Mile Lake Site Near Casper, Wyoming. In: *Society of Petroleum Engineers Journal*, June 1982, p.382-398
- [Kuzmanov1993] Kuzmanov,L; Simov,S D; Valkov,T; Vasilev,D: In-Situ Leaching of Uranium in Bulgaria: Geological, Technological and Ecological Considerations. In: IAEA (Ed.), Uranium in situ leaching. Proceedings of a Technical Committee Meeting held in Vienna, 5-8 October 1992, IAEA-TECDOC-720, Vienna 1993, p.65-73
- [Mays1993] Mays,W M: Restoration of Groundwater at Three In- Situ Uranium Mines in Texas. In: IAEA (Ed.), Uranium in situ leaching. Proceedings of a Technical Committee Meeting held in Vienna, 5-8 October 1992, IAEA-TECDOC-720, Vienna 1993, p.191- 215
- [Molchanov1995] Molchanov,A; Soroka,Y; Isayeva,N; Mordberg,E: The State of Environment on Former Site of In-Situ Leaching of Uranium. In: Slate,S; Baker,R; Benda,G (Eds.), Proceedings of the Fifth International Conference on Radioactive Waste Management and Environmental Remediation, ICM'95, Vol.2 - Management of Low-Level Waste and Remediation of Contaminated Sites and Facilities, ASME, New York, 1995, p.1507-1510
- [Nigbor1982] Nigbor,Michael T; Engelmann,William H; Tweeton,Daryl R: Case History of a Pilot-Scale Acidic In Situ Uranium Leaching Experiment. United States Department of the Interior, Bureau of Mines Report of Investigations RI-8652, Washington D.C., 1982, 81 p.
- [OECD1994] Uranium 1993 Resources, Production and Demand, OECD Nuclear Energy Agency/International Atomic Energy Agency (Ed.), Paris 1994, 311 p.
- [OECD1996] Uranium 1995 Resources, Production and Demand, OECD Nuclear Energy Agency/International Atomic Energy Agency (Ed.), Paris 1996, 362 p.
- [Otton 2009] J.K. Otton, S. Hall: In-situ recovery uranium mining in the United States: Overview of production and remediation issues, International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (URAM 2009), Vienna, Austria, 22-26 June 2009
- [Schmidt1989] Schmidt,C: Groundwater Restoration and Stabilization at the Ruth-ISL Test Site in Wyoming, USA. In: In Situ Leaching of Uranium - Technical, Environmental and Economic Aspects, Proceedings of a Technical Committee Meeting, IAEA- TECDOC-492, Vienna 1989, p.97-126.
- [Tabakov1993] Tabakov,B: Complete Mining of Uranium Deposits in Bulgaria by In-Situ Leaching Mining Systems Used After Conventional Mining. In: IAEA (Ed.), Uranium in situ leaching. Proceedings of a Technical Committee Meeting held in Vienna, 5-8 October 1992, IAEA-TECDOC-720, Vienna 1993, p.105-114
- [Vapirev1996] Vapirev,E I; Dimitrov,M; Minev,L; Boshkova,T; Pressyanov,D S; Guelev,M G: Radioactively contaminated sites in Bulgaria. In: Planning for environmental restoration of radioactively contaminated sites in central and eastern Europe, Vol.1: Identification and characterization of contaminated sites, IAEA-TECDOC-865, Vienna 1996, p.43-63






Further Information

Further Reading


Various

- [Nuclear Fuel's Dirty Beginnings, Environmental Damage and Public Health Risks From Uranium Mining in the American West](#) , by Geoffrey H. Fettus and Matthew G. McKinzie, Natural Resources Defense Council, March 2012, 104 p. (4.1M PDF)
- [Environmental hydrogeology of in situ leach uranium mining in Australia](#) , by Gavin M. Mudd, in: Uranium Mining and Hydrogeology III, B. J. Merkel, B. Planer-Friedrich, C. Wolkersdorfer (editors), 2002
- [Acid In Situ Leach Uranium Mining - 1. USA & Australia](#) , by Gavin Mudd, Paper presented at *Tailings & Mine Waste '00*, Fort Collins, Colorado, USA, January 2000. (PDF)
> Enlarged version in: *Environmental Geology* Vol. 41 (2001), p. 390-403
- [Acid In Situ Leach Uranium Mining - 2. Soviet Block & Asia](#) , by Gavin Mudd, Paper presented at *Tailings & Mine Waste '00*, Fort Collins, Colorado, USA, January 2000. (PDF)
> Enlarged version in: *Environmental Geology* Vol. 41 (2001), p. 404-416
- [An Environmental Critique of In Situ Leach Mining: The Case Against Uranium Solution Mining](#) , by Gavin Mudd, A Research Report for Friends of the Earth (Fitzroy) with The Australian Conservation Foundation, Victoria University of Technology, July 1998, 154 p. (PDF)



IAEA

- [In Situ Leach Uranium Mining: An Overview of Operations](#) , IAEA Nuclear Energy Series No. NF-T-1.4, Nov. 2016, 76 p. (1.0M PDF)
- [Guidebook on Environmental Impact Assessment for In Situ Leach Mining Projects](#) , IAEA-TECDOC-1428, IAEA, Vienna, May 2005, 170 p. (2.5M PDF)
- [Recent Developments in Uranium Resources and Production with Emphasis on In Situ Leach Mining](#) , IAEA-TECDOC-1396, September 2004, 332 p. (4.8M PDF)
- [Manual of acid in situ leach uranium mining technology](#) , IAEA-TECDOC-1239, Vienna, August 2001, 283 p. (5.1M PDF)
- **Uranium in situ leaching.** Proceedings of a Technical Committee Meeting held in Vienna, 5-8 October 1992, IAEA-TECDOC-720, Vienna 1993, 245 p.
- [In Situ Leaching of Uranium: Technical, Environmental and Economic Aspects](#) , Proceedings of a Technical Committee Meeting Organized by the International Atomic Energy Agency and Held in Vienna, 3-6 November 1987, IAEA-TECDOC-492, Vienna 1989, 172 p.

U.S. EPA



- [Ground Water Modeling Studies at In Situ Leaching Facilities and Evaluation of Doses and Risks to Offsite Receptors from Contaminated Ground Water](#) , Draft Technical Report, Revision 2, U.S. Environmental Protection Agency, Office of Radiation and Indoor Air, EPA-402-D-14-002, Dec. 2012, 185 p. (+ Appendices)
- **Environmental Overview of Unconventional Extraction of Uranium** (Final Rept. Nov 80 - Feb 81), by Marlowe, James I, U.S. EPA (Ed.), EPA-600/7-84-006, Cincinnati OH, 1984, 132 p.

U.S. NRC


- [Uranium Sequestration During Biostimulated Reduction and In Response to the Return of Oxidic Conditions In Shallow Aquifers](#) , NUREG/CR-7178, U.S. NRC, Dec. 2014 (10.7MB PDF)
- [Assessing the Potential for Bioremediation of Uranium In Situ Recovery Sites](#) , NUREG/CR-7167, U.S. NRC, June 2014 (13.8MB PDF)

- [Consideration of Geochemical Issues in Groundwater Restoration at Uranium In-Situ Leach Mining Facilities](#) , NUREG/CR-6870, U.S. NRC, January 2007
- [A Baseline Risk-Informed, Performance-Based Approach for In Situ Leach Uranium Extraction Licensees](#) , U.S. Nuclear Regulatory Commission, NUREG/CR-6733, Sept 2001, 200 p. (ADAMS Accession No. ML012840152)
- [An Analysis of Excursions at Selected In Situ Uranium Mines in Wyoming and Texas](#) , by Staub, W.P. ; Hinkle, N.E. ; Williams, R.E.; et al, NUREG/CR-3967, ORNL/TM-9956, 1986, 297 p. (ADAMS Accession No. ML14224A351)
- [Methods of Minimizing Ground-Water Contamination From In Situ Leach Uranium Mining](#) , (Final Report), by Deutsch, W J; Martin, W J; Eary, L E; Serne, R J, U.S. NRC (Ed.), NUREG/CR-3709, Washington DC, 1985, 88 p. (ADAMS Accession No. ML14224A350)
- [Aquifer Restoration Techniques for In-Situ Leach Uranium Mines](#) , by Deutsch, W J; Bell, N E, et al., . U.S. NRC (Ed.), NUREG/CR-3104, Washington DC, 1984, 55 p. (ADAMS Accession No. ML102560104)
- [Ground-Water Elements of In Situ Leach Mining of Uranium](#) , by Thompson, W E; Swarzenski, W V; Warner, D L; et al., NUREG/CR-0311, U.S. NRC, 1978, 199 p. (ADAMS Accession No. ML14224A349)










U.S. Geological Survey

- [Groundwater restoration at uranium in-situ recovery mines, south Texas coastal plain](#) , by Susan Hall, U.S. Geological Survey Open-File Report 2009-1143, 2009, 32 p.
- [Factoring Uncertainty into Restoration Modeling of In-Situ Leach Uranium Mines](#) , by Raymond H. Johnson and Michael J. Friedel, U.S. Geological Survey Open-File Report 2009-1024, 2009, 25 p.

U.S. Bureau of Mines

- **Analysis of Groundwater Criteria and Recent Restoration Attempts After In Situ Uranium Leaching**, by Buma, Grant; et al., (Open File Report). U.S. Bureau of Mines (Ed.), BUMINES-OFR-90-82, Washington DC, 1981, PB-82-246018, 305 p.
- **Case History of a Pilot-Scale Acidic In Situ Uranium Leaching Experiment**, by Nigbor, Michael T; Engelmann, William H; Tweeton, Daryl R, United States Department of the Interior, Bureau of Mines Report of Investigations RI-8652, Washington D.C., 1982, PB-82-212994, 81 p.
(Available for download at [National Technical Reports Library](#) )

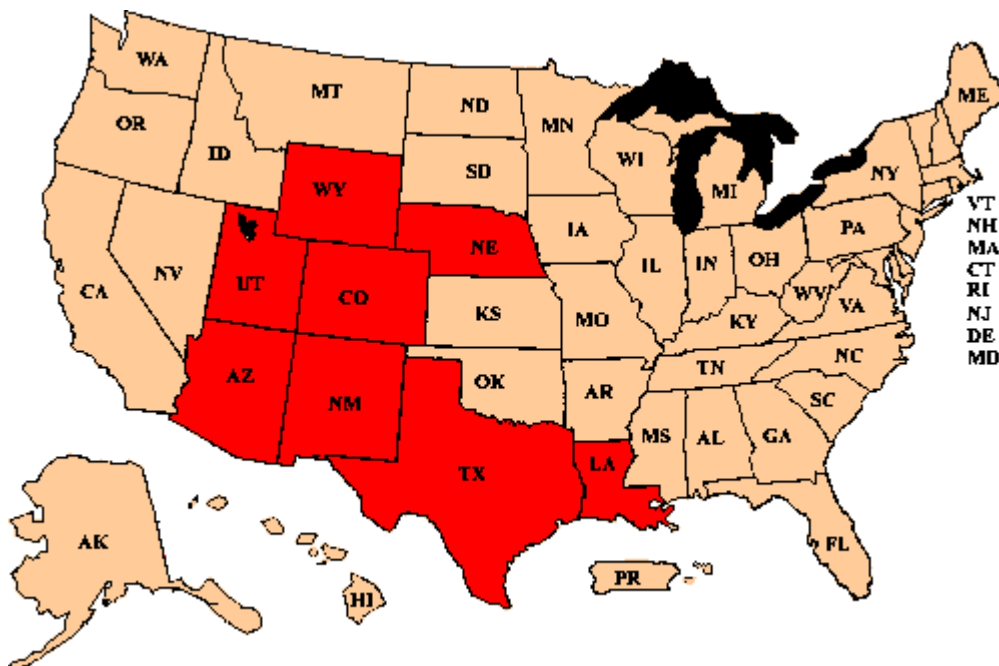
Environmental Impact Statements for uranium in situ leach projects

- [Wheeler River Project, Saskatchewan, Canada](#) , (CEAA)
- [Ludeman satellite in situ recovery project, Wyoming, USA](#) , Aug. 2018 (NRC)
- [Jane Dough extension of Nichols Ranch in situ leach mine, Wyoming, USA](#) , Mar. 2017 (NRC)
- [Reno Creek, Wyoming, USA, NUREG-1910 Supplement 6](#) , Dec. 2016 (NRC)
- [Ross, Wyoming, USA, NUREG-1910 Supplement 5](#) , Feb. 2014 (NRC)
- [Dewey-Burdock Project, South Dakota, USA, NUREG-1910 Supplement 4](#) , Jan. 2014 (NRC)
- Cameco Gas Hills in situ leach project, Wyoming, USA, Oct. 2013 (BLM)
- [Lost Creek, Wyoming, USA, NUREG-1910 Supplement 3](#) , Jun. 2011 (NRC)
- [Nichols Ranch, Wyoming, USA, NUREG-1910 Supplement 2](#) , Jan. 2011 (NRC)
- [Moore Ranch, Wyoming, USA, NUREG-1910 Supplement 1](#) , Aug. 2010 (NRC)

Issues at Operating Uranium Mines and Mills - USA






















(last updated 2 Nov 2025)

Contents:



- [General](#)
- [Arizona](#)
- [Colorado](#) 
- [Louisiana](#)
- [Nebraska](#)
- [New Mexico](#)
- [Texas](#)
- [Utah](#)
- [Wyoming](#) 


Site Index

[Alta Mesa](#) · [Arizona 1](#) · [Brown Ranch](#)  · [Canyon \(AZ\)](#) · [Cañon City](#)  · [Christensen Ranch](#)  · [Cotter mines \(CO\)](#)  · [Crow Butte](#)
[Daneros](#) · [Denison mines \(CO\)](#)  · [Highland \(PRI\)](#)  · [Hobson](#) · [IMC Global](#) · [Irigaray](#)  · [J-Bird](#)  · [Kingsville Dome](#) · [Lance](#) 
[La Sal Mines Complex \(Denison\)](#) · [Lost Creek](#)  · [Mesteña Grande](#) · [Moore Ranch](#)  · [Mt. Taylor](#) · [Nichols Ranch](#)  · [North Butte](#) 
[Palangana](#) · [Pandora](#) · [Pinenut](#) · [Pinyon Plain](#) · [Rim](#) · [Rosita](#) · [Ross](#)  · [Schwartzwalder](#)  · [Smith Ranch](#)  · [South Texas](#)
[Sunday](#)  · [Sweetwater](#)  · [Vasquez](#) · [Velvet](#) · [West Slope Project](#)  · [White Mesa](#)  · [Willow Creek](#) 

> See also Issues for: [New Mining Projects](#) · [Decommissioning Projects](#) · [Legislation & Regulations](#)

> See also Data for: [Deposits, Proposed and Active Mines](#) · [Old Mines and Decommissioning](#)

General

> See also: [National Reports for Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management](#)  (IAEA)

U.S. uranium production increases by 54% to 183.6 t U in second quarter of 2025

DOE EIA's quarterly production report for the second-quarter 2025 reports a uranium production figure of 477,238 lb U₃O₈ [183.6 t U], up from 310,533 lb U₃O₈ [119.4 t U] in the previous quarter.

> Download: [Domestic Uranium Production Report Second-Quarter 2025](#), U.S. DOE EIA, Oct. 1, 2025 (389kB PDF)

U.S. uranium production decreases by 17% to 119.4 t U in first quarter of 2025

DOE EIA's quarterly production report for the first-quarter 2025 reports a uranium production figure of 310,533 lb U₃O₈ [119.4 t U], down from 375,401 lb U₃O₈ [144.4 t U] in the previous quarter.

> Download: [Domestic Uranium Production Report First-Quarter 2025](#), U.S. DOE EIA, June 2025 (323kB PDF)

U.S. uranium production triples to 144.4 t U in fourth quarter of 2024

DOE EIA's quarterly production report for the fourth-quarter 2024 reports a uranium production figure of 375,401 lb U₃O₈ [144.4 t U], up from 121,296 lb U₃O₈ [46.6 t U] in the previous quarter.

> Download: [Domestic Uranium Production Report Fourth-Quarter 2024](#), U.S. DOE EIA, Mar. 13, 2025 (266kB PDF)

U.S. uranium production increases by 24% to 46.6 t U in third quarter of 2024

DOE EIA's quarterly production report for the third-quarter 2024 reports a uranium production figure of 121,296 lb U₃O₈ [46.6 t U], up from 97,709 lb U₃O₈ [37.6 t U] in the previous quarter.

> Download: [Domestic Uranium Production Report Third-Quarter 2024](#), U.S. DOE EIA, Dec. 12, 2024 (265kB PDF)

U.S. uranium production increases by 18% to 37.6 t U in second quarter of 2024

DOE EIA's quarterly production report for the second-quarter 2024 reports a uranium production figure of 97,709 lb U₃O₈ [37.6 t U], up from 82,533 lb U₃O₈ [31.7 t U] in the previous quarter.

> Download: [Domestic Uranium Production Report Second-Quarter 2024](#), U.S. DOE EIA, Sep. 19, 2024 (298kB PDF)

U.S. uranium production increases more than sixfold ... to 31.7 t U in first quarter of 2024

DOE EIA's quarterly production report for the first-quarter 2024 reports a uranium production figure of 82,533 lb U₃O₈ [31.7 t U], up from 12,653 lb U₃O₈ [4.9 t U] in the previous quarter.

> Download: [Domestic Uranium Production Report First-Quarter 2024](#), U.S. DOE EIA, May 13, 2024 (269kB PDF)

U.S. uranium production cut by half ... to 4.9 t U in fourth quarter of 2023

DOE EIA's quarterly production report for the fourth-quarter 2023 reports a uranium production figure of 12,653 lb U₃O₈ [4.9 t U], down from 27,012 lb U₃O₈ [10.4 t U] in the previous quarter.

> Download: [Domestic Uranium Production Report Fourth-Quarter 2023](#), U.S. DOE EIA, Dec. 6, 2023 (260kB PDF)

U.S. uranium production more than triples ... to 10.4 t U in third quarter of 2023

DOE EIA's quarterly production report for the fourth-quarter 2023 reports a uranium production figure of 12,653 lb U₃O₈ [4.9 t U], up from 7,443 lb U₃O₈ [2.863 t U] in the previous quarter.

> Download: [Domestic Uranium Production Report Fourth-Quarter 2023](#) , U.S. DOE EIA, Feb. 2024 (271kB PDF)

U.S. uranium production triples ... to 2.9 t U in second quarter of 2023

DOE EIA's quarterly production report for the second-quarter 2023 reports a uranium production figure of 7,443 lb U₃O₈ [2.863 t U], up from 2,511 lb U₃O₈ [0.966 t U] in the previous quarter.

> Download: [Domestic Uranium Production Report Second-Quarter 2023](#) , U.S. DOE EIA, August 2023 (268kB PDF)

U.S. uranium production reaches all-time low of 0.966 t U in the first quarter of 2023

DOE EIA's quarterly production report for the first-quarter 2023 reports a uranium production figure of 2,511 lb U₃O₈ [0.966 t U], down from 174,712 lb U₃O₈ [67.2 t U] in the previous quarter.

> Download: [Domestic Uranium Production Report First-Quarter 2023](#) , U.S. DOE EIA, May 2023 (257kB PDF)


U.S. uranium production increases 54-fold(!) to 67.2 t U in the fourth quarter of 2022

DOE EIA's quarterly production report for the fourth-quarter 2022 reports a uranium production figure of 174,712 lb U₃O₈ [67.2 t U], up from 3,245 lb U₃O₈ [1.25 t U] in the previous quarter.

> Download: [U.S. DOE EIA: Domestic Uranium Production Report Fourth-Quarter 2022](#) , Feb. 2023 (267kB PDF)

U.S. uranium production decreases by 46% to 1.25 t U in the third quarter of 2022

DOE EIA's quarterly production report for the third-quarter 2022 reports a uranium production figure of 3,245 lb U₃O₈ [1.25 t U], down 46% from 6,042 lb U₃O₈ [2.3 t U] in the previous quarter.

> Download: [U.S. DOE EIA: Domestic Uranium Production Report Third-Quarter 2022](#) , Nov. 2022 (289kB PDF)


U.S. uranium production decreases by 39% to 2.3 t U in the second quarter of 2022

DOE EIA's quarterly production report for the second-quarter 2022 reports a uranium production figure of 6,042 lb U₃O₈ [2.3 t U], down 39% from 9,946 lb U₃O₈ [3.8 t U] in the previous quarter.

> Download: [U.S. DOE EIA: Domestic Uranium Production Report Second-Quarter 2022](#) , Aug. 2022 (287kB PDF)


U.S. uranium production a stable affair at 3.8 t U in the first quarter of 2022

DOE EIA's quarterly production report for the first-quarter 2022 reports a uranium production figure of 9,946 lb U₃O₈ [3.8 t U], slightly down from 9,978 lb U₃O₈ [3.8 t U] in the fourth quarter 2021.

> Download: [U.S. DOE EIA: Domestic Uranium Production Report First-Quarter 2022](#) , May 2022 (303kB PDF)


Heydays of U.S. uranium industry are back: domestic uranium production almost doubled! (...from 2 t in third quarter to 3.8 t in fourth quarter of 2021)

DOE EIA's quarterly production report for the fourth-quarter 2021 discloses a uranium production figure of 9,978 lb U₃O₈ [3.8 t U], after 5,297 lb U₃O₈ [2 t U] in the third quarter.

> Download: [U.S.DOE EIA: Domestic Uranium Production Report Fourth-Quarter 2021](#) , Feb. 2022 (288kB PDF)

U.S. domestic uranium production data actually disclosed for 3rd quarter 2021, after it was withheld for the five preceding quarters: 2 tonnes U

Other than the reports for the previous five quarters, DOE EIA's quarterly production report for the third-quarter 2021 actually discloses a uranium production figure, though it is not very impressive: the total production was 5,297 lb U₃O₈ [2 t U].


> Download: [U.S.DOE EIA: Domestic Uranium Production Report Third-Quarter 2021](#) , Nov. 2021 (294kB PDF)


Creation of a uranium reserve for nuclear weapons activities

DOE to award conversion contract for strategic uranium reserve to Converdyn:

> View [here](#)

DOE awards first contracts for supply of uranium for strategic uranium reserve:

On Dec. 15, 2022, U.S. Department of Energy (DOE) notified the first successful suppliers on the awards for U.S. origin uranium for its strategic uranium reserve. DOE [was seeking](#)  up to an estimated one million pounds of U₃O₈ [384.6 t U], produced at a domestic uranium recovery facility and already in storage at the [Honeywell Metropolis Works uranium conversion facility](#) located in Metropolis, Illinois.

Date	Company	million lbs U ₃ O ₈	t U	\$ million awarded	\$/lb U ₃ O ₈ awarded	\$/lb U ₃ O ₈ spot price	premium awarded on spot price
Dec. 16, 2022	Peninsula Energy Limited 	0.3	115.4	(18.5)	(61.67)	48.00	(+28%)
	Energy Fuels Inc.	(0.3)	(115.4)	18.5	(61.67)		(+28%)
Dec. 20, 2022	enCore Energy Corp.	0.1	38.5	7.05	70.50	47.60	+48%
	Uranium Energy Corp	0.3	115.4	17.85	59.50		+25%
Total/Average		(1.0)	(384.6)	(61.9)	(61.9)		(+29%)

(awards data according to company announcements, values in parentheses guessed)

Interestingly, only the company with the smallest award is based in the U.S. (enCore Energy Corp.), while the others are based in Canada (Energy Fuels Inc., Uranium Energy Corp.) and in Australia (Peninsula Energy Limited). And, it is the U.S.-based company that received the highest premium by far on the spot price, if our guesses are correct.

At spot prices, the cost of the total amount awarded would be \$47.84 million, so the estimated total premium awarded is \$14.06 million. Still, the estimated total of \$61.9 million awarded utilizes only 82.5% of the \$75 million appropriated by Congress for this year.

Six Democrats oppose Energy Department's proposed uranium reserve: A group of six Democrats is criticizing the Energy Department's proposed uranium reserve that could feed U.S. nuclear fuel and boost

American mining.

The Biden administration has argued that creating a uranium reserve could bolster its clean energy goals since nuclear energy doesn't have any emissions. But in their Wednesday (Sep. 15) letter, the lawmakers warn of potentially adverse impacts on nearby communities and say there's not a need to increase U.S. extraction.

"The establishment of a government-funded uranium reserve poses a serious threat to the health of Tribal and environmental justice communities, as well as to the overall environment," said the letter, which was led by Sen. Ed Markey (D-Mass.) and Rep. Raúl Grijalva (D-Ariz.).

"Furthermore, there is no urgent need for domestic uranium. Instead of establishing a uranium reserve, the DOE should focus on the cleanup and remediation of existing toxic waste and conduct extensive outreach with communities affected by current and previous uranium mining operations," they added. (The Hill Sep. 15, 2021)

> Download: [Letter of opposition, Sep. 15, 2021](#) (PDF)

DOE invites public comment on topics related to establishment of Uranium Reserve program:

Submit comments by October 13, 2021 (Comment period reopened).

> Federal Register Volume 86, Number 152 (Wednesday, August 11, 2021) p. 44007-44009 ([download full text](#))

> Federal Register Volume 86, Number 174 (Monday, September 13, 2021) p. 50878-50879 ([download full text](#))

President Biden's 2022 budget proposal omits funding of uranium reserve The Biden administration is not seeking funding for a national uranium reserve created under former President Trump, according to budget documents released by the White House on Friday (May 28). (Bloomberg Law May 28, 2021)

> Download: [FY 2022 President's Budget](#)

Congress approves appropriations of US\$ 75 million for a uranium reserve for nuclear weapons activities:

The Consolidated Appropriations Act, 2021 approved by both chambers of Congress on Dec. 21, 2020, includes appropriations of US\$ 75 million for a uranium reserve for nuclear weapons activities - that is half of the amount shown in the president's budget proposal. The bill now goes to the White House for the president's signature to become law.

> Download: [Text of Consolidated Appropriations Act, 2021](#), Dec. 21, 2020 (8.6MB PDF)

[Assuming the total expenditures of US\$ 66 per lb U₃O₈ produced in the U.S. in 2018 (i.e. US\$ 108.8 million for 1.647 million lb U₃O₈ produced, see: 2019 Domestic Uranium Production Report, DOE EIA, May 2020), the appropriated amount corresponds to 1.136 million lb U₃O₈, or 437 t U, corresponding to approx. 40% of the annual production capacity of the White Mesa Mill alone.]

The act was signed into law by President Donald Trump on December 27, 2020.

President's budget proposes US\$ 150 million for creation of uranium reserve in order to support struggling uranium mining companies:

President Donald Trump's 2021 budget proposed \$150 million for the creation of a U.S. uranium reserve as the administration seeks to help struggling producers of the fuel for nuclear power reactors. The money, if approved by Congress, would begin the process of purchasing uranium, Energy Secretary Dan Brouillette told reporters in a teleconference on the Energy Department's budget. (Reuters Feb. 10, 2020)

> Download: [The Budget for Fiscal Year 2021 \(p.385-430\): Department of Energy](#) (537kB PDF - White House)

Annual U.S. domestic uranium production data withheld for the first time

After the quarterly production data was withheld four times already (see below), now the annual production data is withheld for the first time. In addition, the uranium reserve estimates are withheld for the first time, too.

> Download: [2020 Domestic Uranium Production Report](#) , U.S. DOE EIA, May 2021 (838kB PDF)
What is the purpose of a report titled "2020 Domestic Uranium Production Report", if it withholds the key figures?

Uranium Energy Corp prefers to buy uranium on the spot market rather than mining it

On Mar. 16, 2021, Uranium Energy Corp announced that "we are establishing a physical uranium inventory initiative and have entered into initial agreements totaling \$10.9 million to purchase 400,000 pounds of U.S. warehoused uranium [154 t U] at our account with the [ConverDyn facility](#) in Metropolis, Illinois. This initiative will support three objectives: 1) bolsters our balance sheet as uranium prices appreciate; 2) provides strategic inventory to support future marketing efforts with utilities that could compliment production and accelerate cashflows; and 3) increases the availability of our [Texas](#) and [Wyoming](#) production capacity for [emerging U.S. origin specific opportunities](#) which may command premium pricing due to scarcity of domestic uranium."


On Mar. 17, 2021, Uranium Energy Corp further announced that it has secured 800,000 pounds of additional U.S. warehoused uranium [308 t U], consisting of 500,000 pounds for April delivery and 300,000 pounds for December delivery. Including the previously announced acquisition of 400,000 pounds, UEC has now entered into contracts to purchase a total of 1,200,000 pounds of U₃O₈ [462 t U] at a volume weighted average price of \$28.94 per pound.

On Apr. 6, 2021, Uranium Energy Corp further announced that it has now secured an additional 705,000 pounds of U.S. warehoused uranium [271 t U], with delivery dates out to December 2022. Including the previously announced contracts to acquire 1,400,000 pounds of uranium concentrates [538 t U], UEC has now entered into additional purchase contracts for a total of 2,105,000 pounds of U₃O₈ [810 t U] at a volume weighted average price of ~\$30 per pound.


Quarterly U.S. domestic uranium production data withheld - because it is *too low to meter*?

> Download: [U.S.DOE EIA: Domestic Uranium Production Report, Second-Quarter 2020](#) , Aug. 2020 (318kB PDF)

And, the same happened with the data for the 3rd quarter 2020:

> Download: [U.S.DOE EIA: Domestic Uranium Production Report, Third-Quarter 2020](#) , Nov. 2020 (328kB PDF)

... and the 4th quarter 2020:

> Download: [U.S.DOE EIA: Domestic Uranium Production Report Fourth-Quarter 2020](#) , Feb. 2021 (324kB PDF)

... and the 1st quarter 2021:

> Download: [U.S.DOE EIA: Domestic Uranium Production Report First-Quarter 2021](#) , Apr. 2021 (298kB PDF)

... and the 2nd quarter 2021:

> Download: [U.S.DOE EIA: Domestic Uranium Production Report Second-Quarter 2021](#) , Aug. 2021 (306kB PDF)

U.S. uranium production reaches historic low

"U.S. production of uranium concentrate (U_3O_8) in the **first quarter of 2019** was 58,481 pounds [**22.5 t U**], down 83% from the fourth quarter of 2018 and down 74% from the first quarter of 2018." (emphasis added)

> Download: [Domestic Uranium Production Report - Quarterly, Data for 1st Quarter 2019](#), U.S. DOE EIA, May 1, 2019 (PDF)

"U.S. uranium production in **2018** was the lowest in nearly 70 years:

The United States produced 1.47 million pounds of uranium concentrate [**565 t U**] in 2018, down for the fourth consecutive year and the lowest total since 1950, based on preliminary production data. Uranium production in the United States has declined since its peak of 43.7 million pounds [16,808 t U] in 1980 and has remained below 5 million pounds [1,923 t U] annually for more than 20 years." (emphasis added)

> View: [DOE EIA release May 6, 2019](#)

U.S. uranium production decreased further to 44,569 lb U_3O_8 [**17.1 t U**] in the second quarter, and to 32,211 lb U_3O_8 [**12.4 t U**] in the third quarter, then recovered slightly to 38,614 lb U_3O_8 [**14.9 t U**] in the fourth quarter of 2019.

Preliminary U.S. uranium concentrate production **totaled** 173,875 pounds of U_3O_8 [**66.9 t U**] **in 2019**. This amount is 88% lower than the 1,447,875 pounds of U_3O_8 [556.9 t U] produced in 2018 and is the **lowest annual production on record**.

> Download: [Domestic Uranium Production Report - Quarterly, Fourth-quarter 2019](#), U.S. DOE EIA, Feb. 13, 2020 (PDF)

"U.S. production of uranium concentrate (U_3O_8) in the **first quarter of 2020** was 8,098 pounds [**3.1 t U**], down 79% from the fourth quarter of 2019 and down 86% from the first quarter of 2019." (emphasis added)

> Download: [Domestic Uranium Production Report First-Quarter 2020](#), U.S. DOE EIA, May 2020 (325kB PDF)

Natural Resources Defense Council issues study on environmental impacts of uranium in situ leach mining and related regulatory failures in the U.S.

> See [here](#)

Arizona

- [Arizona 1 mine](#)
- [Canyon \(AZ\) mine](#)
- [Pinenut mine](#)
- [Pinyon Plain mine](#)

> See also Issues for: [New Mining Projects](#) · [Decommissioning Projects](#) · [Legislation & Regulations](#)

> See also Data for: [Deposits, Proposed and Active Mines](#) · [Old Mines and Decommissioning](#)

Arizona 1 mine, Mohave County

> View [deposit info](#)

Comment invited on Air Permit renewal for Arizona 1 uranium mine: ADEQ proposes to issue Air Quality Control Renewal Permit No. 75725 to Energy Fuels Resources (USA) Inc. for the continued operation of the Arizona 1 underground uranium mine located in Mohave County, Ariz.

Submit comments by **June 6, 2019**.

> View: [Public Notice, May 8, 2019](#), and related documents

ADEQ issues Air Permit for Arizona 1 Mine: On Oct. 13, 2016, ADEQ issued Air Quality Permit No. 63895 to Energy Fuels Resources (USA, Inc. for the Arizona 1 uranium mine.

> Download [permit and related documents](#) (ADEQ)

ADEQ invites comment on revised draft Air Permit for Arizona 1 uranium mine:

Submit comments by August 30, 2016.

> Download [draft permits and related documents](#) (ADEQ)

ADEQ issues revised draft Air Permit for Arizona 1 uranium mine:

The Arizona Department of Environmental Quality is still working on developing new, more environmentally protective air quality permits for three uranium mines in the Grand Canyon region.

The action comes after news broke late last year that elevated uranium levels had been measured in soils near [Pinenut](#) uranium mine, located 10 miles north of the Grand Canyon and owned by [Energy Fuels Resources](#). In response, ADEQ decided to suspend its work on air quality permit renewals for all four uranium mines operated by Energy Fuels Resources.

ADEQ is now working to complete drafts of the new air quality permits for public review and comment. The revisions include faster execution of enhanced dust control measures if elevated uranium or radium levels are detected and extensive changes to the required soil sampling and radiation survey plan to mitigate potential impacts from high wind.

The state department will host public hearings on the new draft permits in Flagstaff, Tuba City and Fredonia, which it hopes to begin in early summer. (Arizona Daily Sun Apr. 15, 2016)

> Download: [Energy Fuels Resources \(USA\) Inc. Draft Permit No. 59874](#), March 23, 2016 (398k PDF)

Northern Arizona 'Zombie Mine' Petition calls for reform of uranium mining regulations on public lands:

> View [here](#)

ADEQ invites comment on proposed Air Permit renewal for Arizona 1 uranium mine:

Submit comments by August 21, 2014.

> Download: [Public Notice](#) · [Draft Permit](#) · [Technical Support Document](#) (PDF - ADEQ)

Mining at Arizona 1 mine to cease due to depletion of resources: Subject to the results of additional underground drilling, mining at the Arizona 1 mine is expected to cease in early FY-2014 due to the depletion of its known resources. (Energy Fuels Inc. Nov. 14, 2013)

Court dismisses appeal against reopening of Arizona 1 uranium mine: A federal appeals court has ruled against conservationists and tribes in their challenge of a uranium mine north of the Grand Canyon. The group had sued the U.S. Bureau of Land Management, alleging the agency relied on an outdated and inadequate environmental analysis in allowing the Arizona 1 Mine to resume operation. The 9th U.S. Circuit Court of Appeals ruled Monday (Feb. 4) that the BLM hasn't made any decisions that would trigger a new analysis and that the 1988 operation plan allows for temporary closures. (AP Feb. 3, 2013)

Appeal challenges Arizona 1 uranium mine threatening Grand Canyon: On Nov. 28, 2011, Conservation groups and American Indian tribes filed an appeal in the 9th Circuit Court challenging a lower court ruling that allowed a uranium mine near Grand Canyon National Park to re-open without updating decades-old environmental reviews. The Arizona 1 uranium mine is located near Kanab Creek immediately north of Grand Canyon National Park.

In 2010, conservation groups and tribes sued the Bureau of Land Management for failing to modernize 23-year-old mining plans and environmental reviews prior to allowing Denison Mines to resume uranium mining after the mine was shuttered in 1992. A federal judge in Phoenix this fall sided with the Bureau and the uranium industry saying no new plans or reviews were needed, prompting today's appeal.

The Arizona 1 is one of four existing uranium mines located in Grand Canyon's 1-million-acre watershed where the Obama administration has proposed a 20-year ban on new mining claims and uranium development on existing claims lacking valid existing rights. A final environmental impact statement was issued for the 1-million acre ban in October; a decision finalizing those protections could come as early as today. (Center for Biological Diversity Nov. 28, 2011)

Reopened Arizona 1 uranium mine largely left to regulate itself: [Denison Mines](#) began hauling ore out of the first and only uranium mine to reopen so far, 35 miles southwest of Fredonia, in December 2009. State environmental inspectors didn't arrive for a first inspection at the mine until it had already been open for about nine months. The [Arizona Department of Environmental Quality](#) (ADEQ) had unfilled requests for documents and inspections by engineers that it sought before the mine opened. Mine operators set to work without answering some of these requests.

The first inspection at the mine came in September, and ADEQ inspected at the ground level only, not traveling into the mine that reaches more than 1,252 feet below. Nevertheless, the inspection yielded what ADEQ deemed four "major violations."

- There were no pumps in the mine to eliminate any water there.
- A test measuring the permeability of the rock in the mine hadn't been done.
- A pipe was sticking through a lined pond that is intended to prevent groundwater contamination from ore or water pumped out of the mine.
- Plans for the mine didn't match what inspectors found when they visited, they wrote.

"ADEQ is neither equipped nor inclined to regulate these mines in a way that even remotely ensures against irretrievable harm to the environment," said Taylor McKinnon, public lands campaigns director at the [Center for Biological Diversity](#).

In the same month ADEQ inspectors arrived, federal inspectors concerned with worker safety cited Denison and contractors with air quality violations, failure to properly label power switches, equipment safety violations, lack of firefighting equipment inspections, and with another violation that is still being contested. One contractor was injured at the mine site in 2009. In all, the [Mine Safety and Health Administration](#) found 38 possible mine safety violations at the Arizona 1 Mine in 2010, many of which Denison is contesting. (Arizona Daily Sun Jan. 16, 2011)

Arizona 1 uranium mine operating illegally, EPA says: A uranium mine north of the Grand Canyon is operating in violation of the law, and its owner could face thousands of dollars in fines as a result, the U.S. Environmental Protection Agency said. The agency issued a notice of violation this week to Denison Mines Corp. for its Arizona 1 Mine, which is about 20 miles from the Grand Canyon's northern border. The EPA said Denison failed to notify the agency as to when it would resume mining and that it did not secure the necessary federal approval before ventilating the mine or testing emissions.

Denison President Ron Hochstein said Tuesday (May 4) that he was surprised by the notice and believed the company was operating within the law. He said he was working with regulators to address those issues. (AP May 5, 2010)

> View [older issues](#)

Pinyon Plain mine, Coconino County

(formerly Canyon Mine)

> View [deposit info](#)

Havasupai Tribe complains about not being consulted on uranium ore transport: Uranium haul trucks are once again leaving the Pinyon Plain Mine, and the Havasupai Tribe describes the actions of the state and the

Navajo Nation permitting this hauling as a disregard for "the health risks and dangerous implications of uranium mining."

Energy Fuels, Inc., restarted hauling uranium ore from the Pinyon Plain Mine after a nearly six-month pause. In January, the mining company signed an agreement with the Navajo Nation to allow the trucks to pass through Navajo land.

"The Navajo Nation is not the only Tribe or community affected by this activity," the Havasupai Tribe said in a statement sent to The Arizona Mirror. "This was a blatant disregard for others impacted by the hauling activity, which could have been avoided by allowing our voice to be heard." (Arizona Mirror Feb. 18, 2025)

Drone crashed into Pinyon Plain uranium mine: A northern Arizona man was arrested Wednesday (Feb. 12) after a drone crash at a uranium site near the Grand Canyon caused multiple car accidents, sparking Indigenous rights activists to rally against his criminal charges.

Around 8 a.m., the Coconino County Sheriff's Office responded to reports of a drone flying over the Pinyon Plain Mine, a site designated as "critical infrastructure" located off Highway 64, just south of Tusayan, according to a news release from the deputies.

The area is known for its uranium mining and transport by Energy Fuels Inc., whose efforts to haul the ore through tribal lands have faced active protests from Indigenous rights advocates.

According to the Coconino County Sheriff's Office, mine officials reported that the drone collided with cables connected to a mine shaft transportation system, and the operator fled the scene in a silver Ford pickup truck. (Arizona Republic Feb. 15, 2025)

Protesters challenge renewed hauling of uranium ore from Pinyon Plain Mine: Protesters gathered outside Flagstaff City Hall on Monday (Feb. 10) afternoon to speak up against the transportation of uranium ore from the Pinyon Plain Mine near the Grand Canyon.

Organized by the anti-nuclear group Haul No!, the protest came a week and a half after the Navajo Nation reached a new agreement with mine operator Energy Fuels allowing hauling of uranium across Navajo lands. (Arizona Daily Sun Feb. 13, 2025)

Judge rejects challenge to national monument near Grand Canyon:


> View [here](#)

Energy Fuels and Navajo Nation sign agreement on uranium ore transport: On Jan. 29, 2025, Energy Fuels Inc. and the Navajo Nation announced the signing of a landmark agreement governing the transport of uranium ore along federal and state highways crossing the Navajo Nation. Ore transport from Energy Fuels' Pinyon Plain Mine in northern Arizona to the company's White Mesa Mill in southern Utah is now expected to resume in February 2025.

Additionally, the company has committed to accepting and transporting, at no cost to the Nation, up to 10,000 tons of uranium-bearing cleanup materials from [abandoned uranium mines within the Navajo Nation](#).

Navajo Nation approves regulations for uranium ore transport through reservation:

> View [here](#)

Environmental groups join tribes to protest Pinyon Plain uranium mine: Tribal leaders and conservationists came together Saturday (Aug. 24) to protest a mine extracting uranium south of the Grand Canyon. The [Center for Biological Diversity](#)  estimated around 250 people attended the protest, which included members of the Havasupai and Lakota tribes. They're protesting Energy Fuel's Pinyon Plain Mine. (ABC15 Aug. 24, 2024)

Attorney General requests supplemental Environmental Impact Study for Pinyon Plain uranium mine: Arizona's attorney general has asked the Forest Service to update a nearly 40-year-old environmental review of a uranium mine on the Kaibab National Forest, saying there's new evidence of danger to regional water supplies.

In a letter Tuesday (Aug. 13) to forest supervisor Nicole Branton, state Attorney General Kris Mayes (D) said

scientific advances in groundwater modeling "unequivocally show" that the Forest Service's past findings of no threat to water supplies from the Pinyon Plain mine were wrong.

In addition, Mayes said, a 2016 excavation mishap that's led the mine's operator, Energy Fuels Resources, to pump millions of gallons of water from the mine shaft suggests groundwater is closer to mining operations than believed when the Forest Service completed an environmental impact statement in 1986.

"Failure to supplement the EIS could result in devastating consequences for the region -- especially for vulnerable communities like the Havasupai Tribe," Mayes said. (E&E News Aug. 14, 2024)

> Download: [AZ Attorney General letter to Forest Service](#), Aug. 13, 2024 (PDF)

Protest march against uranium ore hauling through Navajo Nation: Dozens of protestors, led by Navajo Nation President Buu Nygren, First Lady Jasmine Blackwater-Nygren and other leaders, marched on the northbound lanes of Highway 89 in Cameron on Fri, Aug. 2, 2024 against uranium hauling through the reservation. The highway was part of the route taken by trucks from the Pinyon Plain Mine near the South Rim of the Grand Canyon three days earlier when they began uranium ore transportation through a large swath of the nation.

Indigenous leaders and activists held protests over the weekend opposing the start of uranium ore transport from the state's only active uranium mine. (KNAU Aug. 4, 2024)

Governor, Energy Fuels agree to pause uranium ore transports through Navajo Nation: Arizona Governor Katie Hobbs and Energy Fuels have agreed to a pause the transporting uranium ore through the Navajo Nation. The ore was transported from the Pinyon Plain Mine in Tusayan to the [White Mesa Uranium Mill](#) in Blanding, Utah, near the southern Utah-Arizona border Tuesday (July 30). [...] Hobbs and Energy Fuels agreed to pause the shipments through Navajo lands, to give both Energy Fuels and the tribe an "opportunity to engage in good faith negotiations." (KAFF Aug. 1, 2024)

Navajo Nation President deploys police to stop unlawful uranium ore transport on tribal lands: The President of the Navajo Nation announced earlier today that he was sending police to stop the transport of uranium across tribal lands. In his statement, President Buu Nygren said that the shipment was being done illegally. He also stated the lack of notice from the mining company posed a danger to his people. [Energy Fuels Inc.](#), the largest uranium provider in the United States, agreed to give the tribe notice before hauling uranium across exempted highways. According to Nygren, the tribe only found out about the shipment after trucks had departed.

Nygren dispatched tribal police to turn away the shipment. But, according to the Associated Press, the trucks left tribal lands before police could intercept them. (KSL July 31, 2024)

Navajo Nation is drafting regulations for uranium ore transport through reservation:

> View [here](#)

Interconnectivity of groundwater systems near Pinyon Plain/Canyon uranium mine poses risk to people, aquifers, and ecosystems, researchers find: A new research paper published recently in Annual Reviews of Earth and Planetary Sciences, coordinated by scientists from The University of New Mexico and collaborating institutions, addresses the complex nature and societal importance of Grand Canyon's springs and groundwater. The paper, [Hydrotectonics of Grand Canyon Groundwater](#), recommends sustainable groundwater management and uranium mining threats that require better monitoring and application of hydrotectonic concepts.

The data suggest an interconnectivity of the groundwater systems such that uranium mining and other contaminants pose risks to people, aquifers, and ecosystems. The conclusion based on multiple datasets is that groundwater systems involve significant mixing. (University of New Mexico Mar. 25, 2024)

County calls for more environmental monitoring for Pinyon Plain/Canyon uranium mine near Grand Canyon: The Coconino County Board of Supervisors has voiced their disapproval of this uranium mine in the past. On Tuesday (Feb. 20), they voted to affirm their disapproval and request action from the state to monitor

the impacts of this mine. (KTVK/KPHO Feb. 20, 2024)

> View: [Resolution No. 2024-09](#), Feb. 20, 2024

Rumble on the Mountain concert raises awareness toward threats of uranium mining at Pinyon

Plain/Canyon mine to Indigenous communities: Musicians and activists joined forces on Feb. 3 for [Rumble on the Mountain X](#), a benefit concert at the Orpheum Theater [in Flagstaff, AZ] that raised awareness toward mining threats facing Indigenous communities near the Grand Canyon.

The 10th Rumble centered around Pinyon Plain Mine, formerly Canyon Uranium Mine. On Jan. 8, Pinyon Plain extracted uranium ore seven miles from the South Rim of the Grand Canyon for the first time.

Construction for the mine began in 1986 but was not fully completed until 2022.

The mine began production in January after increased international demand for nuclear energy following the 28th United Nations Conference of the Parties (COP28). However, the mining processes raise concerns from tribes located near it, particularly the Havasupai, about negative health effects and environmental harm.

(jackcentral.org Feb. 11, 2024)

USGS partners with Havasupai Tribe to identify potential contaminant exposure pathways from Grand Canyon uranium mining:

A new USGS [U.S. Geological Survey] report, co-produced with the Havasupai Tribe, identifies exposure pathways posed by uranium mining in the Grand Canyon watershed that arise from traditional uses and cultural values placed on resources. Previous models did not take into account Tribal perspectives or traditional uses. [...]

Newly identified exposure pathways for the Havasupai include inhalation, ingestion and absorption from traditional food and medicines as well as ceremonial practices. Incorporating these exposure pathways into future research and risk analyses will lead to results that are more inclusive of Tribal resources and culture.

(USGS Jan. 30, 2024)

> Download: [Expanded Conceptual Risk Framework for Uranium Mining in Grand Canyon Watershed -- Inclusion of the Havasupai Tribe Perspective](#), USGS Open-File Report 2023-1092, by Carletta Tilousi and Jo Ellen Hinck

Groups, scientists urge Arizona governor to close Pinyon Plain uranium mine in newly designated

Grand Canyon National Monument: Echoing pleas from the Havasupai Tribe, Navajo Nation and other Tribes, scientists and Indigenous, faith, recreation and conservation organizations today called on Arizona Gov. Katie Hobbs to close the Pinyon Plain uranium mine, which is located in the country's newest national monument near the Grand Canyon. Closing the mine will safeguard Tribal cultural heritage and prevent permanent damage to the Grand Canyon's aquifers and springs.

The groups are calling on Gov. Hobbs to use her authority to rescind permits issued by the Arizona Department of Environmental Quality and instead issue new permits for closing and cleaning up the mine, also known as Canyon mine.

"This dangerous uranium mine should never have been approved, and we need Gov. Hobbs to fix this terrible mistake," said Taylor McKinnon, Southwest director for the [Center for Biological Diversity](#). "The mining industry and regulators can't ensure that uranium mining won't permanently damage Grand Canyon's aquifers and springs. The governor needs to intervene before more irretrievable damage is done." (Center for Biological Diversity Jan. 29, 2024)

Navajo president warns of uranium ore transports from Pinyon Plain Mine through tribal lands:


President Buu Nygren warned that the new Pinyon Plain Mine established just a few miles south of the national park will transport radioactive materials through Navajo communities.


The mine's owner, Energy Fuels, said it started mining uranium last month. It sits within the newly designated Baaj Nwaavjo I'itah Kukveni national monument and is operating because it was grandfathered in.

Nygren has warned that transporting uranium will occur through several Navajo communities in violation of tribal law. (KJZZ Jan. 15, 2024)

Tribes condemn start of uranium mining at Pinyon Plain Mine south of Grand Canyon: Two northern Arizona tribes this week condemned the start of operations at a uranium mine just south of the Grand Canyon.

The statements came after Canadian-based company Energy Fuels Inc. announced last month that operations at its Pinyon Plain Mine had commenced.

"It is with heavy hearts that we must acknowledge that our greatest fear has come true,"  a statement from the Havasupai Tribal Council read.

Meanwhile, Navajo Nation President Buu Nygren said in a statement that mining remains opposed "by all neighboring tribes that have forever called Grand Canyon their home."  (Arizona Daily Sun Jan. 13, 2024)

> View [older issues](#)

Pinenut mine, Mohave County

> View [deposit info](#)

Energy Fuels closes Pinenut mine for good, after increased uranium level found in soil nearby: [The Arizona Department of Environmental Quality] reported that [Energy Fuels Resources](#) has ceased operations at Pinenut mine and transported all uranium ore to milling operations in Utah. The company is therefore no longer seeking to renew its air quality permit for that location. Permanent closure of the Pinenut mine is a long-term process and will require working with multiple agencies. (Arizona Daily Sun Apr. 15, 2016)

Renewal process for air-pollution permit of three Grand Canyon mines suspended, as fourfold increased uranium level found in soil near Pinenut mine: State environmental officials have suspended the air-pollution permit renewal process for three uranium mines near the Grand Canyon. Recent tests showed uranium content in the soil near one of the mines is four times higher than previously measured. Arizona Public Radio's Ryan Heinsius reports. The tests were conducted in July and October outside the perimeter of the Pinenut Mine facility. The analysis showed uranium in the soil at one out of the five testing sites had spiked since 2011 when the mine reopened.

The Arizona Department of Environmental Quality says the elevated level of the radioactive metal doesn't present an immediate public health risk. But the agency has pushed the mines' owner, Energy Fuels Resources, to boost measures to control radioactive dust. ADEQ has also mandated that the company expand soil testing in the area.

ADEQ is considering the renewal of air-pollution permits for all three mines, but will suspend that process as it evaluates the company's new dust-control plan at the Pinenut Mine. The agency will eventually open a new public comment period and hold meetings for the permit renewals. (KNAU Arizona Public Radio Dec. 30, 2015)

ADEQ proposes to issue Air Quality Control Renewal Permit for Pinenut mine:

Submit comments by January 4, 2015.

> Download [ADEQ Public Notice, Dec. 2, 2015](#)  (PDF)

> Download [Draft Permit](#)  (PDF)

> Download [Draft Technical Support Document](#)  (PDF)

Conservation groups urge BLM to suspend Pinenut uranium mine in response to groundwater contamination: Conservation groups have sent a letter urging federal regulators to suspend operations at a uranium mine near the Grand Canyon, where millions of gallons of uranium-laced groundwater threaten people and wildlife. Records from the U.S. Geological Survey show that the contaminated groundwater -- 80 times the limit set to protect public health and the environment -- have inundated the Pinenut uranium mine immediately north of Grand Canyon National Park. It is unknown whether deep aquifers and nearby springs in the national park are also being polluted.

> View [Grand Canyon Trust release Aug. 4, 2014](#) 

Pinenut uranium mine to continue operation into 2015: On Apr. 23, 2014, Energy Fuels announced that it has revised its previous guidance and currently expects to continue mining at its 100% owned Pinenut Mine

through 2014 and into the 1st quarter of 2015.

Pinenut mine to be placed on care and maintenance due to market conditions: Mining at the Pinenut mine is expected to continue into the middle of FY-2014 (July 2014), at which point the mine is expected to be placed on care and maintenance. Re-starting mining activities at Pinenut would be evaluated in the context of business and market conditions, including the U₃O₈ price environment. (Energy Fuels Inc. Nov. 14, 2013)

Energy Fuels Incorporated proposes to open the Pinenut Mine in Mohave County late this month or in early June, according to a statement from the Bureau of Land Management. (Arizona Daily Sun May 9, 2013)

The state Department of Environmental Quality approved an air quality permit for Denison's Pinenut mine this week. (Arizona Republic Mar. 11, 2011)


On Nov. 12, 2010, the Arizona Department of Environmental Quality started the public comment period for the proposed air quality permit for the Pinenut mine. Comment period ends January 14, 2011.


> View [ADEQ public notice](#) 

On Sept. 1, 2009, the Arizona Department of Environmental Quality issued a Discharge Authorization for the 3.04 General Aquifer Protection Permit (APP) 100300 for the Pinenut Mine to Denison Mines (USA) Corp.

> View [details](#) (AZDEQ)

On June 19, 2009, the Arizona Department of Environmental Quality (ADEQ) issued a public notice opening the public comment period on the Water Quality General Aquifer Protection Permit for Denison Mines Corp.'s Pinenut mine. Comment period ends July 22, 2009.

> Download [ADEQ notice and documents](#)  (select "Public Notices, Meetings and Hearings")

[Denison Mines](#) has been denied a state permit for the reopening of the Pinenut mine: The [Arizona Department of Environmental Quality](#)  said Denison Mines proposed using outdated, 20-year-old liners and impoundment ponds to capture uranium mine-related runoff. In addition, ADEQ said Denison wasn't specific enough in describing pollution-control measures at the proposed mines.

(Arizona Daily Sun May 14, 2008)

Colorado

> View [extra page](#) 


Louisiana

- [IMC Global](#)

> See also Issues for: New Mining Projects · Decommissioning Projects · Legislation & Regulations

> See also Data for: Deposits, Proposed and Active Mines · Old Mines and Decommissioning

By-product uranium production from phosphate in Louisiana to cease

By-product uranium production is to 'permanently' cease at [IMC Global's](#)  Uncle Sam and Faustina facilities in Louisiana. Low uranium prices are cited as the major reason for the decision by senior management. The facilities' combined production of 950 000 lbs U₃O₈ (365.4 tU) last year accounted for approximately 16% of

uranium produced in the US; 1998 production is expected to be similar. Meanwhile IMC's New Wales and Plant City recovery facilities in Florida have remained on 'stand-by' since 1992. (UI News Briefing 98.49, Dec. 9, 1998)

Nebraska

- [Crow Butte ISL](#)

> See also Issues for: New Mining Projects · [Decommissioning Projects](#) · [Legislation & Regulations](#)

> See also Data for: [Deposits, Proposed and Active Mines](#) · [Old Mines and Decommissioning](#)

Crow Butte in-situ leach uranium mine, Dawes County, Nebraska

[General](#) · [Three Crow Expansion](#) · [Marsland Expansion](#) · [North Trend Expansion](#) · [License violations and reportable events](#)

> View [mine details](#)

> View [NRC page](#) 

Uranium mining at Crow Butte is being opposed by Save Crow Butte


General


License renewal of Crow Butte uranium ISL mine


NRC offers opportunity to request a hearing and to petition for leave to intervene on license renewal application for Crow Butte in situ leach uranium mine and Marsland Expansion Area: The U.S. Nuclear Regulatory Commission (NRC) is considering an application for the renewal of Source and Byproduct Materials License Number SUA-1534, which authorizes Crow Butte Resources, Inc., to operate the existing Crow Butte Project in-situ uranium recovery facility and to construct and operate the [Marsland Expansion Area](#). A request for a hearing or petition for leave to intervene must be filed by **October 28, 2025**.

> Federal Register Volume 90, Number 166 (Friday, August 29, 2025) p. 42273-42274 ([download full text](#) )

> Access [Docket ID NRC-2025-0976](#) 

Cameco makes U-turn and now plans to restart rather than decommission Crow Butte in situ leach uranium mine: On Sep. 24, 2024, Crow Butte Resources, Inc. (CBR) applied for a 20-year renewal of Source Material License No. SUA-1534 for the continued operation of the Crow Butte in situ recovery uranium mine. ([License renewal application](#) , Sep. 24, 2024)

On Apr. 30, 2025, Crow Butte Resources, Inc. submitted a [revised license renewal application](#) .

On Sep. 11, 2025, Crow Butte Resources, Inc. submitted a [revised license renewal application](#) .


> See: [decommissioning issues](#)

Cameco requests permit amendment to place all mine units of mothballed Crow Butte in situ leach uranium mine in restoration phase

"Due to unfavorable market conditions and depleted uranium concentrations in the permitted portion of the Chadron aquifer, CBO has suspended production operations and would like to continue restoration activities in as efficient a manner as possible. [...]"

> Download [Cameco Resources letter to Nebraska Department of Environmental Quality \(NDEQ\), June 5, 2018](#) 

NRC approves further 10-year extension of groundwater restoration schedule for Crow Butte in situ leach uranium mine


On Apr. 3, 2018, Cameco submitted to NRC a license amendment request for an alternate groundwater restoration schedule for Mine Units 2-6. The request extends completion of groundwater restoration for these mine units to 2022 - 2025. This constitutes a delay of up to 10 years compared to the originally approved groundwater restoration schedule ([ML092220668](#) )

> Download: [Request for Alternate Decommissioning \(Groundwater Restoration\) Schedule](#) , Apr. 3, 2018

On Dec. 14, 2018, NRC approved the requested 10-year extension of the groundwater restoration schedule.

> Download: [NRC letter to Cameco](#) , Dec. 14, 2018 (PDF)

> Download: [Technical Evaluation Report](#) , Dec. 14, 2018 (PDF)

> Download: [Memorandum - Explanation for why actions qualified for selected categorical exclusion](#) , Dec. 14, 2018 (PDF)

> Download: [License SUA-1534, Amendment No. 4](#) , Dec. 14, 2018 (PDF)

Cameco plans to discontinue U.S. uranium mining operations

On Feb. 9, 2018, Cameco made the following announcement in its quarterly report for the fourth quarter of 2017: "As a result of our decision to defer all wellfield development at the US operations, production will cease in 2018, which is expected to result in production of less than 100,000 pounds." (p.68)

> Download: [Cameco 2017 Q4 MD&A, Financial Statements & Notes](#) , Feb. 9, 2018 (1.7MB PDF)


[This concerns the Crow Butte, [Smith Ranch-Highland](#), and [North Butte](#) operations.]

On Apr. 2, 2018, Cameco notified NRC of the forthcoming cessation of production at the Crow Butte mine: "[...] the remaining production and injection from producing mine units will be shut off in the next 60 days. [...] Within the next 21 months, Cameco resources will submit Alternative Decommissioning Schedules for Crow Butte Resources. [...] All production equipment will remain on standby to provide the option to restart full operations in the future should market conditions warrant. The above mentioned Alternate Decommissioning Schedule will include a request to defer equipment decommissioning [...]."

> Download: [Cameco letter to NRC, Apr. 2, 2018](#) , (PDF)

Sharp rise of uranium value in monitoring well necessitates changes in groundwater restoration regime at Mine Unit 3 of Crow Butte in situ leach uranium mine

"While ensuring stability trends in MU3 [Mine Unit 3], **well P246 (WH7 MU3) exceeded the restoration value for uranium. The value for uranium went from .09 [mg/L] (9/26/14) to 4.04 [mg/L] (3/29/17).** Based on a discussion with Nebraska Department of Environmental Quality (NDEQ), **MU3 was returned to IX/RO treatment** on September 15, 2017 in order to spot treat the well. Spot treatment is currently ongoing in contrast to the requested alternate decommissioning schedule which lists MU3 as in stability monitoring. **It is likely that mining solution from MU7 migrated into the area and impacted the water quality in P246.** In addition to resuming restoration activities around the well, CBO has implemented a monitoring program around MU2 and MU3 in order to prevent a similar event." [emphasis added]

> Download [Annual Report of Changes, Tests, or Experiments, License No. SUA-1534, Docket No. 40-8943](#) , Cameco Resources, Crow Butte Operation, Jan. 23, 2018 (34.1MB PDF)

Cameco's Crow Butte in situ leach uranium mine obtains NRC exemption to simplify determination of occupational doses from inhalation of radionuclides

The U.S. Nuclear Regulatory Commission (NRC) is issuing an exemption to Crow Butte Resources, Inc. (CBR) for the purpose of complying with occupational dose limits in response to a request from CBR dated September 21, 2015. Issuance of this exemption will allow CBR to disregard certain radionuclides that contribute to the total activity of a mixture when determining internal dose to assess compliance with occupational dose equivalent limits at its in situ uranium recovery (ISR) facility in Crawford, Nebraska.

> Federal Register Volume 81, Number 224 (Monday, November 21, 2016) p. 83289-83291 ([download full text](#))

> Download: [NRC License Amendment No. 1 and Safety Evaluation Report](#), Dec. 5, 2016

> Access: [Docket ID NRC-2008-0208](#)

Nebraska DEQ invites comment on permit renewal for wastewater discharge of Cameco's Crow Butte in situ leach uranium mine

The Nebraska Department of Environmental Quality (NDEQ) proposes to reissue with change the National Pollutant Discharge Elimination System (NPDES) permit for the Crow Butte Resources, Inc. d/b/a CAMECO RESOURCES Crow Butte Mine, 86 Crow Butte Rd., Crawford, NE (NPDES# NE0130613; SIC 1094). The mining facility produces uranium yellowcake by in-situ leach mining. The permit would authorize the LAND APPLICATION OF TREATED PROCESS WASTEWATER AT SITES WITHIN THE BOUNDARIES OF CROW BUTTE RESOURCES PROPERTY, located in the White River Basin, as specified by NDEQ. The permit would be issued for a period of up to five years and would restrict pollutant discharges to comply with the requirements of Department regulations.

Submit comments by September 23, 2016.

> View [NDEQ Public Notice](#)

NRC Board rules that tribe's unwillingness to cooperate on identification of Traditional Cultural Properties does not preclude license renewal for Crow Butte in situ leach uranium mine

The Nuclear Regulatory Commission's Atomic Safety and Licensing Board has released a Partial Initial Decision on challenges to renewal of the operating license of the Crow Butte uranium mine southeast of Crawford - and it's pretty much a split decision.

The Licensing Board agrees with opponents, including the Oglala Sioux Tribe, that NRC staff failed to meet National Historic Protection Act and National Environmental Policy Act requirements to work with the tribe to identify Traditional Cultural Properties in the mining lease area, but disagrees that the failures should result in denial of the license renewal.

The board says the unwillingness of the tribe and other intervenors to continue to participate in the consultation process with NRC staff weighs against their demand and that not granting renewal or extension would be an "undue hardship" on mine owner [Cameco Resources](#) and "unnecessary to cure the potential harms at issue." (Chadrad May 27, 2016)

> Download [Partial Initial Decision LBP-16-07, May 26, 2016](#) (427k PDF)

On Oct. 8, 2020, the NRC denied Crow Butte Resources Inc.'s request to review LBP-16-07 (and LBP-15-11).

> Download: [CLI-20-08 Memorandum and Order](#), Oct. 8, 2020 (PDF)

> See also: [NRC invites comment on draft environmental assessment supplement and finding of no significant impact for license renewal of decommissioning Crow Butte in situ leach uranium mine](#)

Cameco defers wellfield development at Crow Butte situ leach uranium mine due to depressed uranium market

On Apr. 21, 2016, Cameco announced that production is being curtailed at Cameco Resources' US operations by deferring wellfield development. The changes are expected to result in a reduction of about 85 positions, including employees and long-term contractors.

The US operations will continue to employ about 170 people to operate existing facilities and restore depleted wellfields, but new wellfield development will be stopped. The US operations will continue ongoing licensing efforts to maintain the option to resume development when market conditions significantly improve.

Cameco now also involved in tax dispute with the United States

> View [here](#)

Truck carrying hydrochloric acid to Crow Butte uranium in situ leach mine overturns

An Industrial Chemical truck from Denver, Colo., turned over approximately two miles from the Crow Butte Uranium Mine as it was making a delivery of hydrochloric acid to the facility. Dawes County Deputy Sheriff Scott Swickert said the accident occurred around 6 a.m. and was caused by the wintry weather conditions. "The trailer got into the soft shoulder of the road and it sucked the trailer into the ditch," he said. A small valve on the trailer broke off in the wreck, and Swickert described the hydrochloric acid as dribbling out. Neither Swickert or Crow Butte Mine knows as yet how much of the acid was spilled.

Ken Vaughan, communications director with Cameco, Crow Butte's parent company, said mine staff helped build a berm around the site of the accident to contain the spill. The Dawes County Sheriff and the Nebraska State Patrol are controlling access to the scene. (Rapid City Journal Feb. 4, 2015)

Nebraska DEQ invites comment on proposed permit renewal for Crow Butte deep disposal well

The [Nebraska Department of Environmental Quality](#) is proposing to renew permit (NE0211670) and re-issue the permit (as NE0211670) to Crow Butte Resources, Inc. (CBR). CBR operates two Class 1 non-hazardous waste injection well designed to accept waste fluids generated at its in-situ uranium mining operation. The injection well is located in the Northwest Quarter of Section 19, Township 31 North, Range 51 West, Dawes County, Nebraska.

Submit comments prior to May 15, 2014.

(Lincoln Journal Star Apr. 3, 2014)

> Download [Nebraska DEQ letter to NRC, Mar. 31, 2014](#) (ADAMS Acc. No. ML14100A234)

Cameco requests further exemption from groundwater restoration schedule at Mine Unit 3 of Crow Butte in situ leach uranium mine

By [letter dated April 30, 2013](#), Cameco requested a further extension of the completion of groundwater restoration at Mine Unit 3 until July 1, 2016. On Aug. 20, 2009, NRC had already approved an extension to July 1, 2013.

Crow Butte uranium mine site evacuated due to threatening wildfire

On Aug. 31 and Sep. 1, 2012, the Crow Butte site was evacuated due to threatening wildfire to the east of the mine. During the evacuation, a crew of five employees remained on-site for security purposes. During the

evacuation, all source material on the site was kept under 24 hour surveillance. The wildfires did not enter the licensed area and as a result there were no releases to the environment. (Cameco letter to NRC, Sep. 11, 2012)

Cameco requests exemption from groundwater restoration schedules at Crow Butte in situ leach uranium mine

By [letter dated February 8, 2012](#), Cameco requested from NRC an exemption from the requirement to complete groundwater restoration within 24 months, because "the imposition of such precise, prescriptive timeframes to groundwater restoration in aquifers that are part of natural systems is not practicable".

By [letter dated June 22, 2012](#), NRC refused to review the exemption request, since it is incomplete. NRC notes in particular the missing of a description of how the exemption would not endanger life, property, or common defense and security, and, how it would be in the public interest. NRC explicitly expresses its dissatisfaction with the progress of groundwater restoration at the Crow Butte site:

- "[...] staff notes that despite several years of effort to restore groundwater at the Crow Butte facility, only one wellfield restoration has been approved by the NRC."

Cameco study claims solubility type classification of yellow cake from in situ leaching is 100% "fast"

> View [here](#)

NRC denies Cameco's request for extension of the period of groundwater restoration at Mine Unit 6 of Crow Butte in situ leach mine

On Dec. 21, 2010, Cameco Resources requested NRC approval for an alternate restoration schedule for Mine Unit #6, extending the period of groundwater restoration to nine years - far beyond the regulatory requirement of 24 months.

On May 21, 2012, NRC denied Crow Butte Resources, Inc.'s request for an alternate restoration schedule for Mine Unit #6.

NRC approves extension of the period of groundwater restoration at Crow Butte in situ leach mine

On Aug. 20, 2009, NRC approved Crow Butte Resources, Inc.'s request to extend the period of groundwater restoration beyond the regulatory requirement of 24 months for each of the mine units currently in restoration (i.e., Mine Units 2 to 5).

NRC staff finds no problem with groundwater impacts of existing in-situ leach uranium mines

> View [here](#)

\$50,000 penalty imposed on Crow Butte Resources for violations at ISL uranium mine

On May 23, 2008, the District Court of Lancaster County, Nebraska, imposed a \$50,000 penalty on Cameco's subsidiary Crow Butte Resources for various violations at its Crow Butte in-situ leach uranium mine. According to the Nebraska Department of Environmental Quality, beginning on or about July 1, 2003, and continuing daily thereafter until March 31, 2006, Crow Butte Resources (CBR) violated its UIC Permit No. NE0122611

- by releasing well development water upon the surface of the ground during CBR's well development and drilling process,
- by using Chadron Formation well development water as drilling water,
- by constructing injection wells and mineral production wells in a manner that had the potential to allow the movement of fluid containing contaminants into an underground source of drinking water,
- by failing to provide written notification until May 12, 2006, upon becoming aware of the noncompliance on or about March 31, 2006.

> Download [Complaint and Consent Decree May 23, 2008](#) (NE DEQ)

License renewal of Crow Butte uranium ISL mine

> For more recent issues, see [decommissioning issues](#)

NRC issues draft Supplement to the Environmental Assessment for the license renewal of mothballed Crow Butte in situ leach uranium mine: The staff of the U.S. Nuclear Regulatory Commission (NRC) has prepared this draft Supplement to the Environmental Assessment (EA) for the renewal of source materials license number SUA.1534 for the Crow Butte Resources, Inc. (CBR) in situ uranium recovery (ISR) facility in Crawford (Dawes County), Nebraska. This draft EA Supplement describes sites of historic, cultural, or religious significance to the Oglala Sioux Tribe that were identified during a field survey of the CBR license area conducted in November 2021 and evaluates the potential environmental impacts of the license renewal on those sites. [...]

Based on the 2014 EA and this EA Supplement, the NRC has preliminarily concluded that the proposed action (renewal of the CBR license) will have no significant environmental impacts on identified sites of significance to the Oglala Sioux Tribe or on any other cultural resources. Therefore, pursuant to 10 CFR 51.31, preparation of an environmental impact statement is not required for the proposed action, and pursuant to 10 CFR 51.32, a FONSI [Finding of No Significant Impact] is appropriate.

> Download: [draft Supplement to the Environmental Assessment](#), Aug. 2022 (PDF)

NRC Board agrees to intervenors' demand to analyze impacts of possible land application of ISL wastewater at Crow Butte: The Atomic Safety and Licensing Board dismissed all contentions filed by intervenors except one: "[...] But we find, in part, for Intervenors on Contention 12 (Contention 12B) and conclude that the EA is deficient as to its discussion of Crow Butte's possible land application of ISL wastewater. The NRC Staff must reach its own independent conclusion, based on technical support in conformance with NEPA as to any potential impacts of selenium on wildlife from Crow Butte's possible land application of ISL wastewater."

> Download: [Second Partial Initial Decision, LBP-16-13](#), Atomic Safety and Licensing Board, Dec. 6, 2016 (1.1MB PDF)

On Nov. 29, 2018, the NRC Commissioners denied the intervenors' petition for review of the Second Partial Initial Decision, LBP-16-13.

> Download: [Memorandum and Order CLI-18-08](#), Nov. 29, 2018 (386kB PDF)

NRC Board to hold supplementary evidentiary hearing on intervenors' contentions against license renewal for Crow Butte uranium ISL mine: The Atomic Safety and Licensing Board gives notice that it will

convene a supplemental evidentiary hearing (on October 23, 2015) to receive testimony regarding Crow Butte Resources' contested application to renew its U.S. Nuclear Regulatory Commission license to operate an in-situ uranium leach recovery facility near Crawford, Nebraska.

> Download [NRC release Oct. 16, 2015](#) (PDF)

> Federal Register Volume 80, Number 194 (Wednesday, October 7, 2015) p. 60720-60722 ([download full text](#))

NRC Board to hold evidentiary hearing on intervenors' contentions against license renewal for Crow Butte uranium ISL mine:

The Atomic Safety and Licensing Board gives notice that it will convene an evidentiary hearing (beginning on Aug. 24, 2015) to receive testimony and exhibits regarding the contested application of Crow Butte Resources, Inc. before the U.S. Nuclear Regulatory Commission seeking a renewal of its license to operate an in-situ uranium leach recovery (ISL) facility near Crawford, Nebraska. The Board also hereby gives notice that it will accept written limited appearance statements from members of the public regarding the License Renewal Application.

Written limited appearance statements may be submitted by August 28, 2015.

> Download: [NRC news release Aug. 6, 2015](#) (PDF)

> Federal Register Volume 80, Number 137 (Friday, July 17, 2015) p. 42552-42554 ([download full text](#))

> Access related documents: [Crow Butte Resources Site](#) (NRC)

NRC renews license for Crow Butte uranium ISL mine: On Nov. 6, 2014, the Nuclear Regulatory Commission announced that it has renewed Crow Butte Resources Inc.'s license to operate an in situ uranium recovery facility in Crawford, Neb., for an additional 10 years. The license now has an expiration date of Nov. 5, 2024.

> Download [NRC release Nov. 6, 2014](#) (PDF)

> Federal Register Volume 79, Number 221 (Monday, November 17, 2014) p. 68490-68491 ([download full text](#))

NRC issues Final Environmental Assessment and finding of no significant impact for license renewal of Crow Butte uranium in situ leach mine:

NRC staff has determined that renewal of NRC license SUA-1534, which would authorize continued operation of the Crow Butte facility in Crawford, Nebraska for a period of up to 10 years will not significantly affect the quality of the human environment.

> Federal Register Volume 79, Number 210 (Thursday, October 30, 2014) p. 64629-64631 ([download full text](#))

> Download [Final Environmental Assessment For The License Renewal Of U.S. Nuclear Regulatory Commission License No. SUA-1534, October 2014](#)

> Access [Docket ID NRC-2008-0208](#)

NRC issues Safety Evaluation Report on license renewal of Crow Butte uranium in situ leach mine: On Dec. 28, 2012, NRC released the Safety Evaluation Report on the license renewal of the Crow Butte uranium ISL mine:

> Download [Safety Evaluation Report License Renewal of the Crow Butte Resources ISR Facility, December 2012](#)

On Aug. 18, 2014, NRC released a revised Safety Evaluation Report on the license renewal of the Crow Butte uranium ISL mine:

> Download [Safety Evaluation Report \(Revised\), License Renewal of the Crow Butte Resources ISR Facility, Dawes County, Nebraska Materials License No. SUA-1534, August 2014](#)

NRC issues draft of license renewal for Crow Butte uranium ISL mine:

> Download [NRC cover letter May 23, 2011](#)

> Download [NRC draft source material license](#)

On Aug. 11, 2011, NRC released another draft of the license renewal for the Crow Butte uranium ISL mine:

> Download [NRC cover letter August 11, 2011](#)

> Download [NRC draft source material license](#)

On Nov. 15, 2012, NRC released another draft of the license renewal for the Crow Butte uranium ISL mine:

> Download [NRC cover letter August 11, 2011](#)

> Download [NRC draft source material license](#)

Geologist raises concern over potential groundwater contamination at Crow Butte uranium ISL mine:

Hannan LaGarry, a Chadron State geology instructor, said the Crow Butte mine has ignored recent studies that show faults and fractures in underground layers of rock that could carry contaminants to aquifers used for drinking and livestock. LaGarry said he's not opposed to uranium mining but is concerned that the mine is relying on outdated studies of underground rock. "In recent years, we've found that the assumptions made by previous workers were false and that newer detailed work shows a different story," he said. (Omaha World-Herald Dec. 14, 2008)

> See also: [Expert opinion regarding ISL mining in Dawes County, Nebraska](#), by Hannan E. LaGarry, Ph. D., July 2008

Opponents to license renewal of Crow Butte uranium-mine granted hearing: Opponents of a uranium mine at Crawford, Neb., that is seeking to renew its license have been granted a hearing by the Nuclear Regulatory Commission to voice environmental concerns. The commission has ruled in favor of granting a public hearing on several contentions raised by the Oglala Sioux Tribe; a tribal environmental group; seven individuals; and a northwest Nebraska environmental group, the Western Resources Council. The hearings likely would be held next spring, a commission spokesman said. (Omaha World-Herald Nov. 25, 2008)

NRC announces establishment of Atomic Safety and Licensing Board for license renewal of Crow Butte uranium ISL mine: This proceeding involves a license amendment application from Crow Butte Resources, Inc. seeking a 10-year renewal of its Source Materials License for the in situ leach uranium recovery facility located in Crawford, Nebraska. In response to a May 27, 2008 Notice of Opportunity for Hearing (73 FR 30426), petitions to intervene and requests for hearing have been submitted by (1) Elizabeth Lorina and Mario Gonzales representing the Oglala Sioux Tribe, (2) Shane Robinson and David Frankel representing multiple individuals and multiple organizations, and (3) Thomas J. Ballanco representing the Oglala Delegation of the Great Sioux Nation Treaty Council.

Federal Register: August 21, 2008 (Volume 73, Number 163) p. 49496-49497 ([download full text](#))

Residents voice opposition to production increase of Crow Butte uranium ISL mine: Crow Butte Resources (CBR), a mining company on the South Dakota and Nebraska border, wants to increase its annual uranium production by 50 percent. To do that, they and their opposition went face to face before the Atomic Licensing Board on July 23, 2008. At the public hearing, dozens of homeowners from Pine Ridge voiced their opposition to CBR's plan to build a uranium mine near Crawford. They say the company's operation near Chadron is destroying natural resources. (KOTA July 23, 2008)

NRC issues Opportunity To Request a Hearing on license renewal request of Crow Butte uranium ISL mine, and Order Imposing Procedures for Access to Sensitive Unclassified Non-Safeguards Information (SUNSI) for Contention Preparation:

A request for a hearing must be filed by July 28, 2008.

Within ten (10) days after publication of this notice of opportunity for hearing any potential party as defined in 10 CFR 2.4 who believes access to SUNSI is necessary for a response to the notice may request access to such information.

Federal Register: May 27, 2008 (Volume 73, Number 102) p. 30426-30430 ([download full text](#))

NRC issues Notice of License Amendment Request of Crow Butte uranium ISL mine, and Opportunity To Request a Hearing:

A request for a hearing must be filed by June 6, 2008.

Federal Register: April 7, 2008 (Volume 73, Number 67) p. 18823-18825 ([download full text](#))

Cameco applies for license renewal of Crow Butte uranium ISL mine: By letter dated Nov. 27, 2007, Crow Butte Resources, Inc. applied for the renewal of Source Materials License No. SUA-1534 for the continued operation of the Crow Butte in situ leach uranium mine.

> Download [renewal application documents](#)

Cameco to increase production from Crow Butte and Smith Ranch-Highland by 70%

On Dec. 4, 2007, Cameco announced that it is targeting to increase the combined production at its Crow Butte and [Smith Ranch-Highland](#) in-situ leach operations by 70% to 4.6 million pounds U₃O₈ [1,769 t U] annually by 2011. The planned production increase requires the restart of the idle [Highland](#) uranium recovery plant.

Crow Butte Resources receives permission for increased plant throughput at in-situ leach mine

By letter dated Oct. 17, 2006, Crow Butte Resources requested from NRC a license amendment to increase the plant throughput from 5000 to 9000 gallons per minute (gpm). An additional production of 150,000 to 250,000 pounds of U₃O₈ [58 to 96 t U] per year is expected.

NRC issued an Environmental Assessment and Finding of No Significant Impact on Oct. 24, 2007.

> Download [Environmental Assessment, Oct. 2007](#) (ADAMS ML072360287)

> Federal Register: October 31, 2007 (Volume 72, Number 210) p. 61693-61694 ([download full text](#))

NRC issued the requested license amendment on Nov. 30, 2007.

Crow Butte in situ leach uranium mine threatened by wild fire

On July 31, 2006, Crow Butte Resources notified the U.S. Nuclear Regulatory Commission of the wild fires east of Crow Butte Resources Central Processing Plant. The NRC was informed of the possible evacuation of the Crow Butte site should the fires continue to burn out of control.

Crow Butte Resources plans to expand In Situ Leach operations

"Division of Fuel Cycle Safety and Safeguards staff has learned that Crow Butte Resources (CBR) plans to expand its in situ leach (ISL) uranium extraction operations in Nebraska by operating up to four satellite facilities. CBR estimates that it will submit a license amendment application to NRC for the first satellite facility in May 2005, and an application for a second satellite facility is targeted for 2006 - 2007. Depending on economics, applications could be submitted to NRC for license amendments for two additional satellite facilities in the 2007 - 2010 time frame. Although a memorandum of understanding to defer active groundwater regulation at ISLs may be executed with the State of Nebraska before the first license amendment is submitted in 2005, NRC must prepare environmental assessments for each application." (U.S. NRC SECY-04-0131 WEEKLY INFORMATION REPORT - WEEK ENDING JULY 16, 2004)

NRC denies Wellfield Unit 1 groundwater restoration approval

By letter dated March 29, 2002, NRC, in a rare move, denied approval for the groundwater restoration at Wellfield Unit 1 of the Crow Butte in-situ leach facility.

"Staff's analysis indicates that concentrations of ammonium, iron, radium-226, selenium, total dissolved solids, and uranium show strongly increasing concentration trends over the stability monitoring period. These trends indicate a reasonable likelihood that license limits would be exceeded in the near future."

> See also [Federal Register: April 22, 2002 \(Volume 67, Number 77\), p. 19598](#)

Cameco writes down Crow Butte ISL property

On Nov. 7, 2000, Cameco announced the writedown of the Crow Butte ISL property. Cameco plans to continue to produce 800,000 pounds U₃O₈ (308 t U) per year.

Nebraska Department of Environmental Quality is proposing relaxed limitations for Crow Butte ISL deep injection well

"The Department is proposing to modify the existing permit by removing the injection limitations on flow rate. The limitation for pH is proposed to be changed from 5.0 - 8.5 to 5.0 - 9.5. Reporting for the temperature of the waste stream is proposed to be removed. The limitations for arsenic, barium, and selenium are proposed to be changed from 1 mg/l to 5 mg/l, 20 mg/l to 100 mg/l, and 2 mg/l to 1 mg/l, respectively. Testing for calcium is proposed to be added to the injection parameters with no injection limitation. Testing for cadmium, chromium, lead, mercury, and silver is proposed to be added with limitations of 1 mg/l, 5 mg/l, 5 mg/l, 0.2 mg/l, and 5 mg/l respectively." [...]

Comments or a request for a public hearing must be submitted by writing to Michael J. Linder, Director, [Nebraska Department of Environmental Quality](#), P.O. Box 98922, Lincoln, Nebraska 68509-8922, prior to October 13, 2000.

License renewal for Crow Butte ISL uranium mine (Nebraska)

The U.S. Nuclear Regulatory Commission has issued a *Finding of No Significant Impact* for the proposed license renewal of the [Crow Butte](#) in-situ leach uranium mine in Nebraska.

Any person whose interest may be affected by this proceeding may file a request for a hearing within 30 days from February 23, 1998.

> See notice in *Federal Register*, February 23, 1998 (Vol. 63, No. 35), p. 9023-9024 ([download full notice](#)).

Three Crow Expansion project of Crow Butte uranium in situ leach mine

> View [License Application](#) (NRC)


On Mar. 19, 2019, Cameco Resources requested from NRC that the Three Crow license amendment application be removed from consideration.

On Oct. 11, 2012, Cameco Resources requested that NRC restart the application process for the Three Crow Expansion Area. Cameco has decided not to pursue the pipeline option at this time.

On Apr. 14, 2011, Cameco Resources requested the NRC suspend review of the Three Crow Expansion Area application so that the option of a pipeline to carry mine fluids directly to the main plant could be evaluated.

On Aug. 3, 2010, Crow Butte Resources, Inc. (CBR) submitted a request for an amendment to Source Materials License SUA-1534 for the development of additional uranium in-situ leach mining resources. The proposed development area is referred to as the Three Crow Expansion Area and will be used as a satellite facility to the main CBR plant.

> Download [submitted documents](#) (ADAMS Acc. No. ML102230009)

On July 12, 2010, the Nebraska Department of Environmental Quality received a Class III Injection Well Application and the corresponding Petition for Aquifer Exemption for Crow Butte Resources, Inc., Three Crow Expansion Area. (ADAMS Acc. No. [ML102210326](#) .

On March 4, 2009, Cameco submitted to NRC a revised notice of intent to request additional amendments to Source Materials License SUA-1534 for the development of additional uranium in-situ leach mining resources. The proposed development area for use as a satellite facility to the main Crow Butte plant is referred to as the Three Crow Expansion Area. It is Cameco's intent to submit a license amendment application, for this expansion area, during the first quarter of 2010.

Marsland Expansion project of Crow Butte uranium in situ leach mine

> View [NRC: Marsland Application](#) 

NRC offers opportunity to request a hearing and to petition for leave to intervene on license renewal application for Crow Butte in situ leach uranium mine and Marsland Expansion Area:


> View [here](#)

NRC denies Oglala Sioux Tribe's petition for review re Marsland Expansion of Crow Butte uranium in situ leach mine:

> Download: [Memorandum and Order CLI-20-01](#) , Apr. 13, 2020 (PDF)

NRC panel to hold hearing on Marsland Expansion of Crow Butte uranium in situ leach mine: The Atomic Safety and Licensing Board hereby gives notice that it will convene an evidentiary hearing to receive testimony and exhibits in this proceeding regarding intervenor Oglala Sioux Tribe's (OST) challenge to the May 2012 application of Crow Butte Resources, Inc., (CBR) seeking to amend the existing 10 CFR part 40 source materials license for its Crow Butte in situ uranium recovery (ISR) site to authorize CBR to operate a satellite ISR facility within the Marsland Expansion Area (MEA) in Dawes County, Nebraska. The evidentiary hearing will concern OST's admitted Contention 2, which raises hydrogeological- related environmental and safety matters regarding the proposed license amendment. In addition, the Board gives notice that, in accordance with 10 CFR 2.315(a) and the procedures specified below, it will entertain oral, written, and audio-recorded limited appearance statements from members of the public in connection with the issues raised by Contention 2. To be considered timely, a written request to make an oral statement must either be mailed, faxed, or sent by email so as to be received by 5:00 p.m. Eastern Time (ET) on Monday, October 12, 2018 *[ehm, well, Oct. 12, 2018, is a Friday, at least in Europe...]*.


> Federal Register Volume 83, Number 149 (Thursday, August 2, 2018) p. 37828-37830 ([download full text](#) )

> Federal Register Volume 83, Number 188 (Thursday, September 27, 2018) p. 48874-48875 ([download full text](#) ) *[this corrects a fax number given, but leaves the date discrepancy unresolved...]*

> Download [NRC news release Aug. 15, 2018](#)  (PDF)

NRC releases final Environmental Assessment for Marsland Expansion of Crow Butte uranium in situ leach mine:

On Apr. 30, 2018, NRC released the Environmental Assessment for the Marsland Expansion of the Crow Butte uranium in situ leach mine.

> Federal Register Volume 83, Number 86 (Thursday, May 3, 2018) p. 19576-19577 ([download full text](#) )

> Download [Enviromental Assessment](#)  (36MB PDF)

> Access [Docket ID NRC-2012-0281](#) 

NRC determines that Marsland Expansion project of Cameco's Crow Butte uranium in situ leach mine would have no adverse impact on federally listed species: "[...] the NRC staff finds that all potential impacts

on the northern long-eared bat and whooping crane resulting from the proposed action would be insignificant or discountable. Therefore, the NRC staff concludes that the proposed action may affect, but is not likely to adversely affect these species. The NRC staff finds that the red knot and black-footed ferret do not occur in the action area, and therefore, the proposed action would have no effect on these species."

> Download: [Biological Evaluation of Impacts to Northern Long-Eared Bat, Whooping Crane, Red Knot, and Black-Footed Ferret, Marsland Expansion Area In Situ Uranium Recovery](#), March 2018 (41.7MB PDF)

NRC releases Safety Evaluation Report for Marsland Expansion of Crow Butte uranium in situ leach mine:

> Download: [Safety Evaluation Report License Amendment for the Crow Butte Resources Marsland Expansion Area In-Situ Recovery Project Dawes County, Nebraska](#), Jan. 2018 (762kB PDF)

NRC releases Draft Environmental Assessment in favour of Marsland Expansion of Crow Butte uranium in situ leach mine:

On Dec. 8, 2017, NRC released a Draft Environmental Assessment and Draft Finding of No Significant Impact on the Marsland Expansion of the Crow Butte uranium in situ leach mine: "[...] the NRC staff has preliminarily determined that amendment of SUA-1534, which would authorize the development of additional ISR operations at the MEA, would not significantly affect the quality of the human environment. Therefore, based on this preliminary assessment, an environmental impact statement (EIS) is not warranted, and, [...] a Finding of No Significant Impact (FONSI) is appropriate."

Submit comments by January 29, 2018.

> Download [NRC news release Dec. 18, 2017](#) (212k PDF)

> Federal Register Volume 82, Number 240 (Friday, December 15, 2017) p. 59665-59666 ([download full text](#))

> Download [Draft Environmental Assessment for the Marsland Expansion Area License Amendment Application](#) (3.5MB PDF)

> Access [Docket ID NRC-2012-0281](#)

On Dec. 7, 2017, NRC released a compiled Environmental Report for the Marsland Expansion of the Crow Butte uranium in situ leach mine:

> Download [compiled Environmental Report](#)

On Sep. 11, 2017, NRC released a revised Environmental Report for the Marsland Expansion of the Crow Butte uranium in situ leach mine:

> Download [revised Environmental Report](#)

On May 16, 2017, NRC released a revised Environmental Report for the Marsland Expansion of the Crow Butte uranium in situ leach mine:

> Download [revised Environmental Report](#)

On Jan. 31, 2014, NRC released Cameco's response to the RAIs dated March 22, 2013 on the Marsland Expansion Area Environmental Report:

> Download [Marsland Expansion Area Environmental RAI](#)

On Jan. 24, 2014, NRC released Cameco's response to the RAIs dated July 3, 2013 on the Marsland Expansion Area Technical Report:

> Download: [Vol. 1](#) · [Vol. 2](#)

On Sep. 6, 2013, NRC released Environmental Report revisions for the Marsland Expansion of the Crow Butte uranium in situ leach mine:

> Download [Environmental Report revisions](#)


On Aug. 21, 2013, NRC released Technical Report revisions for the Marsland Expansion of the Crow Butte uranium in situ leach mine:

> Download [Marsland Technical Report revisions](#)

On May 10, 2013, the Atomic Safety and Licensing Board granted the hearing request of the Oglala Sioux Tribe and admitted it as a party to the proceeding.

On April 19, 2013, Cameco submitted to Nebraska DEQ an application for an Area Permit to install and operate Class I Nonhazardous Waste Injection Wells at the company's Marsland Expansion Area. "The purpose of the injection wells is to dispose of well field bleed water and a small volume of process water from ISR mining operations and wastewater generated by groundwater restoration activities."

> Download [Class I Nonhazardous Waste Injection Wells Area Permit Application](#) 

> Download [revised Class I Nonhazardous Waste Injection Wells Area Permit Application, Sep. 23, 2014](#)  (NMED)

On Feb. 6, 2013, NRC gave notice that an Atomic Safety and Licensing Board (Board) is being established to preside over the following proceeding: Crow Butte Resources, Inc. (Marsland Expansion Area). Hearing requests were filed by the Oglala Sioux Tribe and a consolidated group of petitioners.

> Federal Register Volume 78, Number 29 (Tuesday, February 12, 2013) ([download full text](#) )

NRC announces opportunity to request a hearing and to petition for leave to intervene concerning Marsland Expansion project of Crow Butte uranium in situ leach mine:

Requests for a hearing or leave to intervene must be filed by January 29, 2013.

> Federal Register Volume 77, Number 231 (Friday, November 30, 2012) p. 71454-71458 ([download full text](#) )

> Access [Docket ID NRC-2012-0281](#) 

> Download [Technical and Environmental Report](#)  · [more](#) 

On May 16, 2012, Cameco submitted the license amendment application for the Marsland Expansion. On June 14, 2012, first portions of the Technical Report and the Environmental Report appeared in NRC's ADAMS Document system.

On Oct. 27, 2010, Crow Butte Resources, Inc. advised that submission of the Marsland license amendment application is anticipated during the third quarter of 2011.


On March 4, 2009, Cameco submitted to NRC a revised notice of intent to request additional amendments to Source Materials License SUA-1534 for the development of additional uranium in-situ leach mining resources. The proposed development area for use as a satellite facility to the main Crow Butte plant is referred to as the Marsland Expansion Area. It is Cameco's intent to submit a license amendment application, for this expansion area, during the third quarter of 2012.

North Trend Expansion project of Crow Butte uranium in situ leach mine

> View [License Application](#)  (NRC)

Hearing to be held on withdrawn license application for North Trend Expansion Area of Crow Butte uranium in situ leach mine [?!]: "[...] a hearing is being conducted in this license amendment proceeding." (ASLBP Dec. 20, 2023)

> Federal Register Volume 88, Number 246 (Tuesday, December 26, 2023) p. 88989 ([download full text](#) )

Cameco withdraws North Trend Expansion Area license application for Crow Butte uranium in situ leach mine: On Dec. 18, 2023, Cameco withdrew the North Trend Expansion Area license application. ([ML23352A130](#) )

Cameco suspends North Trend Expansion Area license application for Crow Butte uranium in situ leach mine: On Dec. 16, 2015, Cameco asked NRC to discontinue work on the North Trend Expansion Area

license application and rather prioritize the [Marsland Expansion Area](#) application.

On July 26, 2013, NRC released the Safety Evaluation Report for the North Trend Expansion Area of the Crow Butte uranium in situ leach mine.

> Download: [Safety Evaluation Report License Amendment for the Crow Butte Resources North Trend Expansion Area ISR Facility Dawes County, Nebraska](#) , U.S. Nuclear Regulatory Commission, July 2013

On Aug. 11, 2011, the Nebraska Department of Environmental Quality issued the permit for the construction and operation of the North Trend Expansion Area of the Crow Butte uranium in situ leach mine.

Opposition to aquifer exemption for North Trend expansion of Crow Butte uranium in situ leach mine:


Uncertainties regarding the presence of faults and fractures in the land underlying northwest Nebraska are a major reason that the Crow Butte Resources uranium mine should not receive an 'aquifer exemption' for its proposed North Trend expansion project, opponents of the mine said Monday (Aug. 23).

Making a decision now to allow use of the estimated 1.85 billion gallons [7 million cubic metres] of water in the lower portions of the Chadron formation under the expansion area would be premature, countered David Frankel, an attorney representing mine opponents in hearings before the Nuclear Regulatory Commission.

Detailed research by Chadron geologist Hannan LaGarry indicates that faults and fractures common in the area could link the Chadron aquifer to other water bearing layers, including the Brule and Arikaree, which are used for drinking water, he said. (Rapid City Journal Aug. 25, 2010)

The Nebraska Department of Environmental Quality has scheduled a public hearing regarding a proposal to exempt a portion of the Chadron Aquifer north of Crawford. This portion of the aquifer is associated with a proposed expansion area for the Crow Butte Resources (CBR) uranium mining facility. The proposed exemption would prevent that designated area of the aquifer from being used as a drinking water source in the future. The public hearing is scheduled for Monday, August 23, 2010.

> View [Nebraska DEQ Crow Butte Resources news page](#) 

On January 6, 2010, [Crow Butte Resources](#) submitted to the [Nebraska Department of Environmental Quality](#)  (NDEQ) a revised version of its application for a Class III Underground Injection Control (UIC) Permit for the North Trend Expansion project of its Crow Butte uranium in situ leach mine.


> Download [revised application documents](#)  (ADAMS Acc. No. ML100432281)


The ownership of the Crow Butte Resources uranium mine near Crawford by a Canadian mining company is a legitimate issue for argument in deciding whether the mine should be allowed to expand its operation to a nearby site, a three-member panel of Nuclear Regulatory Commission judges has ruled. In a decision issued Jan. 27, 2009, the NRC judges also said that questions of the impact of low levels of arsenic in water returned to aquifers during mining operations, the relationship between arsenic exposure and diabetes and information about an alleged cluster of pancreatic cancer in the Chadron area can also be raised during hearings on the mine's proposed North Trend expansion. (The Chadron News Feb. 10, 2009)

> Download Memorandum and Order LBP-09-01 Jan. 27, 2009 (ADAMS Acc. No. [ML090270965](#) )

On April 29, 2008, an NRC Atomic Safety and Licensing Board Panel (ASLBP) ordered as follows:

"In this Memorandum and Order, in addition to ruling on three pending matters on which the participants are in dispute, we find that Petitioners WNRC, Owe Aku, and Debra L. White Plume have shown standing to participate in the proceeding, and admit three of their joint contentions, in modified form. The first two of these concern alleged contamination of water resources and potential resulting environmental and health issues; the third concerns the extent of consultation that is required with tribal leaders regarding a prehistoric Indian camp located in the region of the proposed expansion site, under the National Historic Preservation Act."

> Download Memorandum and Order LBP-08-06, April 29, 2008 (ADAMS Acc. No. [ML081200636](#) )

> Download Revised Memorandum and Order LBP-08-06, May 21, 2008 (ADAMS Acc. No. [ML081430342](#) )

On November 12, 2007, seven Petitioners from parts of the poorest region in the United States asked the Nuclear Regulatory Commission (NRC) to participate in decisions relative to uranium mining and its harmful effects in northwestern Nebraska and the Lakota (Sioux) Pine Ridge Indian Reservation in Southwest South Dakota. According to NRC sources, this is the first request to intervene in an NRC proceeding relating to the expansion of an existing uranium mining operation in approximately 17 years. The petitioners are Thomas Cook, Chadron Native American Center, Slim Buttes Agricultural Development Corp., High Plains Community Development Corp., Western Nebraska Resources Council, Debra White Plume, and an Oglala Lakota nonprofit organization called Owe Aku. (UN Observer Dec. 7, 2007)

On Nov. 8, 2007, the Nebraska Department of Environmental Quality dismissed CBR's petition for aquifer exemption, due to deficiencies identified in CBR's Technical Review of Aquifer Exemption Petition dated August 15, 2007.

On May 30, 2007, [Crow Butte Resources, Inc.](#) (CBR) submitted a request for an amendment to Source Materials License SUA-1534 for the development of additional uranium in-situ leach mining resources. The proposed development area for use as a satellite facility to the existing main plant is referred to as the North Trend Expansion Area.



> Download [application documents](#) (ADAMS Acc. No. ML072540671)

License Violations and reportable events at Crow Butte ISL uranium mine (Nebraska)

- Aug. 15, 2025: Injection well fails 5-year mechanical integrity test
- Mar. 15, 2023: Restoration and development pond liner leak
- Dec. 15, 2022: Failure to submit a license-required report to the NRC in a timely manner and failure to revise or generate a new safety and environmental review panel evaluation to reflect changes in facility operations in accordance with license requirements.
- July 21, 2022: Injection well fails 5-year mechanical integrity test
- Feb. 16, 2022: Evaporation Pond 1 liner leak
- Dec. 14, 2021: Evaporation Pond 1 liner leak
- Sep. 22, 2020: Injection well fails 5-year mechanical integrity test
- May 29, 2020: Monitor well excursion
- May 21, 2020: Monitor well excursion
- Mar. 3, 2020: Production well fails 5-year mechanical integrity test
- Jan. 31, 2020: Production well fails 5-year mechanical integrity test
- Jan. 2, 2020: Evaporation Pond 1 liner leak
- Aug. 22, 2019: Monitor well excursion
- July 11, 2019: Production well fails 5-year mechanical integrity test
- June 24, 2019: Production well fails 5-year mechanical integrity test
- June 5, 2019: Monitor well excursion
- May 29, 2019: Evaporation Pond 1 liner leak
- May 2, 2019: Monitor well excursion
- Apr. 18, 2019: Monitor well excursion
- Apr. 9, 2019: Monitor well excursion
- Mar. 27, 2019: Monitor well excursion
- Mar. 25, 2019: Monitor well excursion
- Nov. 28, 2018: Monitor well excursion
- June 1, 2018: Monitor well excursion
- Sep. 12, 2017: 27,287 gallon spill of injection solution
- Aug. 29, 2017: Monitor well excursion
- July 27, 2017: Production well fails 5-year mechanical integrity test

- Mar. 14, 2017: Injection well fails 5-year mechanical integrity test
- June 8, 2016: Evaporation Pond 1 liner leak
- May 5, 2016: two Monitor well excursions
- Apr. 21, 2016: Monitor well excursion
- Apr. 20, 2016: Injection well fails 5-year mechanical integrity test
- Nov. 19, 2015: Monitor well excursion
- Oct. 27, 2015: Monitor well excursion
- Aug. 17, 2015: Injection well fails 5-year mechanical integrity test
- Aug. 13, 2015: Monitor well excursion
- July 9, 2015: Monitor well excursion
- July 2, 2015: Injection well fails 5-year mechanical integrity test
- June 3, 2015: Monitor well excursion
- May 28, 2015: Monitor well excursion
- May 27, 2015: Monitor well excursion
- May 21, 2015: Monitor well excursions
- May 19, 2015: Monitor well excursion
- Apr. 14, 2015: Monitor well excursion
- Feb. 11, 2015: Monitor well excursion
- July 22, 2014: Monitor well excursion
- July 2, 2014: Failure to sample the underdrains of a leaking pond and to submit a corrective action plan
- May 20, 2014: Monitor well excursion
- May 8, 2014: Monitor well excursion
- May 7, 2014: Evaporation Pond 1 liner leak
- Dec. 10, 2013: Monitor well excursion
- Sep. 11, 2013: Monitor well excursion
- Aug. 22, 2013: Well fails 5-year mechanical integrity test
- Aug. 6, 2013: Well fails 15-year mechanical integrity test
- Jun. 5, 2013: Radiation dose in unrestricted area exceeds 0.02 mSv/h standard
- Mar. 14, 2013: Evaporation Pond 1 liner leak
- Jan. 18, 2013: Well fails mechanical integrity test
- Oct. 24, 2012: Well fails 20-year mechanical integrity test
- Aug. 20, 2012: Well fails 5-year mechanical integrity test
- June 4, 2012: Well fails 5-year mechanical integrity test
- May 25, 2012: Monitor well fails 15-year mechanical integrity test
- Oct. 7, 2011: Monitor well excursion
- Aug. 9, 2011: Exceedance of Well Head Manifold Pressure Limitations
- July 18, 2011: two wells fail 5-year mechanical integrity test
- June 1, 2011: Evaporation Pond 1 liner leak
- May 27, 2011: two Monitor well excursions
- May 24, 2011: Monitor well excursion
- Mar. 16, 2011: Monitor well excursion
- Jan. 13, 2011: Monitor well excursion
- July 8, 2010: Monitor well excursion
- July 6, 2010: Well fails 5-year mechanical integrity test
- June 22, 2010: Excursions at two monitor wells "due to increased groundwater levels"
- June 22, 2010: Monitor well excursion
- June 16, 2010: Excursions at three monitor wells "due to increased groundwater levels"
- June 11, 2010: Evaporation Pond 3 liner leak detected
- May 10, 2010: Well fails 5-year mechanical integrity test
- Apr. 13, 2010: Excursion at monitor well due to "natural conditions"
- Dec. 31, 2009: Evaporation Pond 4 Liner Leak
- Nov. 19, 2009: Well fails 15-year mechanical integrity test

- Oct. 15, 2009: Mechanical integrity test missed for two wells
- June 18, 2009: Evaporation Pond 4 liner leak detected
- June 11, 2009: Monitor well excursion
- June 5, 2009: Evaporation Pond 1 liner leak detected
- April 27, 2009: Monitor well placed on excursion status
- April 17, 2009: Production well fails 5-year mechanical integrity test
- June 4, 2008: Exceedance of Well Head Manifold Pressure Limitations
- May 31, 2008: Monitor well placed on excursion status
- May 23, 2008: [\\$50,000 penalty imposed for violations](#)
- May 19, 2008: Monitor well placed on excursion status
- April 29, 2008: Five-year mechanical integrity test missed for 42 wells
- September 26, 2006: Monitor well placed on excursion status
- May 5, 2006: leak detected at Pond 4
- January 19, 2006: Monitor well placed on excursion status
- October 27, 2005: Injection well leak detected
- August 4, 2005: Monitor well placed on excursion status
- June 28, 2005: Monitor well placed on excursion status
- June 17, 2005: Monitor well placed on excursion status
- May 2, 2005: Monitor well placed on excursion status
- May 14, 2004: leak detected at Pond 1
- December 23, 2003: Monitor well placed on excursion status
- December 26, 2002: Monitor well placed on excursion status
- September 10, 2002: Monitor well placed on excursion status
- April 4, 2002: Monitor well placed on excursion status
- December 4, 2001: Monitor well placed on excursion status
- March 2, 2001: Monitor well placed on excursion status
- September 10, 2000: Monitor well placed on excursion status
- May 26, 2000: Monitor well placed on excursion status
- April 27, 2000: Monitor well placed on excursion status
- March 6, 2000: Monitor well placed on excursion status
- July 2, 1999: Monitor well placed on excursion status
- August 7, 1998: Spill of 10,260 gallons of injection fluid
- March 21, 1998: Monitor well placed on excursion status
- August 12, 1997: Discovery of Pinhole Leaks in Upper Liner of Process Water Evaporation Pond

(details on post-Nov.1,1999, events available through [ADAMS](#) , Docket No. [04008943](#) )

New Mexico

- [Mt. Taylor](#)

> See also Issues for: [New Mining Projects](#) · [Decommissioning Projects](#) · [Legislation & Regulations](#)

> See also Data for: [Deposits, Proposed and Active Mines](#) · [Old Mines and Decommissioning](#)

Mt. Taylor mine, Cibola County

Mine Permit No. CI002RE

> View [deposit info](#)

> View [Mine Applications, Regular Existing: Mount Taylor Mine](#)  (NM EMNRD)

> View [more recent issues](#)

Company abandons plan for reactivation of Mt. Taylor uranium mine: In a stunning victory for Native communities, Rio Grande Resources (RGR), owner of the Mt. Taylor uranium mine, notified the Mining and Minerals Division (MMD) of the New Mexico Energy, Minerals and Natural Resources Department of "cessation of mining operations" and RGR's intention "to begin closure plan activity."

RGR had been granted Return to Active status under their permit Dec. 29, 2017. The mine had been in Standby status since 1999.

MASE and Amigos Bravos appealed the permit revision. After hearings May 5, 2018, the Mining Commission issued their Final Order Aug 1, 2018, upholding the Return to Active status. The two organizations then appealed that ruling to the First Judicial District Court in Santa Fe; when that court upheld the Mining Commission decision, the groups appealed to the State Court of Appeals, where the case is currently located. According to RGR, "From initiation of the closeout contracting process to completion of the closeout activities on site is estimated to take about 16 months. The first 5-6 months would be taken up by project management and contractor procurement, followed by 9-10 months of actual construction activities on site from mobilization through demobilization." (Los Alamos Daily Post Jan. 4, 2020)

New Mexico Mining Commission holds meeting and hearing on petition against permit for reactivation of Mt. Taylor uranium mine - petition denied: The New Mexico Mining Commission will hold a regular meeting and a public hearing at 9:00 AM, Monday, May 7, 2018 (and Tuesday, May 8, if necessary). During the meeting, the Mining Commission will conduct a public hearing on Petition 18-01 - In the Matter of the Petition for Review of the Director's Action, dated December 29, 2017, Permit Revision 13-2 to Permit No. CI002RE, filed by [The Multicultural Alliance for a Safe Environment](#) and [Amigos Bravos](#) on February 28, 2018. Petitioners request a review of the Mining and Minerals Division Director's decision to grant Rio Grande Resources' application for a permit revision allowing the Mt. Taylor Mine to return to "active" or "operational" status.

Intervenors and interested participants desiring to present evidence shall submit a written notice of intent to do so to the Commission not later than 5:00 PM, Friday, April 27, 2018.

> Access: [Mining Commission - Meetings and Hearings](#)

> Download: [Notice of Public Meeting and Hearing of the New Mexico Mining Commission](#), Mar. 27, 2018 (41kB PDF)

> Download: [Petition](#), Feb. 28, 2018 (3.5MB PDF)

On July 27, 2018, the New Mexico Mining Commission denied the petition.

> Download: [Final Decision and Order](#) (826kB PDF)

The Gallup Independent reports the Multicultural Alliance for a Safe Environment and Amigos Bravos have asked the New Mexico Court of Appeals to review a lower court ruling that upheld the New Mexico Mining Commission's decision to permit the Mount Taylor Mine to return to active status. (AP Sep. 4, 2019)

Environmental groups fight against state permit for reactivation of Mt. Taylor uranium mine:

Environmentalists are seeking to keep an idle uranium mine in western New Mexico from becoming active again, saying the designation will allow it to delay cleanup.

The Multicultural Alliance for a Safe Environment and Amigos Bravos are asking the New Mexico Mining Commission to review a recent decision by state Mining and Minerals Division Director Fernando Martinez to allow the Mount Taylor mine to return to "active," or operational, status, the Gallup Independent reports. The groups say there is no realistic likelihood that mining will take place for the foreseeable future. "The director's decision directly contradicts the New Mexico Mining Act's plain language, which restricts 'operational' mines to those that are producing minerals," said Eric Jantz, staff attorney at the New Mexico Environmental Law Center, which is representing the groups. "The director has unilaterally created an entirely new category of mine activity - 'zombie mines' - that have been given new life in an effort to avoid cleanup." The Mount Taylor Mine has been on standby status for more than 20 years. Its owner, Rio Grande Resources,

announced in 2014 that it planned to ask regulators to change the status to active. (Albuquerque Journal Mar. 19, 2018)

State issues permit for reactivation of Mt. Taylor uranium mine: On Nov. 22, 2017, Rio Grande Resources notified NRC that the New Mexico Environment Department (NMED) issued a mine active permit the same day, and that the company plans to submit the application for a uranium mill in the fourth quarter of 2022.

State announces hearing on proposed reactivation of Mt. Taylor uranium mine after 25 years of inactivity: The New Mexico Energy, Minerals and Natural Resources Department, Mining and Minerals Division ("MMD") hereby gives notice of a public hearing on the application by Rio Grande Resources Corporation, the operator of the Mount Taylor Mine, for changing the status of the mine from standby to active, and update the closeout plan and required amount of financial assurance under Revision Application 13-2. The public hearing is scheduled for Friday, December 4, 2015 at 10:00 AM.

Submit comments by January 4, 2016 (Comment period extended).

> Download [Public Hearing Notice](#) , Oct. 22, 2015 (PDF - MMD)

> Download [Revision 13-2 related documents](#)  (MMD)

Discharge Permit renewal and modification for Mt. Taylor uranium mine: The New Mexico Environment Department (NMED) issued a draft Discharge Permit renewal and modification (Discharge Permit) to Rio Grande Resources Corporation for the Mt. Taylor uranium mine.

Submit written comments or request public hearing within 30 days from June 27, 2014.

> Download: [Public Notice](#)  (PDF - NMED)




> Download: [DRAFT Discharge Permit DP-61 Renewal and Modification](#)  (655k PDF - NMED)

Court orders new hearing in Mt. Taylor uranium mine permit: In a hearing this morning, state District Court Judge Raymond Ortiz handed a victory to community groups in a case concerning Rio Grande Resources' Mount Taylor uranium mine near Grants. In a ruling from the bench, he agreed that the New Mexico Mining and Minerals Division (MMD) failed to provide the public with meaningful opportunities to participate in the process to renew the mine's standby mining permit.

He focused on three issues:

- The agency failed to allow MASE and Amigos Bravos to raise concerns about environmental safeguards, namely the protection of water from contamination by the mine.
- The agency wrongly declared the company's entire economic viability report off-limits to any member of the public, although the report was an important factor in the permitting decision.
- The agency wrongly issued the permit before considering whether or not the financial assurance (reclamation bond) was adequate, and without letting the public provide input on the bond.


(NMELC July 22, 2013)

Group seeks public hearing over proposed reactivation of Mt. Taylor uranium mine after 23 years of inactivity: Today, the [New Mexico Environmental Law Center](#)  (NMELC) filed a request for a public hearing regarding a proposed permit revision to put the Mt. Taylor uranium mine on active status. The mine, near Grants, NM, has been inactive (on "standby" status) without cleanup for 23 years. The mine's owner, [Rio Grande Resources](#), received a fourth renewal for the standby permit in January 2012, but on April 12, 2013 it notified the public it was seeking a revision to change the mine's status to "active". The NMELC filed the hearing request on behalf of its clients, [Amigos Bravos](#)  and the [Multicultural Alliance for a Safe Environment](#)  (MASE). (NMELC May 10, 2013)

Mine agency to take input on renewal of standby permit requested for Mount Taylor uranium mine:


The New Mexico Mining and Minerals Division has set a public hearing for Rio Grande Resources Corporation's application to renew "Standby Status" for its Mount Taylor Mine on Wednesday, Aug. 17, at 5 p.m. in the Cibola County Convention Center.

A standby permit allows the mine operator to let the mine remain inactive without having to do any clean up.

The permit lasts for five years. The Mount Taylor mine is located one mile northeast of San Mateo. The mine is an existing underground uranium mine that extracted uranium ore from depths of more than 3,000 feet below ground surface using room-and-pillar and stope mining methods. Uranium ore was produced from the mine from 1979 to 1982 and from 1985 to 1990. The mine has been inactive since January 1990. A copy of Rio Grande Resources' application for the renewal of Standby Status is available at the Mother Whiteside Memorial Library and in Santa Fe at the Mining and Minerals Division's office. These documents are also available for viewing on the [MMD website](#) . (Cibola Beacon Aug. 15, 2011)

Rio Grande Resources Corporation (RGR) submitted a Standby Status Renewal Application for its Mt. Taylor Mine. The mine is an existing uranium mining operation using underground mining techniques to extract uranium ore from depths of over 3000 feet below ground surface using room-and-pillar and stope mining methods. There are no milling facilities within the proposed Standby area. The Mine has been inactive since January 1990 until the present.

> View [Standby Status Application](#)  (NM EMNRD)

A groundwater discharge permit is being sought for Mount Taylor Uranium Mine and Mill owned by [Rio Grande Resources](#), according to the [New Mexico Environment Department](#) . Gerald Schoeppner of NMED's Groundwater Quality Bureau said Wednesday that the company has an existing discharge plan for its mine that it's trying to renew, "but that's one of the pieces of the puzzle that's missing - how they're planning to treat their mine water for the dewatering to meet standards."

The Mount Taylor mine previously was a conventional mining operation "and they plan to operate it as a conventional mine in the future," Schoeppner said. The mine site is located just outside the 8,000 foot elevation boundary established in the June 2008 emergency designation of Mount Taylor as a Traditional Cultural Property.

Rio Grande Resources controls uranium operations and mineral resources acquired by General Atomics from Chevron Resources in 1991. The Mount Taylor project, a conventional underground mine, contains the largest uranium resource in the United States and is currently on standby, according to the company's Web site. Chevron began commercial production at Mount Taylor in 1986, initially shipping the ore to its Panna Maria mill in south Texas for processing. The mine was placed on standby in 1989. (Gallup Independent Feb. 19, 2009)

> Download [NMED Public Notice Feb. 13, 2009](#)  (PDF)

> See also: [Cotter aims to reopen Cañon City \(Colorado\) uranium mill in 2014 to process ores from Mt Taylor mine \(New Mexico\)](#)

Texas

- [Alta Mesa ISL](#)
- [Hobson ISL](#)
- [Kingsville Dome ISL](#)
- [Mesteña Grande ISL](#)
- [Palangana](#)
- [Rosita ISL](#)
- [South Texas ISL](#)
- [Vasquez ISL](#)

> See also Issues for: [New Mining Projects](#) · [Decommissioning Projects](#) · [Legislation & Regulations](#)

> See also Data for: [Deposits, Proposed and Active Mines](#) · [Old Mines and Decommissioning](#)

Uranium mining in South Texas is opposed by [South Texas Opposes Pollution \(STOP\)](#) .

Alta Mesa ISL, Brooks County

> View [deposit details](#)

Preliminary Economic Assessment released for enCore Energy's Alta Mesa in situ leach uranium project

On Feb. 27, 2025, [enCore Energy Corp.](#) released a Preliminary Economic Assessment (PEA) for its Alta Mesa in situ leach uranium project.

> Calculate [Mine Feasibility](#)

Preliminary Economic Assessment released for enCore Energy's Mesteña Grande in situ leach uranium project

On Feb. 27, 2025, [enCore Energy Corp.](#) released a Preliminary Economic Assessment (PEA) for its Mesteña Grande in situ leach uranium project.

> Calculate [Mine Feasibility](#)

Uranium production resumes at Alta Mesa in situ leach mine

On June 13, 2024, enCore Energy Corp. announced the successful startup of production at the Alta Mesa Uranium Central Processing Plant and Wellfield.

Uranium production at Alta Mesa in situ leach mine to be resumed in 2024

On Mar. 15, 2023, [enCore Energy Corp.](#) announced that it has made a formal production decision for the resumption of uranium production from the Alta Mesa Processing Plant in early 2024. Alta Mesa will be enCore's second producing location following resumption of uranium production at the South Texas [Rosita Uranium Processing Plant](#) scheduled for 2023.

TCEQ amends and renews permits for deep disposal wells at Alta Mesa in situ leach uranium mine

> Download: [Permit No. WDW365 \(major amendment\)](#), [WDW366 \(renewal\)](#), March 11, 2022 (329kB - TCEQ)

TCEQ approves groundwater restoration performed at Production Area 1 of Alta Mesa in situ leach uranium mine

On Mar 29, 2018, Energy Fuels Inc. announced that it has achieved a major environmental milestone at its Alta Mesa Uranium Project in Texas. On March 16, 2018, the Company received a notice from the Texas Commission on Environmental Quality ("TCEQ") confirming that the Company accomplished final groundwater restoration at Production Area 1 ("PAA1"). Now that TCEQ has deemed wellfield restoration complete, the Company can proceed to well plugging and final closure of PAA1, including a reduction of the reclamation bond on the project and the return of restricted cash.

"Unplanned" fire at Alta Mesa in situ leach uranium mine

"A fire occurred within the Mestena Uranium LLC License Area in the vicinity of PAA-3 on August 9, 2016. The fire was discovered at approximately 1545 CDT by US Border Patrol agents who were conducting activities in the vicinity. Mestena personnel discovered the fire at about the same and upon investigation determined the fire required additional support at which time the local fire department was notified and arrived on site at approximately 1620 CDT to battle the fire.

Fire crews declared the fire out/controlled by 2000 [CDT]. No injuries occurred during the firefighting activities. [...]

The fire burned approximately 60 acres, most of which was within the PAA-3 Mine Area. The fire damaged or destroyed surface infrastructure associated with the in-situ mining activities permitted under UIC permit UR03060PA3. [...]"

([Event Notification Report for August 19, 2016](#) , U.S. NRC)

Mesteña Uranium LLC cited for well plugging deficiencies at exploration wells

On Nov. 23, 2010, the Railroad Commission (RRC) of Texas sent a Deficiency Letter to Mesteña Uranium LLC regarding a Well Plugging Affidavit for Uranium Exploration Permit 125B-1. (Texas RRC Nov. 29, 2010)

TCEQ issues Agreed Order over penalty of \$2,000 to Mesteña Uranium LLC

Texas Commission on Environmental Quality: Enforcement Orders:

An agreed order was entered regarding Mesteña Uranium, L.L.C., Docket No. 2007-1010-UIC-E on December 20, 2007 assessing \$2,000 in administrative penalties with \$400 deferred. (Texas Register, January 18, 2008, Volume 33 Number 3, Pages 449-634, In Addition)

TCEQ issues Agreed Order over penalty of \$2,000 to Mesteña Uranium LLC

Texas Commission on Environmental Quality issues Agreed Order over penalty of \$2,000 to [Mesteña Uranium LLC](#) for failing to secure acceptable financial assurance. (Texas Register, September 21, 2007, Volume 32 Number 38, Pages 6451-6688, In Addition)

> See [older issues](#)

Hobson In Situ Leach mine, Karnes County (Texas)

NRC Docket No. [04008747](#) 

> View [deposit details](#)

> View [decommissioning issues](#)

License renewal for Hobson In Situ Leach processing plant at four-fold capacity

On Nov. 17, 2022, Uranium Energy Corp announced that the Texas Commission on Environmental Quality ("TCEQ") has approved the company's submission for a renewed and expanded radioactive material license ("RML") for its Hobson Central Processing Plant.

UEC's amended RML from the TCEQ increases the Hobson Processing Plant's licensed production capacity to 4 million pounds of U₃O₈ [1,538 t U] annually.


Texas Commission on Environmental Quality proposes Agreed Order imposing \$11,581 penalty on multiple violations at Hobson uranium in situ leach mine

COMPANY: South Texas Mining Venture L.L.P. dba Hobson Mining Project; [...]

RULES VIOLATED: 30 TAC §305.125(1) and §331.67(a)(1)(B), 40 Code of Federal Regulations §146.67(f), and Underground Injection Control (UIC) Permit Number Waste Disposal Well (WDW) 168, Permit Provision (PP) IX.

Recordkeeping Requirements, **by failing to keep complete and accurate records of all monitoring according to permit requirements**; 30 TAC §331.4 and §331.64(d)(4)(A) and UIC Permit Number WDW168, PP VII.F, Operating Parameters, **by failing to cease injection of waste fluids when monitoring indicates a loss of mechanical integrity has been detected**; and 30 TAC §331.64(g) and UIC Permit Number WDW168, PP VIII.H, Monitoring and Testing Requirements, **by failing to conduct corrosion monitoring of well materials on a quarterly basis**;
PENALTY: \$11,581; [..., emphasis added]

Submit comments by May 4, 2020.

> View: [Texas Register, April 3, 2020, Volume 45, Number 14, In Addition: Texas Commission on Environmental Quality, Agreed Orders](#) 

Hobson plant starts processing of uranium-loaded resins from Palangana in situ leach mine

On Dec. 1, 2010, Uranium Energy Corp announced that it has started the processing of the first shipment of uranium-loaded resins at its Hobson processing plant. This shipment and the start of processing follows the Company's announcement on November 17, 2010 of the initial in-situ recovery (ISR) of uranium at Palangana in South Texas.

> See also [Palangana ISL mine](#)

TCEQ invites public comment or request for public meeting about proposed license transfer for Hobson, Tex-1, and Mt Lucas mines

The Texas Commission on Environmental Quality (TCEQ) invites public comment or request for public meeting about the proposed license transfer for the Hobson, Tex-1, and Mt. Lucas mines from Everest Exploration to South Texas Mining Venture L.L.P.

All written public comments and requests must be submitted within 30 days from the date of newspaper publication of this notice.

> View TCEQ notice: [Texas Register, May 28, 2010, Volume 35 Number 22, Pages 4275-4526, In-addition](#) 

> View TCEQ notice: [Texas Register, June 4, 2010, Volume 35 Number 23, Pages 4527-4766, In-addition](#) 

License renewal for Hobson In Situ Leach processing plant (Texas)

On December 22, 2006, Everest Exploration, Inc. submitted on behalf of South Texas Mining Venture, LLP, an application for renewal of the Hobson Facility Radioactive Material Handling License to the Texas Department of State Health Services. This renewal application allows the Hobson Facility to continue operations as a uranium processing facility and provides the regulatory authorities with necessary information concerning the company's plans to increase the facility's processing capacity to over 1,000,000 pounds of U₃O₈ (385 t U) per year. (Energy Metals Corporation April 4, 2007)

License Renewal for Everest Exploration Hobson In Situ Leach mine (Texas)

"[Everest Exploration](#) for renewal of an Underground Injection Control (UIC) Well, Permit No. WDW-168. The Executive Director has prepared a draft permit.

The applicant currently operates an in-situ uranium mine. Wastes generated on-site are non-hazardous. The injected wastes include: barren solution bleed, restoration waste stream, process waste streams, and tailings or wastes produced by or resulting from the extraction or concentration of uranium, other associated wastes such as ground water and rainfall contaminated by the above authorized wastes, spills of the above authorized wastes, and wash waters and solutions used in cleaning and servicing the waste disposal well system equipment which are compatible with the permitted waste streams, reservoir and well materials. WDW-168 was initially put in service in

1979. The facility is located 0.5 mile southwest of [Hobson](#) on Farm-Market Road 81, Karnes County, Texas.

SIGNED MAY 7, 1999" ([TNRCC Items Signed by Executive Director 7 May 1999](#) )

Palangana in-situ leach mine, Duval County (Texas)

> View [deposit info](#)

Palangana uranium in situ leach mine obtains state authorization for operation of fourth Production Area: On May 27, 2015, Uranium Energy Corp announced that the Palangana ISR Mine has received the required permits, and is now fully permitted for extraction in new resource areas with a larger Mine Permit and Aquifer Exemption. The expanded mine area boundary is now 8,722 acres versus 6,200 acres previously and includes Production Area-4.

Production of Palangana in situ leach mine reduced in response to low uranium prices: [Uranium Energy Corp.](#) is cutting production as prices trade at a seven-year low. Uranium Energy will reduce output at its Palangana mine so the project just breaks even, the Vancouver-based company said in a statement today. The savings will be used to develop the company's larger [Goliad](#) and [Burke Hollow](#) projects. (Business Week Sep. 5, 2013)

Palangana uranium in situ leach mine obtains state authorization for operation of third Production Area: On Dec. 7, 2012, Uranium Energy Corp announced the receipt of a Production Area Authorization from the Texas Commission on Environmental Quality, allowing for the commencement of operations at Production Area-3 of the Company's Palangana Mine located in South Texas. With wellfields and well control facilities in place already, operations at Production Area-3 has commenced while operations at Production Areas 1 and 2 are ongoing.

> View [older issues](#)

Vasquez in-situ leach mine, Duval County (Texas)

> View [deposit details](#)

> See [more recent issues](#)

TCEQ approves license renewal for Vasquez in situ leach processing plant

On Nov. 6, 2023, enCore Energy Corp. announced the approval of the renewal of the Radioactive Materials License for enCore's In-Situ Recovery Uranium Central Processing Plant at its Vasquez uranium project.

Vasquez ISL mine shut down

During the fourth quarter of 2008, URI shut down the last wellfield at Vasquez. (URI March 11, 2009)

Vasquez ISL mine production below expectations

"Production costs for the third quarter of 2006 were \$56.92 per pound compared with \$23.57 per pound in the prior year's third quarter. The higher production costs were primarily due to higher capital and operating costs compared with the prior year and also due to the change in the estimated recovery factor of for the Vasquez project from 70% to 50%."

"The Vasquez project has provided significant technical challenges since its inception in 2004 due to the unique

geochemical composition of its ore body and the degree of re-reduction found in the uranium deposited within the formation. When uranium has been "re-reduced" it has in nature been oxidized, reduced and then subjected to additional reductants which results in the uranium being less accepting of oxidation for extraction. These factors have contributed to our production costs at Vasquez rising from \$20.32 per pound in 2005 to over \$46.00 per pound in 2006."

"Our third quarter production consisted of 26,074 pounds [10 t U] from our Vasquez project [...]. Last year's third quarter production of 65,797 pounds [25.3 t U] was produced completely from the Vasquez project. As discussed, given the challenges at this property, its level of production has measurably declined and was below expectations." (URI Nov. 14, 2006)

"[...] Vasquez has continued to operate below expectations. At the beginning of the project in 2004, our mining plan indicated we could produce the [Vasquez](#) property at an annual rate of 700,000 pounds [269 t U]. The geological and chemical problems we experienced in 2005 caused us to revise that estimate downward to an annual capacity of 400,000 pounds [154 t U]. [...]" (URI Sep. 19, 2006)

> See [older issues](#)

Kingsville Dome and Rosita in-situ leach mines, Kleberg County (Texas)

> View deposit data: [Kingsville Dome](#) · [Rosita](#)

> View [decommissioning issues Kingsville Dome](#)

TCEQ approves inclusion of Upper Spring Creek in-situ leach uranium project in Rosita permit

On May 29, 2025, enCore Energy Corp. announced the approval for the inclusion of the Upper Spring Creek In-Situ Recovery ("ISR") Uranium Project in the existing Radioactive Materials License ("RML") from the TCEQ (Texas Commission on Environmental Quality). The current RML includes the Rosita Uranium Project, which has now been extended to cover the Upper Spring Creek Project's Brown Area.

Preliminary Economic Assessment released for enCore Energy's South Texas in situ leach uranium mine project

On Feb. 27, 2025, [enCore Energy Corp.](#) released a Preliminary Economic Assessment for its South Texas in situ leach uranium mine project, including the Upper Spring Creek - Brevard Area and Brown Area, Rosita South - Cadena deposits.

Due to insufficient data, a data set for the [Mine Feasibility Calculator](#) cannot be provided.

Production restarts at Rosita in situ leach uranium mine

On Nov. 30, 2023, enCore Energy Corp. announced the successful startup of uranium production from the South Texas Rosita ISR Uranium Central Processing Plant. The wellfield production patterns are operating, oxygenated water is now circulating through the satellite ion exchange facility and being injected back into the uranium ore body.

On March 5, 2024, enCore Energy Corp. announced the first shipment of uranium from the Rosita Central Processing Plant to be followed by the first sales delivery.

TCEQ approves license renewal for Rosita and Kingsville Dome in situ leach processing plants

On Nov. 6, 2023, enCore Energy Corp. announced the approval of the renewal of the Radioactive Materials License for enCore's In-Situ Recovery Uranium Central Processing Plants at its Rosita and Kingsville Dome uranium projects.

Commissioning starts for refurbished Central Processing Plant at Rosita in situ leach uranium mine

On Nov. 1, 2022, enCore Energy Corp. announced the full completion of refurbishment of its 100% owned Rosita Central Uranium Processing Plant, a licensed, past producing In-Situ Recovery (ISR) uranium plant located approximately 60 miles from Corpus Christi, Texas.

The plant will be undergoing wet commissioning during the remainder of 2022 to be ready for operations in 2023. The Rosita Plant is designed to process uranium feed from multiple satellite operations, all located in the South Texas area.

Rosita uranium ISL Central Processing Plant modernization ongoing

The Rosita Central Processing Plant modernization commenced in July 2021 with a projected budget of less than US\$1 million. Work activities are now 50% complete, on schedule and on budget. Recent major equipment work includes the yellowcake filter press relocation and installation, completion of the ion exchange resin elution and the yellowcake dryer circuits.

[enCore Energy is] targeting completion of the Rosita upgrades by the end of the second quarter 2022 and wellfield commissioning in the first half of 2023 with projects on schedule and on budget. (enCore Energy Corp. Nov. 23, 2021)

Texas Commission on Environmental Quality grants hearing on proposed license renewal and amendment for deep disposal well at Kingsville Dome uranium in situ leach mine

> Download: [TCEQ Marked Agenda April 27, 2018](#)  (PDF - View Item 1)

> Download: [Docket No. 2018-0319-WDW](#) 


State regulator orders US\$ 21,177 penalty with \$4,235 deferred for violations in connection with disposal well at Kingsville Dome uranium in situ leach mine

On Dec. 19, 2016, the Texas Commission on Environmental Quality filed an agreed order to Uranium Resources, Inc., for six violations noted in connection with an underground injection waste disposal well at its Kingsville Dome uranium in situ leach mine. The violations include in particular "failing to maintain annulus pressure of at least 100 pounds per square inch greater than the injection tubing pressure to prevent leaks from the well into unauthorized zones and to detect well malfunctions", among others. The penalty amounts to US\$ 21,177.

> View: [Texas Register, December 30, 2016, Volume 41 Number 53, Pages 10487-10720, In Addition](#) 

On Apr. 4, 2018, the Texas Commission on Environmental Quality adopted an agreed order regarding Uranium Resources, Inc., Docket No. 2016-1222-WDW-E on April 4, 2018, assessing \$21,177 in administrative penalties with \$4,235 deferred.

> View: [Texas Register, April 13, 2018, Volume 43 Number 15, Pages 2205-2314, In Addition](#) 

> Download: [Docket No. 2016-1222-WDW-E](#)  (2.6MB PDF)

Texas Commission on Environmental Quality grants hearing on proposed license renewal and amendment for Kingsville Dome uranium in situ leach mine

On Oct. 7, 2015, the Texas Commission on Environmental Quality (TCEQ) granted the hearing requests of local residents regarding URI's application for renewal and major amendment of the permit for its Kingsville Dome uranium in situ leach mine.

> Download [TCEQ Marked Agenda Oct. 7, 2015 \(84k PDF\)](#) (see Item 4)

> Download [TCEQ Docket No. 2015-1268-UIC](#) (43k PDF file containing download links to actual documents)

The hearing will be held on March 3, 2016, in Kingsville, Texas.

> Download [Notice of Hearing](#), Jan. 26, 2016 (48k PDF)

However, on June 15, 2016, URI requested to withdraw the applications to renew and amend the permit.

> See also: [URI lets license for Kingsville Dome uranium in situ leach mine expire](#)

Elevated uranium concentrations found in off-site domestic well near Kingsville Dome in situ leach uranium mine

"[...] The bleed at PA-3 [production area three] did not contain the increased pressures caused by injection of leaching fluids. A hydraulic gradient was rapidly established between the injection wells and the mine boundary, as shown by a rise in water levels in monitor wells surrounding PA-3. This gradient drove mining solution beyond the mine boundary. These excursions affected a well on the Garcia property, approximately 300 m down gradient of the mine. Since mining began, uranium concentrations in the Garcia well have increased from less than 200 µg/L, to more than 600 µg/L.

This is the first time that contaminants in an off-site domestic well have been linked to ISL uranium mining in the United States of America."

Excursions of Mining Solution at the Kingsville Dome In-situ Leach Uranium Mine, by George Rice, in: [2012 - 2013 Austin Geological Society Bulletin, Volume 9](#) (3.9MB PDF), p. 18-34

Texas Commission on Environmental Quality invites comment on proposed approval of expansion of Rosita uranium in situ leach mine

URI, Inc. (URI) has applied to the Texas Commission on Environmental Quality (TCEQ) for an amendment to Radioactive Material License R03653. URI conducts recovery of uranium by the in situ leach methodology. This amendment authorizes URI to expand operations at their Rosita Project by authorizing an increase of the licensed area and authorizing an additional remote ion exchange unit in the added licensed area.

You may submit public comments or request a public meeting about this application. The TCEQ may grant a contested case hearing on this application if a written hearing request is timely submitted. All written public comments and requests must be submitted within 30 days from the date of newspaper publication of this notice.

> [Texas Register October 8, 2010, Volume 35 Number 41, Pages 9003-9166](#)

Whistleblower speaks out against methods once used by Uranium Resources Inc. at Kingsville Dome uranium in situ leach mine (Texas)

Roland Burrow worked as a wellfield operator for [Uranium Resources, Inc.](#), outside Kingsville, Texas a decade ago. He says the company at the time was regularly flushing high volumes of water into the mine field that would have expanded groundwater pollution beyond its permitted area, posing a potential future risk to the residents of Kingsville. He claims also to have witnessed the falsification of monitoring-well data, which must be regularly submitted to the state to show the contaminated water is contained at the mine site.

He tried unsuccessfully to get the TNRCC and FBI involved, and was fired. He moved a couple counties over, but now a URI offshoot wants to mine in his backyard (at [Goliad](#)), and he's decided to fight.

> Watch video [Uranium mining whistleblower](#) by *paleish*, Sep. 8, 2009 (Youtube)

Kingsville Dome ISL mine to shut down again

During the fourth quarter of 2008, URI shut down one operating wellfield at Kingsville Dome. The two Kingsville Dome wellfields that remained in production at December 31, 2008 are expected to be depleted by the end of the first quarter of 2009. In Kleberg County, the economic downturn is leading to a slowdown at a uranium plant that's been around for two decades. In fact, the company plans to shut down temporarily over the next month and start working on restoration. (URI Mar. 11, 2009)

The uranium mining plant opened up in 1988. Ever since then, critics have asked how the company plans to clean up. With a slow down expected soon, workers have started that process.

Word about the mining coming to end concerns opponents of the uranium mines. South Texas Opposing Pollution (STOP) leaders said these mines need to be cleaned up. "They have been in the process of cleaning up in the last 20 years," said Mark Walsh, a member of STOP. "They have not cleaned out any area yet; Area 1, 2 or 3." (KIII TV3 Jan. 27, 2009)

Startup of Rosita ISL mine delayed and shut down

On June 9, 2008, Uranium Resources, Inc. announced that there has been a delay in the startup of its Rosita wellfield as a result of a number of aquifer related technical issues.

On March 11, 2009, Uranium Resources, Inc. announced that the Rosita wellfield, which proved to be a technically challenging and therefore, higher cost operation, was shut-in during October, 2008, due to lack of economic feasibility in the current price environment.

Production starts from new wellfield at Kingsville Dome ISL mine

Uranium Resources, Inc. announced on July 19, 2007, that it started production at Wellfield 14 located on the Company's Kingsville Dome project in South Texas. The Company expects to produce 120,000 to 140,000 pounds U₃O₈ [46 to 54 t U] over a one-year period from this wellfield. Total production costs are projected to fall within the range of \$25 to \$30 per pound.

The Company plans to bring its next wellfield at Kingsville Dome online in the fourth quarter of this year. The new wellfield should also produce approximately 120,000 to 140,000 pounds U₃O₈ within a twelve-month period.

The Company produced a total of 109,000 pounds U₃O₈ [42 t U] during the first quarter, and 136,000 pounds U₃O₈ [52 t U] during the second quarter 2007.

Restart of Kingsville Dome and Rosita ISL mines delayed

"Delays in restarting production at Kingsville Dome and Rosita have continued. Kingsville was restarted in April 2006. We planned to bring on three new wellfields, one in August and two in September. Weather problems and a shortage of available drill rigs and logging trucks have pushed off the expected startup of these wellfields by at least one month. At Rosita, the shortage of drill rigs and logging trucks has delayed estimated production until the first quarter of 2007. The shortage of drill rigs and logging trucks is the result of intense industry-wide competition for exploration and development tools." (URI Sep. 19, 2006)

Study finds URI Inc failed to restore groundwater quality after in-situ leach mining at Kingsville Dome

Kleberg County Citizen Review Board contracted this study by Dr. George Rice in which he found that Uranium Resources, Inc failed to restore water quality after mining.

[Effects of URI's Kingsville Dome Mine on Groundwater Quality](#), Final Report, Prepared for the Kleberg County URI Citizen Review Board By George Rice, July 2006 (ALTURA)

License renewal for Kingsville Dome ISL mine

Hearing request granted on license renewal for waste disposal injection wells at Kingsville Dome ISL facility

On July 14, 2004, the Texas Commission on Environmental Quality granted the hearing requests by Eleuterio & Enedelia Saenz, Kleberg County and the STOP organization on the applications by URI, Inc., for renewal of permits for two Underground Injection Control wells, WDW-247 (this well has not been constructed) and WDW-248 (constructed), which authorize the continued disposal of industrial nonhazardous waste. The wells are located at the Kingsville Dome Uranium Mine in Kleberg County, approximately eight miles southeast of the City of Kingsville, five miles east of the City of Ricardo, east of Highway 77, and adjacent to Farm Road 1118.

(TEXAS COMMISSION ON ENVIRONMENTAL QUALITY, marked agenda, July 14, 2004)

Extension of Kingsville Dome ISL mine (3rd production area)

Texas regulator approves extension of Kingsville Dome ISL uranium mine

State regulators have given a uranium company the go-ahead to expand its mine near the small South Texas town of Ricardo, despite the protests of residents who say the operation is fouling the groundwater. The Texas Commission on Environmental Quality ruled on Feb. 22, 2006, that Dallas-based Uranium Resources Inc. could begin mining near the rural Kleberg County community. Commissioners even overruled a Texas administrative law judge who had recommended that the company only be allowed to open the new mine after it cleaned up the groundwater in two older mining areas. (San Antonio Express News Feb. 23, 2006)

> Download [Texas Commission on Environmental Quality Commissioners' Marked Agenda Feb. 22, 2006](#) (PDF)

Hearing request granted on application for third production area authorization for the Kingsville Dome Mine

On July 14, 2004, the Texas Commission on Environmental Quality granted the hearing requests by URI, Kleberg County and the STOP organization on the application by URI, Inc., for a third production area authorization for the Kingsville Dome Mine Site under existing Permit No. UR02827-001. The proposed production area authorization number is UR02827-031. The site is located in Kleberg County, approximately eight miles southeast of the City of Kingsville, five miles east of the City of Ricardo, east of Highway 77, and adjacent to Farm Road 1118. The authorization would allow injection into specified zones for the purpose of uranium production. The production zone is the Goliad formation at a depth of 420 feet to 810 feet. (TEXAS COMMISSION ON ENVIRONMENTAL QUALITY, marked agenda, July 14, 2004)

URI plans to resume mining at Kingsville Dome

During 2004, URI plans to continue actively working towards the completion of the permitting for the Kingsville Dome property. It is anticipated that this will be complete by early 2005 allowing the commencement of production at Kingsville Dome later that year. (URI March 23, 2004)

Kingsville Dome and Rosita ISL facilities to be placed on standby

In view of the depressed uranium market, [Uranium Resources, Inc.](#) announced that it plans to shut-in and place on stand-by its [Kingsville Dome](#) and [Rosita](#) in-situ leaching facilities in South Texas no later than the end of the first quarter of 1999. The Company will maintain certain activities at the Kingsville Dome and Rosita sites including the continuation of its ongoing restoration efforts. (URI release Nov. 16, 1998)

Kingsville Dome ISL license violations and reportable events

Uranium Spill - URI, Incorporated - Kingsville, Texas

"On January 24, 2000, the Licensee notified the Agency of a spill of 'bleed water' that occurred on October 26, 1999, when a feed line became disconnected from a main trunk line. A well field operator discovered a flange connection between a feed line and a main trunk line had separated resulting in a 2000 gallon (7.6 m³) spill. The area was on higher ground causing the water to flow down and collect in a low area inside the fenced property. The spill covered an area of approximately 4800 square feet (446 m²) and was contained onsite." [SUMMARY OF INCIDENTS FOR FORTH QUARTER 1999, Texas Department of Health, Bureau of Radiation Control]

Spill of Radioactive Material - URI, Inc. - Kingsville, Texas

"On June 1, 1999, the Licensee notified the Agency of a spill of approximately 9000 gallons (34 m³) of restoration water containing 2.7 parts per million of uranium. The spill was due to a disconnect in the flow line from the well to the disposal pond. All spilled water was contained on-site." [SUMMARY OF INCIDENTS FOR THIRD QUARTER 1999, Texas Department of Health, Bureau of Radiation Control]

Uranium Spill - URI, Inc. - Kingsville, Texas

"On January 22, 1998, the Licensee notified the Agency of a uranium spill involving 15,000 gallons" (57 m³) "of mine solution fluid containing 35 parts per million uranium that occurred on January 22, 1998. The spill occurred along an extraction line and was contained within the licensed area." [SUMMARY OF INCIDENTS FOR FIRST QUARTER 1998, Texas Department of Health, Bureau of Radiation Control]

Uranium Spill - URI - Kingsville, Texas

"On September 29, 1997, the Licensee notified the Agency of a uranium spill involving 5000 gallons" (19 m³) "of pregnant mine solution containing 81 parts per million uranium that occurred on September 29, 1997. The spill occurred along an extraction line and was contained within the licensed area." [SUMMARY OF INCIDENTS FOR FOURTH QUARTER 1997, Texas Department of Health, Bureau of Radiation Control]

Uranium Spill - URI - Kingsville, Texas

"On September 16, 1997, the Licensee notified the Agency of a uranium spill involving 3000 gallons" (11 m³) "of barren mine solution containing 6.7 parts per million uranium that occurred on September 16, 1997. The spill occurred at the end of a lateral line and was contained within the licensed area." [SUMMARY OF INCIDENTS FOR FOURTH QUARTER 1997, Texas Department of Health, Bureau of Radiation Control]

Rosita ISL license violations and reportable events

Uranium Spill - URI, Inc. - San Diego, Texas

"On December 17, 1997, the Licensee notified the Agency of a uranium spill involving 7000 gallons" (26 m³) "of pregnant solution that occurred on December 17, 1997. The spill occurred on the extraction side of a lateral line. The spill was contained and 2500 gallons were recovered and deposited in a disposal pond."
[SUMMARY OF INCIDENTS FOR FOURTH QUARTER 1997, Texas Department of Health, Bureau of Radiation Control]

Uranium Spill - URI, Inc. - San Diego, Texas

"On December 4, 1997, the Licensee notified the Agency of a uranium spill involving 7000 gallons" (26 m³) "of pregnant solution that occurred on December 4, 1997. The spill occurred on the extraction side of a lateral line. The spill was contained and 3500 gallons were recovered and deposited in a disposal pond."
[SUMMARY OF INCIDENTS FOR FOURTH QUARTER 1997, Texas Department of Health, Bureau of Radiation Control]

Uranium Spill - URI, Inc - San Diego, Texas

"On October 13, 1997, the Licensee notified the Agency of a uranium spill involving 6600 gallons" (25 m³) "of pregnant solution that occurred on October 13, 1997. The spill occurred from the extraction side of a line that was attached to a main trunk line to the plant. The spill was caused by improper fusion of two joints. The spill was contained within a licensed area."
[SUMMARY OF INCIDENTS FOR FOURTH QUARTER 1997, Texas Department of Health, Bureau of Radiation Control]

Uranium Spill - URI - San Diego, Texas

"On September 30, 1997, the Licensee notified the Agency of a uranium spill involving 5000 gallons" (19 m³) "of pregnated solution that occurred on September 30, 1997. The spill occurred at the injection side of a lateral line and covered approximately 400 square feet. The spill was contained and deposited in a disposal pond."
[SUMMARY OF INCIDENTS FOR FOURTH QUARTER 1997, Texas Department of Health, Bureau of Radiation Control]

Uranium Spill - URI - San Diego, Texas

"On September 1, 1997, the Licensee notified the Agency of a uranium spill involving 30,000 gallons" (114 m³) "of barren injection water containing 1.5 parts per million uranium that occurred on September 1, 1997. The spill occurred at a booster pump on the main barren trunk line covering approximately 1200 square feet."
[SUMMARY OF INCIDENTS FOR THIRD QUARTER 1997, Texas Department of Health, Bureau of Radiation Control]

> View older issues: [Kingsville Dome](#) · [Rosita](#)

Utah

- [Daneros mine](#)
- [La Sal Mines Complex \(Denison\)](#)
- [Pandora Mine](#)
- [Rim mine](#)
- [Velvet mine](#)


- [White Mesa mill](#) 

> See also Issues for: [New Mining Projects](#) · [Decommissioning Projects](#) · [Legislation & Regulations](#)

> See also Data for: [Deposits, Proposed and Active Mines](#) · [Old Mines and Decommissioning](#)

General

Southern Nevada Water Authority blames uranium mining near Moab for uranium in Colorado River

Southern Nevada's top water official is raising concerns about "measurable quantities" of uranium showing up in the Colorado River, the region's primary source for drinking water. [Southern Nevada Water Authority](#)  chief Pat Mulroy blames uranium mining, particularly near Moab. In a letter Monday to federal Interior Secretary Dirk Kempthorne, Mulroy urges the department to "carefully evaluate" the effect on water quality before authorizing new mining claims near the river. (Salt Lake Tribune June 20, 2008)

Velvet mine, San Juan County

> View [deposit info](#)

Utah DOGM issues tentative approval for construction of Velvet-Wood uranium mine

On Oct. 7, 2025, Anfield Energy Inc. announced that it has received the required approval from the Utah Department of Oil, Gas and Mining (DOGM) for Anfield to commence the advancement of the Company's Velvet-Wood uranium project in Utah to construction. The U.S. Department of the Interior ("DOI") had previously approved the environmental permit for Velvet-Wood as it was previously selected as part of the federal government's national response to the energy emergency declared by President Donald J. Trump. *[Anfield Energy Inc. failed to state that the approval issued on Oct. 2, 2025, is only tentative. The final approval will only be issued, once the surety bond has been received. No mining related disturbance may be created until the surety is received. In addition, the company must also have written acceptance from the Division as well as other applicable agencies.]*

> Download: [Tentative Approval](#) , Oct. 2, 2025 (PDF - DOGM)

> Access: [DOGM Mineral Permit Files](#) 

Protesters rally against reopening of Velvet-Wood uranium mine after fast-track approval

As high-desert winds swept through under a late-morning sun, a small group gathered Saturday (June 21) on public land east of Lisbon Valley in San Juan County to protest the reopening of the Velvet-Wood uranium mine -- Utah's first project approved under a federal fast-track process tied to a declared national energy emergency.

Demonstrators gathered in response to the Bureau of Land Management's approval of an environmental assessment completed just 11 days after the Interior Department ordered a fast-tracked review. (The Times-Independent June 21, 2025)

BLM approves Velvet-Wood uranium mine after "newly accelerated 14-day environmental review process"

On May 23, 2025, the U.S. Department of the Interior announced that it has greenlit the Velvet-Wood uranium and vanadium mine in San Juan County, Utah -- marking the nation's first project approved under a newly accelerated 14-day environmental review process, initiated in response to the national energy emergency declared by President Donald J. Trump.

[The approval was so fast-tracked that even Anfield Energy did not manage to announce it on its website the same day...]

BLM fast-tracks permitting of Velvet-Wood uranium mine

On May 12, 2025, the Department of the Interior announced the expedited permitting review of the Velvet-Wood mine in Utah under its newly established emergency procedures. As part of a strategic response to the national energy emergency declared by President Donald J. Trump on January 20, 2025, the project will undergo "an accelerated environmental review" by the Bureau of Land Management, with a completion timeline of 14 days.

> See also: [Projects added to the fast-track list](#)

Anfield Energy submits Velvet/Wood uranium mine plan of operations

> View: [Water Right Application](#) 

> View: [Velvet/Wood Notice of Intent](#)  (Search: Velvet or M0370040, Document Date 2024-04-29)

> View Plan of Operations (TBA)

Preliminary economic assessment announced for Velvet-Wood and Slick Rock uranium/vanadium mine projects

On March 30, 2023, Anfield Energy Inc. reported the results of a combined preliminary economic assessment ("PEA") for both its Utah-based Velvet-Wood Uranium and Vanadium Project and its Colorado-based Slick Rock Uranium and Vanadium Project. These two projects are located proximal to one another within the prolific Uravan Mineral Belt, and within close distance of the company's [Shootaring Canyon Mill](#) which will act as a centralized mineral processing facility in the PEA.

The PEA is based on a uranium price of US\$ 70 per pound, along with a vanadium price of US\$ 12 per pound. 36.5% of the total revenue is expected to come from the sale of vanadium.

> Calculate [Mine Feasibility](#)

Anfield Resources seeks discharge permit for Velvet uranium mine

Submit comments by Nov. 8, 2019.

> Access: [2019 Public Notices: Water Quality: Anfield Resources-Velvet Mine](#)  (UT DEQ)

Vanadium by-product recovery under consideration for idle Shootaring Canyon uranium mill

> View [here](#)

Positive Preliminary Economic Assessment announced for the Velvet-Wood uranium mine project, assuming uranium price more than doubles

On June 27, 2016, Anfield Resources Inc. reported the results of its Preliminary Economic Assessment ("PEA") with regard to the Velvet-Wood Uranium Project. Velvet-Wood, as discussed herein, consists of two mine areas, located in Lisbon Valley, Utah and the [Shootaring Canyon Uranium Mill](#), located in Ticaboo, Utah.

In the PEA, initial mineral processing will be via conventional vat or heap leaching methods conducted at Anfield's existing mineral processing facility, the Shootaring Mill, which lies approximately 180 miles from the Velvet-Wood mine area. Under this scenario, only those portions of the Shootaring Mill necessary for the final processing of pregnant leach solutions, from either a vat or heap leach facility, will be refurbished. The PEA assumes a uranium sales price of US\$ 65/lb U₃O₈, that is 2.5 times the current spot market price.

Preliminary Economic Assessment commissioned for the Velvet-Wood uranium mine project

On Feb. 10, 2015, [Anfield Resources Inc.](#) announced that it has engaged BRS, Inc. to complete a preliminary economic assessment for the Velvet-Wood Project.

Discharge permit renewal for idle Velvet uranium mine

Submit comments by close of business on June 30, 2014.

> View [Public Notice, May 28, 2014](#)  (Utah DEQ)

Rim mine, San Juan County

> View [deposit info](#)

Utah Division of Water Quality invites comment on proposed renewal of permit for water treatment plant at Energy Fuel's Rim mine

Public comments are invited any time prior to the deadline of the close of business on **June 25, 2016**.

> Download [Public Notice, May 23, 2016](#)  (PDF)

> Download [Fact Sheet Statement of Basis](#)  (PDF)

> Download [Wasteload Analysis](#)  (PDF)

> Download [Draft Permit](#)  (PDF)

Utah Division of Water Quality announces settlement agreement on violations at Energy Fuels' Rim mine

On June 26, 2013, Utah DEQ announced it has reached a settlement agreement with Energy Fuels Resources resolving alleged violations of the Utah Water Quality Act at the Rim mine. Energy Fuels agrees to pay a penalty of US\$ 1,167.

Public comments on the proposed settlement agreement are invited prior to close of business July 26, 2013.

> Download [Notice of Violation and Settlement Agreement, Docket No. I12-04](#) 

Utah Division of Water Quality invites comment on proposed renewal of permit for water treatment plant at Denison's Rim mine

Public comments are invited any time prior to the deadline of the close of business on May 27, 2011.



> Download [Public Notice, April 27, 2011](#)  (PDF)

> Download [Fact Sheet Statement of Basis](#)  (PDF)

> Download [Wasteload Analysis](#)  (PDF)

> Download [Draft Permit](#)  (PDF)

La Sal Mines Complex (Denison), San Juan County, Utah

- > View [deposit info](#)
- > Download [Utah OGM files](#) 
- > View [BLM Moab field office project site](#) 

General

Production restarts at Energy Fuels' La Sal uranium mine

On Dec. 21, 2023, Energy Fuels Inc. announced that, in response to strong uranium market conditions, it has commenced uranium production at its La Sal mine. Ore mined from the mine during 2024 will be stockpiled at the Company's [White Mesa Mill](#) for processing in 2025.

Utah approves La Sal Mines expansion and directs Energy Fuels to reclaim Snowball waste rock pile

On September 2, 2020, the Utah Division of Oil, Gas & Mining issued a "Conditional Approval of Amended Notice of Intention to Commence Large Mining Operations" for the La Sal Mines Complex, La Sal, Utah. This notice combines the 4 mines into one mine: Beaver Shaft, La Sal, Pandora, and Snowball.

DOGM also informed Energy Fuels Resources (USA) Inc. of the need to reclaim the Snowball Mine. DOGM request that Energy Fuels submit a schedule, including interim steps, for reclamation of portions of the Snowball Mine no longer needed for mining operations and complete the reclamation no later than November 30, 2021. The Snowball waste rock is next to a steep, narrow dirt road on BLM land. (Uranium Watch Sep. 8, 2020)

- > Download: [Conditional Approval, Sep. 2, 2020](#)  (DOGM - PDF)

Expansion of La Sal complex uranium/vanadium mines obtains BLM and FS approval

On Feb. 26, 2018, Energy Fuels Inc. announced that it has received approval from the U.S. Bureau of Land Management ("BLM") and U.S. Forest Service ("USFS") for the expansion of its 100%-owned La Sal Complex of uranium/vanadium mines.

- > Download [project documents](#)  (BLM)



Environmental Assessment for La Sal mine released for public comment

On July 5, 2012, BLM released the Environmental Assessment for the La Sal mine for public comment. The public review and comment period will end on August 21, 2012 (comment period extended).

- > Download [Public Notice and Environmental Assessment](#)  (BLM)

On Dec. 2, 2013, BLM announced that the Forest Service has new NEPA requirements under its 36 CFR 218 regulations. The Environmental Assessment (EA), Forest Service Finding of No Significant Impact (FONSI) and Forest Service Decision document will be made available for a 45-day objection period. This is expected to occur in January 2014.

On September 25, 2014, the Manti La Sal National Forest posted the Environmental Assessment and a draft decision and FONSI on its Schedule of Proposed Action (SOPA) report for a 45 day objection period. File objections within 45 days of September 25, 2014.

- > Download [La Sal Mines Complex Project Documents](#)  (Forest Service)
- > Download [Objections filed by Uranium Watch and others](#)  , Dec. 22, 2014 (927k PDF - Uranium Watch)

U.S Forest Service sends decision on La Sal Mines Complex Environmental Assessment back to drawing board:

"On March 20, 2015, US Forest Service (USFS) ruled favorably on Uranium Watch et al.'s Objection to the La Sal Mines Complex Plan of Operations Amendment, the project EA, and the USFS draft Decision Notice and Finding of No Significant Impact (FONSI). In the 38-page decision, the Objection Reviewing Officer found that the FONSI was not supported by the EA and the project record. He instructed the Forest Supervisor to hold the issuance of the Decision Notice until all concerns and instructions in the decision have been addressed. At the end of this process, the Bureau of Land Management (BLM) will issue its final decision." (Uranium Watch Mar. 26, 2015)

> View [Center for Biological Diversity release, March 26, 2015](#)

Activist denounces poor supervision of radon emissions from uranium mines near La Sal

A southern Utah activist wants state regulators to be more thorough and more transparent in how they handle hazardous emissions from Utah's uranium mines. Sarah Fields, representing Moab-based [Uranium Watch](#), told the Utah Air Quality Board this week that state regulators have failed to carry out basic duties when it comes to cancer-causing radon emissions from uranium mines near La Sal in southeastern Utah's San Juan County.

Fields conceded that Denison's operations now release radon at doses lower than those considered harmful by the Environmental Protection Agency, although that hasn't always been the case. She also insisted DAQ (Division of Air Quality) doesn't have all the information it needs to ensure the mines are operating safely. As an example, she questioned if it was appropriate for DAQ to allow a vent - one that had been cited in an August 2010 notice of violation from the EPA - within a quarter-mile of the La Sal School. (Salt Lake Tribune Apr. 5, 2012)

Denison Mines commences operation of La Sal mine without air quality approval order, no BLM plan of operation, and minimal environmental assessment

Denison Mines Corporation (Denison) has begun the operation of the La Sal Mine, one of the mines in the La Sal Mines Complex, without an updated Plan of Operations and Environmental Assessment and without an modified Approval Order from the Utah Division of Air Quality (DAQ). (Uranium Watch June 20, 2011)

Continuing health and safety violations at La Sal Mines Complex

The operators of the La Sal Mine Complex, Denison Mines (USA) Corporation (Beaver Shaft Mine) received 10 citations and 2 orders, Reliance Resources LLC (Pandora Mine) received 5 citations and one order from the Mine Safety and Health Administration (MSHA) for health and safety violations in March. This is in addition to 11 citations in January, with proposed penalties of \$13,372. MSHA has not yet assessed the penalties for the March citations.

Two of the March orders were issued because MSHA found hazardous conditions underground similar to previously identified hazardous conditions that had resulted in sections of the mines being closed off to workers. These included hazardous ground conditions related to scaling and support-the same type of conditions that caused the fatal accident in May 2010-and the need to wear respirators when the radon daughter concentrations exceed 1 Working Level. The mines have previously been cited for these hazardous conditions. (Uranium Watch April 5, 2011)

Additional Information (Pandora Complex Mine ID 4200470):

> Access [MSHA - Mine Data Retrieval System](#)

Community environmental organizations call for EIS for La Sal Mines Complex

[Uranium Watch](#), Canyonlands Watershed Council, Center for Biological Diversity, Glen Canyon Group of the Sierra Club, Grand Canyon Trust, and Living Rivers has called for a full Environmental Impact Statement

(EIS) for the expansion of the La Sal Mines Complex, La Sal, Utah.

The groups submitted comments for the Bureau of Land Management and US Forest Service-Manti-La Sal National Forest environmental review of the November 2010 Plan of Operations Amendment. The comments included an Environmental Protection Alternative. The mining complex is owned by Denison Mines (USA) Corporation, which also operates the Beaver Shaft. Reliance Resources LLC operates the Pandora Mine. (Uranium Watch Jan. 31, 2011)

> Download [Scoping Comments - January 31, 2010](#) (570k PDF)

BLM and Forest Service invite comment on planned expansion of operations at La Sal Mines Complex

The proposed action would approve the following activities on public lands managed by BLM and FS at the La Sal Complex:

- Expansion of an existing development rock pile at the Pandora Mine;
- Temporary construction of drilling sites and access trails for exploration drilling;
- Installation of ventilation holes to provide for inflow and exhaust of air to support underground mining; and
- Compilation of activities previously approved by two existing BLM Plans of Operations, one FS Plan of Operations, and associated amendments into one Plan of Operations that will address the entire La Sal Mines Complex.

BLM's comment period ends January 31, 2011.

> View [BLM announcement Jan. 4, 2011](#)

> Download [La Sal Mines Complex Documents](#) (BLM)

The Forest Services' comment period ends March 24, 2011.

> Download [La Sal Mines Complex Documents](#) (USDA Forest Service)

Daneros mine, San Juan County, Utah

> View [deposit info](#)

> See also: [Uranium Watch Daneros Mine page](#)

BLM approval of Daneros uranium mine expansion lacks additional groundwater monitoring requirement, judges find

[...] Appellants have shown that, based on BLM's analysis in the EA [Environmental Assessment], groundwater infiltration from the perched aquifer into the mine and the potential need for discharge may require additional monitoring under 43 C.F.R. § 3809.401(b)(4). BLM's approval of the monitoring plan without addressing that issue was therefore erroneous. These holdings together constitute our decision on the merits of this appeal.

We defer ordering a remedy for that error, however, on the record before us. [...]

([Order, Interior Board of Land Appeals, IBLA 2018-0107, Oct. 25, 2024](#))

In May [2025], the Board issued its final order, setting aside the BLM's approval of the mine's monitoring plan. The BLM must now go back and ensure that the monitoring plan will provide for early detection of groundwater that could infiltrate into the mine.

Nothing can happen under the mine expansion proposal until the BLM complies with the Federal Land Policy and Management Act's requirement to prevent "unnecessary or undue degradation" of our public lands. (Grand Canyon Trust May 29, 2025)

Expansion of Daneros uranium mine obtains BLM approval

On Feb. 26, 2018, Energy Fuels Inc. announced that it has received approval from the U.S. Bureau of Land Management ("BLM") for the expansion of its Daneros mine.

> Download [project documents](#) (BLM)

BLM invites comment on Environmental Assessment for proposed expansion of Daneros Uranium Mine: The Bureau of Land Management (BLM) Monticello Field Office is seeking public comment on an environmental assessment for a proposal to modify a mine plan for the Daneros Uranium Mine in San Juan County.

The proposed modifications include expanding facilities at two mine portals, adding ventilation holes and expanding the mine surface area from 4.5 acres to 46 acres. Under the modified plan, total production of uranium ore is expected to increase from 100,000 tons over seven years to 500,000 tons over 20 years. Submit comments by August 1, 2016 (Comment period extended).

> View: [BLM release June 15, 2016](#) · [BLM release July 5, 2016](#)

> View/Download: [DOI-BLM-UT-Y020-2016-0001-EA \(Daneros Mine Plan Modification\)](#) (BLM)

BLM seeks public input on proposed operating plan modification for continued development of Daneros uranium mine: "This Modification includes components necessary to support additional mine development and mine operation beyond 2012. This Modification is designed to facilitate mineral development activities for a minimum of five and up to approximately 20 years of continued production, depending on market conditions and other factors."

Scoping comments will be accepted by until March 14, 2014.

> Download [BLM release Feb. 5, 2014](#) (PDF)

> Download [Daneros Plan of Operations, Dec. 2013](#)

Daneros mine to be placed on standby for poor economics: On Oct. 17, 2012, Energy Fuels Inc. announced that it will shift its short-term focus toward lower cost sources of U3O8 production within its asset portfolio. As a result of this revised production strategy, Energy Fuels will be placing the Beaver and Daneros properties on the Colorado Plateau on standby over the course of the first quarter of FY 2013.

> View [older issues](#)

Pandora mine, San Juan County, Utah

> View [deposit info](#)

> Download [Utah OGM files](#)

Production restarts at Pandora uranium mine: On Dec. 21, 2023, Energy Fuels Inc. announced that, in response to strong uranium market conditions, it has commenced uranium production at its Pandora mine. Ore mined from the mine during 2024 will be stockpiled at the Company's [White Mesa Mill](#) for processing in 2025.

Mine Safety and Health Administration settles with Reliance Resources on penalties for fatal accident at Pandora mine in 2010: Mine Safety and Health Administration (MSHA) has settled with Moab based Reliance Resources LLC for penalties associated with the fatal mine accident at the Pandora Mine on May 26, 2010. Reliance Resources operated the mine in La Sal, Utah, for Denison Mines Corporation, a Canadian company. Hunter Diehl was killed when large rock fell on him. He was manually scaling loose material from the rib when it fell.

- MSHA fined both Denison and Reliance Resources \$5,000 each for failing to report the mine accident (later reduced to \$3,500).

- Reliance Resources was also cited for failing to examine ground conditions. The penalty for this violation was \$70,000, but it was reduced to \$49,000.
- The penalty of \$52,500 for not assuring that "scaling shall be performed from a location which will not expose persons to injury from falling material, or other protection from falling material shall be provided," was reduced to \$36,700.
- The company was also fined \$15,200 for violating the provision that "work shall not resume in the blast area until a post-blast examination addressing potential blast-related hazards has been conducted by a person with the ability and experience to perform the examination." This was reduced to \$10,640.

It has taken over three years to resolve these and other contested penalties. There were 46 violations at the Pandora Mine in 2010. (UraniumWatch Oct. 31, 2013)

Pandora mine to be shut down: On Oct. 17, 2012, Energy Fuels Inc. announced that it will cease mining at the Pandora property during the second quarter of FY 2013, pending the depletion of its identified uranium and vanadium resources.

Pandora mine operator fined \$92,600 for fatal accident: The Mine Safety and Health Administration (MSHA) has issued a penalty of \$92,600 to Reliance Resources, LLC, for two violations from the fatal accident on May 26, 2010, at the Pandora Mine (Mine ID 4200470), La Sal, San Juan County, Utah. (UraniumWatch May 7, 2011)

More worker health and safety violations at La Sal mines: The January 2011 Mine Safety and Health Administration (MSHA) inspections resulted in 5 worker health and safety violations at the Pandora Mine for Reliance Resources LLC and 6 violations at the Beaver Shaft for Denison Mines (USA) Corp. All MSHA violations were associated with the failure of the mine operators to properly protect the workers from exposure to radon daughters (short lived, highly radioactive particulates from the decay of radon) in the mines. Both Denison Mines and Reliance Resources were cited for exposure of workers to air with concentrations of radon daughters exceeding 1.0 working level (WL) in active workings and for the failure of workers to wear respirators in areas where the radon daughters exceed 1.0 WL. Reliance Resources was also cited for improper ventilation, not posting inactive workings where radon daughter concentrations are about 1.0 WL, and failure to calculate and record complete individual exposures in active working areas with radon daughter concentrations are more than .03 WL. This followed an inspection of December 20 when Denison was fined \$6,000 for exposure of workers to radon daughters above the acceptable level, improper ventilation, and failure to calculate and document worker exposure to radon daughters, or progeny.

At the beginning of December, Denison was cited for 12 other violations, some for the same violations that Reliance Resources was cited for after Hunter Diehl was killed at the Pandora Mine 2010. Denison failed to correct hazardous conditions associated with scaling and support and failed to have a competent person examine each working place at least once each shift for conditions that may adversely affect safety or health. In 2009 Denison received 13 citations; Reliance Resources received 14; total penalties for all were \$3,629. In 2010, Denison received 34 citations and orders; total penalties of \$18,304. Reliance Resources received 18 citations and orders; total penalties of \$2,664 (this does not include any penalties associated with the fatal Pandora Mine accident on May 26, 2010).

Denison has been adjusting its ventilation system to reduce radon emissions so that they do not exceed the standard for doses to the nearest residents, La Sal School, and road maintenance shed. It is difficult for Denison to meet both the dose standard for off-site exposures to radon and the underground worker exposure standards. (UraniumWatch March 3, 2011)

> Access [MSHA - Mine Data Retrieval System](#) (Mine ID: 4200470)

Judge approves drilling at Pandora uranium mine in Manti-La Sal National Forest: A federal judge will allow a uranium mining company to drill several new holes in the Manti-La Sal National Forest. Three Moab conservation groups had asked Judge Dale A. Kimball to halt the drilling planned by [Denison Mines Corp.](#) at its Pandora Mine, claiming the U.S. Forest Service permitted the project without an adequate environmental study. Uranium Watch, Center for Water Advocacy and Living Rivers argued that Denison would create

radioactive air emissions and heavy metal contamination if it drills 16 exploration holes and two radon vent holes, a project approved by the Forest Service. Kimball gave more weight to Denison's environmental expert, who said there was no significant risk of environmental harm. Kimball also wrote that the Forest Service followed procedural rules when it allowed the project without environmental assessments or impact statements. (Salt Lake Tribune Sep 14, 2010)

Groups file suit to stop expansion of Pandora uranium mine in La Sal, Utah: Uranium Watch, Center for Water Advocacy, and Living Rivers, conservation groups located in Moab, Utah, yesterday (July 29) filed suit in federal district court in Salt Lake City to halt uranium exploration and the construction of radon vent holes on U.S. Forest Service land in the Manti-La Sal National Forest in La Sal, Utah.

The complaint filed with the United States District Court for the District of Utah challenges a decision by the Moab/Monticello Ranger District to permit the drilling of 16 exploration drill holes and 2 radon vent holes as part of the expansion of the Pandora Uranium Mine.

Radon is vented to the surface from the underground mine operations so that the miners will not breathe in the radon gas and be exposed to the short-lived highly radioactive particles that are produced when radon decays. The proposed radon vents would add to the amount of radon gas and radioactive particulates released in the vicinity of the community of La Sal, on the south slope of the La Sal Mountains. In 2009, the amount of radon released from the uranium mines in La Sal jumped from 300 Curies to over 4,500 Curies, according to Denison's annual reports to the Utah Division of Air Quality. Radon is released from vents near the Beaver Shaft not far from the La Sal Elementary School. (Uranium Watch, July 30, 2010)

Uranium miner dies in rockfall accident in Pandora mine: A 28-year-old uranium miner from Moab died Wednesday (May 26) morning after he was hit by falling rock in the Pandora mine near LaSal, San Juan County. (The Salt Lake Tribune May 26, 2010)

Federal regulators faulted a Utah company for safety lapses in the death of a uranium miner who was killed by a large rock slab he was peeling off a tunnel wall near La Sal. A Mine Safety and Health Administration report released Thursday (Sep. 23) said Reliance Resources LLC of Moab was cited for inadequate worker training and failing to test a tunnel wall for loose rock. The citations were rescinded after the company took corrective measures. The report says 28-year-old Hunter Diehl ("deal") of Moab was using a pry bar to pull off loose slabs May 26 when one fell on top of him. He was pronounced dead later at a hospital. Reliance Resources operates the Pandora mine for another company, [Denison Mines \(USA\) Corp.](#) (Business Week Sep. 24, 2010)
> Download [MSHA Report of Investigation, Sep. 23, 2010](#) (355k PDF)

A public input period is under way to comment on an air-quality permit for the Pandora uranium mine in La Sal, San Juan County. Moab-based [Uranium Watch](#) has requested a hearing. Director Sarah Fields raised a concern about the proximity of venting to an elementary school. The deadline for written comments is July 3, 2009. (The Salt Lake Tribune June 9, 2009)

> View [Utah DEQ DAQ Permits out for public comment](#) ("Denison Mines (USA) Corp, La Sal Mine")

On Sep. 14, 2006, [International Uranium Corp.](#) announced it has reached an agreement with Reliance Resources, LLC to conduct contract mining at the Company's Pandora Mine, located near LaSal, Utah. The Pandora Mine is a previously developed mine last operated in the late 1980's. Mining activities are underway and ore shipments to the Company's White Mesa Mill in Blanding, Utah will begin in early October 2006.

White Mesa uranium mill (Utah)

> See [extra page](#) !

Wyoming

> View [extra page](#) 

HOME WISE Uranium Project > Mining & Milling > Issues > Operating Uranium Mines and Mills - North America >
--