Canada's Nuclear Regulator

The Science of Safety

CNSC Research Report 2014–15

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The Science of Safety: CNSC Research Report 2014–15

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Message from the President

I am pleased to introduce the Canadian Nuclear Safety Commission's (CNSC) second annual research report. As it has done for many years, the CNSC has carried out a wide range of scientific research to help it deliver its mandate to protect the health and safety of Canadians and the environment, as well as to meet Canada's international commitments on the peaceful use of nuclear energy.

I believe that to fulfill our mandate we must strive to be open and transparent in all our activities. We must work hard to provide Canadians with credible and independent information, and to demonstrate that our regulatory decisions are solidly based on science and sound principles. I also believe that Canada now stands at the forefront of many nations in making the regulation of nuclear energy an open and publicly accessible activity.

This report is part of our ongoing effort to ensure that Canadians have access to the science that informs our work. Readers will note that all of our completed research is publicly available on our website, and is posted in the form submitted by the report authors. I encourage all readers to read this work, should they have an interest.

That's the science of safety.

Michael Binder

Introduction

Purpose of the report

The CNSC carries out a wide variety of research to support its mandate. This research, which is highly specialized and often contains scientific and technical language, is made available to the public via the CNSC website or through its library. This report aims to summarize, for a more general audience, the research and research-related activities carried out by the CNSC over the past fiscal year. To assist in understanding some of the technical language in the document, a glossary of terms has been provided. Words that are underlined are linked to a definition in the glossary.

Regulatory research

Our research supports timely, science-based regulatory judgements and decisions. It assists in identifying problems that may give rise to health, safety, security or environmental hazards. Regulatory research is used to validate the adequacy of safety margins and may lead to safety enhancements where needed. We look at the long-term performance of waste management facilities and incorporate the latest science into human and ecological risk assessment modelling. From waste safety to environmental protection, the CNSC's research helps develop tools and techniques to address potential issues, and contributes to the development of safety standards.

The CNSC research program's objectives include:

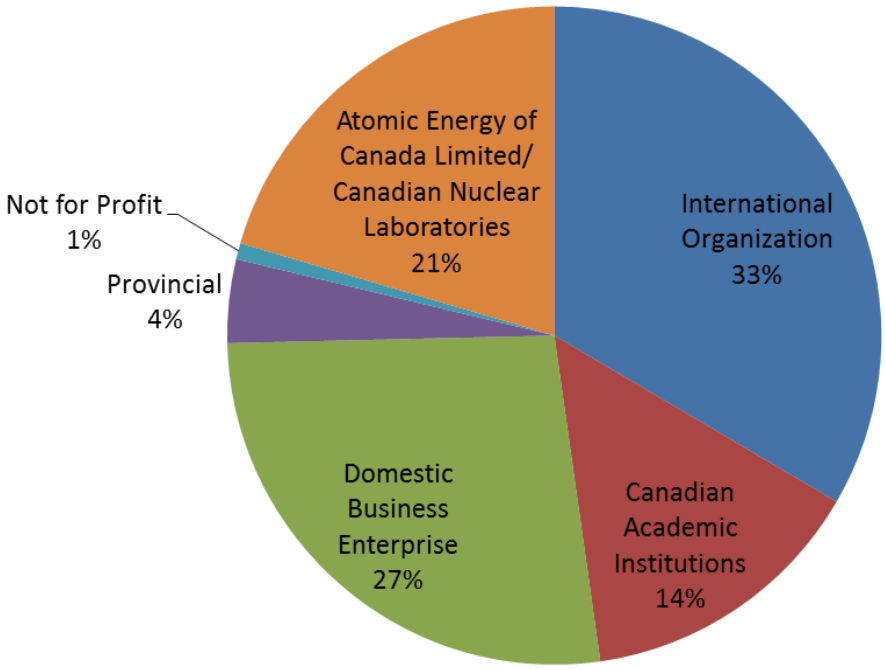
- acquiring independent advice to support regulatory decisions
- assisting in the development of tools capable of addressing health, safety, security or environmental issues
- aiding in the development of nuclear safety standards

The following chapters include brief descriptions of the research projects and other collaborative efforts completed at the CNSC between April 1, 2014 and March 31, 2015. Most of these projects took multiple years to finalize. Although many were related to the regulation of nuclear power plants, we focus on every aspect of the nuclear industry regulated by the CNSC – from uranium mines and mills, through waste repositories, to life-saving medical devices and radioactive substances encountered in our day-to-day activities.

Our research universe

The CNSC research program funds research in the private sector, academic institutions, and governmental/non-governmental organizations, both in Canada and internationally. The majority of the CNSC's research is carried out through competitive contracting processes. A significant amount of work is performed in collaboration with national and international partners to share costs and information.

Percentage of CNSC projects by research organization



Many of our research partners are institutions of higher education: Carleton University, McMaster University, University of Toronto, University of Manitoba, University of Ontario Institute of Technology, Queen's University, and the University Network of Excellence in Nuclear Engineering. Among many international partners, the CNSC collaborates with the International Atomic Energy Agency, the Nuclear Energy Agency and the United States Nuclear Regulatory Commission.

The CNSC has a small grant budget used to facilitate the sharing of information on our mandate, to encourage outreach, and to fund smaller research projects. We have highlighted several grant projects in this report. In addition to the work carried out through the CNSC's research program contracts and grants, our staff publish scientific papers on subjects related to program activities. A list of these scientific papers is found in the annex.

Ensuring the safety of nuclear power plants

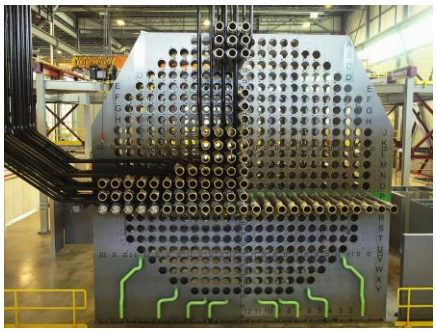
Nuclear power plants are complex systems with many components that must be able to withstand years of exposure to intense heat and irradiation. By ensuring that these facilities operate safely over the long term, we effectively protect communities where nuclear power is generated. A significant portion of the CNSC's regulatory research focuses on making sure plant systems and components are up to the challenge. The following paragraphs provide a brief summary of the research projects undertaken by the CNSC to help evaluate the continued safety and reliability of nuclear power plant systems and equipment.

Aerial photograph of the Darlington Nuclear Generating Station, located near Bowmanville, Ontario.

Each nuclear power plant in Canada has multiple safety systems designed to prevent accidents and reduce their effects (should one occur). All of these systems are maintained and inspected regularly to ensure that they meet or exceed strict safety standards established by the CNSC.

Did you know? The target lifespan for CANada Deuterium Uranium (CANDU) reactors was projected to be about 30 years. Current research results, the approach to facility operations, and mid-life refurbishment support extending operation well beyond 30 years.

CANDU accident safety margins



A mockup calandria from Ontario Power Generation's Darlington training facility.

The calandria contains the fuel surrounded by coolant carrying the heat away in pressure tubes. It must be demonstrated that plant safety systems will prevent fuel melting in the unlikely event of a loss-of-coolant accident.

While the complete failure of a large-diameter pipe in a nuclear power plant is highly unlikely, there is a need to better understand the probabilities and consequences of such a failure. The CANDU Owners Group developed a software program, PRAISE-CANDU, which could be used to provide input information to assess safety margins associated with large break loss-of-coolant accidents. The objective of this project was to obtain an independent third-party technical evaluation of the PRAISE-CANDU code development process, and to determine its acceptability for use in safety margins analysis. A literature review of the acceptance of probabilistic fracture mechanics codes for regulatory decision making in other countries was also undertaken. Results indicate that the PRAISE-CANDU models are current and versatile, and should be adequate to support risk-informed decision making applications, subject to further verification and validation activities.

Refer to the CNSC website for the final report: *Third Party Review of PRAISE-CANDU Probabilistic Fracture Mechanics Code*.

Incorporating aging effects into probabilistic safety assessment applications

To ensure the safety and proper performance of aging systems, structures and components, the changes that occur with time and use in a nuclear power plant must be understood. A methodology known as probabilistic safety assessment (PSA) is one of the most effective tools used to derive reliability insights for systems, structures and component. A PSA provides essential input for risk-informed decision making. The research project, performed by ENCONET Consulting, was among the very first attempts to incorporate aging effects into specific PSA models within a nuclear power plant and to observe its impact on the overall assessment results. The project aimed to determine a methodology and appropriate regulatory approach to address aging effects.

Refer to the CNSC website for the final report: *Incorporating Ageing Effects into PSA Applications*.

Testing steam generator tube integrity

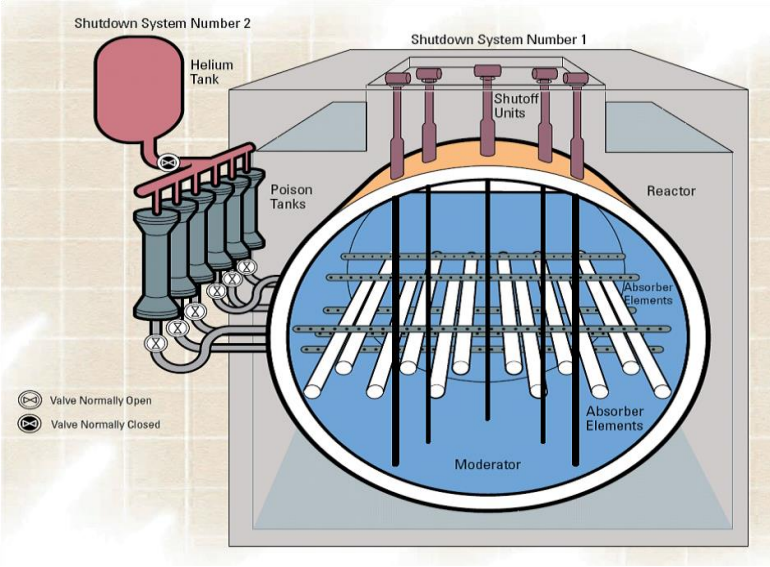
If a main steam line in a CANDU nuclear power plant was to break, the pressurized heated water in the steam generator would be suddenly exposed to surrounding atmospheric conditions. This rapid reduction in pressure would cause the water to boil, producing what is called a "blowdown". The purpose of this research project was to gain an improved understanding of the physical process involved during a blowdown, and to ensure the steam generators' integrity during such an event.

An experimental facility was modelled and built at McMaster University to study the effects of a hypothetical main steam line break accident and to prevent tube failures in industrial steam generators and make predictions of structural tube failures under a range of conditions. The final report includes a set of original experimental data, an analysis of the experimental project findings to date, and a discussion of the proposed strategy to develop a methodology to predict tube bundle loading in the simulated environment. Additional experiments are planned to assist in the development of theoretical formulations and computational tools for assessing tube loading and their structural integrity during hypothetical accident conditions.

Refer to the CNSC website for the final report: *Loading of Steam Generator Tubes during Main Steam Line Break*.

How is nuclear power generated?

All nuclear power plants in Canada use the CANDU design – a safe, reliable reactor technology. CANDU reactors produce electricity through a process known as fission. Fission is the process of splitting natural uranium atoms inside the reactor, releasing radiation and heat. The heat from the reactor core is transported and transferred to a steam generator via heat exchangers. Steam rises vertically in steam generators, parallel to the tubes, until it reaches a U-bend region where it is led to the turbine. The heat from the reactor turns water into steam in the steam generators, creating a force that turns the turbines and generators, which in turn produce electricity.



Schematic of a CANDU reactor vault and assembly. Canadian reactors are required to have two independent, fast-acting and equally effective systems to shut down the entire reactor if necessary. This is an example of redundancy, which ensures that no single line of failure leads to an unacceptable outcome, and is just one example that proves Canada's commitment to nuclear safety.

Protecting workers

The CNSC limits the amount of radiation that Canadian nuclear workers receive. We ensure that contamination levels and radiation doses received by individuals are monitored, controlled and maintained as low as reasonably achievable. Our research helps us protect workers on the front lines of Canada's nuclear industry and is based on the strongest, most up-to-date evidence.

Underground tunnels at Cigar Lake in northern Saskatchewan. These tunnels are reinforced with concrete to ensure a safe working environment. The CNSC has full-time staff in Saskatoon and Ottawa who periodically perform inspections to evaluate operations and verify compliance with regulatory requirements and licence conditions.

Did you know? An estimated 40,000 people work in Canada's nuclear industry. There are also more than 800,000 nuclear industry workers and over 2 million healthcare workers who work safely with radiation worldwide, every day.

Updated uranium mining health assessment

The radioactive decay of uranium produces radon gas, whose decay products can be attached to airborne dust or particles where they might be inhaled or ingested. In uranium miners, this is believed to contribute to their risk of developing lung cancer. The CNSC contracted the Occupational Cancer Research Centre (Cancer Care Ontario) to perform a study that focuses on the relationship between lung cancer mortality and incidence compared to occupational radon exposure among Ontario uranium miners. The results of the study will help build on the understanding of health effects associated with radon exposure by examining 25 years of additional data since the last analysis, and by examining an expanded cohort which increases the number of observations used in the statistical analysis.

The results suggest a strong relationship between exposure and lung cancer incidence and mortality. While other cancers were examined, no clear dose response relationship was observed. The project provides up-to-date estimates for cancer risk from occupational radon decay product and gamma radiation exposure.

Refer to the CNSC website for the final report: *Ontario Uranium Miners Cohort Study*.

What is radon?

Radon is an odourless, colourless radioactive gas that occurs naturally in the environment as a result of the decay of uranium. As uranium undergoes radioactive decay, it emits alpha, beta and gamma radiation, along with a series of products that include radon. In turn, radon decays through a series of four very short-lived radioactive decay products, in the form of solid, electrically charged particles called radon progeny: polonium-218, polonium-214, lead-214 and bismuth-214. The two that pose a health risk are polonium-218 and polonium-214.

Aerial view of Cameco's Cigar Lake uranium mine. Regulation of radon decay products in Ontario uranium mines began in the early 1950s, as a guideline suggested by the Atomic Energy Control Board (later replaced by the CNSC).
Concentrations of radon decay products in the air inside uranium mines are strictly controlled and must be monitored at all times to protect workers.

Protecting the environment

One of the cornerstones of the CNSC's mandate is to ensure that environmental harm in every segment of the nuclear industry – from uranium mines to power plants and waste storage sites – is minimized. The CNSC monitors all releases of radioactive substances in the environment that result from licensed activities. We evaluate long-term safety issues for radioactive waste management in crystalline and sedimentary rocks, and look at ecological risk-assessment modelling.

Nuclear energy worker conducting an environmental water sample assessment to monitor contamination levels. To complement its existing and ongoing compliance activities, the CNSC implemented the Independent Environmental Monitoring Program to verify that the public and environment around CNSC-regulated nuclear facilities are not adversely affected by releases to the environment. This verification is achieved through independent sampling and analysis by the CNSC.

Did you know? Natural radiation has always been around us, and accounts for approximately 60 percent of our annual dose. This radiation comes from space, the ground, the food we eat, and even within our bodies, and is referred to as "background radiation".

Defining quality guidelines for aquatic environments

The CNSC ensures that liquid effluents from uranium mining are monitored for their effects on the aquatic environment. Aquatic environments downstream of uranium mining and milling operations in northern Saskatchewan are exposed to a variety of chemical and physical disturbances. The individual and combined effects of released contaminants on freshwater organisms have rarely been analyzed in scientific literature. In this study, the reference condition approach was used to predict expected benthic invertebrate communities from northern Saskatchewan's Athabasca Basin, to document the effects of uranium mining and milling on freshwater environments with modern information. In this approach, an expected reference condition in the absence of human influences was used to identify impacted communities that differed significantly from natural regional compositions.

The results of this study are being incorporated into a manuscript for submission to a peer-reviewed scientific journal, and will become available on the CNSC website on publication.

Monitoring the health and reproductive fitness of biota

Some types of radiation have enough energy to knock electrons out of their orbit, giving atoms a positive charge. This type of radiation is called ionizing radiation. Alpha radiation is a type of ionizing radiation. Due to their size and charge, alpha particles are barely able to penetrate skin and can be stopped completely by a sheet of paper. However, they can potentially be harmful if ingested or absorbed into the body. This study contributes to a better understanding of the effects of alpha radiation at low levels of exposure, by assessing the health, growth and reproductive fitness of fish and mammals exposed to alpha-emitting radionuclides.

Aerial view of Canadian Nuclear Laboratories in Chalk River, formerly known as Atomic Energy of Canada Limited.

The objective was to evaluate whether long-term exposure to ionizing radiation could affect the health and reproduction of fish and mammals. McMaster University and Atomic Energy of Canada Limited provided data for this research project. The results show no significant effects on the growth, physical condition and reproductive fitness of fish and small mammals. This study is expected to improve the ability to assess ecological risks associated with the release of alpha-emitting radionuclides and inform current policies on uranium mining and milling in Canada.

Refer to the CNSC website for the final reports: *Effects of Chronic Exposure to Alpha-Emitting Radionuclides on Health and Reproductive Fitness of Biota: report on mammals, report on fish studies.*

The CNSC laboratory

The CNSC's laboratory was designed to provide radiation instrument calibration and various sample analysis services to the CNSC. The lab has expanded its capabilities to also perform research projects and provide training courses and expert advice in selected areas, such as field sampling and radiation instrumentation. The CNSC laboratory is involved in a number of research activities, many of which involve collaboration with other organizations

Tritium transport in the terrestrial environment

In 2012, the CNSC started collaborative research with the University of Ottawa on the environmental dispersion of tritium released to air from the tritium processing facility in Pembroke. The results of this study will be used to better understand the uncertainties of the transformation of atmospheric tritium species (in both wet and dry fallout) into organically bound tritium in foods, and in soils and plants. As a result of this research project, the CNSC's laboratory services implemented state-of-the-art techniques to measure different species of tritium in air, plants, food and soil. Since developing this capability, the CNSC lab has performed over 3,000 tritium analyses. Some of the findings for this project were published in a peer-reviewed journal; work is also underway to prepare a second manuscript.

Factors controlling the release of radium-226 from submerged uranium mine tailings

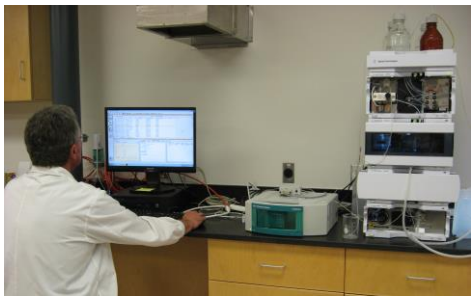
A CNSC senior lab analyst verifies a radium tailing sample using alpha spectroscopy.

The CNSC has a joint research project with CANMET (Natural Resources Canada) to enhance the predictability of radium-226 releases from uranium mine tailings over long periods of time. The results of this work will be used to support CNSC licensing decisions on the remediation of legacy uranium mine sites and the transfer of such facilities to institutional control. The study employed laboratory methods designed to discern mechanisms of radium attachment and subsequent release in uranium mine tailings, using field samples at two sites: Denison mine site (Elliot Lake, Ontario) and Gunnar mine site (Saskatchewan). The main focus was the development of tools to identify and differentiate the radium attenuation and release mechanisms that have evolved at legacy sites. Knowledge of these processes will help guide remediation options to reduce uncertainties in licensing decisions, particularly for costly remediation options at legacy sites.

Uranium reference materials intercomparison exercise

The CNSC laboratory participated in an intercomparison exercise organized by the International Atomic Energy Agency (IAEA) with five other laboratories tasked to quantify 69 impurities in two uranium materials. The results highlight of the current state of the practice and yielded consensus values for the two analyzed materials. These results are suitable for use in laboratory standards to partially fill a gap in the availability of uranium reference materials characterized for impurities.

Determination of hydrazine at Ontario nuclear power plant discharge points



A CNSC senior technical specialist uses a high-performance liquid chromatograph connected to an amperometric detector to determine concentrations of hydrazine.

To enhance the CNSC's capability to verify compliance with the proposed federal water quality guidelines, the CNSC laboratory developed an analytical method for determining quantities of hydrazine in freshwater samples. In collaboration with Environment Canada, this successfully developed and validated method was applied to measure the concentrations of hydrazine in Lake Huron samples collected at discharge points near the Bruce nuclear power plant, and Lake Ontario samples collected at discharge points near the Pickering and Darlington nuclear power plants. The concentrations of hydrazine measured in lake water samples were found to be comparable to background concentrations.

Independent Environmental Monitoring Program

The CNSC has implemented an Independent Environmental Monitoring Program (IEMP) to verify that the public and the environment around licensed nuclear facilities are safe. It is separate from – but complementary to – the CNSC's ongoing compliance verification activities, such as reviews of compliance reports and regular inspections. The monitoring program aligns with those of other national and international regulatory bodies. The program is also being implemented at facilities belonging to every segment of the nuclear fuel cycle: uranium mines and mills, uranium and nuclear processing facilities, nuclear power plants, research and medical isotope production facilities, and waste management facilities.

The IEMP involves taking samples from public areas around licensed facilities, and measuring and analyzing the amount of radiological (nuclear) and non-radiological (hazardous) substances in those samples. CNSC staff collect samples of air, water, soil, sediment, vegetation (such as grass and weeds), and some food (such as meat and produce) in publicly accessible locations such as parks, residential communities and beaches. Samples are prepared and analyzed at the CNSC laboratory in Ottawa. The results are published on an interactive IEMP dashboard, available on the CNSC's website.

A CNSC laboratory technician prepares a batch of environmental samples by using a dry freezing apparatus.

Spotlight on CNSC research staff

Dr. Patsy Thompson, Director General of the CNSC's Directorate of Environmental and Radiation Protection and Assessment, has led the directorate since 2006.

From radiation protection scientists to nuclear engineers to environmental experts, the CNSC has a variety of technical specialists involved in research. The CNSC's Dr. Patsy Thompson has been recognized as a significant contributor to research throughout her entire scientific career. Dr. Thompson completed a Ph.D. in Aquatic Sciences (Toxicology) in 1990 and was a National Research Council Post-Doctoral Fellow from 1991 to 1993. Her research focused on physiological and adaptive responses to toxic stress from exposures to environmental contaminants (trace metals, organics).

Dr. Thompson has been with the Canadian Nuclear Safety Commission (formerly Atomic Energy Control Board) since 1993. Her initial focus was on the development of approaches for, and conducting, assessments and research on environmental impacts and effects on biota of radioactive discharges from nuclear facilities. More recently, her work has included research and assessments of the health risks of exposure to ionizing radiation. Dr. Thompson has published more than 30 papers in peer-reviewed scientific journals and has made 29 presentations at international scientific conferences. Dr. Thompson has participated in technical committees, coordinated research projects and technical cooperation missions at the IAEA, was chair of the subcommittee on genotoxicity of the Inter-Governmental Aquatic Toxicity Group, and was a member of the International Commission on Radiological Protection's Task Group on Environmental Protection. She has also acted as an expert advisor to various governments on the environmental fate and effects of radioactivity in the environment. Dr. Thompson was appointed as scientific advisor for the Conseil Scientifique at the Institut de Radioprotection et de Sûreté Nucléaire in 2009. She has been the Canadian representative on the IAEA's Radiation Safety Standards Committee since 2009, and the Canadian representative on the United Nations Scientific Committee on the Effects of Atomic Radiation since 2014.

Regulating radioactive waste management facilities

The CNSC licenses, regulates and monitors Canada's radioactive waste management facilities to verify that they are operating safely. Radioactive waste produced in Canada is managed in specially designed facilities. Currently, all used nuclear fuel in Canada is held onsite in interim surface storage facilities, which are the responsibility of the nuclear power plant operator. As with any other nuclear facility, the CNSC imposes rigorous requirements on the operations of radioactive waste management facilities, and verifies that facilities comply with established safety requirements through inspections and audits.

Map of Canadian radioactive waste management facilities. The different waste classifications (low-level, intermediate-level and high-level radioactive waste) are generally organized according to the degree of containment and isolation required to ensure safety in the short and long terms. The hazard potential of the different types of radioactive waste is also considered.

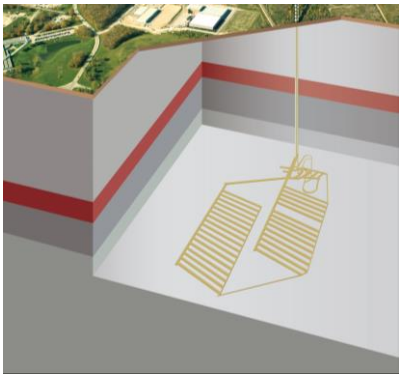
Did you know? The CNSC's commitment to international standards and best practices ensures that the management of radioactive waste in Canada meets the highest requirements for health, safety, security and environmental protection. Through participation in international fora, the CNSC stays informed of best practices in radioactive waste management. The CNSC ensures that proper security measures are in place for nuclear facilities, and that nuclear sector workers' health is protected.

CNSC regulatory research on deep geological repositories

As the Canadian nuclear regulator, the CNSC is responsible for licensing geological repositories intended to provide for the long-term management of radioactive waste. The CNSC uses a comprehensive licensing framework that covers the entire lifecycle of a geological repository from site preparation to construction, operation, decommissioning (closure and post-closure) and, finally, release from licensing. A deep geological repository is constructed underground – usually several hundred metres below the surface – in a stable host rock. In Canada, there are two long-term radioactive waste management initiatives underway that may result in the construction of geological repositories.

- The first is Ontario Power Generation's Deep Geologic Repository for low-and intermediate-level radioactive waste from the Bruce, Pickering and Darlington nuclear generating stations. Examples of these types of radioactive waste include contaminated clothing from nuclear power plants and used reactor core components, respectively. This does not include used nuclear fuel. This initiative is currently undergoing a regulatory review and no regulatory decisions have been made.

- The second initiative is the Nuclear Waste Management Organization's Adaptive Phased Management project for the long-term management of Canada's used nuclear fuel. The plan is to contain and isolate the used nuclear fuel in a deep geological repository in a willing host community with suitable geology. Currently, no licence application has been submitted by the NWMO to the CNSC for this project.



Schematic of Ontario Power Generation's Deep Geologic Repository project.

The CNSC's safety-oriented research program investigates several aspects of long-term deep geological repository safety. Research results have supported the regulatory review of OPG's submissions for a DGR for their low- and intermediate-level radioactive waste. The results may also be used in future submissions. CNSC's research is not meant to duplicate research done by the proponent, but rather to identify gaps in information and to verify key safety aspects for deep geological repositories.

Since 1978, the CNSC has been involved in independent and internationally collaborative research on the safe, long-term management of used nuclear fuel in deep geological repositories. Early research activities focused on the suitability of granitic Canadian Shield rock to host this type of repository. However, the NWMO is currently looking for a voluntary community, with a site that is technically acceptable, in either granitic rock formations of the Canadian Shield, or in sedimentary rock formations. At the same time, there is an initiative in Canada from Ontario Power Generation for a deep geologic repository for its low- and intermediate-level radioactive waste, at approximately 680 metres deep in a sedimentary formation. In response to the above two initiatives, the CNSC has expanded its technical expertise on granitic rock to include knowledge and understanding of deep geological disposal is proposed in sedimentary rock.

Therefore, the CNSC is conducting a research program to evaluate long-term safety issues related to deep geological repositories for radioactive waste and used nuclear fuel in sedimentary rock under the Coordinated Assessment Research Program (CARP). This program consists of independent scientific research, conducted by CNSC staff in collaboration with national and international experts and organizations. In addition to carrying out the research projects described below, CARP monitors and

reviews state-of-the-art scientific advancements and participates in international fora to exchange information and knowledge on geological repositories.

Focus areas

Geological repositories rely on multiple barriers for the long-term containment and isolation of radioactive waste. Such barriers include host rock, engineered barrier systems, type of waste, waste containers and other factors. Since 2008, the CNSC's research has focused on the host rock, conducting research on the performance of sedimentary rock as a barrier against the migration of contaminants. These projects, performed in collaboration with Canadian universities, the German Geological Survey, the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) in France, and the Canada Centre for Mineral and Energy Technology, have provided CNSC staff with invaluable experimental data. The results of these projects have been published in peer-reviewed journals, reports, conference abstracts and papers, and workshops. The topics of completed and ongoing research investigation include the following two examples.

Example 1 – Long-term performance of engineered barrier systems

Emplacement of the mockup waste container into an experimental disposal cell at the Tournemire Underground Research Laboratory in France.

Canada continues to collaborate with other regulators and technical support organizations. France's IRSN is carrying out a series of experiments to assess the long-term performance of bentonite sealing material that would be used to seal galleries and shafts excavated into bedrock, once waste has been placed into a deep geological repository. The performance of the sealing materials over the long term (e.g., 1 million years) depends on several factors. For example, one aspect of these experiments was investigating how the sealing material will respond to resaturation from the surrounding groundwater. This is only one of the topics explored in this collaboration. CNSC staff have generated numerical models of bentonite performance over the long term. These models have been used, and will continue to be used, to assess technical submissions on deep geological repositories.

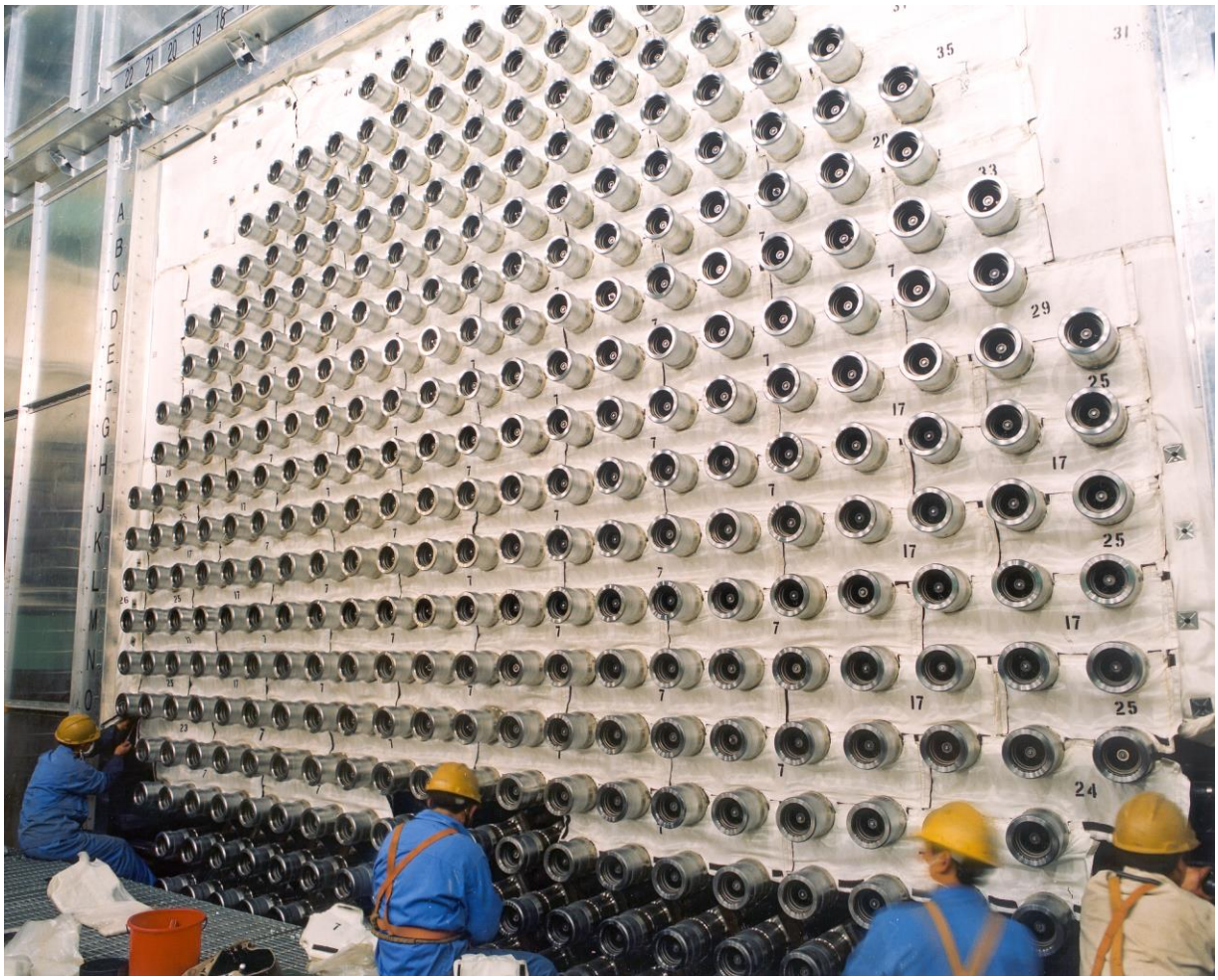
Refer to the CNSC website for the final report: *Constitutive Modelling of Tournemire Shale*.

Example 2 - Natural analogues

One of the more difficult technical challenges involved in the long-term management of radioactive waste in a deep geological repository is the very long timeframes required by safety assessments. In the case of Ontario Power Generation's Deep Geologic Repository project, the safety assessment timeframe is 1 million years, a timeframe that goes well beyond anything that can be considered experimentally (see example 1). Natural analogues provide information at time and spatial scales that are relevant for the development of the long-term safety case, which cannot be filled by experiments and numerical modelling alone. In collaboration with the University of Manitoba, a review of current geoscientific literature was carried out to assess and access data and information that would be relevant for the safety case for a Canadian deep geological repository. Several recommendations are expected on the use of natural analogues to support the safety case. The final report will be available on the CNSC website on completion.

Advancing regulatory perspectives

There is growing international interest in the development of nuclear reactor technology. The CNSC ensures that emerging technologies meet Canadian regulatory requirements. We look at activities that impact the ability of structures, systems and components to meet and maintain their design basis given new information arising over time and taking changes in the external environment into account.



A picture of a reactor component called the calandria. The calandria is a cylindrical, low pressure stainless-steel vessel that houses the CANDU reactor's moderator and fuel. Theses reactors use natural uranium as fuel and heavy water as the coolant and moderator.

Did you know? Nuclear reactors have a variety of uses ranging from research applications, materials testing, medical applications and, more well-known to most, electrical power generation. The CNSC regulates activities associated with all of these uses.

Preparing to regulate activities involving new reactor technologies

Early nuclear power plants around the world, such the Douglas Point Nuclear Generating Station, were small and similar in typical power output to mid-sized fossil-fired generating facilities which have a capacity of 250 megawatts of electrical power. Over the past several decades, nuclear power reactor technologies have progressively grown in power output to take advantage of economies of scale. In Canada, regulation of activities around the use of nuclear power have continually adapted with the evolving technologies. With relatively recent new-build proposals in Canada, the CNSC refocused on providing neutral technology requirements and guidance for proponents seeking to propose the use of technologies different from the CANDU designs that currently compose 100 percent of Canada's nuclear power fleet. Technological innovation in this industrial sector is advancing at an accelerating pace, requiring the CNSC to understand the implications of these innovations on regulation.

There is growing international interest in the development of more efficient fission reactor technologies with enhanced safety features. This interest extends beyond traditional generation of electricity into areas such as water purification and high-quality steam for energy-intensive industrial operations. In some cases, industry is developing smaller reactor designs that could be used to provide these benefits in places where energy has been very costly and difficult to generate; for example, in remote areas of the Canadian north.

Examples of emerging technology types include:

- third-generation traditional nuclear power plants which technologically evolved from existing operating reactor technologies; these power plants are being constructed in many countries
- fourth-generation reactor technologies – not deployed yet but significant research is in progress and, in many cases, early prototypes were built and operated decades ago; these technologies are being designed to use more novel materials and fuel concepts to further improve on efficiencies
- small modular reactors – smaller versions of the above concepts, some with additional features to permit them to be used on sites that cannot accommodate a larger facility; these technologies are also being developed to be much more standardized with some versions being constructed in a few countries

Computer-generated image of a Westinghouse AP-1000 pressurized water reactor under construction in China and the United States.

Regulators around the world, including the CNSC, are being approached with questions about the licensing process and their readiness to license these technologies. In Canada, one of the key concerns revolves around applicability of regulatory requirements to new technologies, because certain technological evolutions may challenge the interpretation and application of requirements.

Regulatory requirements for new small reactors

CNSC staff have, for the past few years, been investigating the implications of emerging technologies and asking ourselves if existing requirements remain valid within our risk-informed approach or if there are any gaps we need to address. We also continue to participate in the Multinational Design Evaluation Programme (MDEP), which provides nuclear regulators the opportunity to share their collective

knowledge in the areas of regulatory framework, vendor inspections and the review of potential new nuclear power plant designs.

Among many other research activities, the CNSC contracted Hatch Limited to perform a design survey of small modular reactors. In addition, the Canadian nuclear regulatory framework was reviewed to assess whether the current and proposed regulatory documents adequately address small modular reactor licensing challenges. Small modular reactor designs and the ways in which they incorporate inherent and passive safety characteristics are summarized in the subsequent report. Although the report, completed in 2014, indicated that the existing regulatory framework is generally adequate, a number of recommendations were made to consider providing supplementary requirements and guidance for passive and inherent safety features in new designs. The CNSC is working on addressing these recommendations.

Refer to the CNSC website for the final report: *Survey of Design and Regulatory Requirements for New Small Reactors*.

Study on international decommissioning practice

Picture of the now-decommissioned Douglas Point Nuclear Generating Station.

The aim of this project was to conduct a literature research to provide international benchmarking on decommissioning strategies. More specifically, the study looked at lessons learned from the decommissioning of nuclear facilities to provide a gap analysis between the current Canadian and international regulatory frameworks. The Canadian regulatory approach for decommissioning is similar to the approach adopted in most of the other countries considered in this review. Some practices were noted in Finland, France, Germany, Italy, Sweden, the United Kingdom and the United States which might be beneficial for Canada to adopt. CNSC staff are examining how to best implement these practices. The report also included recommendations to address the identified gaps.

Refer to the CNSC website for the final report: *International Benchmarking on Decommissioning Strategies*.

Continued international collaboration

The CNSC reviews common international research needs to ensure the leveraging of resources. This includes collaborating with other countries that use CANDU technology and working with other regulators to ensure that research knowledge can be used consistently. To achieve this, the CNSC works bilaterally and multilaterally with partners around the world. The CNSC supports research through the Nuclear Energy Agency, the United States Nuclear Regulatory Commission, and the IAEA.

The CNSC's President, Dr. Michael Binder, signing a memorandum of understanding with Mr. Norov Tegshbayar, Director General of the Nuclear Energy Agency, the Government of Mongolia's nuclear regulatory agency. From September 22 to 26, 2014, the CNSC signed memoranda of understanding to cooperate and exchange nuclear information with the Mongolian Nuclear Energy Agency, the Swedish Radiation Safety Authority and the Polish National Atomic Energy Agency.

"I am pleased to have these arrangements with our CNSC regulatory counterparts," said President Binder. "International partnerships are part of the CNSC's ongoing commitment to international best practice. It is a two-way street: we share our know-how with regulatory bodies of other countries, and we learn from the experiences of others."

Supporting international safeguards

"Safeguards" refer to a system of international inspections and other verification activities undertaken by the IAEA. This system evaluates Canada's, as well as other nations, compliance with their obligations on the peaceful use of nuclear materials. Through the Canadian Safeguards Support Program, the CNSC is one of the Member States supporting the IAEA in its move towards a more adaptable and flexible way of evaluating safeguards. In fiscal year 2014–15, Canada provided two technical experts to the IAEA. The first expert, from the CNSC's Information Management and Technology Directorate, will work on designing a secure and electronic communication channel. This will allow for the upload of official State reports and other secure communications to the IAEA and will facilitate the secure outward delivery of safeguards reports to the IAEA. A second expert from Defence Research and Development Canada was supplied to the IAEA to work towards the full integration of the use of synthetic aperture radar for safeguards purposes. The use of radar imagery will enhance the IAEA's confidence in drawing effective and efficient safeguards conclusions for Member States, and will contribute to the CNSC's mandate to uphold Canada's international obligations on the peaceful use of nuclear energy.

2014 Symposium on International Safeguards: Linking Strategy, Implementation and People. CNSC participants made significant contributions to the symposium, including the CNSC's own Karen Owen-Whitred's high-profile role as special rapporteur (pictured above, second from right). CNSC staff also presented on Canadian safeguards projects and contributed to sessions as panelists and chairs.

Nuclear material accountancy and reporting

One of the major areas of work in safeguards research focuses on the characterization of materials at the early stages of the fuel cycle. Licensees possessing nuclear material (uranium, thorium and plutonium) are required to report their holdings, and any inventory changes, to the CNSC. The CNSC uses these reports to establish a national system of accounts for nuclear material. This system of accounts helps fulfill Canada's obligations on IAEA safeguards agreements and Canadian bilateral nuclear cooperation agreements.

The CNSC carried out two research projects that addressed the challenging aspects of nuclear material measurements at two large Canadian bulk handling facilities. The first project was initiated with the goal of increasing the validity of the CNSC's analysis of Cameco's material accountancy practices. Third-party experts RadSci Research reviewed the measurement uncertainties declared by Cameco for the uranium contents of specific in-process vessels at the Port Hope Conversion Facility. The project involved a site visit to the facility, during which Cameco supplied the contractors with the data required to carry out their analysis. RadSci Research produced a report with their evaluation on the facility's measurement system and recommendations for improvement. The CNSC will use the information in the report to evaluate the facility's calculation of its nuclear material balance, and work together with the facility to look at the possibilities of improving their measurement system.

The purpose of the second project was to verify the Cameco Blind River Refinery's uranium trioxide (UO_3) tote bin accountability scale, which IAEA measurements had indicated may be biased. During the investigation process, it was found that the Blind River Refinery's scale displayed approximately a 70-kg bias for each 13-tonne full UO_3 tote bin. This bias contributes to errors in the annual material balance evaluation required for safeguards accounting. Cameco has instituted actions to correct this bias and the CNSC is evaluating the adequacy of those actions.

Did you know? Cameco Corporation owns and is licensed to operate the Blind River Refinery in Blind River, Ontario. This facility refines uranium concentrate (yellowcake) from uranium mines around the world, including northern Saskatchewan, to produce uranium trioxide (UO_3), an intermediate product of the nuclear fuel cycle.

The UO_3 is then shipped from the refinery to the Port Hope Conversion Facility for further processing. The conversion facility processes UO_3 into both uranium dioxide (UO_2), which is used to manufacture fuel for power reactors in Canada, and uranium hexafluoride (UF_6), which is exported to companies in other countries for fuel enrichment and fabrication.

Guidance on safeguards implementation and technologies

The CNSC has used its considerable experience in the field of safeguards to contribute to multiple IAEA initiatives aimed at providing guidance in safeguards implementation to Member States. Various safeguards instruments, such as the VXI Integrated Fuel Monitor system and the Digital Cerenkov Viewing Device, have been developed for surveillance of CANDU facilities and for spent fuel verification. The CNSC supports the IAEA by providing inspector training in using these instruments which assist IAEA inspectors in making credible compliance assessments of any Member States that operate CANDU reactors. The CNSC also provided monetary support and participated in user acceptance testing as the IAEA developed the SPRICS 2.0 integrated software package which facilitates the management of tasks supported by Member State Support Programmes by consolidating all task information.

The CNSC was able to share its success in implementing Safeguards by Design by playing a significant role in the development of IAEA Safeguards by Design guidance documents for designers and operators of new nuclear facilities. Safeguards by Design is defined as the process of including international safeguards considerations throughout all phases of a nuclear facility lifecycle: from the initial conceptual design, through facility construction and operations, design modifications, and decommissioning. The CNSC, in cooperation with 11 other Member States, also assisted the IAEA in the development of four safeguards implementation practice guides. Two of the guides were developed in 2013 and published in December 2014 and February 2015, respectively. The IAEA is now performing an internal review of the remaining two guides and plans to have them published by the end of 2015. The two published guides, as well as many other useful documents are available on the IAEA website.

Application of safeguards to geological repositories

The CNSC's Raoul Awad presenting on security and safeguards in radioactive waste management at the IAEA 58th General Conference in Vienna, Austria.

The CNSC had the opportunity to represent Canada in two recent meetings of the Application of Safeguards to Geological Repositories group, which were held in Oskarshamn, Sweden during May 2014 and in Gyeongju, South Korea, during April 2015. The Application of Safeguards to Geological Repositories group explores methods for applying IAEA safeguards to repositories for safeguarded material, with emphasis on deep geological repositories for spent fuel. These meetings allowed the CNSC to ensure Canadian involvement in the development of safeguards on deep geological repositories and the advancement of Canadian technology to solve deep geological repository safeguards issues. Going forward, the CNSC plans to participate and represent Canada in the 2016 Application of Safeguards to Geological Repositories meeting, which will take place in Washington, DC.

Strengthening the next generation

Our research is strengthening the next generation of scientists. Building Canada's future scientific capacity is key to maintaining a safe, strong and innovative nuclear sector. The CNSC is committed to reaching out to young Canadians and capturing their interests early in their scientific careers.

CNSC students in a turbine hall during a maintenance outage. CNSC inspectors check that personnel in the turbine hall are wearing their dosimeters and the proper clearance badges. Inspectors check gamma levels, verify that radiation and danger signs are posted in appropriate places, and ensure that interzonal whole-body count monitors are functioning properly.

Did you know? Power plants, whether they are coal, gas, oil or nuclear, all work in a similar way. Heat is required to turn water into steam. The steam spins large turbines, which drive generators that produce electricity. In a nuclear power station, the steam generator performs the same work as a boiler in a coal-, gas- or oil-fired station; it uses nuclear fuel to boil water.

Putting students in the spotlight

First-prize student poster winner from Western University with UNENE President, Dr. Basma Shalaby.

The CNSC is a significant supporter of the University Network of Excellence in Nuclear Engineering (UNENE). UNENE is a not-for-profit organization that brings together Canadian universities, nuclear power utilities, research and regulatory agencies in support of nuclear education, as well as research and development capabilities at Canadian universities. Among many activities, UNENE has an annual student workshop that allows students to showcase their work through a poster session. The poster session attracts graduate students from universities across Canada, allowing them a valuable opportunity to present their research to industry and CNSC representatives. The CNSC continued to support the annual student poster session with a grant. Refer to UNENE website for more information.

Validation of fire codes

The CNSC provided funding to the University of Waterloo's Department of Mechanical and Mechatronics Engineering to validate fire models. The project uses a series of fire and smoke propagation experimental data obtained in a dedicated facility as part of the Organisation for Economic Co-operation and Development PRISME project. The findings to date have been published and presented at several venues: Canadian section of the Combustion Institute in Saskatoon (Canada), FM Global FireFoam fire modelling workshop in Norwood (USA) and the International Technical Meeting on Fire Safety and Emergency Preparedness for the Nuclear Industry (FSEP) in Mississauga (Canada).

Did you know? In the unlikely event of an accident at a major nuclear facility, such as a nuclear power plant, many different groups would be involved in the response. The CNSC requires nuclear power plant operators to have both a fire response capability and a security team to respond to different incidents that may occur onsite.

In addition to their emergency plans and procedures, operators must also maintain dedicated emergency response facilities, equipment, and an emergency response organization comprised of qualified and trained staff.

CNSC co-op student in a firetruck purchased as emergency mitigation equipment for a nuclear power plant.

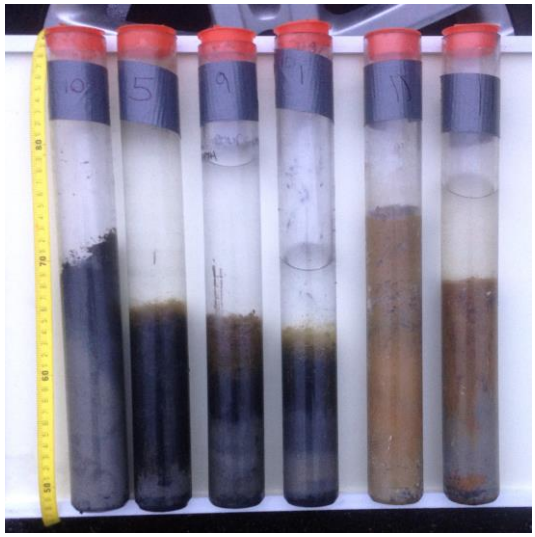
Nuclear energy literacy

Student Energy is a global non-profit organization that is creating a movement of young leaders committed to transitioning the world to a sustainable energy future. The organization has a suite of energy programs and is planning to expand its literacy program to include education on nuclear power and the safety precautions in place in the nuclear industry. The CNSC provided Student Energy a grant to support its expansion into nuclear literacy by increasing the roster of nuclear educational materials.

Research on the long-term evolution of uranium tailings

This project is investigating the geochemical and mineralogical characteristics of uranium mine tailings from the Denison tailings management area in Elliot Lake. This is a collaborative project with the University of Toronto, and the topic of a Master of Science (MSc) thesis to be completed in August 2015 and co-supervised by CNSC staff. The analytical results are being correlated with a previous CNSC research project focused on radium in Denison samples. Correlation of analytical results, observations, and calculated phase diagrams are being used to develop a geochemical model of tailings evolution. This study will contribute to identifying appropriate strategies for the management of uranium tailings over the long term, in support of regulatory licensing decisions on the monitoring and decommissioning of uranium mines in Canada.

University of Toronto MSc student collecting data in October 2014.



Gravity core samples from the Denison tailings management area in Elliot Lake.

Supporting the Deep River Science Academy summer program

Deep River Science Academy 2014 summer camp participants. While in attendance, students also participated in a number of extracurricular events. These included an evening lecture series hosted by the Canadian Nuclear Society's Chalk River branch, hiking in Algonquin Park, and a trip to Parliament.

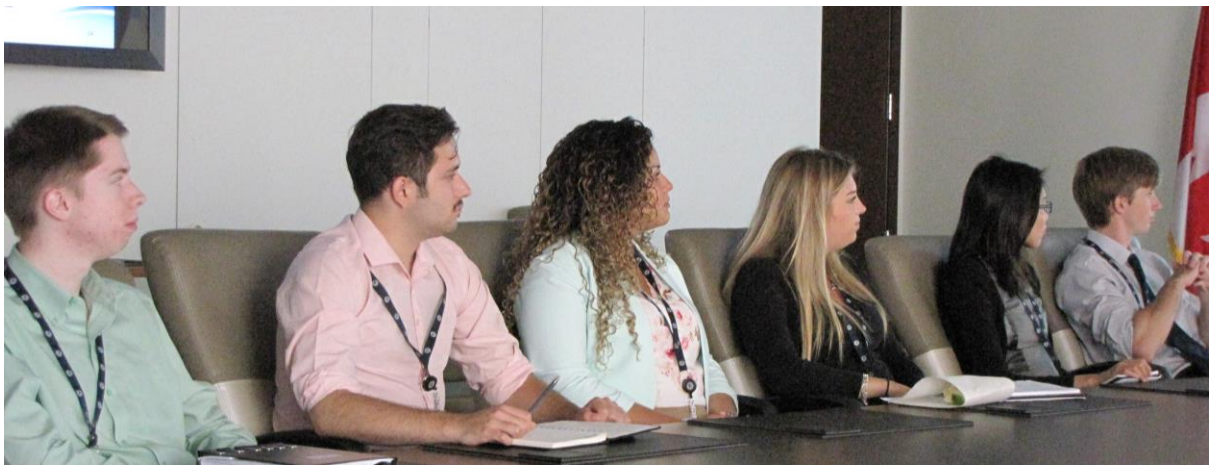
The Deep River Science Academy offers high school students the experience of hands-on scientific research under the mentorship of a university-level tutor and a professional scientist or engineer. Their work includes setting up experiments, gathering and analyzing data, writing technical reports, and presenting scientific findings. The CNSC has continued its longstanding support of the Deep River Science Academy by providing a grant for their summer program. The Academy's students perform research work, much of which is at the Chalk River Laboratories and is in the nuclear subject area; the CNSC supports the opportunity for young people to undertake projects in a research environment.

The CNSC also provided additional funding for the George Laurence Modelling Project with the Deep River Science Academy. As part of the activities, two students were mentored to perform physics modelling of Canada's first man-made critical chain reaction by George Laurence. After the discovery of nuclear fission chain reactions in 1939, Canadian nuclear physicist Dr. George Laurence was interested in the potential power the reactions could provide. Laurence performed pioneering experiments to test the possibility of a nuclear fission chain reaction in a carbon-uranium arrangement (or "pile" in early nuclear fission terminology). The two high-school students worked under the guidance of a research assistant/tutor to develop virtual models that closely replicated the outcome of George Laurence's uranium pile. This project was undertaken with the support of Atomic Energy of Canada Limited (now Canadian Nuclear Laboratories) and hinged on the use of modern software which can model reactor outputs. The students researched historical documents and papers written by George Laurence and others to determine what they thought the uranium pile would have "looked like" or how it was compiled. After developing a number of models, they input them into the software to see if they could replicate the result that George Laurence obtained in the 1940s. Refer to the Deep River Science Academy website for more information.

CNSC co-op program

The CNSC offers a unique co-op program for students pursuing careers in the areas of science and engineering. Over the course of 15 months, students are assigned to four different divisions where they have the opportunity to work with and learn from some of the world's foremost leaders in science, engineering and the environment. Students are exposed to the industry through facility and site inspections, licensee meetings, conferences, and various training courses. The co-op program has continued to grow in size and has captured the interest of many academic institutions across Canada. From technical specialists to project officers to nuclear and administrative professionals, the CNSC is always looking for talented individuals who are engaged, curious and eager to learn.

2014–15 co-op students with technical co-op program manager, Peter Gilmour.



Science and engineering students attending end-of-term co-op presentations. Pictured above is Chantal Yacoub (third from left), main author of the *The Science of Safety,* and co-author Kyle Cormier (second from left). After each rotation, co-op students are required to present an overview of their work term. This provides students an opportunity to enhance their presentation skills in a practical environment.

CNSC research in the years ahead

Comprehensive research is required to ensure the safe, continued operation of aging CANDU reactors in Canada. The ongoing refurbishment of the current CANDU fleet will be a major industry focus over the next 15 years, resulting in various research opportunities. The CNSC's research will continue to advance knowledge in assessing the safety margins of reactor pressure tubes, steam generators and other major components while taking aging degradation into account. Probabilistic analysis is also emerging as an important method to evaluate risk and uncertainty. Research in this area will provide confidence in the use of probabilistic safety assessments for risk-informed decision making. This research also supports regulatory reviews of licensees' use of advanced statistical approaches, in evaluating, for example, severe accidents and reactor trip set points.

The CNSC will continue to collaborate with other nuclear regulators to share information and best practices that ensure the safe long-term management of radioactive waste. Through the CNSC's Coordinated Assessment Research Program, regulatory research will seek to advance knowledge about the long-term suitability of underground radioactive waste storage in response to proposed deep geological repository sites. Research in this area is expected to expand as the industry progresses in developing alternative waste management facilities.

The CNSC will continue to perform regulatory research to support our staff and communicate research needs within the Government of Canada. Regulatory research will always focus on health, safety, security and the environment. The CNSC will continue to fulfill its mandate in disseminating objective scientific, technical and regulatory information to the public.

Glossary of terms

benthic invertebrate communities: The species composition of small aquatic organisms living in lake, stream and river sediments; the species present and their relative numbers are a biological indicator of the overall health of the aquatic environment.

bentonite: A type of absorbent clay with swelling properties commonly used as a filling and sealing material.

calandria: A cylindrical, unpressurized, stainless-steel vessel that holds a CANDU reactor's moderator. Pressure tubes containing the fuel and coolant span the two endplates of the calandria.

cohort: A group of people who can be analyzed for statistical purposes.

deep geological repositories: An underground, long-term management facility to store radioactive wastes.

Digital Cerenkov Viewing Device: A portable device that amplifies Cerenkov radiation emitted by spent fuel under water, which allows inspectors to verify inventories of spent enriched fuel.

electron: A stable elementary particle having a negative electric charge of 1.6×10^{-19} coulombs and a mass of 9.1×10^{-31} kg.

decommissioning: The process of safely eliminating radiological hazards from a facility.

high-level waste: Primarily used nuclear fuel that has been declared as radioactive waste. This type of waste also includes small amounts of radioactive waste from medical isotope production and other applications that generate significant heat via radioactive decay.

hydrazine: A non-radioactive chemical used to reduce corrosion.

intermediate-level waste: Waste that has been exposed to alpha radiation, or that contains enough long-lived radionuclides to require isolation and containment.

ionizing radiation: A form of radiation that is capable of adding or removing electrons as it passes through matter (such as air, water, or living tissue). Examples are alpha particles, gamma rays, X-rays and neutrons.

loss-of-coolant accident: A type of reactor accident that results in a loss of coolant due to a break in the primary heat transport system.

low-level waste: Waste material that is more radioactive than clearance levels and exemption quantities allow.

material balance evaluation: An activity performed to determine if recorded material inventory matches the physical material inventory. Differences in inventory at a material balance area can be explained as measurement uncertainty or as a reflection of other causes.

moderator: A material used to slow down or "moderate" neutrons produced by nuclear fuel. The moderator reduces neutron energy to slow neutrons to speeds at which they are more efficient in causing fission and generating a strong chain reaction.

probabilistic safety assessment: The probability, progression and consequences of equipment failures or transient conditions to derive numerical estimates that provide a consistent measure of safety.

radon progeny: Radon decay products that emit radiation hazardous to people's health when inhaled.

radioactive waste: Any liquid, gas or solid that contains a radioactive substance and which has been declared to be waste.

radionuclide: A nucleus of an atom that possesses properties of spontaneous disintegration. Nuclei are distinguished by their mass and atomic number. This term is often used synonymously with radioisotope.

reference condition approach: A statistical study design where the biological community at a potentially impacted site is compared to the biological communities at a variety of non-impacted or "reference" sites.

safety margins: A margin to the value of a safety variable for a barrier or system at which damage or loss would occur. Safety margins are considered for those systems and barriers whose failure could contribute to radiological releases.

synthetic aperture radar: A method of generating high-resolution remote sensing imagery when viewing with optical imagery is difficult or impossible. Synthetic aperture radar uses an airborne or satellite radar system to generate images by using the flight path to simulate the necessary large antenna, or aperture, electronically.

Annex: CNSC technical papers, presentations and articles

The CNSC's competence is well recognized by peers through papers published in scientific journals, conferences, workshops, and meetings of the Nuclear Energy Agency and International Atomic Energy Agency (IAEA). The CNSC submitted and presented two papers at the 13th International Society for Rock Mechanics congress in Montreal. Among the 475 peer-reviewed papers that were published in the Congress proceedings, a CNSC paper was chosen as one of the 10 best papers of the symposium. This paper, written by the CNSC's Dr. Son Nguyen, focuses on excavation damage in rock formations in deep geological repository applications.

The following is a list of 42 technical papers, presentations and articles published or presented by CNSC staff over the past fiscal year.

Subject	Presented at or published in	Date	Publisher or location delivered	Authors	Type
Laboratory investigation on the mechanical behaviour of Tournemire argillite	Canadian Geotechnical Journal	March 2015	NRC Research Press	H. Abdi, D. Labrie, T.S. Nguyen, J.D. Barnichon, G. Su, E. Evgin, R. Simon, and M. Fall	Peer-reviewed journal article
Human factors evaluation - Why? What? When?	The American Nuclear Society 9th International Topical Meeting on Nuclear Plant Instrumentation, Control and Human-Machine Interface Technology	February 22–26, 2015	Charlotte, North Carolina, U.S.	Alice Salway	Abstract of a technical paper
Impact of environmentally based chemical hardness on uranium speciation and toxicity in six aquatic species	Environmental Toxicology and Chemistry, 34(3):562-574	2015	Elsevier	Goulet R.R.; P.A. Thompson; K.C.Serben; C.V. Eickoff	Open-access, peer-reviewed journal article
Performance-based approach to the security of radioactive sealed sources: a Canadian perspective	The Journal of Physical Security, Volume 7(3), 2014	November 11, 2014	Argonne National Laboratory	Raphael Duguay	Peer-reviewed journal article
Evaluating the effects of uranium mining on benthic invertebrate communities in the Athabasca Basin of northern Saskatchewan	Society for Environmental Toxicology and Chemistry North America Meeting 35th Annual Meeting	November 9–13, 2014	Vancouver, BC	Kilgour, B.W., M. McKee and B. Dowsley	Conference presentation and poster
Establishing and advancing electronic nuclear material accounting capabilities: A Canadian perspective	IAEA's Symposium on International Safeguards: Linking Strategy, Implementation and People	October 20–24, 2014	Vienna, Austria	Jennifer Sample	Abstract of a technical presentation

Subject	Presented at or published in	Date	Publisher or location delivered	Authors	Type
Applicability of simplified human reliability analysis methods for severe accidents	7th International Conference on Modelling and Simulation in Nuclear Science and Engineering	October 18–21, 2015	N/A	G. Banaseanu	Abstract
Radiation protection during decommissioning of nuclear facilities in Canada	Technical Meeting on Occupational Radiation Protection	September 29, 2014	Vienna, Austria	N. Gadbois	Workshop presentation
Analyzing heat transfer between used nuclear fuel bundles in spent fuel pools using COMSOL Multiphysics	19th Pacific Basin Nuclear Conference (PBNC 2104)	August 24–28, 2014	Vancouver, BC	C.J Krasnaj and W. Grant	Abstract of a technical presentation
A stochastic-deterministic approach for evaluation of uncertainty in the predicted maximum fuel bundle enthalpy in a CANDU postulated LBLOCA event - Paper 319	The 19th Pacific Basin Nuclear Conference (PBNC 2014)	August 24–28, 2014	Vancouver, BC	D. Serghiuta / J. Thoammakkil	Abstract
A stylized approach for evaluation of incremental change in CANDU ROP/NOP trip functional failure probability under aging conditions - Paper 318	The 19th Pacific Basin Nuclear Conference (PBNC 2014)	August 24–28, 2014	Vancouver, BC	D. Serghiuta / J. Thoammakkil	Abstract
Basis for the derivation of the safety goals and new challenges	The 19th Pacific Basin Nuclear Conference (PBNC 2014)	August 24–28, 2014	Vancouver, BC	S. Yalaoui - additional presenters	Abstract
Cyber security for remote monitoring and control of small reactors	The 19th Pacific Basin Nuclear Conference (PBNC 2014)	August 24–28, 2014	Vancouver, BC	C.H. Jung	Abstract
Finite element analysis of heat transfer between spent CANDU fuel bundles in spent fuel pools	The 19th Pacific Basin Nuclear Conference (PBNC 2014)	August 24–28, 2014	Vancouver, BC	Cody Krasnaj - additional presenters	Abstract
Testing and qualification of confidence in statistical procedures	19th Pacific Basin Nuclear Conference (PBNC 2014)	August 24–28, 2014	Vancouver, BC	D. Serghiuta, J. Tholammakkil, N. Hammouda; A. O'Hagan - UK	Abstract of a technical paper
Understanding and verification of severe accident mitigation actions	The 19th Pacific Basin Nuclear Conference (PBNC 2014)	August 24–28, 2014	Vancouver, BC	Q. Lei - additional presentors	Abstract
Establishing and advancing electronic nuclear material accounting capabilities: a Canadian perspective	55th Annual Meeting of the Institute of Nuclear Materials Management	July 22, 2014	Atlanta, Georgia, U.S.	Jennifer Sample	Abstract of a technical presentation

Subject	Presented at or published in	Date	Publisher or location delivered	Authors	Type
Testing of statistical procedures for use in optimization of reactor performance under aged conditions	22nd International Conference on Nuclear Engineering ICONE22	July 7–11, 2014	Prague, Czech Republic	D. Serghiuta, J. Tholammakkil, N. Hammouda; A. O'Hagan - UK	Abstract of a technical presentation
Statistical analysis of common cause failure events using ICDE data	PSAM12	June 22–27, 2014	N/A	S. Yalaoui	Abstract
Balanced design of a CANDU 6 NPP: Insights from full and simplified PRA models	PHWR Safety 2014 / CANSAS 2014	June 23–26, 2014	Ottawa, ON	A. Patel, Y. Akl, G. Banaseanu, R. Gheorghe	Abstract
Evaluation of severe accident mitigation actions through simulation	PHWR Safety 2014 / CANSAS 2014	June 23–26, 2014	Ottawa, ON	Q. Lei, C. French, P. Devitt and A. Viktorov (CNSC)	Abstract of a technical presentation
Numerical prediction of heat transfer and pressure tube/calandria tube deformation during a contact boiling test	PHWR Safety 2014 / CANSAS 2014	June 23–26, 2014	Ottawa, ON	A. Tanase, A. Delja, A. Oussoren, J. Szymanski	Abstract of a technical presentation
Overview of CANDU safety R&D in Canada	PHWR Safety 2014 / CANSAS 2014	June 23–26, 2014	Ottawa, ON	W. Shen	Abstract
Regulatory evaluation of the research and development activities in support of nuclear safety	PHWR Safety 2014 / CANSAS 2014	June 23–26, 2014	Ottawa, ON	A. Viktorov	Abstract of a technical presentation
Regulatory perspective on CANDU feeder lifecycle management	PHWR Safety 2014 / CANSAS 2014	June 23–26, 2014	Ottawa, ON	S. Liu, S. Eom & J. Jin	Abstract
Fukushima accident implications on PSA and on the licensing of NPPs in Canada	Probabilistic Safety Assessment & Management (PSAM 12) Conference	June 22–24, 2014	Honolulu, Hawaii, U.S.	Y. Akl, S. Yalaoui	Abstract
Overview of CNSC approaches for assessment and management of fish mortality resulting from the operation of Canadian nuclear generating stations	2014 American Fisheries Society Annual Meeting	June 17–18, 2014	Quebec, QC	K. Ji	Conference Presentation

Subject	Presented at or published in	Date	Publisher or location delivered	Authors	Type
Radiation protection training and exercises related to severe accident management	EG-SAM International workshop on Occupational Radiation Protection in Severe Accident Management - Sharing Practices and Experiences	June 17–18, 2014	NEI, Washington DC, U.S.	S. Djeffal	Workshop presentation
Mechanics of bedded argillaceous rocks – the HG-A experiment at Mont Terri	NWMO Geoscience seminar	June 9–11, 2014	Collingwood, ON	T.S. Nguyen and Le D.A.	Workshop presentation
Regulatory research on geological disposal of radioactive wastes	NWMO Geoscience seminar	June 9–11, 2014	Collingwood, ON	T.S. Nguyen and K. Lange	Workshop presentation
Fukushima Daiichi nuclear accident: Health implications	Canadian Radiation Protection Association Annual Conference, Vancouver, British Columbia	May 27, 2014	Vancouver, BC	Julie Burtt (presenter), Rachel Lane	Conference Presentation
Enhancement of the maintenance regulation and oversight	The 10th International Conference on CANDU Maintenance	May 25–27, 2014	Toronto, ON	Y.C. Liu	Abstract
An overview of Canada's regulatory research program on deep geological repositories	Geological Association of Canada / Mineralogical Association of Canada May 2014	May 22, 2014	GACMAC	J.L. Brown, S. Nguyen, G. Su, K. Lange	Conference presentation
CANDU heat sinks improvements as a follow up to Fukushima Daiichi accident "The regulator perspective"	ENC 2014, The European Forum to discuss Nuclear Technology Issues, Opportunities & Challenges	May 11–15, 2014	Marseille, France	N. Mesmous and C. Harwood (CNSC)	Abstract of a technical presentation
Regulatory framework and insights from fire PSA of Canadian nuclear power plants	OECD/NEA International Workshop on Fire PRA	April 28–30, 2014	Garching, Germany	U. Menon	Abstract of a technical presentation
CANDU safety research and development in Canada: Current progress and challenges	2014 Canada-China Conference on Advanced Reactor Development (CCCARD-2014)	April 27–30, 2014	Niagara Falls, Ontario	W. Shen (CNSC), F. Doyle (CANDU Owners Group)	Abstract of a technical presentation
Simultaneous gas and water flow in damage-susceptible bedded argillaceous rock	Canadian Geotechnical Journal, 10.1139/cgj-2013-0457	April 17, 2014	NRC Research Press	T.S. Nguyen (CNSC) and A.D. Le	Peer-reviewed journal article

Subject	Presented at or published in	Date	Publisher or location delivered	Authors	Type
Emergency mitigating equipments – post Fukushima actions at Canadian nuclear power plants portable AC power sources	CSNI International Workshop on Robustness of Electrical Systems of NPPs in Light of the Fukushima Dai-Ichi Accident	April 1–3, 2014	Paris, France	Jasmina Vucetic, Ram Kameswaran and Krishnan Ramaswamy (CNSC)	Abstract of a technical presentation
A coupled hydro-mechanical model for simulation of gas migration in host sedimentary rocks for nuclear waste repositories	Geology, Vol. 17, pp. 24-44	March 25, 2014	NRC Research Press	Son Nguyen (CNSC)	Peer-reviewed journal article
Hydro-mechanical response of a bedded argillaceous rock to excavation and water injection	Canadian Geotechnical Journal. 10.1139/cgj-2013-0324	March 25, 2014	NRC Research Press	A.D. Le and T.S. Nguyen	Peer-reviewed journal article
Leukemia, lymphoma and multiple myeloma mortality (1950–1999) and incidence (1969–1999) in the Eldorado uranium workers cohort	Environmental Research	March 1, 2014	Elsevier	Lydia B. Zablotska, Rachel S.D. Lane, Stanley E. Frost, Patsy A. Thompson	Peer-reviewed journal article
Maintenance regulation and oversight for Canadian nuclear power plants	The 2014 EPRI Maintenance Rule Workshop	February 5–6, 2014	Charlotte, North Carolina, U.S.	Yong Chang Liu	Abstract of a technical presentation