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Oral Presentation

Exposé oral

Submission from the Ontario Clean Air Alliance

Mémoire de la Ontario Clean Air Alliance

In the Matter of

À l'égard de

Ontario Power Generation Inc., Pickering Nuclear Generating Station

Ontario Power Generation Inc., centrale nucléaire de Pickering

Request for a ten-year renewal of its Nuclear Power Reactor Operating Licence for the Pickering Nuclear Generating Station

Demande de renouvellement, pour une période de dix ans, de son permis d'exploitation d'un réacteur nucléaire de puissance à la centrale nucléaire de Pickering

Commission Public Hearing – Part 2

Audience publique de la Commission – Partie 2

June 2018

Juin 2018

Canada

Ontario Clean Air Alliance Submission to the Canadian Nuclear Safety Commission re: Ontario Power Generation's Application for a 10-Year Renewal of the Pickering Nuclear Station's Operating Licence

May 3, 2018

It is the Ontario Clean Air Alliance's (OCAA) submission that the Pickering Nuclear Station should be closed on August 31, 2018, when its licence expires since its continued operation creates an "unreasonable risk" to the health, safety and financial well-being of the residents of the Greater Toronto Area (GTA).

The Pickering Nuclear Station is surrounded by at least twice the population of any other nuclear station on the continent. Accidents happen, as we've seen many times in the past. Specifically, according to a report prepared by Dr. Ian Fairlie, a *Fukushima-level* accident at the Pickering Nuclear Station could:

1. cause approximately 26,000 cancers of which approximately half would be fatal;
2. require the evacuation of more than 150,000 homes and more than 650,000 people for 30 to 100 years or more, including the complete evacuation of the City of Pickering for at least 100 years;
3. cause a $125 billion loss in the value of single family homes in the GTA; and
4. require the re-routing of Highways 401, 404 and 407 and the CN/CP/GO rail lines to avoid highly contaminated areas.[1]

It is simply undeniable that a major incident at Pickering would result in catastrophic outcomes – for our health, our economy and our environment. We should only accept such a severe risk profile if there are no alternatives to meet a critical need. That is not the case with the Pickering Nuclear Station since importing power from Quebec offers a viable alternative to continuing to operate the Pickering Nuclear Station.

According to an Ontario Clean Air Alliance Research report, we can close the Pickering Nuclear Station and lower our electricity bills by $1.1 billion per year by importing Quebec water power.[2] The Quebec Government and Hydro Quebec have both made it abundantly clear that they would welcome an agreement to export significantly more power to Ontario. Hydro Quebec's average export price in 2017 was 4.7 cents per kWh, half of the Pickering Station's fuel and operating costs alone (9.2 cents per kWh).

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[1] Ian Fairlie, *A Fukushima-Level Nuclear Accident at Pickering: An Assessment of Effects*, Ontario Clean Air Alliance Research, (March 2018).
[2] Ontario Clean Air Alliance Research, *We have better choices: It's time to close the aging Pickering Nuclear Plant*, (April 3, 2018).

The Independent Electricity System Operator has told the OCAA that we have sufficient existing transmission capacity to import enough power from Quebec to replace the power produced by Pickering and needed in Ontario. In the few hours a year (less than 1%) when there may be some import constraints, Ontario has more than sufficient natural-gas fired generation to fill the gap, just as it does during the 30% of the hours (on average) of the year when Pickering is offline for repairs.[3]

According to a public opinion survey, conducted by Oraclepoll Research in September 2017, 82% of the residents of Scarborough, Pickering and Ajax support importing Quebec water power to close Pickering and lower our electricity bills.[4]

We cannot justify the risks and uncertainty of operating an aging nuclear plant surrounded by millions of people when there are perfectly viable, popular, lower cost and much safer alternatives.

What then should we do with Pickering if we close it when its license expires in August, 2018? According to the International Atomic Energy Agency, '*immediate dismantling'* is the preferred decommissioning strategy when nuclear plants are closed.

According to a report prepared for Ontario Clean Air Alliance Research by Ralph Torrie, immediate dismantling of the Pickering Nuclear Station could create 32,000 person-years of direct and indirect employment and permit much of the Pickering site to be returned to the City of Pickering within approximately 14 years (i.e., by 2032).[5] This would be a tremendous boost for the City of Pickering, opening major new opportunities for waterfront revitalization, similar to what is occurring in Mississauga where the former site of the Lakeview Coal Plant is being transformed into new neighbourhoods, parks and offices.

In addition, according to a report prepared for the OCAA by Dr. Gordon Thompson, the large levels of spent nuclear fuel at the Pickering site pose significant radiological risks, proliferation risks, and program risks.

For example, if the Pickering Nuclear Station's licence is renewed, by 2024 there will be more *plutonium* in the Pickering Waste Management Facility (PWMF) than in ALL active nuclear warheads worldwide. While this plutonium is not warhead grade, it is perfectly adequate for constructing low-yield weapons that would still have devastating impacts.

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[3] Ontario Clean Air Alliance Research, *We have better choices: It's time to close the aging Pickering Nuclear Plant*, (April 3, 2018).
[4] Oraclepoll Research, *Pickering Nuclear Station Survey Report*, (September 2017).
[5] Ralph Torrie, Torrie Smith Associates, *Direct Decommissioning of the Pickering Nuclear Station: Economic and Other Benefits*, (March 2016).

We need to end the denial of the risk posed by this waste and acknowledge that a long-term off-site storage solution is nowhere in sight. Pickering may well become a long-term waste storage site by default, which means that the sooner we stop producing difficult to manage, high-risk waste, the better.

Dr. Thompson states that the immediate dismantling of the Pickering Nuclear Station would facilitate a reconfiguration of the PWMF to substantially reduce the risks posed by storing spent nuclear fuel (including plutonium) at Pickering. Specifically, Dr. Thompson is recommending the following measures, referred to as HOSS (Hardened Onsite Storage), to increase security:

1. The dry storage containers with the spent nuclear fuels be placed inside free-standing, above-ground, attack-resistant, reinforced-concrete vaults (i.e., large boxes with heavy doors) cooled by natural convection of air;
2. Each vault roof be covered by a layer of gravel and rock;
3. Each vault floor be a few meters above grade;
4. All of the vaults be completely surrounded by a boundary structure, which in cross-section would be partly a reinforced concrete wall and partly a gravel-and-rock berm;
5. The boundary structure would form a continuous perimeter except for one access portal protected by heavy gates;
6. The road passing through the access portal should have chicanes;
7. The boundary structure be designed to appear, from the outside, ugly and threatening; and
8. Signs describing the facility's hazardous contents be built into the exterior of the boundary structure.

According to Dr. Thompson, the new facility could be constructed on land currently occupied by electrical switchyards and parking lots at the station. This would consolidate the significant waste that has accumulated at Pickering into a much more secure facility while allowing for surrounding areas to be transformed into a public park, assuming achievement of the necessary level of decontamination.[6]

Recommendations

1. The Pickering Nuclear Station should be permanently shut down when its existing operating licence expires on August 31, 2018.
2. The Pickering Nuclear Station should be completely dismantled and decommissioned between 2018 and 2032.
3. The Pickering Waste Management Facility (PWMF) should be reconfigured to substantially reduce the risks posed by storing spent nuclear fuel (including plutonium) at Pickering.

[6] Gordon Thompson, Institute for Resource and Security Studies, *Storage of Spent Nuclear Fuel at the Pickering Site: Risks and Risk-Reducing Options*, (May 2018).

Attachment 1

A Fukushima-Level Nuclear Disaster at Pickering:

An Assessment of Effects

DANGER – DO NOT CROSS – DANGER – DO NOT CROSS – DANGER

by Dr. Ian Fairlie
for Ontario Clean Air Alliance Research

March 2018

Foreword

by Jack Gibbons, Chair OCAA

This report considers what would happen if a serious nuclear accident, similar in extent to what took place in Fukushima, Japan in March 2011, were to occur at the Pickering Nuclear Station just east of Toronto. In other words, what would happen if similar levels of radiation and a similar fallout distribution pattern occurred after an accident at Pickering?

The answer is alarming. The modelling done by radiation expert Dr. Ian Fairlie finds that an estimated 26,000 cancer cases would arise over subsequent years, of which roughly half would be fatal. Large areas of the Greater Toronto Area, including potentially Pickering, Markham, Newmarket, Aurora and northern Scarborough, would need to be evacuated and would become uninhabitable in some cases for 100 years or more.

This report considers what would happen if a serious nuclear accident, similar in extent to what took place in Fukushima, were to occur at the Pickering Nuclear Station.

Major transportation links, including Highways 401, 404 and 407 and the CN / CP / GO Transit rail lines would now pass through heavily contaminated "no go" areas, probably requiring massively expensive re-routing or detours. Meanwhile, thousands of residents would essentially lose their homes with evacuation and no-entry periods ranging from 30 to more than 100 years affecting access to more than 154,000 homes. The economic losses of these uninsured housing losses (homeowner insurance does not cover nuclear accidents and Ontario Power Generation's liability is capped at $1 billion[1]) would exceed $125 billion. Of course, the economic consequences would extend far beyond these housing losses, with all economic activity grinding to a halt in a major part of the eastern Greater Toronto Area.

It is important to note that the exact chain of events that led to the Fukushima disaster does not have to be replicated to result in an accident of a similar scale here. Nuclear energy, by its very nature, presents extraordinarily high consequences for failure. Assurances that "it can never happen here" should be contrasted with the surprising regularity of nuclear accidents, with one major accident occurring roughly every 10 years worldwide.[2] This unfortunate history, of course, started with a major accident at the Chalk River reactor in Ontario in 1952.[3] (For a full list of the many accidents at nuclear plants around the world, see https://en.wikipedia.org/wiki/List_of_nuclear_power_accidents_by_country)

A common theme in these and many other high impact, low probability events (such as airplane crashes) is human error. For example, one study concerning the failure of valves in nuclear reactors reported that "human error was responsible for 47.4% of the failures in Boiling Water Reactors and 45.7% in Pressurised Water Reactors. The main causes of failure were design and maintenance errors. Administration, fabrication, installation, and operator errors were the other human causes of valve failure."[4]

The Pickering Nuclear Station is the fourth oldest nuclear stations in North America and one of the largest.[5] It relies on systems – including computer systems – designed in the 1960s and '70s. Many experts have noted that the plant has fundamental design flaws that would be unacceptable in newer facilities, a positive void coefficient and a shared containment system for multiple reactors that leaves it prone to the kind of cascading failures that devastated Fukushima. (See http://www.cleanairalliance.org/pickering-safety/ for more on the plant's safety issues, including how its design could lead to a nuclear chain reaction dangerously speeding up when there is a loss of coolant accident).

The Pickering Station is surrounded by more people (within 30 km) than any other nuclear plant on the continent.

The Pickering Station is surrounded by more people (within 30 km) than any other nuclear plant on the continent.[6] It is also on the shores of Lake Ontario, an interconnected Great Lake that supplies millions of people with drinking water. It is highly questionable whether such a plant would ever be built in a location like this today. That is partly because we also understand the growing range of threats to such high-risk facilities, including cyberattacks. For example, the U.S. Department of Homeland Security issued an urgent report in July 2017 warning that hackers had targeted the Wolf Creek Nuclear Operating Corporation, which runs a nuclear power plant in Kansas.[7]

The Pickering Nuclear Station also has the highest operating costs of any nuclear plant in North America,[8] so the fundamental question becomes is it worth the risk of continuing to operate this aging plant? This question is especially pertinent given that demand for electricity in Ontario has been steadily dropping for the last decade – demand has fallen by the equivalent of the power needed to supply all the homes in the City of Toronto twice over since 2005.[9] Currently, roughly half of the power Pickering produces is exported out of province, often at a loss.[10]

Meanwhile, the Province of Quebec has made it very clear that it is interested in making a deal to supply Ontario with safe, waste-free water power. In the summer of 2017, it was reported that Hydro Quebec had offered Ontario power for 20 years at a cost of five cents a kilowatt hour (kWh).[11] This is roughly half of Pickering's current per kWh operating cost and roughly a third of what Ontario Power Generation (OPG) is seeking to be paid for power from rebuilt or extended-life reactors at Pickering and Darlington.

In January 2018, Hydro Quebec signed a deal to supply Massachusetts with power at a cost of 3 to 5.3 cents per kWh.[12] The CEO of Hydro Quebec stated at the time that the company would be pleased to make a similar deal with Ontario. Meanwhile costs for other sources of renewable energy continue to fall. The Province of Alberta, for example, recently received bids to supply wind power at a rock bottom cost of 3.7 cents per kWh.[13] This is even lower than the 6.3 cents Quebec agreed to pay in its last wind power auction, an example of the trend toward ever lower costs for solar and wind. In Ontario, meanwhile, the Independent Electricity System Operators reports that energy efficiency savings cost it 2.2 cents per kWh in 2016 and projects that there remains massive potential to increase efficiency.[14]

The consequences of a major accident at the Pickering would be severe. Safer and less expensive options for meeting our power needs are readily available. There seems little reason to continue operating a high-risk facility that has already surpassed its design life. It is time to stop risking lives and turn to safer alternatives.

The consequences of a major accident at the Pickering would be severe. Safer and less expensive options for meeting our power needs are readily available.

Endnotes

1 http://nuclearsafety.gc.ca/eng/acts-and-regulations/acts/nuclear-liability-and-compensation-act.cfm

2 https://en.wikipedia.org/wiki/List_of_nuclear_power_accidents_by_country
See also https://nuclear-energy.net/nuclear-accidents

3 https://nuclear-energy.net/nuclear-accidents/chalk-river.html

4 http://158.132.155.107/posh97/private/Dissertation_resources/Human_factors/Human_errors.html

5 Ontario Clean Air Alliance Research Inc., *Closing the Pickering Nuclear Station in 2018: A Cost-Benefit Analysis*, (June 17, 2016), page 1.

6 Ontario Clean Air Alliance Research Inc., *Closing the Pickering Nuclear Station in 2018: A Cost-Benefit Analysis*, (June 17, 2016), page 1.

7 https://www.nytimes.com/2017/07/06/technology/nuclear-plant-hack-report.html

8 Ontario Power Generation, *2015 Nuclear Benchmarking Report*, (November 2015), page 69.

9 Ontario Clean Air Alliance, "Ontario's nuclear dreams no match for the reality of falling electricity demand", *Bulletin*, (January 22, 2018).

10 Ontario Clean Air Alliance Research Inc., *How we can close the Pickering Nuclear Station and lower bills*, (September 27, 2016).

11 Pierre Couture, "Hydro Quebec l'Ontario en ligne de mire", *Journal de Montreal*, (August 16, 2017).

12 Ross Marowits, "Hydro-Quebec says U.S. export deal will keep local power rates below inflation", *National Post*, (January 25, 2018).

13 https://www.alberta.ca/release.cfm?xID=511572D67D28E-C09C-E3E6-BA37A772B-4C34AF6

14 Ontario Clean Air Alliance Research Inc., *Making the most of our efficiency potential to lower rates*, (September 26, 2017).

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About the Author

Dr. Ian Fairlie is an independent Canadian consultant on environmental radioactivity. He has a PhD from Imperial College of Science, Technology and Medicine in London UK ; an MSc from the Medical College of St Bartholomew's Hospital in London UK; and a BSc from Western University in Canada.

Dr. Fairlie's doctoral studies at the Imperial College of Science Technology and Medicine in the UK and at Princeton University in the US examined nuclear waste technologies. He has been an employee of, and consultant to, UK government departments and UK environmental regulators for many years. He was also the scientific Secretary to the UK Government's Ministerial Committee Examining Radiation Risks of Internal Emitters (www.cerrie.org). In addition, Dr. Fairlie has acted as consultant to the European Parliament, World Health Organization, and local governments.

Dr. Fairlie's areas of expertise include the dosimetric impact of nuclear reactor emissions and he has written extensively on epidemiology studies of child leukemias near nuclear facilities, and the hazards of tritium. More information is available at www.ianfairlie.org.

Cover photo of Fukushima Station: Greenpeace International

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Executive Summary

This report examines what would happen if a serious nuclear accident, similar in extent to that at Fukushima, Japan in March 2011, were to occur at the Pickering Nuclear Station east of Toronto. In this report, we have modeled what would happen if similar amounts of radioactivity were released and a similar fallout distribution pattern occurred after an accident at Pickering.

Our models estimate that 26,000 cancer cases would arise over subsequent years, of which approximately half would be fatal. Large areas of the Greater Toronto Area, including Pickering, Markham, Newmarket, Aurora and northern Scarborough, would need to be evacuated and would become uninhabitable in some cases for 100 years or more.

We used very conservative assumptions in determining these estimates, for example excluding health impacts such as thyroid cancers and radiation-related strokes and cardiovascular illnesses for which widely accepted risk factors are not available. We also only partially accounted for the higher risks faced by women and did not factor in the higher risks for children and older people when exposed to radiation. We also assumed that areas with the highest exposures would remain effectively evacuated.

However, even with these conservative assumptions, our estimate of cancer cases is significantly higher than for Fukushima for the simple reason that the Pickering NGS is located in a large, densely populated urban area while Fukushima Prefecture is largely rural.

Fukushima also benefitted from winds that, at the time of the accident, were blowing out to sea. For Pickering, similar winds could blow radioactivity out across Lake Ontario, but the fallout for surrounding and cross-lake populations would still be dire. And given that 2.2 million people live within 30 kilometres of the plant, we can confidently say that there are likely no scenarios under which a Fukushima-scale accident would not have severe consequences.

As it is, our models also estimate that more than 154,000 houses would be affected by evacuation orders and re-entry prohibitions lasting from 30 to more than 100 years. Hundreds of thousands of residents would lose their homes. The economic value of single residence house losses alone is estimated to exceed $125 billion. Of course, the economic consequences would extend far beyond the loss of homes.

We conclude that the continued operation of the Pickering NGS creates a "hostage to fortune" situation for everyone in Ontario. The Ontario Government has the clear duty to protect its citizens from the very serious consequences that would arise if a Fukushima-level accident were to occur at the Pickering NGS.

Inspecting the remains of the Fukushima Nuclear Plant

1. Introduction

This report examines what would happen in Ontario should a Fukushima-level nuclear accident occur at the Pickering Nuclear Generating Station (PNGS). The six operating reactors at Pickering NGS have lengthy histories of accidents, serious leaks, poor performance, and high operating costs. Many concerns have been expressed that there are more people within 30 kilometres of the PNGS than any other nuclear station in North America. In fact, it lies within the Greater Toronto Area with a population exceeding 6 million people (Statistics Canada, 2017).

In 2014, the German Government's Strahlengschutzkommission (SSK – German Commission on Radiological Protection) called[1] for contingency planning for "accidents whose radiological effects mirror those of Fukushima." Accordingly, this report will discuss the consequences of a serious nuclear accident, similar to that at Fukushima, Japan in 2011, occurring at Pickering. In particular, it assumes that the same amounts of fallout that actually occurred in Japan would be distributed over the Greater Toronto Area (GTA).

It is reasonable to do this as the situations at Pickering and Fukushima have many features in common:

- The Fukushima nuclear power station had six reactors; Pickering has six operating reactors and two that have been idled and defueled. At Fukushima, three reactors were on line at the time of the accident. At Pickering NGS, all six operational reactors could be operating at any given time.
- The three Fukushima nuclear units that exploded had generating capacities of 440, 780 and 780 MW, for a total of 2,000 MW. The net in-service capacity of the Pickering Nuclear Generating Station currently is 3,094 MW[2]
- Located beside large bodies of water
- Located in areas with mainly flat topographies
- Large quantity of zirconium alloy cladding present (the cause of H_2 explosions)
- No protection against hydrogen detonations (as at Fukushima)
- Very old reactors past their design operating lifetimes, and
- Operating within a government nuclear culture and a closed management system that does not acknowledge high levels of nuclear risks.

The report assumes a major nuclear accident at Pickering would release the same quantity of radioactivity as the Fukushima accident in 2011. It assumes the same weather patterns that occurred in Japan and the same deposition patterns. Based on these parameters, we then superimposed the radioactive fallout pattern from Fukushima on Southern Ontario, centred on Pickering NGS, to map potential fallout areas here. Our maps are based on radioactive fallout maps created by independent Japanese scientists and by the Japanese Government from official Japanese fallout data.

[1] https://www.ssk.de/SharedDocs/Beratungsergebnisse_E/2014/Notfallmassnahmen_e.html

[2] Ontario Energy Board Docket No. EB-2016-0152, Exhibit A, Tab 4, Schedule 3, Page 2

The use of maps to illustrate the effects of nuclear accidents is neither new nor unprecedented. For example, as we shall show below, many maps were published of the radioactive fallout at Fukushima. In addition the 2006 TORCH Report (cricket.biol.sc.edu/chernobyl/papers/TORCH.pdf) shows several official maps of the radioactive fallout from the Chernobyl nuclear catastrophe in 1986, which affected much of Europe and eventually travelled right around the world.

More recently, Professor Frank von Hippel, senior research physicist at Princeton University, Dr. Michael Schoeppner, former postdoctoral researcher at Princeton, and Dr. Edwin Lyman, senior scientist at the U.S. Union of Concerned Scientists co-authored a paper (www.sciencemag.org/news/2016/05/spent-fuel-fire-us-soil-could-dwarf-impact-fukushima) that modelled the serious effects of hypothetical radionuclide releases if an accident were to occur at U.S. nuclear fuel storage sites. This paper contained maps illustrating the radioactive plumes across northeast United States (www.tandfonline.com/doi/full/10.1080/08929882.2017.1318561).

Our report also estimates the collective doses and the numbers of cancer cases and fatal cancers arising from a Fukushima-style accident as if this had occurred at Pickering. It also estimates the time periods that heavily contaminated areas would need to be evacuated, and the losses in market values of single residence homes located in the long-term evacuation zones.

2. What Happened at Fukushima?

On March 11, 2011, the Great Tōhoku earthquake, with a magnitude of 9.0 - 9.1 on the Richter scale, occurred in the Pacific Ocean about 120 kilometres from the Fukushima Daiichi Nuclear Power Plant in Japan. This initiated huge tsunamis, about 15 metres high, which swamped the power station 40 minutes later.

Immediately after the earthquake, the three operating reactors were shut down, due to the cessation of electricity supplies to and from the Japanese grid as a result of the earthquake. However large amounts of heat continued to be generated by radioactive decay of the nuclear fuel. The following tsunami then flooded the basements of the reactor buildings, thereby disabling the emergency generators needed for powering the pumps to cool the reactors. From March 12th-15th, the insufficient cooling led to a series of hydrogen explosions,[3] large scale releases of radioactive aerosols, gases and other material, and nuclear meltdowns in Units 1, 2, and 3. Loss of cooling also caused the storage pool for spent fuel at Unit 4 to overheat on March 15th due to decay heat from its spent fuel rods.

In July 2012, the Japanese Parliament established the Fukushima Nuclear Accident Independent Investigation Commission,[4] which found that the causes of the accident had been foreseeable and that the plant operator, Tokyo Electric Power Company (TEPCO), had failed to meet basic safety requirements such as risk assessment, preparing for containing collateral damage, and developing evacuation plans.

In October 2012, TEPCO admitted that it had failed to take necessary measures for fear of inviting lawsuits or provoking protests against its nuclear plants. A large number of lawsuits against TEPCO and the Japanese Government are currently winding their way through the Japanese courts.

[3] The precise nature of these explosions remains a matter of debate.

[4] https://reliefweb.int/sites/reliefweb.int/files/resources/NAIIC_report_lo_res2.pdf

AIR PHOTO SERVICE

Destroyed reactors at Fukushima

Almost seven years later, the accident is continuing. TEPCO is still spraying cooling water on the destroyed reactors in order to avert further explosions. Neither TEPCO nor the Japanese Government knows the precise whereabouts or the conditions of most of the melted fuels inside or under the ruined reactors. TEPCO is still discharging contaminated cooling water into the Pacific Ocean.

The toll from the Fukushima nuclear disaster is high.

- Over 160,000 people[5] were evacuated from the most contaminated areas. The Japanese Government is currently trying to force evacuees to return to their contaminated homes by threatening financial penalties, albeit with little success.
- Many cases of post-traumatic stress disorder (PTSD), depression, anxiety disorders and suicides arose from the evacuations themselves.
- Approximately 12,000 workers[6] were exposed to high radiation levels.
- From UNSCEAR data[7], it can be estimated that approximately 5,000 fatal cancers will arise in future from radiation exposures, plus similarly high rates of radiogenic strokes, cardiovascular diseases and hereditary diseases.
- An as yet unquantified number of thyroid cancers is expected to arise.
- Official figures reveal that between 2011 and 2015 about 2,000 deaths occurred from the radiation-related evacuations due to ill-health and suicides, especially among elderly people.[8]
- 8% of Japan's land area (30,000 km^2), including parts of Tokyo, were contaminated.[9]
- Economic losses have been authoritatively estimated[10] at more than U.S. $188 billion.

Despite this high toll, Japan was actually lucky in terms of radiation exposures as over 80% of the radioactive emissions from the reactors were carried by prevailing winds out to sea: only 20% fell on land.[11] If 100% of the radioactive emissions had landed on the Japanese mainland, the toll would have been much greater.

Radioactive water storage tanks

5 http://www.ianfairlie.org/wp-content/uploads/2015/08/Summing-up-the-Effects-of-the-Fukushima-Nuclear-Disaster-10.pdf

6 Fukushima Nuclear Accident Independent Investigation Commission https://reliefweb.int/sites/reliefweb.int/files/resources/NAIIC_report_lo_res2.pdf

7 http://www.unscear.org/docs/reports/2013/13-85418_Report_2013_Annex_A.pdf

8 http://www.reconstruction.go.jp/topics/main-cat2/sub-cat2-1/20141226_kanrenshi.pdf

9 http://www.unscear.org/docs/reports/2013/13-85418_Report_2013_Annex_A.pdf

10 https://www.reuters.com/article/us-tepco-fukushima-costs/japan-nearly-doubles-fukushima-disaster-related-cost-to-188-billion-idUSKBN13Y047

11 thereby contaminating the offshore U.S. aircraft carrier USS Ronald Reagan and its ~3,000 crew.

3. Radiation Exposures to the Japanese People

Japanese people were exposed to radiation in two separate time periods: during the first pass of the radioactive plumes; and over subsequent years from the radioactive fallout deposited on the ground.

During the First Pass

The first pass occurred when radioactive plumes[12] from the stricken reactors passed through populated areas. These plumes consisted of radioactive gases, vapours and volatilised solids such as tritium, carbon-14, cesium-137, etc. (see www.who.int/ionizing_radiation/a_e/fukushima/faqs-fukushima/en/).

People living in the paths of these plumes were exposed to radiation in a variety of ways:

- Via external radiation (gamma radiation, beta radiation)
- Direct radiation from the radioactive gases in the plume
- Direct radiation from fallout deposited on the ground (mainly Cs-134, Cs-137)
- Direct radiation from re-suspension and re-deposition of fallout
- Via internal radiation (mostly beta radiation)
- Inhalation of radioactive gases (e.g. H-3 [tritium], C-14, I-131, Xe-133, Xe-135, Kr-85) and vapours in the passing plume
- Inhalation of fallout re-suspended by natural and man-made processes
- Absorption of radioactivity through the skin (tritium and C-14)[13]
- Ingestion of radioactively contaminated food and water (tritium and C-14)[14]

KYOKO YOKOMA, EXPOSURE: TALES FROM FUKUSHIMA

Radiation monitoring station

During Subsequent Years

After the plumes have passed and deposited their fallouts, people can be exposed to continuing radiation mainly from Cs-137 and Cs-134 which have relatively long half-lives (30.1 and 2.06 years, respectively) and which were volatilised in large amounts during the Fukushima accident.

The main exposures are from the direct radiation emanating from the plume's fallout deposited on the ground, with smaller exposures from the inhalation of ground matter re-suspended by natural and man-made processes, and from the ingestion of food and water contaminated by re-suspended fallout.

[12] Contrary to what many people assume, the plumes resulted when the reactors were deliberately vented by TEPCO to avoid explosions, and not from the explosions themselves at the units.

[13] https://www.voanews.com/a/japan-fukushim-tritium-contaminated-water-into-pacific/3995414.html

[14] https://www.nature.com/articles/srep36947

Exposures also result from the many hundreds of poorly managed “bag farms” (see back cover photo), which contain radioactive topsoil, from radioactive waste sites, from municipal waste incinerator emissions, and from consumption of contaminated wild foods such as boar, mushrooms and fish.

These exposures can continue for years and even decades,[15] as discussed in section 9.

[15] http://www.ianfairlie.org/news/new-unscear-report-on-fukushima-collective-doses/#_ftn1

4. Could a Major Nuclear Accident Happen at Pickering?

The Fukushima catastrophe was due to the coincidence of two main factors. First, rare events of nature (i.e., a force 9.0 earthquake and its accompanying tsunami) and, second, the technical vulnerability of the Fukushima reactors to these events.

As regards to the first matter, possible events include earthquakes, extreme weather occurrences, malevolent (terrorist) attacks, airplane crashes, electromagnetic pulses from the sun, and electricity blackouts.

On plane crashes, in 2008 the Canadian Nuclear Safety Commission (CNSC, 2008) severely questioned Ontario Power Generation (OPG) on the matter. It "…asked OPG if it had considered the probability of an aircraft crash near the Pickering B nuclear plant. OPG answered that this type of question was not of public domain but added that this scenario and its impact were considered. To a second question from the Commission to find out if there was a no-fly zone over PNGS, OPG answered negatively. OPG added that the level of risk or frequency of an airplane accident did not require such a consideration."[16]

On seismic risks, in 2011, the CNSC acknowledged that potential seismic risks exist near Pickering and Darlington Nuclear Generating Stations and acknowledged that in recent years they had both experienced minor damage due to low magnitude earthquakes (CBC News, 2011).

Small earthquakes (below magnitude 3 on the Richter scale) occur regularly in Lake Ontario near the Pickering and Darlington nuclear stations. As stated above, according to the CNSC (CBC News 2011, 2013) larger earthquakes (above magnitude 3) have already caused noticeable damage to these stations. The St. Lawrence Rift Zone runs under Lake Ontario, and independent Ontario seismologists have stated that seismic hazards along the St. Lawrence Rift Zone are underestimated (Wallach et al 1998, p.763). CNSC and OPG claim that emergency plans exist for these earthquakes.

As regards to the second matter of reactor vulnerability, potential matters include human error, reactor design flaws, reactor malfunctions, the growing risk of cyberattacks and the old age (>40 years) of the reactors. If a nuclear accident or accidents were to occur at Pickering, the consequences would depend on the circumstances of the accident, the number of reactors online at the time of the accident, how long the reactors had been operating since they were last refuelled, and crucially, on the wind directions and strengths at the time of the accident and for days afterwards.

It is important to note however that this study does NOT make any assumptions or develop any scenarios regarding a specific possible accident at Pickering. Instead it uses actual Japanese fallout patterns, weather patterns and published dose contours and transplants these to Ontario, centred on Pickering.

[16] http://www.suretenucleaire.gc.ca/eng/the-commission/pdf/2008-12-10-Decision-PickeringB-e-Edocs3330500.pdf see pp. 17; 75.

At 47 years old, the Pickering Nuclear Station is the 4th oldest in North America and the 7th oldest in the world. It has officially exceeded its "design life" and is surrounded by more people (within 30 kilometres) than any other nuclear plant in North America.

5. Maps of Radioactive Fallout

If a severe accident were to occur, fallout from the resulting radioactive plumes would be deposited downwind of the nuclear station. As stated earlier, fallout patterns are best visualised by maps, and many maps of Fukushima's radioactive fallout have been published.

On the following pages are two dose contour maps of Fukushima's radioactive fallout that have been superimposed on Southern Ontario. The first, Figure 1, shows the contours of lower (pale blue) doses and the second, Figure 2, the contours of much higher doses. The Japanese maps and the Ontario maps onto which these have been superimposed have identical scales and are similar in orientation.

Figure 1 is based on an original map of the contours of radiation doses from Cs-134 and Cs-137 fallout in March 2011 created by Professor Yukio Hayakawa, a vulcanologist at Gunma University in Japan. He is an acknowledged expert on the mapping of radioactive fallout from volcanic eruptions and is independent of the nuclear industry. His own map of Fukushima fallout can be found at kipuka.blog70.fc2.com/blog-entry-418.html. The Japanese map showing simplified dose contours (dark green and magenta) can be found at i.pinimg.com/originals/d6/67/0b/d6670b14b39f517832f355ffd38aa317.jpg

The radiation dose rate from fallout in the pale blue areas lies between 0.25 µSv/hour and 0.5 µSv/hour (radiation dose units are explained in the box on this page). The radiation dose unit here is microsieverts per hour, which is a millionth of a sievert (Sv) per hour. However, we need to multiply this by the 8,760 hours in one year to obtain the yearly exposure. When we do this, the doses in the pale blue areas lie between 2.5 and 5 mSv in the first year and in the magenta area greater than 5 mSv in the first year.

The range of estimated first year doses (2.5 to 5 mSv) used in this report is broadly consistent with the (1.0 to 7.5 mSv) range of first year doses estimated by UNSCEAR (2013) for non-evacuated areas of Fukushima Prefecture.

The fallout data sources from which Professor Hayakawa compiled his dose contour map are comprehensive and were obtained from the following sources:

- Fallout data from aerial monitoring maps from the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) (August 31, 2011 revised version)
- Map plots from the Japanese MEXT (www.nnistar.com/gmap/fukushima.html)
- The Hayakawa team's own detailed measurements in mountainous area (Gunma and Tochigi Prefectures)
- Horiba scintillator radioactivity measurements
- Local data from a number of individual sources

Radiation Dose Units

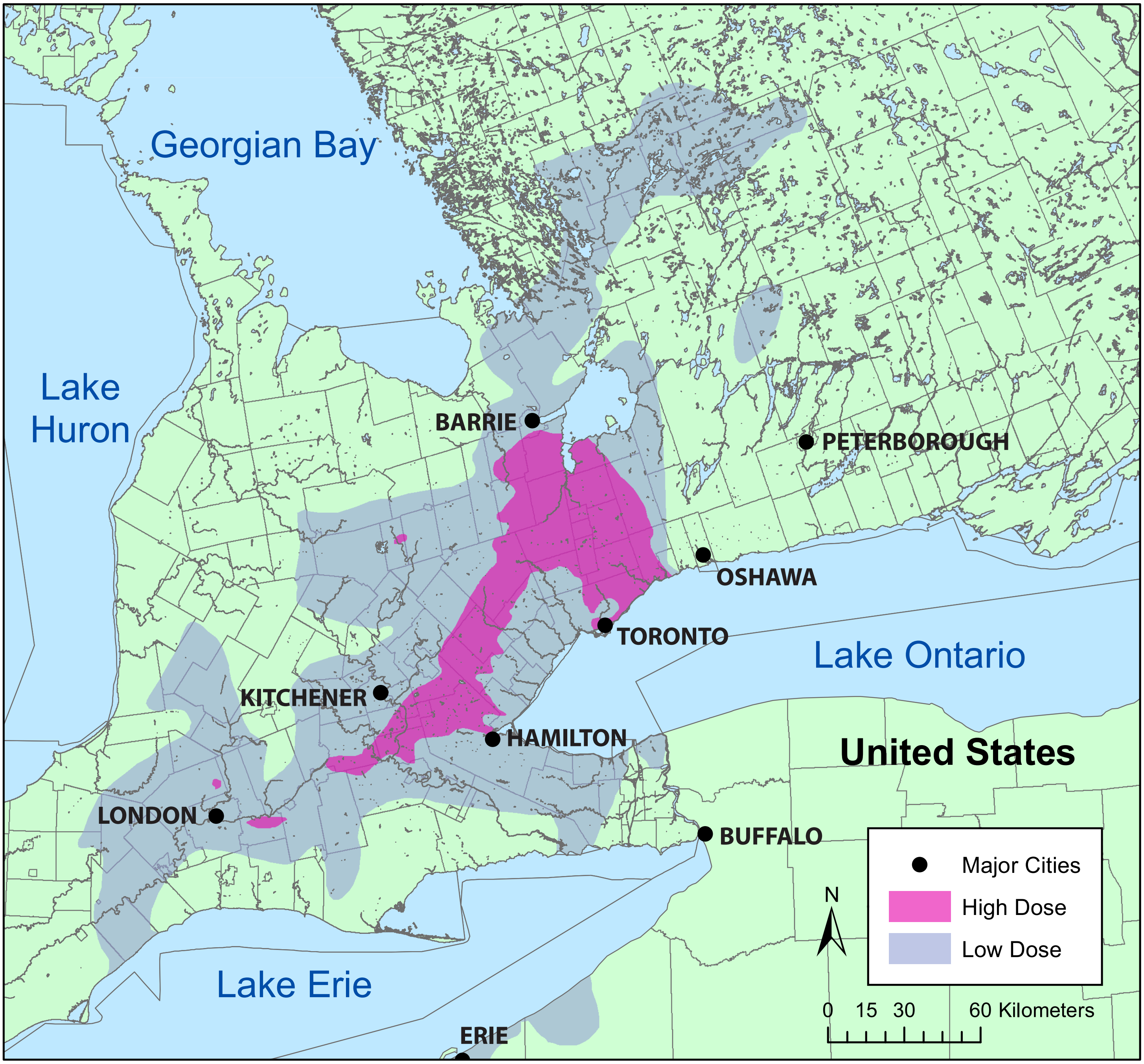
Exposures to radiation are usually measured in sieverts (Sv). In general terms, one Sv means that one joule of radiative energy has been absorbed in one kilogram of tissue. This is a very large amount of radiation. For example, 6 Sv is often considered a fatal radiation dose.

One millisievert (mSv) is equal to one thousandth of a sievert. One mSv is the annual public limit for radiation exposures in Canada.

Even this is often too large and a smaller unit is used. One millionth of a sievert is one microsievert (µSv) and there are 1,000 µSv in a mSv.

Their relationships are as follows: 1 Sv = 1,000 mSv = 1,000,000 µSv

Figure 1: Low Doses (light blue area)
Fukushima Fallout Centred on Pickering Superimposed on Southern Ontario

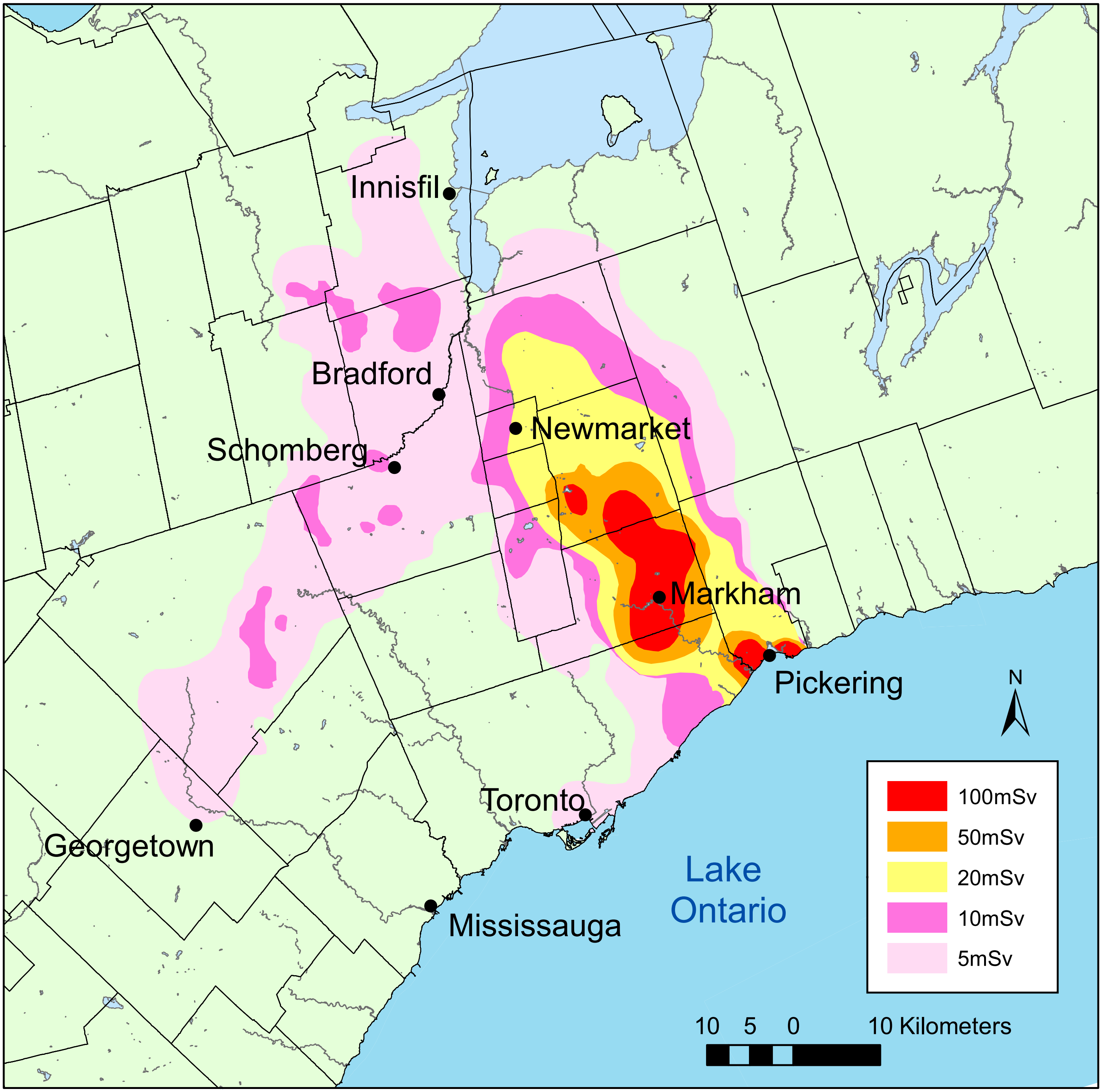


Credits: Dose contours as discussed in report. Contours reproduced with permission of Dr. Yukio Hayakawa, adapted by Edinburgh Energy and Environment Consultancy and Lynx Graphic Design.

Statistics Canada. Boundary Files. 2006. Statistics Canada Catalogue No. 92-160-X2006001. Published by Statistics Canada. http://www12.statcan.gc.ca/census-recensement/2011/geo/bound-limit/bound-limit-2006-eng.cfm Reproduced and distributed on an "as is" basis with the permission of Statistics Canada.

United States Census Bureau. TIGER/Line Shapefile, 2016, nation, U.S., Current County and Equivalent National Shapefile. 2016. Published by United States Census Bureau.

Figure 2: High Doses (red, orange and yellow areas)
Fukushima Fallout Centred on Pickering NGS Superimposed on Toronto and Surrounding Areas



Credits: Dose contours derived from Institut de Radioprotection et de Sûreté Nucléaire Report DRPH/2011-10 (IRSN, 2011) adapted by Edinburgh Energy and Environment Consultancy and Lynx Graphic Design.

Statistics Canada. Boundary Files. 2006. Statistics Canada Catalogue No. 92-160-X2006001. Published by Statistics Canada. http://www12.statcan.gc.ca/census-recensement/2011/geo/bound-limit/bound-limit-2006-eng.cfm Reproduced and distributed on an “as is” basis with the permission of Statistics Canada.

The Japanese map created by Professor Yukio Hayakawa reveals the widespread extent of fallout from Fukushima, including areas of greater Tokyo. This map is not used on official Japanese websites as it shows fallout in areas that Japanese authorities do not include in most of their own maps, especially areas in and near Greater Tokyo. The main reason for this exclusion is that Japanese radiation authorities prefer not to observe the Linear No Threshold model[17] of radiation's effects adhered to by all other radiation authorities around the world (i.e., UNSCEAR, WHO, IRSF, ICRP, BEIR VII and CNSC). For this reason, the Japanese Government's Ministry of Education, Culture, Sports, Science and Technology (MEXT) refrains from showing doses below 5 mSv per year in its maps. This practice is scientifically inaccurate. Such doses should be shown as radiation's adverse effects exist even at very low exposure levels. Accordingly, we have shown them in Figure 1.

Figure 2 is ultimately based on an official dose contour map produced during aerial monitoring by the U.S. Department of Energy and the Japanese Ministry of Education, Culture, Sports, Science and Technology (August 31/2011 revised version available at radioactivity.nsr.go.jp/en/contents/4000/3180/24/1304797_0506.pdf).

Unlike Figure 1, in Figure 2 it is reasonable to use official sources as these show doses down to 5 mSv per year. The colour legends indicate doses in the first year only. This map indicates that, if the Fukushima accident had occurred at Pickering NGS, very high radiation exposures would have occurred in Greater Toronto and its surrounding areas.

Assuming the same releases and weather patterns seen at Fukushima occur at Pickering, we can use these maps to assess average doses and population numbers affected and thereby estimate collective doses and expected numbers of future cancer cases and cancer deaths in Ontario. The detailed calculations are shown next.

[17] This assumes that radiogenic harm declines linearly with doses all the way to zero, without a threshold. In other words, there is no 'safe' dose of radiation.

Over 160,000 people were evacuated in the wake of the Fukushima disaster.

6. Estimated Collective Doses in the Toronto Region (First Year)

The average dose rate in the first year in the light blue areas in Figure 1 is the average of 0.25 + 0.5 µSv per hour = 0.375 µSv per hour. This equates to an average dose of 3.285 mSv per year (i.e., x 8,760 hours in a year[18]). To obtain collective doses we need to multiply this figure by the populations affected (listed in Appendix A). The total population in the light blue areas is currently 5,820,276.

Therefore, we can multiply average dose in the area bounded by light blue – 3.285 mSv – by 5,820,000 people to obtain a collective dose of 19,120 person Sv in the first year.

For Figure 2, it is necessary to estimate the populations in the red, orange, yellow, and pink areas. This was done by examining the dose contours in Figure 2 and matching them with the populations of affected municipalities from Statistics Canada (2017). The results are shown in Appendix B. It is acknowledged that this procedure will introduce uncertainties, as it is assumed that populations are homogenously distributed over all land areas. However, this is a routine assumption used in estimating collective doses.

As it is difficult to precisely differentiate the maroon from the pale blue areas in Figure 1, this procedure may involve some double counting of areas in Figures 1 and 2. However, considerable efforts were made to minimize this and there could also be small overlooked areas that would mitigate any double counting. The effect of any double counting on this report's final collective dose estimate would be small in any case. The average annual dose in Figure 1's pale blue area is small – only 3.75 mSv per year. So even in the unlikely event that 100,000 people were double counted, the resulting collective dose would only be 370 person Sv – about 2% of the original estimated collective dose.

Figure 2 shows dose contours (in red) of a first year dose of 100 mSv in four highly exposed areas – parts of Markham, Whitchurch/Stouffville, Richmond Hill and Pickering – with a total of 210,000 people. Assuming this to be an average dose (some people will have higher doses and some lower), then these highly exposed areas would receive a first year population dose of 210,000 x 100 mSv = 21,000 person Sv.

However, it is conservatively assumed that this area would be evacuated therefore lowering exposure. But because evacuations are unlikely to be fully effective, it is also assumed that a quarter of the first year dose will accrue, i.e., 5,250 person Sv. This estimate is based on the understanding that evacuations are only about 75% effective based on actual experience at Fukushima (information communicated orally to the author during study tours to Fukushima Prefecture in 2015 and 2016) and due to the following factors:

- residents who refuse to be evacuated
- residents who return
- emergency personnel who are exposed
- late evacuees who are contaminated with radioactivity
- the safety areas for evacuees may not be free of fallout, and
- it may take several months for all evacuations to take place.

[18] Several studies have shown that, as indoor Cs-137 concentrations are similar to outdoor concentrations, reductions to take into account that people live indoors are unconservative.

The map also gives a smaller dose area (orange) with an average first year dose of 50 mSv. Assuming a smaller population of 146,000 x 50 mSv x 0.25, we obtain a collective dose of 1,825 person Sv for this area.

For the yellow dose area of 20 mSv in the first year and a 297,000 population with 75% evacuating, we arrive at a collective dose of 297,000 x 20 mSv x 0.25 = 1,485 person Sv.

For the dark pink 10 mSv dose area in the first year, we take the population of 383,000 and arrive at a collective dose of 383,000 x 10 mSv = 3,830 person Sv. No reduction is applied here for evacuation as this only occurs for average doses greater than 20 mSv.

For the light pink 5 mSv dose area in the first year, we use the population of 1,818,000 to obtain a collective dose of 1,818,000 x 5 mSv = 9,100 person Sv.

These figures are set out in Table 1 below. In total, during the first year, the exposed areas of Figures 1 and 2 add to 40,610 person Sv, correct to two significant figures. (In view of the uncertainties here, only two significant figures are used in the estimated total.)

Table 1. Collective Doses from First Year Exposures

	Average Dose in First Year – mSv	Assumed Fraction Evacuated	Populations (see appendices A and B)	Collective Doses – Person Sv
Figure 1				
Pale Blue Area	3.285	not evacuated	5,820,000	19,120
Figure 2				
Red area (evacuated)	100	75%	210,000	5,250
Orange area (evacuated)	50	75%	146,000	1,825
Yellow area (evacuated)	20	75%	297,000	1,485
Dark Pink area	10	not evacuated	383,000	3,830
Light Pink area	5	not evacuated	1,818,000	9,100
TOTAL				**40,610**

7. Estimated Collective Doses (Years 2 to 10)

After the passage of the plumes, exposures will continue mostly from the plumes' fallout on the ground, initially mainly from Cs-134 (half-life = 2.06 years) and later from Cs-137 (half-life = 30.1 years).

In the past, it had been assumed that weathering would result in the relatively quick disappearance of radiocesiums from soil. However recent data on continuing high levels of Cs soil concentrations after Chernobyl (Drozdovitch et al, 2007) have indicated this is not the case and that Cs concentrations persist for decades. Drozdovitch et al tracked radioactivity beyond residence time on vegetation to include its migration into soil, using a weathering attenuation factor with two half-life time constants of 2.4 years and 38 years – both considerably longer than previous estimates (Beyea J, E Lyman and F von Hippel, 2013). As a practical example of this, in the U.K., persistently high Cs concentrations in soils in Cumbria and Wales from Chernobyl fallout lasted from 1986 until 2012. The result was that the U.K. Government had to issue food restriction orders prohibiting the sale of lamb from farms in these areas until 2012 (Fairlie, 2016).

It is therefore necessary to estimate the doses that occur over a longer time period than the first year. An additional nine years is chosen to make a 10-year period in total, as this is roughly the time period for which we have comparable experience (i.e., seven years since Fukushima in 2011). During this period, doses will decline in a similar fashion to that indicated in the graph below.

Graph 1: Dose Decline Curve

It is difficult to calculate accurately the average doses for years 2 to 10 as insufficient data are available, especially the initial ground concentrations of Cs-134 and Cs-137. For the first year, most of the dose will come from Cs-134 as it is considerably more radioactive[19] than Cs-137. On the other hand, Cs-134 decays more quickly than Cs-137, so that after about three years, the dose contribution from the latter exceeds the former.

Using the dose conversion factors and dose/surface concentration ratios published in Section E of the IAEA report on *Generic Procedures for Assessment and Response During a Radiological Emergency* (IAEA, 2000), it is possible to make the following estimates of the doses arising in years 2 to 10 inclusive. (See box opposite.)

For the pale blue areas in Figure 1, it is calculated that an average adult dose of 12.95 mSv will accrue over the years 2 to 10 after the accident – an approximately fourfold increase over the first year dose of 3.285 mSv. The total collective dose is 5,820,276 x 12.95 mSv = 75,370 person Sv.

For exposures in Figure 2, as doses will decline in the same way we can apply the same increase factor of four to the figures in Appendix B to obtain the collective doses set out in Table 2. No doses accrue in the red, orange and yellow areas as we conservatively presume that they remain evacuated.

Table 2. Collective Doses from Exposures in Years 2 to 10

	Average Dose Over 2-10 yrs	Population	Collective doses person Sv
Figure 1 Pale blue area	12.975 mSv	5,820,000	75,500
Figure 2 Dark pink area	10 x 4 = 40 mSv	383,000	15,320
Figure 3 Light pink area	5 x 4 = 20 mSv	1,818,000	36,360
TOTALS			**127,200**

The sums of the collective doses for the first year and years 2 to 10 from Figures 1 and 2 are set out in Table 3 below.

Table 3. Total Collective Doses

Exposures	Collective Doses Person Sv
First Year	40,610
Years 2- 10	127,200
TOTAL	**167,810**

In conclusion, it is estimated that the collective dose to Ontario from a Fukushima-level nuclear accident at Pickering would be 167,810 person Sv. As is conventional in scientific reports, rounding to two significant figures will be performed at the end of all calculations.

[19] The specific activity of Cs-134 is over 100 times greater than that of Cs-137

[23] Including the U.S. city of Erie, Pennsylvania, which was also affected

Calculations for External Doses from Cs Exposures for Years 2-10 after Fukushima

Assumptions Used

A. The first year average dose in Figure 1 pale blue areas = 3.285 mSv.

B. The initial soil Cs contamination from fallout is 50% from Cs-137 and 50% from Cs-134.[20]

C. Dose coefficients for Cs-137 = $6.5 \text{x} 10^{11}$ mSv/h per Bq/m^3 and Cs-134 = $17.0 \text{x} 10^{11}$ mSv/h per Bq/m^3: i.e. the Cs-134 dose coefficient is 2.615 times greater than the Cs-137 dose coefficient.

D. The dose coefficients (mSv/h per Bq/m^3) for external exposure are taken from IAEA data. (The values are based on homogeneous distribution in soil.)[11]

Methodology

Using a 50/50 mixture of Cs-134 and Cs-137, the dose contribution per Bq from Cs-134 = 2.615/2.615 + 1 = 72.3%

Therefore, in the first year, 72.3% of the average dose of 3.285 mSv = 2.375 mSv is from Cs-134. Similarly, in the first year, 27.7% of 3.285 mSv = 0.910 mSv is from Cs-137.

The table below indicates annual doses from both Cs-134 and Cs-137 as estimated by the radioactivity decay program www.radprocalculator.com/Decay.aspx

Year	Dose from Cs-134 mSv	Dose from Cs-137 mSv	Totals mSv
1	2.375	0.910	3.285
2	1.697	0.889	
3	1.213	0.869	
4	0.867	0.849	
5	0.620	0.830	
6	0.443	0.811	
7	0.317	0.793	
8	0.227	0.775	
9	0.162	0.757	
10	0.116	0.740	
TOTALS	**5.662**	**7.313**	**Years 2-10 = 12.975**

Therefore, the ratio of dose from years 2-10 to that from the first year = 12.975/ 3.285 = 3.95.

The ratio of 4.0 (to two significant figures) is consistent with other estimates produced using different assumptions and methodologies. For example, Ishikawa (2016) and Nagataki et al (2016) discuss the UNSCEAR (2013) ranges of estimated doses and cite a ratio of 3.3 for 10- year to first-year doses.

In addition, a ratio of 4 for the ratio of first year dose to the dose for years 2-10 is estimated by Tsuneki (2013) (in Japanese). [22]

[20] This is a reasonable assumption for two reasons. First, the UNSCEAR report on Fukushima (2013) stated on page 41 of Annex A that almost equal amounts of Cs-134 (9.0 PBq) and Cs-137 (8.8 PBq) were emitted at Fukushima. Second, Japanese MEXT data for 2011 as reproduced by Tsuneki (2013) indicate equal surface contributions of the two nuclides in 2011 in Japanese areas affected by fallout. See table 5.1 page 107 labelled Cesium 134 and 137 Fallout concentrations in Japanese cities in 2011. From MEXT Ministry of Education, Culture, Sports, Science and Technology "Results of environmental radiation level survey (monthly)."

[21] http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/37/101/37101600.pdf Reproduced from table 5.1.

[22] See Table 5.3 of on page 123 of the pdf version. Title of table - "Approximate estimate of annual dose when outdoor radiation dose rate from cesium was 1 μSv/h as of March 2012". http://www.gakushuin.ac.jp/~881791/radbookbasic/rbb20130117.pdf

GREENPEACE INTERNATIONAL

Farm produce remains contaminated by Fukushima's fallout and radiation levels remain unsafe in many areas of Fukushima Prefecture.

8. Estimated Numbers of Cancer Cases and Cancer Deaths in Ontario

We now need to estimate the likely numbers of (a) cancer cases and (b) fatal cancers expected to arise from this collective dose. Some official reports consider only fatal cancers but since the number of survivable cancer cases is usually double the number of fatal cancers, we need to consider these as well.

We shall use the latest official radiation risk estimates published in 2006 by the U.S. National Academy of Sciences in its report on the *Biological Effects of Ionizing Radiation - Part 2 BEIR VII* (US NAS, 2006). Table ES-1 (page 15) of the BEIR VII report contains the BEIR Committee's preferred estimates of the lifetime attributable of incidence (i.e., cases) and mortality (i.e., deaths) for all solid cancers. The U.S. report contains separate figures for males and females,[24] but these have been averaged here to simplify matters. The risks are presented in BEIR VII per 0.1 Sv but these have been presented per Sv here again to make matters clearer.

Finally, it is necessary to explain that the BEIR Committee's risks in 2006 were estimated using a Dose and Dose Rate Effectiveness Factor (DDREF). This reduced the Committee's preferred risks by a factor of 1.5. However, since the BEIR report's publication in 2006, new evidence has emerged showing that DDREFs should no longer be used. For example, neither the UNSCEAR (2013) nor the WHO (2012, 2013) reports on Fukushima used DDREFs in deriving their Fukushima risk estimates.

The WHO Report (WHO, 2013) on page 32 explained why as follows:

"Based on the findings of the two meta-analyses discussed above (74,92), which showed similar risks for protracted and acute exposures, the WHO- HRA Expert Group considered it prudent to base risk calculations on models derived from the atomic bomb survivors cohort without applying any modification factor for low dose or low dose rate. This decision, which represents a departure from standard practice in radiation risk assessment, was not unanimous as two members {out of 13} expressed a dissenting opinion."

This decision has been followed by the UNSCEAR (2013) report and by other reports since then.

Table 4. Absolute Radiogenic Risks of Cancer Cases and Fatal Cancers from Table ES-1 of BEIR VII (Risks to Males and Females Averaged)

Effect	Numbers per 100,000 People Exposed to 1 Sv	Radiation Risk	Radiation Risk Without DREF of 1.5
Cancer Cases (fatal and non-fatal)	10,500	10.5% per Sv	15.75% per Sv
Fatal Cancers	5,100	5.1% per Sv	7.65% per Sv

[24] It should be noted that these estimates are for risks to adults. Radiogenic risks to babies, infants, children, adolescents and to pregnant women are higher.

This report will therefore estimate the numbers of cancer cases and fatal cancers in Ontario as shown in Tables 5 and 6. The central estimates, correct to two significant figures, are that 26,000 cancer cases would arise, of which 13,000 (approximately half) would be fatal.

Table 5. Estimated Numbers of Cancers Cases in Ontario[25]

Collective Dose Person Sv	Risk of (Fatal and Non-fatal) Cancer Cases	Number
167,810	15.75%	26,430

Table 6. Estimated Numbers of Fatal Cancers in Ontario[25]

Collective Dose Person Sv	Risk of Fatal Cancer	Number
167,810	7.65%	12,840

[25] including Erie PA, US

9. Estimated Time Periods of Evacuations

Estimates can be made of time periods that the red, orange and yellow zones in Figure 2 would need to remain evacuated. These estimates were made using the online software at www.radprocalculator.com using the following assumptions:

- Cs-137 concentrations on contaminated land decline exponentially in line with Cs-137 radioactive decay with a half-life of 30.1 years
- linearity between Cs-137 concentrations and dose, and
- no external factors such as clean-ups, forest fires, and flash floods.

Ten mSv/a is the Ontario Government's recommended[20] "lower level" above which evacuations "should be applied unless valid reasons exist for deferring action." Such reasons are not defined in the emergency response plan.

In the yellow (20 mSv/a) zone, it is calculated that it would take about 30 years for the average dose rate to decline from 20 to 10 mSv/a, at which time it would be permissible to lift the evacuation orders. Similarly, in the orange zone, it would take about 70 years for the dose rate to decline from 50 to 10 mSv/a. And in the red zone, it would take about 100 years for the dose rate to decline from 100 to 10 mSv/a.

It therefore can be seen in Figure 3, that the red, orange and yellow zones of the Greater Toronto Area (GTA) may need to remain evacuated for about 100, 70 and 30 years respectively.

Some uncertainty would exist with these time estimates, as there is limited experience to draw upon. But they are in line with the situation at Chernobyl, where the ~3,000 km^2 evacuation zone remains in force with no prospect of being lifted despite it being more than 30 years since the accident. At Fukushima, about seven years after the accident, most of the evacuation zones are still in force with little prospect of major changes. In a few areas where average doses are now estimated by the Japanese Government to have fallen below 20 mSv/a (the Japanese threshold[27]), the government is attempting to compel[28] evacuees to return with limited success. (The author has visited Fukushima Prefecture twice in recent years during study tours to Japan, and it is apparent that many Fukushima citizens no longer trust their government or TEPCO and remain reluctant to return to their former homes.)

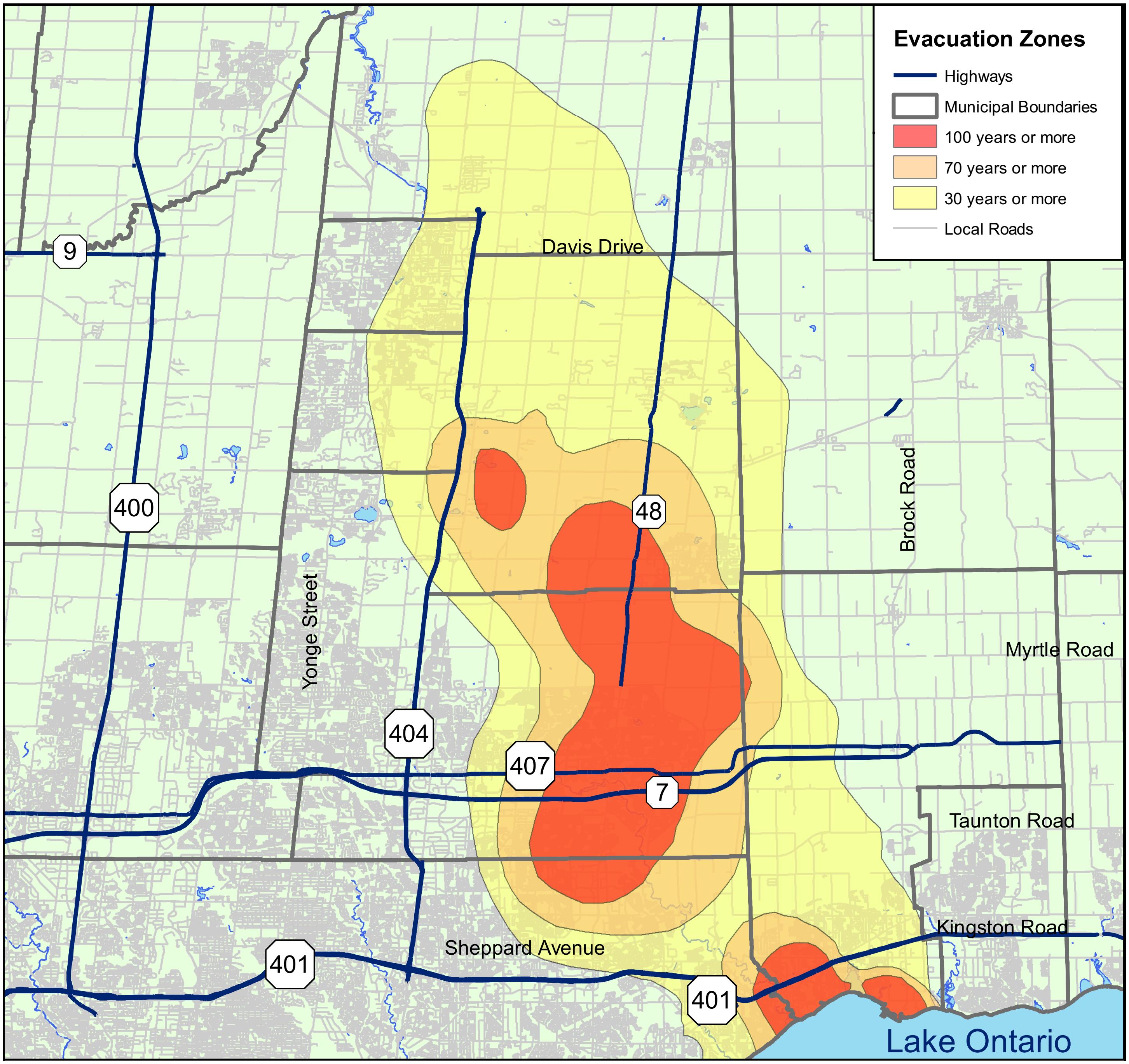
It is recognised that the above are simple estimations with large uncertainty ranges. However, they give an approximate indication of the time periods required for evacuations after a Fukushima-level disaster at Pickering.

[26] Provincial Nuclear Emergency Response Plan. Ontario Government. See Annex E – Protection Action Levels. https://www.emergencymanagementontario.ca/english/beprepared/ontariohazards/nuclear/provincial_nuclear_emergency_response_plan.html#P2618_168284

[27] Fukushima Nuclear Accident Independent Investigation Commission https://reliefweb.int/sites/reliefweb.int/files/resources/NAIIC_report_lo_res2.pdf

[28] by ceasing state compensation payments to evacuated residents

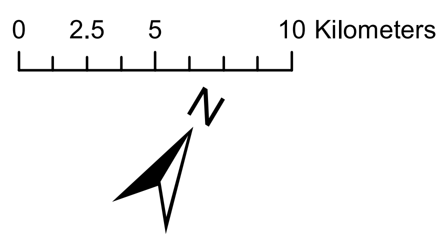
Figure 3: Time Periods of Evacuations



Source: Statistics Canada. Boundary Files. 2017. Statistics Canada Catalogue No. 92-160-X2016002. Published by Statistics Canada. http://www12.statcan.gc.ca/census-recensement/2011/geo/RNF-FRR/index-2011-eng.cfm?year=16 Reproduced and distributed on an "as is" basis with the permission of Statistics Canada.

Statistics Canada. Road Network File. 2017. Statistics Canada Catalogue No. 92-500-X2017001. Published by Statistics Canada. http://www12.statcan.gc.ca/census-recensement/2011/geo/RNF-FRR/index-2011-eng.cfm?year=16 Reproduced and distributed on an "as is" basis with the permission of Statistics Canada

ArcGIS for Desktop: 10.1.5, [Computer software]. (2017). Redlands, CA: ESRI.



Scale 1:270,000

10. Conservative Dose Estimation

In this report, significant efforts were made to avoid the overestimation of radiation doses. As a result, the dose estimates in this report should be viewed as underestimates rather than overestimates for the following reasons:

- A 10-year cut-off is used for collective doses, even though UNSCEAR and the EU use 70 years. This is because of the uncertainty about actual doses accruing in future years due to possible clean-up efforts, forest fires (which re-suspend radionuclides) and possible people movements into and out of affected zones.
- It is assumed that large-scale evacuations would take place for areas where average dose levels exceed 10 mSv (Ontario threshold for evacuations[29]) and will continue until they fall below this level.
- Doses from the plume overhead in the first year are not estimated because it is not possible to reconstruct them from the available data.
- Adult risk factors for fatal and non-fatal cancers are used: higher risk factors could have been used to take into account the increased radiogenic risks to babies, children, old people and the risks of genetic effects. This would have approximately doubled the risk factors.
- Risk factors were averages of the rates for both males and females. Women's risks from radiation exposures are about 50% greater than men's risks.
- Deaths from radiogenic cardiovascular disease, including strokes, have not been added. This would have approximately doubled the estimated number of deaths. The reason is that the existence of this risk and its risk factor are still not widely acknowledged even though the evidence for them is robust and from statistically significant Japanese bomb survivor data (Shimizu et al, 2010).
- A major source of conservatism is that this report assumes Fukushima levels of radioactive emissions in Ontario, which were due to explosions at three reactors with a total capacity of 2,000 MW. Pickering NGS currently has six operating reactors with a total capacity of 3,094 MW. If all six were assumed to explode (due to a common mode accident, e.g., earthquake and tsunami), it would be reasonable to assume that the radioactive releases would be approximately 50% greater than at Fukushima.

[29] Provincial Nuclear Emergency Response Plan. See https://www.emergencymanagementontario.ca/english/beprepared/ontariohazards/nuclear/provincial_nuclear_emergency_response_plan.html#P2618_168284

Mandatory long-term evacuations could result in the loss of $125 billion in assets for residents.

11. Economic Losses: House Value Loss

In Appendix C, we outline just one aspect of the economic price Ontario would pay for a Fukushima-scale accident at Pickering: housing value loss as a result of long-term evacuations and no re-entry orders. The estimated loss of $125 billion in housing value for homes within evacuation zones is in line with the estimates of economic losses at Fukushima of U.S.$ 188 billion (Can$ 236 billion). Home insurance policies routinely exclude coverage of nuclear accidents and OPG's total liability in the event of a nuclear accident is capped at $1 billion,[30] meaning homeowners would have no ready source of compensation for losses.

Of course, the loss of businesses, schools, hospitals and other infrastructure within the evacuation areas would rapidly inflate this loss figure further. Additionally, 26,000 cancer cases (half fatal) would also present an enormous economic and logistical strain on the health care system.

12. Conclusions

Cancer and Other Health Effects

This report estimates that, if a Fukushima-level nuclear accident were to happen at Pickering NGS, 26,000 cancer cases would arise of which 13,000 (approximately half) would be fatal (correct to two significant figures). This is a very large number compared, for example, to the 668 deaths estimated to arise each year if coal-fired power stations were permitted to continue operating in Ontario (DSS, 2005).

The kinds of cancer that could arise include cancers of the bone, lung, skin, intestine and other soft tissues. Blood cancers (e.g., leukemias and lymphomas) would also occur.

Thyroid cancers (TC) would be expected to arise similar to the epidemics of thyroid cancers after the Chernobyl nuclear disaster in 1986 (Fairlie, 2016). These are usually considered separately as they depend mainly upon specific thyroid exposures to radioiodine intakes. Stable iodine is an effective prophylactic and the Ontario Government has already pre-issued stable iodine (KI) tablets to residents within 10 kilometres of Pickering and will also send them to other residents who request them. However, it is hard to estimate how many people would actually ingest KI tablets in the event of an accident. Therefore, in this report the likely number of thyroid cancer cases which would arise has not been estimated.

Other radiation effects not considered here are long-term genetic (i.e., hereditary) effects, teratogenic effects (from doses to embryos and fetuses), eye cataracts, and cardiovascular disease plus stroke. The main reason for these exclusions is that there are, as yet, few internationally agreed risk factors for these effects.

[30] http://nuclearsafety.gc.ca/eng/acts-and-regulations/acts/nuclear-liability-and-compensation-act.cfm

It is recognized that the cancer estimates derived in this report will have uncertainty ranges. It is difficult to assign numerical limits to these uncertainties. This is the reason the two WHO (2012, 2013) and UNSCEAR (2013) reports on Fukushima cited earlier do not include uncertainty ranges in any of their estimates. Nevertheless, this report's estimates indicate the likely scale of the cancer effects if a Fukushima-level disaster were to occur at Pickering NGS.

In comparison, at Fukushima, UNSCEAR (2013) estimated a collective dose of 48,000 person Sv from which it can be estimated that about 5,000 fatal cancers would arise in future.[31] The reason why the effects in Ontario would be greater than those in Japan is that Southern Ontario is considerably more populated than Fukushima Prefecture, which is a largely rural area.

Long Term Evacuations and No Re-entry Zones

The report also shows that, if a Fukushima-level accident were to occur at Pickering, many thousands of people in the Greater Toronto Area could be exposed to high levels of radiation – over 100 mSv per year. Millions of Greater Toronto residents and workers could need to be evacuated for long periods of 30, 70 or 100 years as indicated in Figure 3. In other words, parts of Greater Toronto could become uninhabitable for several decades or longer.

Economic Losses

Finally, this report estimates that losses of home property values would exceed $125 billion. However, this is a partial estimate as similar losses would also have occurred in business, industrial, commercial, governmental and municipal properties, and in apartment and condominium values as well.

It is difficult to contemplate or internalize such huge consequences. In sum, the continued operation of the Pickering NGS creates a hostage to fortune for everyone living in the Province of Ontario.

Over 2,000 years ago Cicero, the Roman orator and lawyer, wrote "*Salus populi suprema lex esto*" – the health of the people is the highest law. By this standard, the Ontario Government has the clear duty to protect its citizens from the very serious consequences that would arise if a Fukushima-level accident were to occur at the Pickering NGS.

[31] See http://www.ianfairlie.org/news/assessing-long-term-health-effects-from-fukushimas-radioactive-fallout/

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The explosions at three reactors at the Fukushima Daiichi Nuclear Station had devastating consequences for the people of Japan.

The Fukushima accident is estimated to have resulted in $236 billion in economic losses for Japan.

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Appendix A: Populations in Contaminated Areas in Figure 1

Populations in pale blue areas in Figure 1 (average dose = 3.285 mSv/a)

Toronto City (50%)	1,365,786
Mississauga	721,599
Brampton	593,638
Hamilton	536,917
Kitchener-Cambridge-Waterloo	523,894
London	494,069
St. Catharines	406,074
Barrie	197,059
Oakville	193,832
Guelph	131,794
Markham (35%)	115,138
Halton Hills	61,161
Brantford (50%)	49,360
Woodstock	40,902
Stratford	31,465
Orangeville	30,734
Vaughan (10%)	30,623
Grimsby	27,314
Dundas	24,285
Fergus	20,767
Bracebridge	16,010
West Lincoln	14,500
Strathroy	14,401
Ingersoll	12,757
Gravenhurst	12,311
Elmira	11,988
Norwich	11,001
Caledonia	9,674
EastZorra-Tavistock	7,129
St. Marys	7,265
Huntsville	6,482
Komoka	1,754
Erie PA (US*)	98,593
Total	**5,820,276**

All data from Statistics Canada (2017)
(*from United States Census Bureau)

Appendix B: Populations in Contaminated Areas in Figure 2

Estimates of Affected Populations in Municipalities

Municipality	Estimated Percent of Land Area That Is Contaminated	Estimated Affected Population
100 mSv areas		
Pickering	100%	92,000
Markham	25%	82,000
Richmond Hill	6%	13,000
Whitchurch-Stouffville	50%	23,000
Sub Total		**210,000**
50 mSv areas		
Markham	12%	42,000
Richmond Hill	15%	30,000
Whitchurch-Stouffville	25%	11,000
Scarborough	10%	63,000
Sub Total		**146,000**
20 mSv areas		
Newmarket	50%	42,000
Markham	12%	7,000
Richmond Hill	10%	20,000
Whitchurch-Stouffville	25%	11,000
East Gwillimbury	90%	22,000
Ballantrae	100%	3,000
Pleasantville	100%	7,000
Aurora	50%	27,000
Scarborough	25%	158,000
Sub Total		**297,000**

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Municipality	Estimated Percent of Land Area That Is Contaminated	Estimated Affected Population
10 mSv areas		
Newmarket	25%	21,000
East Gwillimbury	10%	2,000
Schomberg	40%	1,000
Markham	6%	3,000
Richmond Hill	6%	12,000
Scarborough	40%	253,000
Mt. Albert	50%	2,000
Newmarket	25%	21,000
Markham	12%	7,000
Aurora	50%	27,000
Bradford - West Gwillimbury	20%	7,000
Caledon	40%	27,000
Sub Total 10 mSv		**383,000**
5 mSv areas		
Newmarket	25%	21,000
Markham	37%	123,000
Richmond Hill	50%	98,000
Scarborough	25%	158,000
Schomberg	40%	1,000
Mt. Albert	50%	2,000
Brampton	25%	148,000
North York	25%	163,000
Vaughan	25%	77,000
Toronto	30%	820,000
Nobleton	100%	5,000
Bradford -West Gwillimbury	80%	28,000
Innisfil Heights	100%	37,000
Thornton	100%	137,000
Sub Total 5 mSv		**1,818,000**
Grand Total		**2,854,000**

Population data from Statistics Canada (2017)

Appendix C: Estimates of House Values Lost in Each Municipality

We have used data from the Municipal Property Assessment Corporation (2016) to calculate house values that would be lost if the Pickering Nuclear Station were to suffer a Fukushima-level accident and long-term evacuation and no re-entry orders were issued.

The values were determined by first estimating the average value of houses in each Ontario municipality (for City of Toronto in the case of Scarborough). This estimate was based on residential housing value assessments[32] made by the Municipal Property Assessment Corporation (MPAC) in 2016. Average values for single-detached, semi-detached, row house or any other single-attached dwellings were determined. (Values of apartments in apartment blocks were not included.)

These average house values were multiplied by the number of houses estimated to be lost from such an accident. The three evacuation zones areas of 30 years, 70 years and 100 years (see Figure 3) were digitized over a shapefile (GIS geographic file) map of the Greater Toronto Area. Based on the boundaries of the evacuation zones in Figure 3, the number of houses were counted within each zone based on the count for single-detached, semi-detached, row house or any other single-attached house dwelling for each of the census tracts of Greater Toronto Area municipalities (the census tracts were based on data collected from the 2016 Canadian Census).

For census tracts that were partially located inside the evacuation zones, estimates of how many dwellings would be affected were determined by examining how much of the local street network was located within each evacuation zone. The detailed calculations for each municipality are set out in the following table.

The main conclusion here is that estimated losses of house property values would exceed $125 billion. However, this is very much a partial estimate as greater losses would likely have occurred in business, industrial, commercial, governmental and municipal properties, and in apartment values as well.

These very large losses are commensurate with the estimates of economic losses at Fukushima of U.S.$ 188 billion (Can$ 236 billion).

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[32] housing value assessment for East Gwillimbury from a report by Canadian Real Estate Wealth (2016)

Residence Values in Ontario Municipalities

All Areas	**Total Estimated Loss**
Estimated Dwelling Count (Based on figures from 2016 Canadian census)	153,969
Multiplied by each municipality's average housing value (According to 2016 MPAC assessment and Canada Real Estate Wealth)	$125,642,400,000
Pickering	**Estimated Loss**
Estimated Dwelling Count (Based on figures from 2016 Canadian Census)	23,037
Multiplied by **$563,000** (According to 2016 MPAC assessment)	$12,969,831,000
Scarborough	**Estimated Loss**
Estimated Dwelling Count (Based on figures from 2016 Canadian Census)	39,508
Multiplied by **$770,000** (According to 2016 MPAC assessment)	$30,421,160,000
Markham	**Estimated Loss**
Estimated Dwelling Count (Based on figures from 2016 Canadian Census)	59,487
Multiplied by **$991,000** (According to 2016 MPAC assessment)	$58,951,617,000
Whitchurch-Stouffville	**Estimated Loss**
Estimated Dwelling Count (Based on figures from 2016 Canadian Census)	14,085
Multiplied by **$741,000** (According to 2016 MPAC assessment)	$10,436,985,000
Newmarket	**Estimated Loss**
Estimated Dwelling Count (Based on figures from 2016 Canadian Census)	9,857
Multiplied by **$655,000** (According to 2016 MPAC assessment)	$6,456,335,000
Richmond Hill	**Estimated Loss**
Estimated Dwelling Count (Based on figures from 2016 Canadian Census)	188
Multiplied by **$1,028,000** (According to 2016 MPAC assessment)	$193,264,000
East Gwillimbury	**Estimated Loss**
Estimated Dwelling Count (Based on figures from 2016 Canadian Census)	1,571
Multiplied by **$921,450** (According to 2016 report from Canadian Real Estate Wealth)	$1,447,597,950
Aurora	**Estimated Loss**
Estimated Dwelling Count (Based on figures from 2016 Canadian Census)	6,079
Multiplied by **$770,000** (According to 2016 MPAC assessment)	$4,680,830,000
Uxbridge	**Estimated Loss**
Estimated Dwelling Count (Based on figures from 2016 Canadian Census)	157
Multiplied by **$540,000** (According to 2016 MPAC assessment)	$84,780,000

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Radioactively contaminated topsoil and debris is stockpiled throughout Fukushima Prefecture.

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Attachment 2

We have better choices:

It's time to close the aging Pickering Nuclear Plant

By closing the Pickering Nuclear Station when its licence expires in August 2018, the Government of Ontario can increase public safety, eliminate money-losing electricity export sales, lower our electricity costs, create jobs and return most of the station's waterfront site to the local community for redevelopment and new park land.

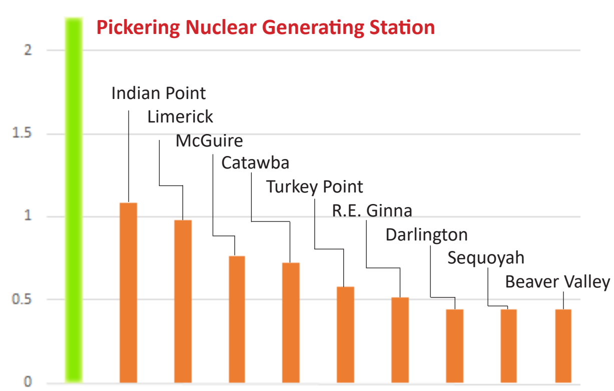
Public Safety

The Pickering Nuclear Station is the 4th oldest nuclear station in North America and one of the largest. It was originally designed to operate for 30 years, but it is now 47 years old. It is surrounded by more people (2.2 million within 30 km) than any other nuclear station on the continent.

According to a report by radiation biologist Dr. Ian Fairlie, a Fukushima-level accident at Pickering could cause 26,000 cancers, lead to the decades-long evacuation of more than 650,000 people and result in a $125 billion loss in the value of single-family homes.[1] In fact, Dr. Fairlie found that consequences would be much more severe around Pickering due to its location in a dense urban area compared to what occurred in Fukushima, which is in a largely rural location.

Nuclear plants are by their very nature high risk. Accident probability may be low, but consequences are almost unimaginably high, which is why no private insurer will underwrite a nuclear plant or provide homeowner coverage for a nuclear-related event. As it is, Ontario Power Generation's accident liability is limited to $1 billion – a fraction of the actual potential costs of a severe accident.

10 North American nuclear plants with the highest surrounding populations
(in millions within 30 km.)



Eliminating Money-Losing Electricity Export Sales

During many hours of the year (e.g., at night and during weekends) Ontario's nuclear reactors produce more electricity than is consumed in Ontario. Since the inflexible Pickering and Darlington reactors cannot lower their output during off-peak hours, we are required to export our surplus nuclear generation to the U.S. These exports are typically sold at prices that are below the cost of production. In fact, sometimes we actually have to pay our American neighbours to take our surplus nuclear power.

Only roughly half of Pickering's output is needed to keep the lights on in Ontario.[2] By closing Pickering we can avoid the loss of $737 million per year racked up by exporting the plant's surplus power at less than its cost of production.[3]

POWER EXPORT LOSSES:

You owe:

$737 MILLION

Buying lower cost water power from Hydro Quebec

Pickering's operating costs (9.2 cents per kWh) are higher than those of any other nuclear station in North America.[4]

Hydro Quebec has offered to provide us with water power for the next 20 years at a cost of 5 cents per kWh.[5] By buying Quebec water power, to displace Pickering's power that is used in Ontario, we can save an additional $407 million per year.[6]

Ontario's current transmission connections with Quebec can carry sufficient power to replace the power produced by Pickering that is used by in Ontario. According to the Independent Electricity System Operator (IESO), our current system is sufficient to import 16.5 to 18.5 TWh per year from Quebec.[7] Currently, we use roughly 10 TWh of power from Pickering in Ontario. For just $220 million, we could make these connections even more robust by increasing our peak hour import capacity with Quebec by 2,050 MW[21] (by comparison, OPG is paying $500 million to build a radioactive water storage facility at Darlington[11]).

Quebec has sufficient power available for export at least 99%[8] of the time (a far higher level of availability than Pickering, which is offline approximately 30% of the time[9]). During the handful of coldest hours of winter when Quebec may not have power available, Ontario can use its gas-fired generation stations, as it does when one or more of Pickering reactors are offline now.

During the second half of 2017, OPG's price for nuclear power was 8.1 cents per kWh.[12] In contrast Hydro Quebec's average price of its export sales in 2017 was only 4.7 cents per kWh.[13] Nuclear prices are certain to continue rising (OPG has told the Ontario Energy Board that it must raise its price for nuclear power to 16.5 cents per kWh by 2025 to pay for the re-building of Darlington's reactors[14]) while Quebec Hydro has offered to lock in low rates in 20-year contracts.[10] This means the price difference between nuclear and Quebec imports is only going to grow.

Cost of nuclear power in 2017:

Cost of Quebec Water Power in 2017:

Cost effective renewable energy

Of course, we can also tap into increasingly low-cost power from the sun and wind to help replace these aging nuclear stations. In the last round of Ontario's Large Renewable Procurement program, the average cost of wind power was 8.6 cents per kilowatt hour (kWh)[15] – less than the cost of producing power at Pickering. But both Quebec (6.3 cents/kWh[16]) and Alberta (3.7 cents/kWh[17]) have recently received even lower bids for wind power – part of a worldwide trend toward ever lower prices for renewable sources. Experts suggest that the cost of solar power will fall to 5-6 cents (U.S.) per kWh by 2025.[18] By combining these sources with water power from Quebec, we can create a much more efficient and responsive energy system that provides zero carbon, waste-free power 24/7.

Creating jobs

According to the International Atomic Energy Agency, immediate dismantling of reactors after they are shut down is the preferred approach.[19]

However, Ontario Power Generation is planning to **delay dismantling** until 30 years after the plant is shutdown. A 30-year delay will have little impact on radioactivity levels in the plant or the complexity of dismantling it, but will allow OPG to defer expenditures while laying off much of the current workforce.

By immediately dismantling and decommissioning Pickering after it closes, we can create 32,000 person-years of direct and indirect employment by 2032.[20] This will permit most of the 300 hectare Pickering waterfront site to be revitalized and returned to the local community by 2032.

The full cost of the decommissioning can be funded by money that is already in Ontario Power Generation's Nuclear Decommissioning Fund.

Immediate decommissioning = 32,000 person years of employment

Conclusion

By closing the Pickering Nuclear Station on August 31, 2018, the Government of Ontario can increase public safety, save Ontario's electricity consumers $1.1 billion per year, create 32,000 person-years of employment and return most of the station's site to the local community by 2032. This is a far better option than continuing to operate an unneeded nuclear plant long past its original life expectancy in the midst of our largest urban area.

Endnotes

1 Ian Fairlie, *A Fukushima-Level Nuclear Disaster at Pickering: An Assessment of Effects*, Ontario Clean Air Alliance Research Inc., (March 2018).

2 Independent Electricity System Operator, *Assessment of Pickering Life Extension Options: October 2015 Update*, (October 30, 2015), page 12.

3 According to Ontario Power Generation, Pickering's total output in 2019 will be 19.4 billion kWh and its operating cost will be 9.2 cents per kWh. In 2017 Ontario's average electricity export price was 1.6 cents per kWh (Hourly Ontario Energy Price or HOEP). [19.4 billion kWh x 50% x (9.2 – 1.6 cents per kWh) = $737 million.] Ontario Energy Board Docket No. EB-2016-0152, Exhibit E2, Tab 1, Schedule 1, Table 1 and Exhibit L, Tab 6.5, Schedule 7 ED-018; and http://www.ieso.ca/en/power-data/data-directory.

4 Ontario Power Generation, *2015 Nuclear Benchmarking Report*, page 69.

5 In 2017 Hydro Quebec offered to sell Ontario 8 billion kWh per year for 20 years at a price of 5 cents per kWh. www.BuyQuebecPower.ca. According to the Eric Martel, CEO of Hydro Quebec, his company can provide Ontario with up to 14 billion kWh per year. As Mr. Martel noted: "We can be a solution for Ontario. Thankfully, the interconnections already exist. There's nothing to build." Frederic Tomesco, "Chinese Demand Thwarts Hydro-Quebec Plans to Add Foreign Assets", *Bloomberg*, (March 1, 2018).

6 [19.4 billion kWh x 50% x (9.2 – 5 cents per kWh) = $407 million.] See also endnote #3.

7 IESO, *IESO Response to Questions from the Ontario Clean Air Alliance*, (November 2014).

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10 http://nationalpost.com/pmn/news-pmn/canada-news-pmn/hydro-quebec-awarded-major-20-year-electricity-deal-from-massachusetts

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12 Ontario Power Generation Inc., *Management's Discussion and Analysis*, (December 31, 2017), page 5.

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15 http://www.ieso.ca/corporate-ieso/media/news-releases/2016/03/ieso-announces-results-of-competitive-bids-for-large-renewable-projects

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18 https://www.pv-magazine.com/2016/06/15/irena-forecasts-59-solar-pv-price-reduction-by-2025_100024986/

19 Ralph Torrie, Torrie Smith Associates, *Direct Decommissioning of the Pickering Nuclear Station: Economic and Other Benefits*, (March 2016), page 4.

20 Ralph Torrie, Torrie Smith Associates, *Direct Decommissioning of the Pickering Nuclear Station: Economic and Other Benefits*, (March 2016), page 6.

21 Independent Electricity System Operator, *Ontario-Quebec Interconnection Capability,* (May 2017), page 23.

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Ontario Clean Air Alliance Research gratefully acknowledges the support of the M.H. Brigham Foundation, the Echo Foundation and the Taylor Irwin Family Fund at the Toronto Foundation

Attachment 3

Pickering Nuclear Station Survey Report

ONTARIO
CLEAN AIR
ALLIANCE

BY

oraclepoll
RESEARCH

September 2017

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METHODOLOGY & LOGISTICS

Overview

- Ontario Clean Air Alliance Research commissioned Oraclepoll Research to conduct a telephone survey of residents, 18 years of age or older from Scarborough, Ajax and Pickering, Ontario. The survey covered issues related to the Pickering Nuclear Station.
- This report represents the findings from that survey of N=500 residents that includes an executive summary and results by question section.

Study Sample

- The survey screened to certify that only voting age residents, 18 years of age or older, that were residents of each community were interviewed.

Logistics

- Interviews were conducted between the days of September 7th and September 14th, 2017.
- All surveys were conducted by telephone at the Oraclepoll call centre facility using live person-to-person interviewing (CATI) and random number selection (RDD).
- The dual sample frame database used was inclusive of land lines as well as cell phone-only households. A total of 20% of all interviews were monitored and the management of Oraclepoll Research supervised 100%.
- Initial calls were made between the hours of 6:00 p.m. and 9:00 p.m. Subsequent call-backs of no-answers and busy numbers were made on a (staggered) daily rotating basis up to 5 times (including at least one weekend call) until contact was made. In addition, telephone interview appointments were attempted with those respondents unable to complete the survey at the time of contact.

Confidence

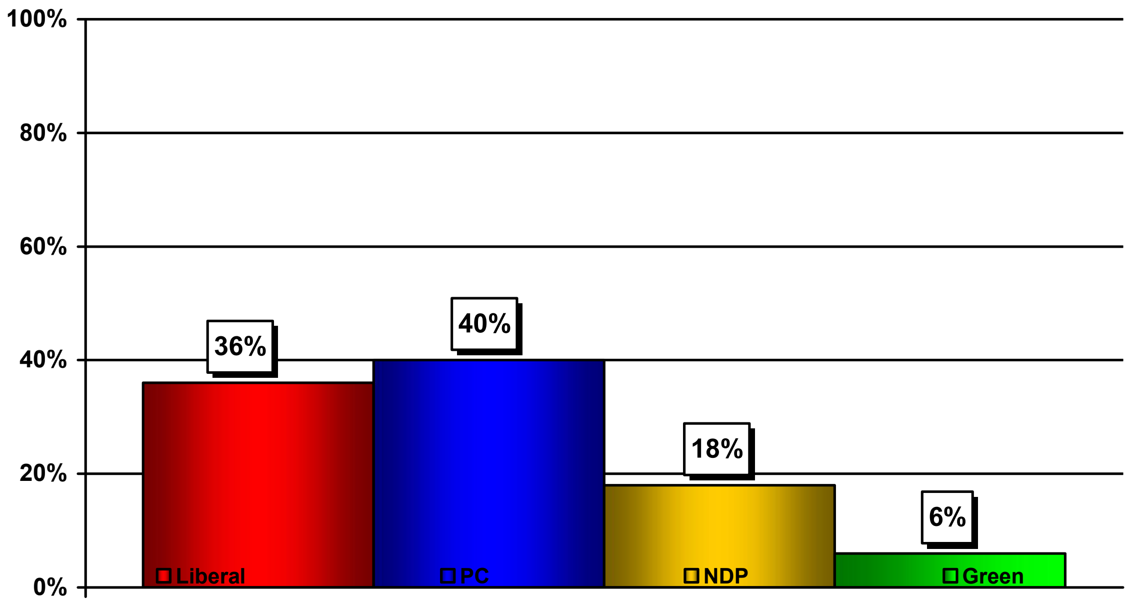
- The margin of error for the N=500 sample is ±4.4% 19/20 times.

EXECUTIVE SUMMARY

Vote Intent

All respondents were first asked about their vote intent if a Provincial Election were held.

"If a provincial Election were held today, which Party and their local candidate would you most likely vote for or be leaning towards?"



Among decided voters in the areas surveyed, the PC's have the backing of 40% of the electorate, while the Liberals are supported by 36% and the NDP by 18%, while 6% declared that they will vote Green. A total of 23% of voters were undecided or did not know who they will back.

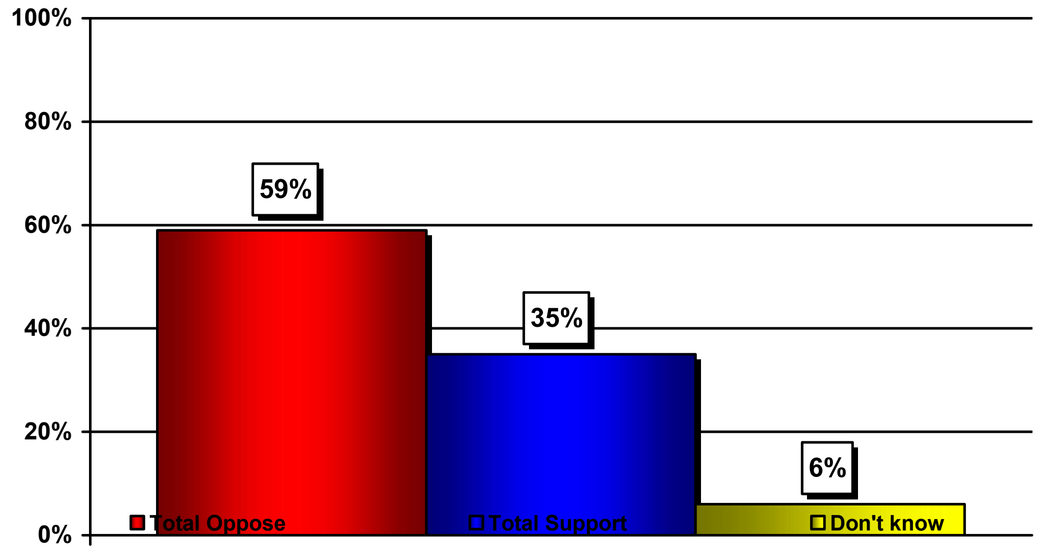
PC support (decided) was strongest among older residents 65+ (50%) and 51-64 (46%), among the highest earners in the $90,000+ cohort (54%) and with more males (50%) compared to females (28%). Younger respondents 18-34 (43%) and 35-50 (37%) preferred the Liberals, as did those in the $50,000 - $59,999 income range (47%) and females (46%) in relation to males (27%). Those backing the NDP also tended to be younger in the 18-34 category (23%), while Green support was for the most part consistent across all demographic groups.

Keeping Pickering Open Until 2024

All respondents were then read the following preamble describing the aging Pickering Nuclear Station and were then asked if they opposed or supported keeping it open until 2024.

Q2. "The Pickering Nuclear Station is the oldest nuclear power station in Canada and the 4th oldest in North America at 46 years. Its reactors have reached the end of their "design life" or the lifespan that the plant's components were designed to operate. Ontario Power Generation wants to keep the Pickering Station operating until 2024."

"Would you say that you strongly support, support, oppose or strongly oppose keeping the Pickering Nuclear Station operating until 2024?"



Almost six in ten or 59% of voters oppose (26%) or strongly oppose (33%) keeping the Pickering Station open until 2024, compared to 35% that support (27%) or strongly support (8%) a continuation of its operation. A total of 6% did not know or had no opinion.

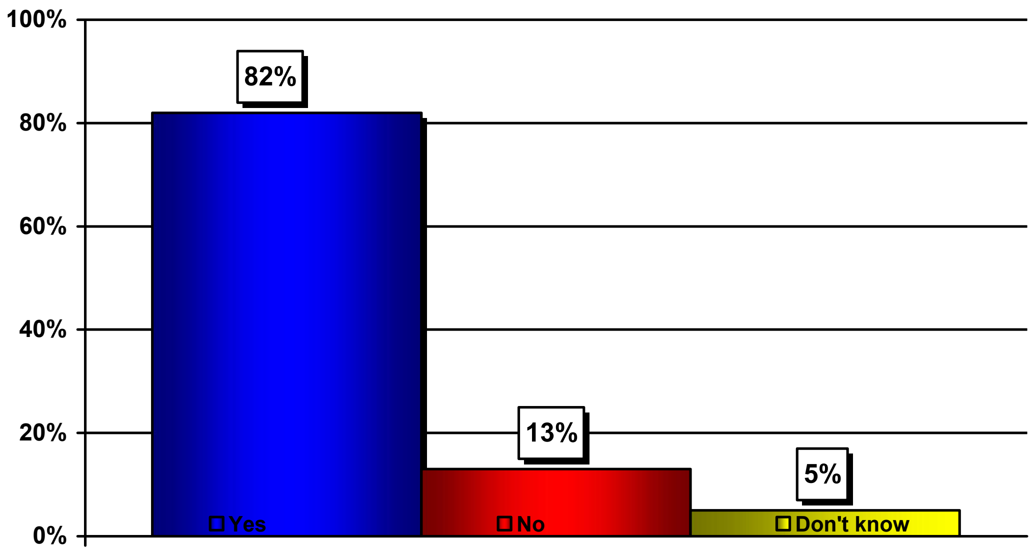
Millennials 18-34 were most inclined to oppose (69%) keeping the Station open, while seniors 65+ had the highest support (49%) for its continued operation. Those earning $90,000+ had an elevated level of support (42%), while opposition was strongest among those in the middle cohorts of $50,000 - $59,999 (65%) and $60,000 - $89,999 (64%). Opposition was also highest among females (65%), Green's (100%), New Democrats (69%), Liberals (68%), as well as residents of Scarborough (64%) and Ajax (61%). Opposition was lower among males at 52% (41% supported), PC's at 42% (52% supported) and Pickering residents at 52% (41% supported).

A Lower Cost Replacement & Closure

The next preamble outlined the high operating costs of Pickering to respondents and the low-cost plan by the province of Ontario to purchase electricity from Hydro Quebec. They were then asked if they felt Pickering should be closed if this lower priced energy replacement were made available.

Q3. "The government of Ontario and Hydro Quebec are negotiating a long-term electricity contract at 5-6 cents per kilowatt hour to supply Ontario with energy. Currently, the Pickering nuclear power station has the highest operating costs of any nuclear station in North America at 9 cents per kilowatt hour."

"In your opinion, should the Pickering nuclear power station be closed if this lower cost replacement for power is available?"



More than eight in ten or 82% of voters feel that the Pickering nuclear power station should be closed if this lower cost Hydro Quebec electricity replacement is made available. Only 13% do not feel it should be closed and 5% were unsure.

Support for closure was strongest among younger residents 18-34 years of age (89%), those earning less than $50,000 per annum (90%) and among more females (84%) in relation to males (79%). All Green Party supporters (100%) and a very strong number of NDP (90%) and Liberals (86%) support the closure as did a still significant 71% of PC's – although Tory backers had the highest percentage of those that would not (21%). Voters residing on Ajax (85%), closely followed by Scarborough (84%) most support the closure as did 77% of those in Pickering.

RESULTS BY QUESTION

Q1. If a provincial Election were held today, which Party and their local candidate would you most likely vote for or be leaning towards?

VOTE INTENT INCLUDING UNDECIDED'S		
	PC	31%
	Liberal	28%
	Don't know / Undecided	22%
	NDP	14%
	Green Party	5%
	Total	**100%**

DECIDED VOTE INTENT		
	PC	40%
	Liberal	36%
	NDP	18%
	Green Party	6%
	Total	**100%**

		NDP	PC	Liberal	Green Party
AGE	18-34	23.4%	26.2%	43.0%	7.5%
	35-50	15.0%	41.6%	37.2%	6.2%
	51-64	17.0%	46.2%	31.1%	5.7%
	65 or older	16.7%	50.0%	28.3%	5.0%

		NDP	PC	Liberal	Green Party
INCOME	Less than $50,000	20.0%	34.5%	38.2%	7.3%
	$50,000 to $59,999	20.0%	26.7%	46.7%	6.7%
	$60,000 to $89,999	18.1%	37.5%	41.7%	2.8%
	$90,000 or more	16.5%	54.1%	23.3%	6.0%

		NDP	PC	Liberal	Green Party
GENDER	Male	17.3%	50.0%	27.4%	5.3%
	Female	19.1%	28.1%	45.5%	7.3%

Q2. The Pickering Nuclear Station is the oldest nuclear power station in Canada and the 4th oldest in North America at 46 years. Its reactors have reached the end of their "design life" or the lifespan that the plant's components were designed to operate. Ontario Power Generation wants to keep the Pickering Station operating until 2024. <u>Would you say that you strongly support, support, oppose or strongly oppose keeping the Pickering Nuclear Station operating until 2024?</u>

	Strongly support	8%
	Support	27%
	Oppose	26%
	Strongly oppose	33%
	Don't know	6%

		Strongly support	Support	Oppose	Strongly oppose	Don't know
AGE	18-34	1.5%	23.4%	27.7%	40.9%	6.6%
	35-50	3.0%	31.3%	29.1%	28.4%	8.2%
	51-64	12.7%	25.4%	26.8%	31.0%	4.2%
	65 or older	19.5%	29.9%	18.4%	28.7%	3.4%

		Strongly support	Support	Oppose	Strongly oppose	Don't know
INCOME	Less than $50,000	11.3%	26.3%	27.5%	31.3%	3.8%
	$50,000 to $59,999	10.5%	22.8%	22.8%	42.1%	1.8%
	$60,000 to $89,999	8.7%	15.2%	27.2%	37.0%	12.0%
	$90,000 or more	7.4%	34.4%	25.2%	27.6%	5.5%

		Strongly support	Support	Oppose	Strongly oppose	Don't know
GENDER	Male	11.6%	28.8%	23.2%	29.2%	7.2%
	Female	4.8%	25.6%	29.2%	36.0%	4.4%

		Strongly support	Support	Oppose	Strongly oppose	Don't know
VOTE	NDP	5.7%	21.4%	28.6%	40.0%	4.3%
	PC	17.5%	34.4%	21.4%	20.1%	6.5%
	Liberal	2.9%	23.9%	24.6%	43.5%	5.1%
	Green Party	-	-	29.2%	70.8%	-

Q2. (continued) **<u>Would you say that you strongly support, support, oppose or strongly oppose keeping the Pickering Nuclear Station operating until 2024?</u>**

		Strongly support	Support	Oppose	Strongly oppose	Don't know
AREA	Pickering	10.8%	30.5%	20.4%	31.1%	7.2%
	Ajax	6.0%	26.3%	29.3%	31.7%	6.6%
	Scarborough	7.8%	24.7%	28.9%	34.9%	3.6%

Q3. The government of Ontario and Hydro Quebec are negotiating a long-term electricity contract at 5-6 cents per kilowatt hour to supply Ontario with energy. Currently, the Pickering nuclear power station has the highest operating costs of any nuclear station in North America at 9 cents per kilowatt hour. <u>In your opinion, should the Pickering nuclear power station be closed if this lower cost replacement for power is available?</u>

	Yes	82%
	No	13%
	Don't know	5%

		Yes	No	Don't know
AGE	18-34	89.1%	10.2%	0.7%
	35-50	83.6%	10.4%	6.0%
	51-64	76.1%	16.2%	7.7%
	65 or older	77.0%	17.2%	5.7%

		Yes	No	Don't know
INCOME	Less than $50,000	90.0%	7.5%	2.5%
	$50,000 to $59,999	82.5%	8.8%	8.8%
	$60,000 to $89,999	79.3%	14.1%	6.5%
	$90,000 or more	78.5%	17.2%	4.3%

		Yes	No	Don't know
GENDER	Male	79.2%	14.8%	6.0%
	Female	84.4%	11.6%	4.0%

		Yes	No	Don't know
VOTE	NDP	90.0%	7.1%	2.9%
	PC	71.4%	21.4%	7.1%
	Liberal	85.5%	10.9%	3.6%
	Green Party	100.0%	-	-

		Yes	No	Don't know
AREA	Pickering	76.6%	18.6%	4.8%
	Ajax	85.0%	9.6%	5.4%
	Scarborough	83.7%	11.4%	4.8%

Attachment 4

Direct Decommissioning of the Pickering Nuclear Generation Station:
Economic and Other Benefits

by Ralph Torrie, Torrie Smith Associates,
with research assistance from Brian Park
for Ontario Clean Air Alliance Research

March 2016

Foreword

Ontario Clean Air Alliance Research commissioned Torrie Smith Associates to look at the economic implications of de-commissioning the Pickering Nuclear Station.

The Pickering Station is Ontario's oldest commercial-scale nuclear station. Construction on the eight reactor plant started in 1966 and took almost 20 years to complete. As with every other nuclear project in Ontario's history, construction costs went massively over budget, with Pickering B costing more than double the initial estimated cost.

Pickering has had a checkered operational history with numerous performance issues. In 1997, four Pickering A reactors were shut down for repairs after a scathing safety review. In the end, only two units were eventually re-started (Units 1 and 4) with the other two "A" reactors mothballed.

Today, the Pickering Nuclear Station is one of North America's highest-cost nuclear stations. In 2014, Pickering's fuel and operating costs alone (8.16 cents per kWh[1]) were more than double the average market price of electricity (3.60 cents per kWh[2]). As a result, the Independent Electricity System Operator was required to provide Ontario Power Generation (OPG) with "out-of-market" payments of approximately $900 million to subsidize Pickering's operating deficit.[3]

The Pickering Nuclear Station is one of North America's highest-cost nuclear stations and the aging plant is currently operating beyond its original "design lifetime."

Currently, the plant is operating beyond its original "design lifetime" which came to a close in 2015. In other words, systems are being pushed past the operational period for which they were originally designed despite the materials problems caused by the intensely inhospitable environment inside the reactor cores that have taken their toll over years of operation.

The Pickering Station is now surrounded by a large and growing urban area, and is closer to a major urban centre – Toronto – than any other nuclear plant in North America. Recently, OPG was ordered to proactively distribute potassium iodide (anti-radiation) pills in the 10 kilometre potential radioactive fallout zone around the plant and to ramp up efforts to distribute them throughout the 50 kilometre potential fallout zone around the station that includes the entire City of Toronto and parts of its northern and eastern outer suburbs.

The Ontario Government now says that it wants the Pickering Plant to continue operating until 2024. This is a reversal of its earlier position that the plant should close no later than 2020. There is no question that the earlier deadline makes much more sense for both performance and safety reasons.

When the reactors are permanently shutdown, the question becomes: "What happens next?" No jurisdiction has ever decommissioned a CANDU nuclear station. But with Pickering permanently closed, we cannot simply walk away from its highly radioactive remains.

Torrie Smith's analysis finds that there are major advantages to proceeding with decommissioning work immediately rather than following OPG's proposed approach of leaving the plant dormant for 30 years before proceeding.

There are significant risks to relying on investment growth to pay for decommissioning costs.

The first advantage is cost and cost certainty. Torrie Smith calculates that direct decommissioning can save $800 million to $1.2 billion on the total cost of decommissioning, in part by avoiding the costs of securing and maintaining the site for 30 years. It also ensures that the financial risk of a first-of-its-kind project is not pushed forward for 30 years, but dealt with today.

The entire estimated cost of Pickering can be covered by the Decommissioning Fund, including the net cost of moving forward the work. Relying on investment growth to cover deferred decommissioning costs is high risk, particularly in a slow growth economy. In our view, it is better to use funds set aside specifically for decommissioning to deal with the problem at hand.

The second advantage is a smooth transition from an operating facility to a decommissioning project. This would better ensure continued employment for many Pickering workers and would also ensure that existing expertise and plant-specific knowledge was readily available to assist with the decommissioning work. Thirty years from now, there will be few, if any, people left in the workforce with firsthand experience of Pickering's difficult operating history. Essentially, we will need to train a whole new set of workers to undertake work on a plant with which they have no familiarity.

The third advantage is safety. There is actually no particular reason – other than relying on investment growth to increase decommissioning funds – to wait 30 years to begin the work. The most radioactive component of the site – spent fuel and heavy water used for cooling – will have to removed immediately in any case. Working within the radioactive environment of the closed plant will be no different than it was when staff worked on reactor re-start projects at both Pickering and Bruce. What is different is that a 30-year wait will allow corrosion and decay to take a further toll on the plant, thereby increasing safety risks. It is far better to deconstruct and safely store the remains of the plant now.

All of this makes direct decommissioning the logical way to proceed. Torrie Smith calculates that direct decommissioning will create 16,000 person years of employment, which is greater than the 15,400 person years of employment that OPG estimates would be created by its proposed Darlington re-build project (assuming all four Darlington reactors are rebuilt). But just as importantly, the funds to decommission Pickering will come from a dedicated Decommissioning Fund whereas the funds for the Darlington Re-Build will come from electricity consumers, meaning the Pickering project will have no impact on electricity rates while the Darlington project will increase rates.

Decommissioning, whether direct or deferred, raises the question of how to store low- to high-level radioactive waste, the often ignored legacy of Ontario's heavy dependence on nuclear power. As Torrie Smith note, the high level waste at Pickering – fuel and heavy water – will have to be removed and stored immediately whichever path is chosen – direct or delayed decommissioning.

Decommissioning raises the issue of how to deal with radioactive waste, an often ignored aspect of Ontario's heavy dependence on nuclear power.

Unfortunately, there are no truly "good" solutions to the problem of waste storage. The industry's preferred solution of deep geologic storage for high-level wastes raises many concerns, from leakage to how to move radioactive waste hundreds or thousands of kilometres. The process to develop such high-level sites is also proceeding at a glacial pace in the face of serious concern from citizens and communities being asked to host such a facility.

Meanwhile, OPG's proposed deep geologic facility for low- and intermediate-level waste at the Bruce Nuclear Station on the shores of Lake Huron has been hugely controversial, located as it is near the source of drinking water for 40 million North Americans. The new federal government has indicated it wants to step back and review plans for this site.

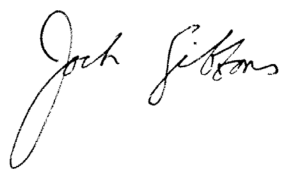
Generally, we believe hardened onsite storage is a better solution. For spent fuel storage, such hardened storage will be a significant step up from the current temporary warehousing of waste. For other materials, the advantage is keeping the problem contained and in sight while the process of radioactive decay slowly reduces the threat posed by lower level wastes.

The final critical advantage of embarking on direct decommissioning is developing expertise in the nuclear industry's one and only growth sector: dismantling shut down facilities. Currently, shutdowns have been proposed for two nuclear plants right across the lake in New York State[4] with growing pressure to shut down a third – the Indian Point station outside of New York City.

Vermont recently closed its only nuclear plant and is starting the decommissioning process.[5] The Pilgrim Nuclear Plant in Massachusetts will close in 2019.[6] Overall, the United States has the world's largest, but oldest, fleet of reactors and economic pressures could lead to closure of dozens of units over the next decade, particularly single reactor plants according to the World Nuclear Industry Status Report[7].

More directly, there are CANDU units in Korea, Romania, Argentina and China where technology-specific expertise in decommissioning may prove valuable in the not-too-distant future.

Ontario can save money, provide a better transition for workers and develop a new, highly marketable area of expertise by proceeding directly with decommissioning of the Pickering Nuclear Station. The time to act is now.



Jack Gibbons
Chair
Ontario Clean Air Alliance Research

Endnotes

1 Ontario Energy Board Docket No. EB-2013-0321, Exhibit JT1.14.

2 http://www.ieso.ca/Pages/Power-Data/price.aspx

3 In 2014 the Pickering Nuclear Station produced 20 billion kWh. 20 billion kWh x (8.16 – 3.60 cents per kWh) = $912 million. Ontario Power Generation, *Performance Report for Pickering Nuclear: 2014 Results*.

4 http://www.bloomberg.com/news/articles/2015-11-02/entergy-to-close-james-a-fitzpatrick-nuclear-power-plant-ighwq4q9 and http://www.poughkeepsiejournal.com/story/news/2015/10/22/new-deal-on-ginna/74380570/

5 http://vydecommissioning.com/

6 https://www.bostonglobe.com/metro/2015/10/13/entergy-close-pilgrim-nuclear-power-station-nuclear-power-plant-that-opened/fNeR4RT1BowMrFApb7DqQO/story.html

7 Mycle Schneider and Antony Froggat, *World Nuclear Industry Status Report 2015*, page 108

Direct Decommissioning of the Pickering Nuclear Generation Station: Economic and Other Benefits

Torrie Smith Associates

by Ralph Torrie, Torrie Smith Associates,
with research assistance from Brian Park
for the Ontario Clean Air Alliance Research

About the Author

Ralph Torrie is an expert in the field of energy, environment and climate change response strategies, with 35 years of entrepreneurial, management and consulting experience that includes hundreds of initiatives in research, business development, and public policy. He is a principal of Torrie Smith Associates, a research and software development firm he founded, and he has an ongoing interest in electric power planning issues in Ontario that dates to his involvement with the Royal Commission on Electric Power Planning in the 1970s. He also spent two years as Assistant Coordinator of the Energy Research Group of the United Nations University and the International Development Research Centre, and six years as a corporate executive, first as Vice President at ICF International and then as Managing Director at Navigant, both publicly traded U.S. based firms with significant Canadian operations.

Acknowledgements

Research supported by the Echo Foundation and the Taylor Irwin Family Fund at the Toronto Foundation.

Introduction

According to current plans, the Pickering Nuclear Generating Station (PNGS) will be the first of Ontario Power Generation's nuclear plants to be permanently shut down.[1] Two of its eight 500 megawatt (MW) reactors have been shut down since 1997 and the other six are operating on ad hoc license extensions that expire in 2018.[2] Under Ontario Power Generation's (OPG's) preferred strategy of "deferred decommissioning," the utility proposes to put the plant in a safe shutdown state and let it sit idle for 30 more years before commencing dismantlement.

In today's dollars, the estimated cost for decommissioning the eight-unit station will be \$5 billion, including the cost of mothballing and maintaining the radioactive plant in a safe shutdown state for several decades. This paper explores the economic, employment, and other benefits of an alternative strategy in which the multi-year process of dismantling begins immediately after shutdown and is completed by 2030.

When a nuclear reactor reaches its "end-of-life" and is shut down for the last time, it must be "decommissioned." But dismantling and disposing of a defunct nuclear power reactor is not your average demolition project. First the nuclear fuel is removed and stored as high-level nuclear waste while the water is also drained from the reactor in preparation for the dismantling and disposal of the reactor components, the steam generators and the miles of piping and other equipment that make up a nuclear power plant.

Even with the fuel removed, the interior components of the reactors remain radioactively contaminated – a large part of the plant is essentially radioactive waste. Decommissioning, therefore, requires the use of robotics and shielded working environments whether the plant is dismantled immediately after defueling or 30 years later.

Meanwhile, the low- and intermediate-level radioactive waste that results from the plant's dismantling must be prepared for shipment to either temporary or permanent waste disposal sites (should such a permanent site be developed), all while minimizing public and worker exposure. It is an expensive and labour intensive process and while no CANDUs have yet been decommissioned, OPG's \$5 billion estimate for the Pickering Station (\$630 million per reactor) is on the low end of the estimated cost range — the estimate for decommissioning the single unit CANDU in New Brunswick is over \$900 million.[3]

Ontario Power Generation's planned approach is called "deferred decommissioning" — the reactors are put in a state of "safe shutdown" after defueling and dewatering and then left idle for 30 years or more before final dismantlement and disposal. Most of the costs (and the related job creation) are postponed for more than 30 years.

However, international nuclear regulatory agencies discourage use of the deferred commissioning approach and recommend instead "direct decommissioning," the practice of dismantling the reactors immediately after permanent shutdown. This paper provides an initial review of the economic and other benefits that would go along with the adoption by OPG of the industry best practice of direct decommissioning, beginning with the Pickering Nuclear Generation Station.

1 Ten of the other 12 large power reactors owned by OPG (at the Darlington and Bruce nuclear stations) will reach their "end of life" dates during the 2020s at which time they will either be decommissioned or "refurbished." The term "refurbishment" refers to the rebuilding of the reactor core "from the inside out" in order to extend its operating life. The early stages of rebuilding are similar to decommissioning insofar as it involves removing the fuel, the pressure tubes and other components inside the primary containment envelope. Rebuilding however is much more expensive and capital intensive (fewer jobs created per dollar spent) than decommissioning as it requires new reactor components to be manufactured, installed, commissioned and licensed for operation. The cost of any reactor rebuild will be added to the future price of electricity in Ontario. The cost of decommissioning, on the other hand, will be paid from the "Nuclear Decommissioning Fund", a special savings fund OPG is required to maintain and which, as of January 2015, had a balance of more than \$7.4 billion.

2 OPG has indicated it would like to further extend the life of the aged Pickering Station beyond its current 2018 license expiration, perhaps for as much as another six years.

Deferred Decommissioning – OPG's planned approach

The most recently revised plan and cost estimates for the decommissioning of the Pickering Nuclear Station are based on the current end-of-life dates for the reactors, with the six remaining units shutting down between 2017 and 2019. The two reactors that have been shut down since 1997 have already been defueled and dewatered and the remaining six units would be prepared for dormancy over the 2018-2020 period at an estimated cost of $270 million. The cost of maintaining the plant throughout the dormancy period is estimated by OPG to be $644 million, not counting what has already been spent on Pickering A. In addition, the cost of managing all the low-level radioactive waste that would be generated during the dormancy period is estimated to be in excess of $350 million. These are the premiums associated with the deferred approach to decommissioning and most of this money could be saved by proceeding with direct decommissioning.

After the dormancy period, the reactors and all their auxiliary systems and buildings would be systematically dismantled and the site remediated at an estimated cost of $2.4 billion, not including the cost of managing and disposing of the low- and intermediate-level waste. Managing and disposing of the radioactive waste generated during both the dormancy period and the final dismantlement adds another $1.6 billion to the total cost estimate, including a contribution to the cost of spent fuel management during the period after the plant is shut down and before the availability of a long-term repository.[4]

Adding it all up, OPG's estimated cost for decommissioning and disposing of the Pickering Station totals $4.9 billion, not including costs already incurred prior to 2012 (mainly for the defueling and dewatering of Units 2 and 3). With OPG's proposed "deferred decommissioning" this spending would be spread out over the next several decades, with 50% of the expenditures (and the associated job creation) occurring after 2050. The $4.9 billion expenditure would generate direct employment of 20,000 person-years.[5]

Direct Decommissioning

With the direct decommissioning, many of the activities are the same, but the annual cost of maintaining the plant in a dormant state for decades is eliminated and the activities associated with preparing the plant for dormancy can be eliminated or integrated with the activities required to prepare the plant for dismantling. Low-level waste generation during the dormancy period is also eliminated leading to additional cost savings. The timeline for direct decommissioning is compressed to 12-14 years, as compared with the 42 years required for deferred decommissioning. There will be some offsetting expenditures, but we estimate savings from the elimination of the 30-year dormancy period total at least $800 million and could be as high as $1.2 billion.

Conservatively assuming the lower savings figure, this would reduce the cost of decommissioning the eight-unit Pickering NGS to $4.1 billion, compared to OPG's estimated $4.9 billion for deferred decommissioning.

3 Unless otherwise indicated, we have used 2012$ throughout this report, consistent with the cost estimates provided by OPG. OPG's risk contingency factor of four percent has been pro-rated to component costs. As a rough indicator, 2012$ can be converted to 2016$ by multiplying by 1.05.

4 Except for this relatively small contribution, the cost of long-term management of the highly radioactive spent fuel from the reactors is not counted as a cost of decommissioning. OPG's estimated cost for the long-term management of the spent fuel from the Pickering Station is $4.3 billion.A separate savings fund has been created for the cost of long-term management of the spent fuel.

5 Employment estimates in this report are for direct job creation only, and are consistent with CANDU decommissioning studies. Indirect and induced employment generated would more than double the estimated job creation of most OPG expenditures.

While OPG is required to maintain a fund to cover decommissioning costs, current regulations and the deferral of the work into the second half of the century allow OPG to set aside only $2.75 billion for the decommissioning of the Pickering station and then rely on compound interest and passage of time to ensure that there will be sufficient funds in the decommissioning account in 2050 to pay for the work.

With direct decommissioning, costs are reduced, but spending is moved forward in time, effectively increasing the present value of the station decommissioning cost. While the cost of direct decommissioning of Pickering is lower than for deferred decommissioning ($4.1 billion vs. $4.9 billion), the net present value of direct decommissioning is $2.9 billion, compared with $2.75 billion for deferred decommissioning. The increase in present value from moving the expenditures forward is almost completely offset by the real savings from the direct decommissioning approach. The residual $150 million difference is relatively small compared to the $1 billion-plus *surplus* in the Decommissioning Fund[6], so the cost of the switch to direct decommissioning of the Pickering NGS can be covered without any additional charges to Ontario electricity ratepayers.

The direct decommissioning option eliminates the labour required to watch over and keep the reactors safe during the 30-year dormancy period and delivers more than twice as many jobs as deferred decommissioning during the next 15 years. Between 2016 and 2030, the direct decommissioning scenario would generate 16,000 person-years of employment, which is greater than the 15,400 person-years of employment that would be created by the execution phase of the proposed Darlington Re-Build (2016-2026) project.[ii] And, as noted above, the decommissioning jobs would be paid for from the Nuclear Decommissioning Fund that has been established for just this purpose. Unlike nuclear plant rebuilds, decommissioning costs would not contribute to electricity rate increases.

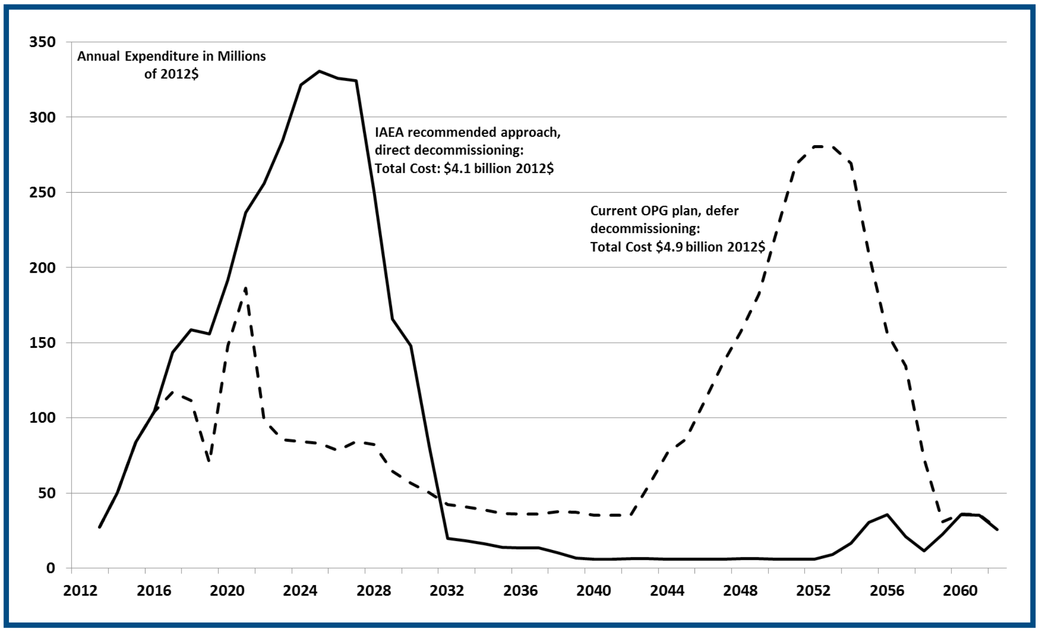
The Benefits of Direct Decommissioning

With direct decommissioning, dismantling is not postponed for decades but proceeds immediately after the reactor has been defueled and dewatered. Historically, the deferred decommissioning approach was preferred, and it prevailed 25 years ago during OPG's nuclear expansion era. Since then, however, as further experience and insights have been gained from nuclear power programs around the world, the strategy-of-choice has shifted to direct decommissioning in recognition of the disadvantages, costs and risks of the long dormancy period that characterizes postponing dismantlement compared to the relative cost savings and lower risks of immediate dismantlement.

Experience with decommissioning in Germany in the 1990s, for example, showed that immediate dismantlement was cheaper, safer and less risky than deferral, and that deferral was not justified on the basis of assumed better dismantling techniques in the future.[iii] Over the past 15 years, the arguments for immediate dismantlement have strengthened such that "the emerging international trend is more towards immediate dismantling than was previously the case (e.g. France, Italy, United Kingdom, Spain, Japan)."[iv]

6 The balance in the Nuclear Decommissioning Fund at the beginning of 2015 was $7.35 billion. The purpose of the Fund is to cover the present value of the deferred decommissioning and because OPG's policy is to defer dismantlement of the reactors for decades into the future, the requirements of the Fund are sensitive to the assumed end-of-life dates for the reactors, the discount rate, and the predicted cost of the future decommissioning. The Fund increases each year according to the return its investments make, less any withdrawals to pay for decommissioning activities, plus any contributions from OPG necessary to cover the utility's asset retirement obligations for the nuclear stations. At the beginning of 2015 the liability was $6.2 billion, putting the fund in a $1.1 billion "surplus" position.

Figure 1. Direct vs. Deferred Decommissioning Expenditures: Pickering Nuclear Station



The International Atomic Energy Agency states clearly in its General Safety Requirements that "the preferred decommissioning strategy shall be immediate dismantling."[v] While the IAEA recognizes there can be special circumstances that militate against immediate dismantlement, there are a number of reasons why immediate dismantlement is preferred, including:

- ***Cost Savings.*** As we have shown for the Pickering G.S., with the deferred decommissioning approach, the cost of preparing the reactors for the dormancy period and then maintaining them in a secure and safe shutdown state for decades adds up to about 25% of the cost of decommissioning, net of waste handling and disposal costs. Direct decommissioning, on the other hand, increases the likelihood that some of the plant's systems, such as ventilation systems and lifting and moving equipment, will be useable in the decommissioning activity, providing additional cost savings. And there is no case for deferring decommissioning on technological grounds as there might have been 25 years ago — the technology required for decommissioning is available and its cost has not been an issue.

- ***Availability of knowledgeable staff***. As pointed out in the Nuclear Energy Agency (NEA) review, "the knowledge of staff that has been involved with the facility over a long period of time will be invaluable during its characterization prior to decontamination and dismantling as well as during dismantling. This is particularly true of staff involved in its construction and in any subsequent modification."[vi]

- ***Radiological Risk.*** The argument that the dormancy period is necessary in order to allow radioactivity levels to subside has not proven out in practice. It would take much more than 30 years before the radiological hazard inside a CANDU would be low enough to avoid the use of remote cutting technologies and worker shielding. Immediate dismantlement also eliminates both the radiological exposure and radioactive waste that would be generated over the 30-year dormancy period. Indeed, the bulk of the low-level radioactive waste generated during deferred decommissioning accumulates during the dormancy period. Notably, radiological hazards have not prevented OPG from proposing to proceed with nuclear plant rebuilding without delay, a process that involves similar and, in some cases, identical tasks to be carried out inside the same contaminated primary containment envelope as is the case for dismantlement.

- ***Local economic impact***. Direct dismantling is more consistent with a smooth transition in the local economy after a power plant shuts down. As discussed above with regard to the Pickering NGS, adoption of a direct dismantling strategy for that plant would cause a major, positive impact on employment at the station that would continue throughout the 2020s.

- ***Provincial and federal government benefits***. Money for funding the decommissioning of OPG's reactors is collected as part of the price of electricity in Ontario, and as of January 2015 OPG's Decommissioning Fund had a balance of more than $7 billion. Putting some of this money back into the Ontario economy now by proceeding with the direct decommissioning of the Pickering Nuclear Station will create jobs and stimulate economic activity while returning significant tax revenue to both the provincial and federal governments.

- ***Financial Risk.*** The approach taken in Ontario in which OPG is only required to set aside today's present value of the future cost of the postponed dismantling of its reactors runs the risk that in the decades ahead the Decommissioning Fund will not earn the necessary real rate of return to ensure there are sufficient funds to cover the cost of decommissioning the Pickering reactors in the 2050s. Once the reactors shut down, they will no longer be contributing revenue to the cost of decommissioning so any shortfall that develops because of underperformance of the fund will have to be made up by future ratepayers or the Province of Ontario. Over the long dormancy period, the Decommissioning Fund will be subject to all the risks attached to any long-term investment, which is why the OECD Nuclear Energy Agency review concluded that "regardless of country or fund management arrangements, however, accumulated reserves held for long periods of time are exposed to considerable risk from inflation, money market losses, economic crises and conflicts involving major changes of state institutions. This leads to the clear international view that, as regards to the security of funding, decommissioning should be carried out as soon after closure as the necessary funds are available"[vii] and that "***it is not good practice to use the lower current-day funding requirements associated with a net present value calculation as justification for taking a deferred dismantling approach***" [emphasis added].[viii]

The financial risk of the present-value approach is exacerbated by the risk that the decommissioning cost estimates are themselves too low. This is a difficult risk to assess as OPG does not publish the details of its decommissioning plans and there is no actual CANDU decommissioning experience to use as a reference point. Indeed, another reason for proceeding with direct decommissioning of the Pickering NGS would be to reduce the uncertainty in the cost estimates so that any necessary adjustments to the Decommissioning Fund can be made while the other reactors are still operating.

At the height of OPG's nuclear expansion activity, Atomic Energy of Canada Ltd. conducted a "detailed study of the various procedures and costs associated with decommissioning a CANDU reactor"[ix] and then concluded that the deferred decommissioning option for a 600 MWe CANDU, assuming a 30-year dormancy period, would cost $60 million in 1975 dollars or about $240 million in 2010 dollars. By 2010, the decommissioning cost estimate for the 600 MWe CANDU plant at Point Lepreau had nearly quadrupled — to $900 million — and the firm that prepared the estimate warned that:

> *It has been TLG's experience that the results of a risk analysis, when compared with the base case estimate for decommissioning, indicate that the chances of the base decommissioning estimate's being too high is a low probability, and the chances that the estimate is too low is a higher probability.*[x]

Conclusions

Direct decommissioning has emerged as the internationally preferred strategy for nuclear power plants and this review suggests that such an approach would deliver financial, economic, employment, and safety benefits to Ontario. At no cost to Ontario power consumers, injecting money from the Decommissioning Fund into the Ontario economy at this time in order to proceed with the dismantling and disposal of the Pickering Nuclear Generation Station would:

- ✓ create needed economic stimulus and employment;
- ✓ save $800 million in the overall cost of decommissioning the station;
- ✓ generate 16,000 person-years of direct employment between 2016 and 2030, and more than twice this many when indirect and induced employment impacts are included;
- ✓ significantly reduce the volume of radioactive waste that would otherwise be generated by the plant over the next 40 years;
- ✓ return hundreds of millions in tax revenue to Ontario and other levels of government; and
- ✓ generate the experience Ontario will need to properly manage its own nuclear fleet while positioning it as a world leader in the fast-growing global market for nuclear decommissioning technologies and services.

Endnotes

i OPG's plans and detailed cost estimates for decommissioning are not public, but we were provided with the following summary cost information in response to a Freedom of Information request: "2012 ONFA Reference Plan Update Program Summary Cost Estimate Report" (W-REP-00400-0004-R00, 2011-11-22), "2012 ONFA Reference Plan Update Station Decommissioning Summary Cost Estimate Report", (W-REP-09600-00010-R01, 2011-11-22), "2012 ONFA Reference Plan Update L&ILW Operations Summary Cost Estimate Report", (05386-REP-0400-00003, November 2011), "2012 ONFA Reference Plan Update L&ILW Long Term Management Summary Cost Estimate Report", (00216-REP-00400-00004, November 2011) "2012 ONFA Reference Plan Update Used Fuel Storage Cost Estimate Report" (06819-REP-00400-00003-R01, 2011-11-28), and "2012 ONFA Reference Plan Update Long Term Used Fuel Management Summary Cost Estimate Report", (W-REP-0400-00005-R01, 2011-11-22).

We were also able to draw on the decommissioning plans for the Point Lepreau NGS in New Brunswick and for the Gentilly 2 NGS in Quebec, both of which are accessible on public web sites:

TLG Services, Inc., "Decommissioning Cost Study for the Point Lepreau Generating Station", prepared for New Brunswick Power Nuclear, Document N29-1632-002, Rev. 0, June 2010. Accessed on the web site of New Brunswick Energy & Utilities Board, http://www.nbeub.ca/opt/E/get_document.php?doc=30.52.pdf&no=5369.

TLG Services Inc., "Preliminary Decommissioning Plan for the Gentilly 2 Nuclear Generating Station", prepared for Hydro-Quebec, 2000. Accessed from the web site of Quebéc Bureau d'audiences publiques sur l'environnement, http://www.bape.gouv.qc.ca/sections/mandats/gentilly-2/documents/liste_documents-DA-DB-DC.htm.

ii According to OPG, the Darlington Re-Build Project would create 30 million person hours of field work, which is equivalent to 15,400 person-years of employment. See http://www.opg.com/generating-power/nuclear/stations/darlington-nuclear/darlington-refurbishment/Pages/Semi-Annual-Performance-Report.aspx.

iii European Commission, "Decommissioning of nuclear installations in the European Union: Supporting document for the preparation of an EC communication on the subject of decommissioning nuclear installations in the EU", compiled by P. Vankerckhoven, DG XI/C.2, Directorate-General Environment, Nuclear Safety and Civil Protection, 1999. EUR 18860 EN.

iv NEA/OECD, "Selecting Strategies for the Decommissioning of Nuclear Facilities: A Status Report", NEA No. 6038, 2006.

v International Atomic Energy Agency, "Decommissioning of Facilities", Section 5 of General Safety Requirements Part 6 (GSR Part 6), issued 2014.

vi NEA/OECD, "Selecting Strategies for the Decommissioning of Nuclear Facilities: A Status Report", NEA No. 6038, 2006, p.21.

vii NEA/OECD, "Selecting Strategies for the Decommissioning of Nuclear Facilities: A Status Report", NEA No. 6038, 2006, p. 19.

viii NEA/OECD, "Selecting Strategies for the Decommissioning of Nuclear Facilities: A Status Report", NEA No. 6038, 2006, p. 10.

ix G.N. Unsworth, "Decommissioning of CANDU Power Stations", Report AECL-6332, April 1979.

x TLG Services, Inc., "Decommissioning Cost Study for the Point Lepreau Generating Station", prepared for New Brunswick Power Nuclear, Document N29-1632-002, Rev. 0, June 2010. Accessed on the web site of New Brunswick Energy & Utilities Board, http://www.nbeub.ca/opt/E/get_document.php?doc=30.52.pdf&no=5369. Section 3, p.8.

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Attachment 5

IRSS. INSTITUTE FOR RESOURCE AND SECURITY STUDIES

Storage of Spent Nuclear Fuel at the Pickering Site:
Risks and Risk-Reducing Options

by
Gordon R. Thompson

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Prepared under the sponsorship of
Ontario Clean Air Alliance Research

Abstract

Ontario Power Generation (OPG) owns and operates a nuclear generating station at the Pickering site. Nuclear reactors at the site discharge spent nuclear fuel (SNF) assemblies that are stored at the site, initially under water and then in dry storage containers at the Pickering Waste Management Facility (PWMF). In February 2018, the Canadian Nuclear Safety Commission (CNSC) renewed the PWMF operating license for ten years.

Storage of SNF at Pickering poses risks. This report provides illustrative analyses of those risks in three categories – radiological risk, proliferation risk, and program risk. These analyses show that neither OPG nor CNSC has properly assessed the risks posed by storing SNF at Pickering.

This report provides illustrative analyses of options for reducing the risks it identifies, and outlines an integrated package of risk-reducing options. That package, featuring reconfiguration of the PWMF, could substantially reduce risks while also yielding other benefits. Reconfiguration of the PWMF would be facilitated by early shutdown and early decommissioning of the Pickering reactors.

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The Institute for Resource and Security Studies (IRSS) is an independent, nonprofit, Massachusetts corporation, founded in 1984. Its objective is to promote sustainable use of natural resources and global human security. In pursuit of that mission, IRSS conducts technical and policy analysis, public education, and field programs. IRSS projects always reflect a concern for practical solutions to resource and security problems.

About the Author

Gordon R. Thompson is the executive director of IRSS and a senior research scientist at Clark University, Worcester, Massachusetts. He studied and practiced engineering in Australia, and received a doctorate in applied mathematics from Oxford University in 1973, for analyses of plasma undergoing thermonuclear fusion. Dr. Thompson has been based in the USA since 1979. His professional interests encompass a range of technical and policy issues related to sustainability and global human security. He has conducted numerous studies on risks associated with nuclear facilities, and on options for reducing those risks. For example, Dr. Thompson prepared a report in 2000 for the Standing Committee on Energy, Environment, and Natural Resources of the Canadian Senate, examining the radiological risk associated with the Pickering A nuclear generating station.

Acknowledgements

This report was prepared by IRSS under the sponsorship of Ontario Clean Air Alliance Research. The author gratefully acknowledges comments on a draft of the report by Jack Gibbons, Ian Fairlie, Marvin Resnikoff, and Gordon Edwards. However, the author, Gordon Thompson, is solely responsible for the content of the report.

Contents

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Tables

Figures

1. Introduction

Ontario Power Generation (OPG) owns and operates a nuclear generating station at the Pickering site in Ontario. CANDU reactors at the site produce steam that is used in turbo generators to produce electricity. These reactors discharge spent nuclear fuel (SNF) assemblies that are stored at the site.[1] SNF assemblies are initially stored under water in irradiated fuel bays, and are subsequently transferred to dry storage containers (DSCs).

The DSCs are stored at the Pickering Waste Management Facility (PWMF), which is on the Pickering site. Some irradiated reactor components, arising from reactor refurbishment during the period 1984-1992, are also stored at the PWMF. Those components are not addressed here.

In October 2016, OPG applied to the Canadian Nuclear Safety Commission (CNSC) for renewal of the PWMF operating license through August 2028.[2] In the application, OPG requested authorization to build a new DSC processing building, and to expand the capacity of the PWMF to store DSCs. OPG implies that the expansion would allow all SNF assemblies discharged from the Pickering reactors over their operating lifetimes to be stored in DSCs at the PWMF.[3]

In February 2018, CNSC announced its renewal of the PWMF operating license, as requested by OPG.

Purpose and scope of this report

This report examines risks posed by storage of SNF at Pickering, either in irradiated fuel bays or in DSCs. In addition, this report identifies options for reducing those risks. Three categories of risk are examined here. These categories, which are defined in Section 2, are:

- Radiological risk
- Proliferation risk
- Program risk

This report does not claim to provide a comprehensive assessment of the risks it examines. Nor does this report claim to identify and characterize a full suite of risk-reducing options. Instead, this report provides illustrative analyses of risks and risk-reducing options. These analyses are sufficient to support the conclusions and recommendations proffered in this report.

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[1] OPG often refers to nuclear fuel discharged from a reactor as “used fuel”. The term “spent nuclear fuel” is more common internationally, and is used here. Also, OPG often refers to a “fuel bundle”. The term “fuel assembly” is more common internationally, and is used here.
[2] OPG, 2016.
[3] OPG, 2016, Section 3.1.2.

Relevant experience of this author

The author has over four decades of experience investigating risk issues related to nuclear facilities in North America, Europe, Asia, and elsewhere. These investigations have been sponsored by various governmental and non-governmental entities. In the course of that work, the author has written numerous technical reports, made presentations in various governmental and non-governmental contexts, and served as an expert witness in various official proceedings.

Nuclear-risk work by the author has included a number of investigations of the potential for commercial or military nuclear facilities to be attacked directly or to experience indirect effects of violent conflict. For example, in 2005 the author was commissioned by the UK government's Committee on Radioactive Waste Management (CORWM) to prepare a report on reasonably foreseeable security threats to options for long-term management of UK radioactive waste.[4] The time horizon used in that report was, by CORWM's specification, 300 years.

The author has considerable experience examining risk issues related to nuclear facilities in Canada. An early example of that experience was consulting to the Ontario Nuclear Safety Review, which was established by the Ontario government in December 1986. In that consulting capacity, the author prepared a September 1987 report[5] that was appended to the Review's final report.[6] A more recent example was the preparation of a February 2014 report, sponsored by Greenpeace Canada, examining risk issues related to refurbishment of the Darlington nuclear generating station.[7] The latter report identifies a number of reports, prepared by the author across the period 1987-2014, that address risk issues related to Canadian nuclear facilities. The findings of those reports, and of the February 2014 report itself, are incorporated here by reference.

Discussion of malevolent acts

This report discusses potential attacks and other malevolent acts associated with storing SNF. Any analyst who discusses acts of this kind must be careful to avoid disclosing information that could enhance the probability or impact of a malevolent act. This report provides no such information. The report is suitable for general distribution.

Structure of this report

The remainder of this report has seven sections. Section 2 identifies types of risk relevant to storing SNF at Pickering. Section 3 discusses risk-assessment practices. Section 4 examines OPG's plan for storing SNF at Pickering. Section 5 provides illustrative

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[4] Thompson, 2005.
[5] Thompson, 1987.
[6] Hare, 1988.
[7] Thompson, 2014.

analyses of risks posed by storing SNF at Pickering, and Section 6 provides illustrative analyses of risk-reducing options. Conclusions and recommendations are set forth in Section 7, and a bibliography is provided in Section 8. Documents cited in this report are listed in the bibliography.

2. Types of Risk Relevant to Storing SNF at Pickering

In this report, the general term "risk" is defined as the potential for unintended, adverse outcomes. There are various categories of risk, as discussed below.

Managing risk is one of the major responsibilities related to the design or appraisal of a substantial action. In the context of this report, the relevant action is the storage of SNF at the Pickering site.

Table 2-1 sets forth general principles for the design or appraisal of an action option. These principles reflect the author's professional opinion. They are consistent with present and emerging practices worldwide, in fields including engineering, that are guided by the concept of sustainable development.

From Table 2-1, one sees that managing risk is one of five major objectives to be pursued in designing an action option. Accordingly, the option should be designed so that, if possible, its response to a hazardous event is to either ride out that event or fail in a controlled manner. Emergency response (e.g., sheltering or evacuation of exposed populations) would provide a second line of defense if the option cannot ride out a hazardous event.

Table 2-2 sets forth three categories of risk that are posed by commercial nuclear facilities, such as the nuclear reactors and SNF storage facilities at the Pickering site. For each category, Table 2-2 provides a general definition and lists mechanisms whereby risks in this category could be manifested. The three categories are:

- <u>Radiological risk</u>: Potential for harm resulting from unintended exposure of humans and their environment to ionizing radiation.
- <u>Proliferation risk</u>: Potential for diversion of fissile material or radioactive material to weapons use.
- <u>Program risk</u>: Potential for the functioning of a facility to diverge substantially from the original design objectives.

In each category, risk is a "potential" for unintended, adverse outcomes. This potential can be characterized, in part, by the probability of occurrence of events that lead to unintended, adverse outcomes. That probability, and the degree of its uncertainty, might be susceptible to estimation in quantitative or qualitative terms, or might be unknowable. Also, that probability and its uncertainty might vary over time or might vary in response to changing circumstances.

The "arithmetic" definition of risk, and its deficiencies

A flawed definition of risk is widely used in the nuclear industry and its regulators. In that definition, risk is the arithmetic product of a numerical indicator of harmful impacts and a numerical indicator of the frequency (i.e., probability) of occurrence of those impacts.[8] That definition is hereafter designated as the "arithmetic" definition of risk.

The author has, in various reports and declarations, discussed the deficiencies of the "arithmetic" definition. For example, these deficiencies are discussed in the author's February 2014 report on risk issues related to refurbishment of the Darlington station.[9]

In summary, the "arithmetic" definition of risk, in the context of commercial nuclear facilities, is severely flawed from at least four overlapping perspectives:

- Numerical (i.e., quantitative) estimates of impacts and their frequencies are typically incomplete and highly uncertain.
- Significant aspects of impact and frequency are not susceptible to numerical estimation.
- Impacts that are quantitatively large could be accompanied by severe, adverse qualitative impacts that would otherwise remain dormant.
- Devotees of the arithmetic definition typically argue that equal levels of "risk", as they define it, should be equally acceptable to citizens. That argument may be given a scientific gloss, but is actually a statement laden with subjective values and interests. An informed citizen could reject that argument on reasonable grounds.

Despite these severe flaws, the "arithmetic" definition of risk underlies various practices in the nuclear regulatory arena. Two interrelated practices are especially prominent. One practice is to describe impacts in terms of their frequency-weighted values. In that way, large impacts are made to seem small if their supposed frequency is low. The second practice is to ignore impacts whose supposed frequency is less than some threshold value. In both cases, impacts and their frequencies are typically discussed in exclusively numerical terms.

3. Risk-Assessment Practices

Risks in a particular category (e.g., radiological risk), in a particular situation (e.g., storage of SNF at Pickering), can be assessed by compiling available information about: (i) the potential for unintended, adverse outcomes; and (ii) the characteristics of those outcomes. Relevant information could be quantitative or qualitative.

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[8] Often, the arithmetic product will be calculated for each of a range of impact scenarios, and these products will be summed across the scenarios.
[9] Thompson, 2014.

The author has, in various reports and declarations, discussed the assessment of risk related to nuclear facilities, including facilities in Canada. For example, risk assessment is discussed at length in the author's February 2014 report on risk issues related to refurbishment of the Darlington station.[10]

Two aspects of risk assessment are briefly discussed here, drawing upon the author's previous writing. One aspect is the use of probabilistic risk assessment. The second aspect is the risk environment.

Probabilistic risk assessment

Beginning in the 1970s, the nuclear industry and its regulators have developed an analytic art to examine the risk posed by nuclear facilities. That art is known as probabilistic risk assessment (PRA). It has mostly been used to examine radiological risk, but can be applied to proliferation risk and program risk.

Sometimes, the PRA art is referred to as probabilistic "safety assessment", but "risk assessment" is a more honest description. Much of the early work on PRA development was done by the US Atomic Energy Commission (AEC) and by the US Nuclear Regulatory Commission, which took over AEC's regulatory function in 1975.

In the context of radiological risk, analysts have developed an array of PRA techniques to estimate the frequencies and impacts of unintended releases of radioactive material from a nuclear facility. Most of that work has focused on commercial nuclear reactors. However, PRA techniques can be applied to other nuclear facilities, such as SNF storage facilities.[11]

Experience shows that PRA can be a useful art, provided that its limitations are kept firmly in mind. It can provide valuable knowledge about the potential occurrence of hazardous events at a nuclear facility, and about the responses of the facility to those events. That knowledge can help to identify risk-reducing options.

Important limitations of PRA include:

- PRA techniques do not account for systemic institutional weaknesses, gross errors, or malevolent acts, although these factors could strongly influence risk.
- PRA techniques exclude factors that are not quantifiable, although these factors could strongly influence risk.
- PRA practice assumes a constant risk environment, although the risk environment could change substantially, thereby strongly influencing risk.
- PRA findings have large, irreducible uncertainty.
- PRA cannot provide a comprehensive, objective assessment of risk.

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[10] Thompson, 2014.
[11] PRA techniques can also be applied to non-nuclear facilities such as chemical plants.

The risk environment

Radiological risk, proliferation risk, and program risk at a particular nuclear facility are influenced by "internal" and "external" factors.[12] Major internal factors include the design, quality of construction, and mode of operation of the facility. The external factors, taken together, are here termed the "risk environment".

Factors constituting the risk environment could operate at spatial scales ranging from the global (e.g., the potential for worldwide economic crisis, war, or pandemic) to the local (e.g., the potential for storm surge at a coastal site). These factors could change over temporal scales ranging from hours (e.g., the occurrence of an unexpected attack on a facility) to centuries (e.g., societal decay).

Relevant factors in the risk environment could include:

- Institutional arrangements and culture.
- Laws and regulations.
- Trends in technology.
- Management, workforce, and supplier capabilities.
- Economic and political status of a facility.
- Site characteristics (e.g., proximity of population centers).
- Economic conditions.
- Potential for violent conflict.
- Potential for societal disorder or decay.

Canada is fortunate in having a risk environment that is, at present, comparatively benign and stable. Other countries are less fortunate. In that context, it is illuminating to imagine the incidents that could have occurred in Syria, Iraq, and similarly violence-afflicted countries if nuclear facilities analogous to those at the Pickering site had been operating in these countries prior to the violent conflict they have experienced in recent decades.

As discussed below, storage of SNF could continue at Pickering for centuries into the future. In that context, it would be imprudent to assume that the risk environment in Canada will remain comparatively benign and stable.

4. OPG's Plan for Storing SNF at Pickering

Figure 4-1 shows the Pickering site and the two areas – Phase I, and Phase II – where the PWMF operates. Two DSC storage buildings are now located at the Phase I area, and a third DSC storage building is now located at the Phase II area. Pursuant to the recent

[12] The term "external" is used in PRA practice to describe a class of accident-initiating events such as earthquakes. The term is used here in a different but related sense.

renewal of the PWMF operating license, OPG intends to construct three additional DSC storage buildings at the Phase II area.

Figure 4-2 shows the configuration of a DSC. It has the capacity to store 384 SNF assemblies. It is constructed in the form of inner and outer carbon-steel shells separated by reinforced concrete. The nominal thickness of each carbon-steel shell is 13 mm and the concrete thickness is 520 mm.[13]

The DSC storage buildings are commercial-type structures whose primary functions are weather protection and radiation shielding. Each building has a concrete slab floor at about grade level. The lower portion of each building wall consists of precast concrete panels that provide radiation shielding. The upper portion consists of metal panels.[14]

When the three additional DSC storage buildings are operational, the PWMF will have the capacity to store 3,002 DSCs, according to OPG. If each DSC is loaded with 384 SNF assemblies, the total number of SNF assemblies stored in DSCs at the PWMF could reach 3,002 x 384 = 1,152,768.[15]

Inventories of hazardous constituents of SNF at Pickering

SNF at Pickering contains various types of hazardous material. Here, for illustration, attention is focused on two hazardous constituents of SNF – Cs-137, and plutonium.

Cs-137 is a product of the fission of uranium or plutonium. It has a half-life of 30 years. In 5% of its decays, it yields stable Ba-137. In 95% of its decays, it yields Ba-137m, a metastable radionuclide that has a half-life of 2.6 minutes and emits a gamma photon of energy 0.66 MeV while decaying to stable Ba-137.

Cs is a comparatively volatile element. Thus, Cs isotopes are released comparatively liberally when nuclear fuel is overheated. That behavior was evident in, for example, the Chernobyl reactor accident of 1986 and the Fukushima reactor accidents of 2011. Given that behavior, and the decay properties of Cs-137, the inventory of Cs-137 at a nuclear facility is an important indicator of radiological risk.

Table 4-1 provides a rough estimate of the inventory of Cs-137 in SNF at Pickering, as of 2024. OPG could provide a more accurate estimate. Assuming that all Pickering reactors are shut down by 2024, and no SNF is removed from the site, the inventory of Cs-137 at Pickering would decline after 2024 with a half-life of 30 years.

One sees from Table 4-1 that one DSC at Pickering would contain about 3.6 PBq of Cs-137 in 2024. (Note: 1 PBq = 1 x 10^{15} Bq, and 1 Bq = 1 disintegration per second.) The Pickering sitewide inventory of Cs-137 in 2024 would be about 10,800 PBq.

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[13] OPG, 2016, Section 1.5.1.
[14] OPG, 2016, Section 1.5.4.
[15] OPG, 2016, Table 1.

These amounts of Cs-137 at Pickering can be compared with the amounts shown in Table 4-2. That table shows, for example, that about 6.4 PBq of Cs-137 was deposited on Japan's land surface due to the Fukushima reactor accidents of 2011. Also, at the time of those accidents, the spent-fuel pools of the four affected reactors at Fukushima contained about 2,200 PBq of Cs-137. The potential for release of Cs-137 at Pickering is discussed in Section 5.3.

As mentioned above, a second hazardous constituent of SNF at Pickering – namely, plutonium – is addressed here. Estimated inventories of plutonium are provided in Table 4-1. That table shows, for example, that one DSC at Pickering contains about 29 kg of plutonium. The Pickering sitewide inventory of plutonium in 2024 would be about 88,000 kg.

For comparison with these inventories, note that the critical mass of a bare sphere of plutonium (pure Pu-239, alpha-phase) is about 10 kg. The radius of that sphere is about 5 cm. With addition of a natural uranium reflector about 10 cm thick, the critical mass would be reduced to about 4.4 kg, comprising a sphere with a radius of about 3.6 cm, the size of an orange. The critical mass could be further reduced using implosion techniques. An implosion device built to a modern design could achieve a nuclear explosion using 2 to 3 kg of plutonium.[16]

Nuclear warheads deployed by the nuclear-weapon states each contain, on average, about 3 to 4 kg of plutonium.[17] The world's inventory of military plutonium, at the end of 1994, was about 249,000 kg, mostly held by the former USSR and the USA. About 70,000 kg of that plutonium was in operational warheads.[18]

When plutonium is created in a fission reactor, heavier isotopes of plutonium – including Pu-240 and Pu-241 – are increasingly formed as fuel burnup increases. Nuclear weapon designers prefer to use plutonium with a high fraction of Pu-239, which requires the discharge of fuel at a low burnup – typically about 0.4 GWt-day per Mg HM.[19] The "weapon grade" plutonium in US nuclear warheads typically contains about 93% Pu-239 and 6.5% Pu-240.[20] Nevertheless, according to Frank Barnaby, "reactor-grade" plutonium with a Pu-239 content of 60% could be used to make a functioning nuclear warhead.[21] Also, Carson Mark and colleagues say:[22] "The difficulties of developing an effective [nuclear explosive] design of the most straightforward type are not appreciably greater with reactor-grade plutonium than those that have to be met for the use of weapons-grade plutonium."

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[16] Barnaby, 1992.
[17] Albright et al, 1997, page 34.
[18] Albright et al, 1997, Table 14.2.
[19] Albright et al, 1997, page 21.
[20] Cochran et al, 1987, page 136.
[21] Barnaby, 1992.
[22] Mark et al, 2009, Conclusions.

According to Canadian Nuclear Laboratories, the plutonium in SNF from CANDU reactors typically contains about 69% Pu-239 and 25% Pu-240.[23] Presumably, similar fractions apply at Pickering. Thus, the plutonium in SNF at Pickering is "reactor grade". This plutonium could, nevertheless, be used to make nuclear weapons.

Timing of SNF-related future events at Pickering:
OPG's vision

Figure 4-3 shows a projection by OPG of a timeline of events at Pickering following final shutdown of the reactors. In Figure 4-3, reactor shutdown is completed in about 2020. OPG currently expects reactor shutdown to be completed in about 2024.

One sees from Figure 4-3 that all SNF at Pickering would be placed in DSCs by a time point 13 years after reactor shutdown. Also, in this projection, all SNF would have been removed from the Pickering site by a time point 30 years after reactor shutdown, or soon thereafter. This projection is misleading, as discussed in Section 5.2.

OPG's October 2016 application to CNSC for renewal of the PWMF operating license does not provide a timeline analogous to the one in Figure 4-3. Nor does the application provide, or make reference to, a plan for the various steps that would be required to implement such a timeline. The application does mention Canada's efforts to develop a deep geological repository for SNF, but does not discuss a schedule for that development.[24]

Protection of SNF against attack

OPG's application for renewal of the PWMF operating license provides a brief, non-specific description of the measures that OPG is using, and expects to use, to protect the PWMF against attack.[25]

Table 4-3 describes some potential modes and instruments of attack on a nuclear generating station. Also shown are defense measures now deployed at stations in the USA. One can see from the table that nuclear stations in the USA have a comparatively "light" defense. They are not defended against the full spectrum of attacks that could be mounted by a group of people acting without support from a government.

Publicly available evidence indicates that defenses at Canadian nuclear generating stations, such as Pickering, are no more robust than defenses at US nuclear stations.[26] Thus, SNF now stored at Pickering, either in irradiated fuel bays or in the PWMF, has a comparatively light defense. OPG's application for PWMF license renewal does not

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[23] CNL, 2016, Table 2-3.
[24] OPG, 2016, Section 3.8.2.
[25] OPG, 2016, Section 2.12.
[26] Relevant evidence includes site photographs.

identify any substantial strengthening of this defense in the future.[27] Moreover, it is likely that the overall defense of the Pickering site will become less robust after the Pickering reactors are shut down. For example, the size of the security workforce is likely to decline.

5. Risks Posed by Storing SNF at Pickering: Illustrative Analyses

5.1 Overview

As mentioned in Section 1, this report does not claim to provide a comprehensive assessment of the risks posed by storing SNF at Pickering. Instead, it provides illustrative analyses that are sufficient to support the conclusions and recommendations proffered in Section 7.

Findings about program risks affect the assessment of radiological risks and proliferation risks, as will be seen below. Thus, discussion of risks begins here by examining program risks.

CNSC Staff have provided a benchmark for assessing risks posed by storing SNF at Pickering. In a February 2017 document, the Staff recommended renewal of the PWMF operating license.[28] In support of that recommendation, the Staff proffered the following overall conclusions:[29]

> "CNSC staff conclude the following with respect to paragraphs 24(4)(*a*) and (*b*) of the NSCA [Nuclear Safety and Control Act], in that OPG:
>
> 1. is qualified to carry on the activity authorized by the licence; and,
>
> 2. will, in carrying out that activity, make adequate provisions for the protection of the environment, the health and safety of persons and the maintenance of national security and measures required to implement international obligations to which Canada has agreed."

Analyses presented here contradict these conclusions. These analyses show that OPG, in operating the PWMF, will **not** [emphasis added] "make adequate provisions for the protection of the environment, the health and safety of persons and the maintenance of national security".

5.2 Program Risks

Program risk is the potential for the functioning of a facility to diverge substantially from the original design objectives. In the context of storing SNF at Pickering, program risk

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[27] OPG, 2016, Section 2.12.
[28] CNSC Staff, 2017, Section 1.4.
[29] CNSC Staff, 2017, Section 1.3.

could be manifested in various ways. Here, attention is focused on three possible manifestations, as follows:

- SNF could be stored at Pickering for a significantly longer period than OPG now expects.
- The quality of operation of the PWMF, and of related facilities at Pickering, could degrade significantly over time.
- The PWMF could eventually become a "repository by default".

These manifestations of program risk were foreseen, and studied, by the US Department of Energy (DOE), in the context of the proposed radioactive-waste repository at Yucca Mountain.

The Yucca Mountain EIS

In 2002, DOE published its final environmental impact statement (EIS) for the Yucca Mountain project.[30] The EIS considered a Proposed Action – namely, construction and operation of the Yucca Mountain repository. It also considered a No-Action Alternative – namely, abandonment of the Yucca Mountain project, with continued storage of SNF and other high-level radioactive waste forms at commercial and DOE sites in the USA.

The EIS considered two scenarios – Scenario 1, and Scenario 2 – for the No-Action Alternative. In describing Scenario 1, the EIS says:[31]

> "Under Scenario 1, 72 commercial sites and 5 DOE sites would store spent nuclear fuel and high-level radioactive waste for 10,000 years. Institutional control, which would be maintained for the entire 10,000-year period, would ensure regular maintenance and continuous monitoring at these facilities that would safeguard the health and safety of facility employees, surrounding communities, and the environment. The spent nuclear fuel and immobilized high-level radioactive waste would be inert material encased in durable, robust packaging and stored in above- or below-grade concrete facilities. Release of contaminants to the ground, air, or water would not be expected during routine operations."

In describing Scenario 2, the EIS says:[32]

> "DOE and commercial utilities intend to maintain control of the nuclear storage facilities as long as necessary to ensure public health and safety. However, Scenario 2 assumes no effective institutional control of the storage facilities after approximately the first 100 years to provide a basis for evaluating an upper limit of potential adverse human health impacts to the public from the continued

[30] DOE, 2002.
[31] DOE, 2002, Section 7.2.1.
[32] DOE, 2002, Section 7.2.2.

> storage of spent nuclear fuel and high-level radioactive waste. After about 100 years, Scenario 2 assumes that there would be no effective institutional control and that the storage facilities would be abandoned. Therefore, there would be no health risks for workers during that period. For the long-term impacts after about 100 years and for as long as 10,000 years, the analysis assumed that the spent nuclear fuel and high-level radioactive waste storage facilities at 72 commercial and 5 DOE sites would begin to deteriorate and that radioactive materials would be released to the environment, contaminating the local atmosphere, soil, surface water, and groundwater."

Both scenarios are somewhat stylized. Many variants of these scenarios are possible. These scenarios do, however, capture an important truth about the management of high-level radioactive waste in the USA. There is, at present, no credible, site-specific plan to place SNF and other high-level waste into a repository in the USA. Thus, for the foreseeable future, SNF from commercial reactors in the USA will remain at reactor sites or, perhaps, will be transferred to interim storage facilities at other sites.

Failure of the US effort to dispose of SNF and other high-level radioactive waste

The author has written a paper about the history of the US effort to dispose of high-level radioactive waste.[33] The period covered begins with the effort's inception in 1957 and continues through 2007. One milestone during that period was passage of the Nuclear Waste Policy Act in 1982. Writing in early 2008, the author predicted:[34]

> "On balance, a range of technical and political factors suggest that the Yucca Mountain project will lose momentum and eventually be cancelled, and that commercial spent fuel will remain at reactor sites for at least the next several decades."

Events have fulfilled that prediction. Now, six decades after work began in the USA to develop a repository for high-level radioactive waste, there is no current prospect of opening a repository. This failure reflects technical and political factors that are discussed in the author's paper. Interestingly, proponents of nuclear energy contributed substantially to the failure, by undermining the principles behind the Nuclear Waste Policy Act.[35]

In 2014, the US Nuclear Regulatory Commission published a generic EIS for continued storage of SNF. That EIS identified three possible timeframes for continued storage of SNF at reactor sites in the USA. The possible timeframes are:[36]

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[33] Thompson, 2008.
[34] Thompson, 2008, Section 8.
[35] Thompson, 2008, Section 8.
[36] NRC, 2014, Section ES.12.

- 60 years beyond the licensed life for reactor operations;
- 160 years beyond the licensed life for reactor operations; or
- indefinitely.

Canada's effort to dispose of SNF

An overview of Canada's effort to dispose of SNF is provided in a 2011 report by the International Panel on Fissile Materials.[37] The Panel's report says that Canada's effort began in the mid-1960s. One milestone over the subsequent decades was the creation, in 2002, of the Nuclear Waste Management Organization (NWMO).

In 2005, NWMO recommended a three-phase approach – termed Adaptive Phased Management – to developing a deep geological repository for SNF.[38] The first phase, lasting about 30 years, would culminate in selection of a site for a repository. Also, during that phase, a decision would be made whether or not to construct a shallow underground facility for centralized interim storage of SNF. The second phase, lasting about 30 years, would culminate in completion of the final design for a repository. If a decision were made to not construct a facility for centralized interim storage, then all SNF discharged from the Pickering reactors would remain at Pickering until some time point after completion of the second phase. In that context, NWMO expects that removal of SNF from a reactor site, such as Pickering, would occur over a period of about 30 years.

Construction of a Canadian facility for centralized interim storage of SNF could be problematic in various respects. For example, that project would increase the monetary and political costs of managing SNF. Budget overruns, schedule overruns, or technical failures in the project could undermine political support for subsequent construction of a repository. Citizens could become concerned that this interim-storage facility, envisioned by NWMO as a shallow underground facility, would become a "repository by default", despite its limited capability for long-term confinement of radioactive material. That prospect, which is discussed again below, could provide a reasonable basis for opposing the facility. In light of such factors, construction of a centralized interim-storage facility seems unlikely.

Timeline for SNF storage at Pickering

If there is no centralized interim-storage facility in Canada, NWMO's timeline for repository development suggests that all SNF discharged from the Pickering reactors will remain at Pickering for at least six decades into the future. Thereafter, this stock of SNF might be removed from the Pickering site over the following three decades. That timeline for SNF removal is considerably longer than the timeline projected by OPG in Figure 4-3.

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[37] Feiveson et al, 2011, Section 2.
[38] NWMO, 2005, Section 1.5.

Various technical and political factors could substantially extend the timeline for repository development beyond that envisioned by NWMO, thereby extending the timeline for storage of SNF at Pickering. For example, funds now earmarked for repository development could be dissipated over time, or could be insufficient. In that case, much of the cost of repository development would fall upon future citizens who gain no benefit from the electricity produced by the nuclear stations now operating in Canada. Citizens' resentment of this obligation could be encouraged by political opportunists. In the resulting political climate, adverse outcomes in repository development – such as budget overruns, schedule overruns, scandals, accidents, or technical failures – could reduce political support for the repository project to the point where it is cancelled or its timeline extends indefinitely.

Quality of operation of SNF facilities at Pickering

Various factors, similar to those discussed above, could cause the quality of operation of the PWMF, and of related facilities at Pickering, to degrade significantly over time. In the Yucca Mountain EIS, Scenario 2 for the No-Action Alternative involves sudden cessation of institutional control of SNF storage at about the 100-year time point. Gradual degradation of institutional control could be more likely. For example, a long period (e.g., several decades) of uneventful operation of the PWMF might feed a culture of complacency within the institutions involved, leading to gradual degradation of operational quality.

A repository by default

As discussed above, a Canadian facility for centralized interim storage of SNF could become a "repository by default". This term means that the facility would become, as a practical matter, the long-term resting place for the material it holds. That outcome might, or might not, be formally acknowledged by the responsible authorities. By comparison with a deep geological repository – the long-term resting place envisioned by NWMO – the interim-storage facility would have limited capability for long-term confinement of radioactive material.

In the context of the Yucca Mountain EIS, the No-Action Alternative implies that each of the facilities storing SNF at commercial reactor sites in the USA would become a "repository by default". These facilities might experience ongoing institutional control – in Scenario 1 – or that control might cease after about 100 years – in Scenario 2.

As mentioned above, various technical and political factors could substantially extend the timeline for development of a deep geological repository beyond the timeline envisioned by NWMO. Moreover, credible events could reduce political support for the repository project to the point where it is cancelled or its timeline extends indefinitely. At that point, the PWMF could become a "repository by default", despite the fact that it would have very limited capability for long-term confinement of radioactive material.

5.3 Radiological Risks

Radiological risk is the potential for harm resulting from unintended exposure of humans and their environment to ionizing radiation. In the context of storing SNF at Pickering, radiological risk could be manifested in various ways. Here, attention is focused on three possible manifestations, as follows:

- Loss of water from an irradiated fuel bay at Pickering, arising from an accident or an attack, could expose SNF assemblies to air or steam, leading to an atmospheric release of radioactive material.
- An attack affecting one or more DSCs could lead to an atmospheric release of radioactive material.
- Degradation of one or more DSCs, and of SNF assemblies contained within them, could contaminate the surrounding environment with radioactive material.

The potential for each of these manifestations to occur is influenced by program risks at Pickering. Notably, as discussed in Section 5.2, SNF could be stored at Pickering for an extended period, and/or the quality of operation of SNF facilities at Pickering could degrade over time. Either outcome would increase radiological risks at Pickering.

Loss of water from an irradiated fuel bay

The irradiated fuel bays at Pickering and similar CANDU nuclear stations are analogous to the SNF pools that serve light-water reactors (LWRs). There are, however, important differences between CANDU irradiated fuel bays and SNF pools at LWRs, as discussed below.

It is widely acknowledged that SNF pools at LWRs pose a significant radiological risk, because they are now used in a high-density configuration. Water could be lost from such a pool in various ways, potentially leading to exposure of SNF assemblies to air or steam. That exposure could lead to a runaway, exothermic reaction of zircaloy fuel cladding with air or steam, resulting in a substantial release of radioactive material to the atmosphere.

The author has discussed the issue of SNF-pool radiological risk in various documents. One example is an October 2012 report related to refurbishment of OPG's Darlington nuclear station.[39] Another example is a January 2013 handbook on assessment of SNF radiological risk.[40] The findings of both documents are incorporated here by reference.

The significance of SNF-pool radiological risk, in an LWR context, can be illuminated by examining the Fukushima reactor accidents of 2011. One source of illumination is a

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[39] Thompson, 2012.
[40] Thompson, 2013a.

2016 paper by Frank von Hippel and Michael Schoeppner.[41] Their paper shows that a runaway, exothermic reaction – a "pool fire" – in the SNF pool of Fukushima #1 Unit 4 was narrowly avoided during the Fukushima accidents. Von Hippel and Schoeppner examined the potential offsite impacts of such an event. They say:[42]

> "This article reviews the case of the spent fuel fire that almost happened at Fukushima in March 2011, and shows that, had the wind blown the released radioactivity toward Tokyo, 35 million people might have required relocation."

In an October 2012 report referenced above, the author examined the relevance of the pool-fire issue to the storage of SNF in irradiated fuel bays at CANDU stations such as Pickering.[43] The report notes that the design of a CANDU station differs in various ways from that of an LWR station. For example, the fuel assemblies are significantly different. CANDU fuel is driven to a comparatively low burnup, and can be stored under (light) water in a compact configuration without the presence of neutron-absorbing plates. Yet, CANDU fuel and LWR fuel both employ zircaloy cladding. Thus, they share the potential for exothermic reaction of zircaloy with steam or air.

The author found that OPG and CNSC were aware that loss of water from an irradiated fuel bay at a CANDU station is an event to be feared. Unfortunately, however, neither entity had performed the investigations needed to determine if a pool fire could occur at a CANDU station.[44] The author recommended investigations to correct that deficiency, saying:[45]

> "Due to the differences between CANDU and LWR designs, findings about SNF radiological risk at LWR stations cannot be directly applied to CANDU stations. CNSC and the Canadian nuclear industry, as the principal custodians of CANDU technology, have an obligation to thoroughly investigate SNF radiological risk at CANDU stations."

To the author's knowledge, neither OPG nor CNSC, nor any other entity, has performed the recommended investigations.

An attack on stored SNF

As mentioned above, an irradiated fuel bay at Pickering could experience loss of water as a result of an accident or attack. The irradiated fuel bays are adjacent to, and operationally connected with, nuclear reactors. Thus, the potential for an attack on an irradiated fuel bay at Pickering is intertwined with the potential for an attack on one or more reactors at Pickering. These intertwined potentials, although important, are not

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[41] von Hippel and Schoeppner, 2016.
[42] von Hippel and Schoeppner, 2016, Abstract.
[43] Thompson, 2012.
[44] Issues that should be investigated include the potential for induced ignition of exposed zircaloy cladding by incendiary material. That potential is relevant to some attack scenarios.
[45] Thompson, 2012, Section 3.

addressed here. Instead, attention is focused here on the potential for an attack affecting one or more DSCs at Pickering.

As mentioned in Section 1, in 2005 the author was commissioned by the UK government's Committee on Radioactive Waste Management to prepare a report on reasonably foreseeable security threats to options for management of UK radioactive waste.[46] CORWM specified that the report should use a time horizon of 300 years. In that way, CORWM acknowledged that SNF and other radioactive-waste forms could remain in temporary storage facilities, including facilities analogous to the PWMF, for at least 300 years.

Some general findings are offered here regarding the potential for an attack on an SNF storage facility. These findings draw from the author's 2005 report for CORWM, and on other analyses by the author. These findings are relevant to an attack affecting one or more DSCs at Pickering. The findings are:

- Table 5.3-1 describes some potential objectives of an attack on a radioactive-waste storage facility or transport operation. These objectives are relevant to radiological risks, as discussed here, and to proliferation risks, as discussed in Section 5.4. Motives of various kinds, rational or irrational, could underlie these objectives.
- Table 5.3-2 describes three categories of potential attack on a radioactive-waste storage facility or transport operation. These categories differ in the closeness of contact during the attack. They cover attacks involving various levels of resourcing and sophistication. These potential attacks could be relevant to radiological risks and/or proliferation risks.
- Table 5.3-3 describes four types of potential attack on a nuclear reactor or SNF-storage facility. These types differ in the scale of violence involved in the attack. An important finding is that precise, informed targeting could release more radioactive material than would be released by a more violent attack.
- Table 5.3-4 illustrates the capability of a particular instrument of attack – the shaped charge. Many people with military experience are familiar with shaped charges. These devices can be obtained via black markets, are comparatively easy to manufacture, and have been used by insurgents in Iraq and elsewhere. One can see from Table 5.3-4 that a small shaped charge, which can be carried by an individual, could penetrate a DSC of the type used at Pickering.

The knowledge and practical skills needed to successfully attack a nuclear facility are, unfortunately, widely available around the world. Many thousands of people have extensive experience, typically gained through military service, with the modes and instruments of attack that are discussed here. While the great majority of these people have no interest in attacking a nuclear facility, only a few people would be needed to mount an attack. It is not clear that either OPG or CNSC understands the scope of this threat.

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[46] Thompson, 2005.

Defense of the PWMF against attack is discussed in Section 4. That discussion shows that OPG now provides a comparatively light defense of the PWMF, and does not envision substantial strengthening of this defense in the future. The discussion above shows that a group of people, acting without support from a government, could potentially overcome the PWMF defense, creating a substantial release of radioactive material from one or more DSCs.

The radiological impacts of an attack affecting DSCs at Pickering would depend upon the characteristics of the resulting release of radioactive material, and upon the manner in which that material would move through the environment. An atmospheric release would be of particular concern, especially if weather patterns led to deposition of radioactive material in densely populated locations.

A sense of the scale of potential radiological impacts can be obtained by comparing entries in Tables 4-1 and 4-2. For example, Table 4-1 shows that one DSC at Pickering could contain about 3.6 PBq of Cs-137. An atmospheric release of about that size could potentially be achieved by precise, informed targeting of two DSCs.[47] Table 4-2 shows that the Fukushima accidents of 2011 led to deposition of about 6.4 PBq of Cs-137 on the land surface of Japan. That deposition led to substantial relocation of populations, and to an expensive program of land decontamination that has generated massive amounts of radioactive waste.

Degradation of DSCs and SNF assemblies

Over time, the materials constituting DSCs and stored SNF assemblies could degrade, by corrosion or otherwise. As a result, radioactive material could leak from one or more DSCs, thereby contaminating the surrounding environment. The potential for such radioactive contamination would increase if the quality of operation of SNF facilities at Pickering degraded over time.

NWMO has acknowledged that interim storage of SNF at reactor sites, or at a centralized facility, if excessively prolonged, could lead to a variety of adverse outcomes. In that context, NWMO says:[48]

> "The NWMO believes that the risks and uncertainties concerning the performance of these storage approaches over the very long term[49] are substantial in the areas of public health and safety, environmental integrity, security, economic viability and fairness."

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[47] In other words, the atmospheric release fraction of Cs from an affected DSC could be about 50%.
[48] NWMO, 2005, Section 1.6.
[49] NWMO implies that the "very long term" could begin after 175 years. See: NWMO, 2005, Section 1.6.

In the USA, concern about future degradation of SNF assemblies and dry-storage canisters, and about other outcomes, has drawn attention to the need to equip SNF-storage facilities with dry transfer systems. Such a system is sometimes referred to as a "hot cell". A 2012 report from Idaho National Laboratory discusses various aspects of dry transfer systems. The report says:[50]

> "The potential need for a dry transfer system (DTS) to enable retrieval of used nuclear fuel (UNF) for inspection or repackaging will increase as the duration and quantity of fuel in dry storage increases…………..Uses for a DTS can be broadly binned into two categories – [1] retrieval of stored fuels for inspection and other research, development, and demonstration (RD&D) applications or [2] for repackaging. Repackaging could be needed for recovery from an unplanned event or discovery of an unforeseen condition; to repair, replace, or overpack a compromised cask or canister; to replace aging canisters; and/or to reconfigure storage or transport packages to meet future storage, transport, or disposal requirements."

The same report makes three major recommendations including:[51]

> "Recommendation 2: A repackaging and remediation capability [i.e., a dry transfer system] should be integrated into the design of future facilities where UNF [i.e., SNF] will be consolidated."

The PWMF stores SNF from eight nuclear reactors. Thus, it provides "consolidated" storage of SNF. Moreover, the PWMF could store SNF for a century or longer into the future. Accordingly, the above-quoted recommendation in the Idaho National Laboratory report applies to the PWMF.

5.4 Proliferation Risks

Proliferation risk is the potential for diversion of fissile material or radioactive material to weapons use. In the context of storing SNF at Pickering, proliferation risk could be manifested in various ways. Here, attention is focused on three possible manifestations, as follows:

- Plutonium could be extracted from SNF that has been misappropriated from the PWMF, and this plutonium could be employed in the actual or threatened detonation of a nuclear weapon.
- Radioactive material could be extracted from SNF that has been misappropriated from the PWMF, and this material could be employed in the actual or threatened use of a radiological dispersal device (RDD) or a radiation exposure device (RED).

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[50] Carlsen and Raap, 2012, Summary.
[51] Carlsen and Raap, 2012, Section 6.

- SNF assemblies, or rods in those assemblies, could be misappropriated from the PWMF and employed directly in the actual or threatened use of an RDD or an RED.

Misappropriation of plutonium

As shown in Table 5.3-1, one of the general purposes of an attack on a radioactive-waste storage facility, such as the PWMF, could be to misappropriate plutonium. Table 5.3-1 lists functional tasks and desired impacts associated with that purpose.

Defense of the PWMF against attack is discussed in Section 4. That discussion shows that OPG now provides a comparatively light defense of the PWMF, and does not envision substantial strengthening of this defense in the future. Accordingly, misappropriation of SNF from the PWMF could potentially be accomplished by a group of people acting without support from a government.[52]

Extraction of plutonium from misappropriated SNF would require access to a workshop with the mechanical capability to remove fuel pellets from SNF assemblies, and the chemical capability to separate plutonium from the fuel pellets. The knowledge required to perform these tasks can be found in documents available around the world.[53] Radiation shielding in the workshop could be comparatively rudimentary if the workers were willing to accept a high risk of radiation injury.

Using the separated plutonium to make a functional nuclear weapon would require additional skills and resources. However, the group separating the plutonium might not use it to make a nuclear weapon. They might, instead, sell the plutonium into international black markets. Alternatively, they might threaten to sell or weaponize the plutonium in order to extort money or some other reward.

Table 4-1 shows that the 384 SNF assemblies in a DSC at Pickering could contain about 29 kg of plutonium. Access to that amount of plutonium could potentially allow a non-government group to make a few nuclear weapons that might be comparatively unsophisticated but could be highly destructive if detonated.

Misappropriation of radioactive material

OPG has proposed to construct and operate a deep geologic repository (DGR) for low-level and intermediate-level radioactive waste. In 2013, the author wrote a report about

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[52] The ionizing radiation field surrounding SNF would not necessarily provide an effective barrier against misappropriation. See: Thompson, 2005, Section 7. Note that the radiation field surrounding a CANDU SNF assembly is much lower than the field surrounding an LWR SNF assembly, for the same fuel age since discharge.

[53] For example, in the 1970s, acknowledged experts wrote a document describing a small, simple facility that could extract Pu from SNF and convert the Pu to metal buttons. That document remains publicly available. Its citation is voluntarily withheld here.

the potential for malevolent acts in the context of the DGR.[54] The findings of that report are incorporated here by reference.

One of the issues addressed in that report was the potential for employment of misappropriated radioactive material in the actual or threatened use of a radiological dispersal device or a radiation exposure device. The US Federal Emergency Management Agency (FEMA) has categorized these devices as forms of radiological weapons of mass destruction (WMD). FEMA has defined radiological WMD as follows:[55]

> "Any weapon or device designed to release radiation or radioactivity at a level dangerous to human life without a nuclear explosion. Examples include Radiological Dispersal Device (RDD); Radiation Exposure Device (RED); deliberate radiological contamination of food, water, or consumables; deliberate damage to radioactive material in use, storage or transport or to an associated facility (such as a nuclear power plant)."

Note that use of an RDD would involve dispersal of radioactive material into the surrounding environment. People in that environment could be exposed to ionizing radiation via external exposure, inhalation, skin contamination, or ingestion of contaminated substances. By contrast, an RED would not disperse radioactive material, but would be hidden in a location such that people nearby would unknowingly experience external exposure.

Table 4-1 shows that one SNF assembly at Pickering could contain about 9.3 TBq of Cs-137. (Note: 1 TBq = 1 x 10^{12} Bq, and 1 Bq = 1 disintegration per second.)

For comparison, note that the US Nuclear Regulatory Commission has specified that the Quantity of Concern for Cs-137 is 1 TBq. The Quantity of Concern corresponds to a Category 2 source in the IAEA Code of Conduct on the Safety and Security of Radioactive Sources.[56]

Radioactive material in SNF stored at Pickering could cause substantial harm if employed in the actual or threatened use of an RDD or an RED. This material could be extracted from SNF that has been misappropriated from the PWMF. Alternatively, SNF assemblies, or rods in those assemblies, could be misappropriated from the PWMF and employed directly.

As discussed above, OPG now provides a comparatively light defense of the PWMF, and does not envision substantial strengthening of that defense in the future. Accordingly, misappropriation of SNF, or components of SNF, from the PWMF could potentially be accomplished by a group of people acting without support from a government.

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[54] Thompson, 2013b.
[55] FEMA, 2011/2012.
[56] Thompson, 2013b, Table 3.

Analysts have sought to estimate the adverse impacts of potential RDD incidents. The scale of impact could vary substantially, according to the characteristics of the device, the location of the incident, and other factors. The impacts would have health, economic, social, and environmental components. Estimating the direct health component for a particular incident is conceptually straightforward, although subject to a variety of scientific complexities and uncertainties. By contrast, estimating the economic and social components would involve the prediction of human behavior and the assigning of monetary values to human preferences. Findings of this kind are highly sensitive to the assumptions that are made.

Consider, for example, a 2007 study – sponsored by Defence Research and Development Canada – to estimate the economic impact of an open-air explosion of an RDD at the CN Tower in Toronto.[57] The assumed release would consist of 37 TBq of Cs-137. The estimated economic impact varies considerably, according to the cleanup standard that is assumed in the analysis. That standard is expressed in terms of the radiation dose rate that would remain after completion of the cleanup. For a cleanup standard of 5 mSv per year, the estimated economic impact would be $28 billion, whereas for a cleanup standard of 0.15 mSv per year the economic impact would be $250 billion.

A release of 37 TBq of Cs-137 could be accomplished by incorporating several SNF assemblies from Pickering into an RDD. Table 4-1 shows that four SNF assemblies would suffice in 2024. The RDD could, for example, be built into a vehicle that is driven to the point of use. The release would not be limited to Cs-137, but would also contain other radioisotopes that increase the adverse impacts.

6. Risk-Reducing Options: Illustrative Analyses

The risks discussed in Section 5 could be reduced, to varying degrees. Some of the available risk-reducing options could reduce several risks at the same time. Thus, it could be possible to assemble a set of risk-reducing options into an integrated package. Within such a package, risk-reducing measures would be mutually supportive. A package of that kind is sketched here.

Attention is focused here on risk-reducing options that would be implemented entirely within the existing boundaries of the Pickering site, and that would not rely upon ongoing support from beyond those boundaries. Reliance on ongoing external support would be imprudent, given the likelihood that SNF will be stored at Pickering for a century or longer.

Limitations of risk reduction

It is perhaps obvious, but deserves restating, that there is no "good" package of risk-reducing options in the context of storing SNF at Pickering. The amount of SNF that has

[57] Cousins and Reichmuth, 2007.

already been created at Pickering is large. This SNF contains hazardous materials such as Cs-137 and plutonium. The SNF has zircaloy cladding that could react exothermically with air or steam, potentially driving a release of radioactive material. The Pickering site is suboptimal as an SNF-storage site from perspectives including defensibility, proximity of populations, and potential to contaminate Lake Ontario. Given these factors, risk-reducing measures could ameliorate risks but could not eliminate them.

Types of risk-reducing measure

Table 6-1 describes four types of measure for defense of a radioactive-waste storage facility, or transport operation, against attack. These measures can be thought of as risk-reducing measures in the context of attack. Some of these measures would also reduce risks associated with accidents initiated by events such as earthquake, aircraft crash, or fire.

The risk-reducing measures in Table 6-1 vary in the extent to which they would be active (e.g., firefighting capability) or passive (e.g., packaging material in forms that resist fire). In the context of storing SNF at Pickering, a prudent decision maker would, in general, prefer risk-reducing measures that are passive. These measures would not rely on ongoing external support, and would be comparatively unaffected by degradation of the quality of operation at Pickering.

Protective deterrence

One of the four types of defense measure shown in Table 6-1 is “facility robustness”. As can be seen from the table, defense measures of this type are primarily passive. Thus, if these measures are well designed, they could be reliable and difficult to overcome. If those characteristics are readily apparent, deployment of these measures could significantly reduce the probability that an attack would be mounted. These measures could deter attacks by altering attackers' cost-benefit calculations. That form of deterrence can be termed “protective deterrence”.

Incorporation of protective deterrence into the design of hazardous facilities, such as the PWMF, could yield benefits in terms of Canada’s national security. The risks posed by these facilities could be substantially reduced without any need for increased policing, surveillance of populations, curtailment of civil liberties, or related interference with citizens’ lives.

Advantages of early shutdown and decommissioning of reactors

The timeline for shutdown and decommissioning of the Pickering reactors would influence program, radiological, and proliferation risks. Shutdown of these reactors earlier than is now envisioned by OPG could, in various ways, reduce risks in all three categories. A similar finding holds for decommissioning of these reactors earlier than is now envisioned by OPG.

Early shutdown of the Pickering reactors would reduce the amount of SNF to be stored at the PWMF, yielding commensurate reductions in radiological and proliferation risks. Also, shutdown of the reactors would quickly eliminate the radiological risks directly posed by their operation. In addition, early shutdown of the reactors could reduce the future time period during which SNF would be stored in irradiated fuel bays at Pickering, thereby reducing the associated radiological and proliferation risks.

These reductions in risks could be viewed from differing perspectives. From a perspective based on acceptance of prevailing risks, these reductions could appear to be small in comparison with the aggregated risks accumulated at the Pickering site since reactors began operating there in 1971. A person holding that view would note that OPG already envisions shutdown of all Pickering reactors by 2024.

A different perspective emerges from a closer look at the acceptance of prevailing risks. The author has, beginning in 1987, done numerous studies of risks associated with nuclear stations in Canada, including the Pickering station. Findings of those studies are incorporated in this report by reference. These findings show that neither OPG nor CNSC, nor any other entity, has ever published a comprehensive, credible assessment of risks associated with the Pickering station. Accordingly, it has not been possible for anyone to reach a fully informed judgment that those risks are acceptable.[58]

From the latter perspective, early shutdown of the Pickering reactors would provide a long-overdue opportunity to re-examine Pickering-related risks. Shutdown of the reactors would allow the re-examination to focus on the risks posed by storing SNF at Pickering over coming decades or, potentially, centuries. The re-examination could be especially vigorous and influential if early shutdown of the Pickering reactors were widely seen as repudiating a previous operating culture in which risks were accrued at Pickering without ever being properly assessed. Repudiation of that culture could help to create a decision-making climate that would allow the consideration, and adoption, of measures to substantially reduce the risks posed by storing SNF at Pickering.

OPG currently envisions deferred decommissioning of the Pickering reactors. Ralph Torrie and Brian Park, in a 2016 report, argue that early decommissioning – which they term "direct" decommissioning – would be preferable. Their report says:[59]

> "The timeline for direct decommissioning is compressed to 12-14 years, as compared with the 42 years required for deferred decommissioning. There will be some offsetting expenditures, but we estimate savings from the elimination of the 30-year dormancy period total at least $800 million and could be as high as $1.2 billion."

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[58] It has been possible, using the precautionary principle, to judge that those risks are unacceptable.
[59] Torrie and Park, 2016.

An additional argument for early decommissioning is that it would facilitate a reconfiguration of the PWMF, as discussed below. Moreover, any cost savings from early decommissioning could help to offset costs for reconfiguring the PWMF.

Reconfiguration of the PWMF

A proposed reconfiguration of the PWMF is sketched here. This reconfiguration would assemble a set of mutually-supportive, risk-reducing measures into an integrated package. Detailed design of the reconfigured PWMF would be done in parallel with a thorough process of risk assessment, involving iterations between design and risk assessment.

The proposed reconfiguration of the PWMF could employ DSCs of the existing type, or another type of container for dry storage of SNF. The adequacy of the existing DSCs would be one of the issues addressed in iterations between design and risk assessment. The following discussion assumes, for simplicity, that DSCs of the existing type would be used.

The reconfigured PWMF would be located on the Pickering site to the North of the reactors, on land currently occupied by electrical switchyards[60] and parking lots. DSCs would be placed inside free-standing, above-ground, attack-resistant, reinforced-concrete vaults (i.e., large boxes with heavy doors) cooled by natural convection of air.[61] Each vault roof would be covered by a layer of gravel and rock. Each vault floor would be a few meters above grade. All of the vaults would be in an area completely surrounded by a boundary structure. That structure, in cross-section, would be partly a reinforced-concrete wall and partly a gravel-and-rock berm. The boundary structure would form a continuous perimeter except for one access portal protected by heavy gates. The road passing through the access portal would have chicanes. The top of the boundary structure would be higher than the vault roofs. Trenches surrounding the vaults would drain to catch basins outside the boundary structure, and the drains would be protected against entry. Vaults might be separated from each other by berms.

The boundary structure would be designed to appear, from the outside, ugly and threatening. Signs describing the facility's hazardous contents would be built into the exterior of the boundary structure. After decommissioning of the Pickering reactors is completed, the land surrounding the reconfigured PWMF would become a public park with unrestricted access, assuming achievement of the necessary level of decontamination.

A dry transfer system, as discussed in Section 5.3, would be built within the area enclosed by the boundary structure.

[60] In Figure 4-1, the caption "Pickering NGS" covers part of an electrical switchyard.
[61] DSCs could be fastened in place inside the vaults, perhaps by floor bolts.

Benefits from reconfiguration of the PWMF

The proposed reconfiguration of the PWMF could substantially reduce the risks posed by storing SNF at Pickering, and could yield other benefits. Mechanisms for yielding risk reduction and other benefits could include:

- The size and architecture of this facility, and its proximity to populations, would reduce the likelihood that it would be forgotten and thereby become a repository by default.
- The facility would have a well-defined, defensible boundary.
- SNF stored in the facility would be protected against a wide range of potential attacks and severe accidents.
- The facility would demonstrate the role of protective deterrence and its potential contribution to Canada's national security.
- Water leakage from vaults would drain to external catch basins that could be monitored by independent agencies or citizen scientists, thereby reducing the potential for radioactive contamination of Lake Ontario.
- The drainage system would limit pooling of aircraft fuel near DSCs in the event of aircraft impact, thereby reducing fire duration.
- During routine operation the facility would require a comparatively small workforce.
- The dry transfer system would allow repackaging of SNF if SNF assemblies or DSCs become damaged or degraded.
- The public would gain access to Lake Ontario from the Pickering site.

The proposed reconfiguration of the PWMF would provide hardened, on-site storage (HOSS) for SNF from the Pickering reactors. Various citizen groups in Canada and the USA have called for a HOSS approach to storing SNF. While providing HOSS, the PWMF reconfiguration that is proposed here would also provide additional benefits as described in this report.

7. Conclusions and Recommendations

Conclusions

C1. Illustrative analyses performed here show that storing SNF at Pickering, in the manner planned by OPG, would pose substantial risks in three categories – radiological risk, proliferation risk, and program risk.

C2. Illustrative analyses performed here show that an integrated package of risk-reducing measures, featuring reconfiguration of the PWMF, could substantially reduce the above-stated risks while also yielding other benefits.

C3. Reconfiguration of the PWMF would be facilitated by early shutdown and early decommissioning of the Pickering reactors.

C4. Neither OPG nor CNSC has properly assessed the risks posed by storing SNF at Pickering or the opportunities for reducing those risks.

C5. Contrary to findings of the CNSC staff with respect to paragraphs 24(4)(*a*) and (*b*) of the Nuclear Safety and Control Act, OPG, in operating the PWMF, will **not** [emphasis added] "make adequate provisions for the protection of the environment, the health and safety of persons and the maintenance of national security".

Recommendations

R1. An independent entity should be commissioned to prepare a detailed design of a reconfigured PWMF as sketched here; the design should be done in parallel with a thorough process of risk assessment, involving iterations between design and risk assessment.

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Table 2-1
Principles for Design or Appraisal of an Action Option

Objective	Design Approach to Meet Objective
#1. Fulfill human needs	Design the action option to fulfill individual and societal needs with optimal efficiency, consistent with objectives #2 through #5
#2. Meet specifications re. cost, schedule, and performance	Integrate systems (i.e., human, natural, and manufactured systems) whose attributes are proven by experience and refined through adaptive management
#3. Build and preserve assets	Design for preservation and enhancement of: • Human capital • Natural capital • Manufactured capital
#4. Create opportunities for future actions	Design the action option for: • Reversibility • Resilience • Flexibility • Adaptability
#5. Manage risk	Prepare for hazardous events (i.e., events that could lead to unintended, adverse outcomes) by: • Identifying and characterizing potential hazardous events • Designing the action option to ride out hazardous events or to fail in a manner consistent with objectives #1 through #4 • Planning for emergency response

Table 2-2
Some Categories of Risk Posed by a Commercial Nuclear Facility

Category	Definition	Mechanisms
Radiological risk	Potential for harm resulting from unintended exposure of humans and their environment to ionizing radiation	Exposure arising from: • Release of radioactive material via air or water pathways, or • Line-of-sight exposure to unshielded radioactive material or a criticality event
Proliferation risk	Potential for diversion of fissile material or radioactive material to weapons use	Diversion by: • Non-State actors who defeat safeguards procedures and devices, or • The host State
Program risk	Potential for the functioning of a facility to diverge substantially from the original design objectives	Functional divergence due to: • Failure of facility to enter service or operate as specified, or • Policy or regulatory shift that alters design objectives or facility operation, or • Changed economic and societal conditions, or • Accident or attack affecting the facility

Notes:
(a) In this report, the general term "risk" is defined as the potential for unintended, adverse outcomes. There are various categories of risk, including the three categories in this table.
(b) In the case of radiological risk, the events leading to unintended exposure to ionizing radiation could be accidents or attacks.
(c) The term "proliferation risk" is often used to refer to the potential for diversion of fissile material, for use in nuclear weapons. Here, the term also covers the potential for diversion of radioactive material, for use in radiological weapons.

Table 4-1
Estimated Inventories of Cs-137 and Plutonium in SNF at Pickering in 2024

SNF Constituent	Estimated Inventory in 2024		
	In one SNF assembly	In one DSC (384 assemblies)	At Pickering Site (equivalent to 3,002 DSCs)
Cs-137	9.3×10^{12} Bq	3.6×10^{15} Bq	10.8×10^{18} Bq
Plutonium	0.076 kg	29.2 kg	87,610 kg

Notes:
(a) It is assumed here that the mass of an SNF assembly is 20 kg HM (heavy metal) and its burnup is 7 GWt-days per Mg HM. See: Feiveson et al, 2011, Section 1.
(b) It is assumed here that 1 GWt-day of fission energy yields 1.17×10^{14} Bq of Cs-137. Decay of Cs-137 while fuel is in a reactor is neglected. See: Thompson, 2013a, Table II.2-3.
(c) Operational periods of reactors at Pickering are assumed here (following OPG, 2018) to be:

- Units #1 to #4: 1971-1997
- Unit #4: 2003-2022
- Unit #1: 2005-2022
- Units #5 to #8: 1983-2024

A Cs-137 decay factor is calculated from the mid-point of each operational period until 2024. Each of these factors is then weighted by the fraction of total operational reactor-years represented by its period. These weighted factors are summed to yield a representative Cs-137 decay factor for the period 1971-2024. That factor is 0.57. It is applied to all SNF discharged from the Pickering reactors.
(d) The mass fraction of plutonium in SNF is assumed here to be 0.38% of HM. See: CNL, 2016, Table 2-1.

Table 4-2
Amounts of Cs-137 Related to the Chernobyl and Fukushima #1 Accidents

Category	Amount of Cs-137 (PBq)
Chernobyl release to atmosphere (1986)	85
Fukushima #1 release to atmosphere (2011)	37 (range: 20-53)
Deposition on Japan due to the Fukushima #1 atmospheric release	6.4
Pre-release inventory in reactor cores of Fukushima #1, Units 1-3 (total for 3 cores)	760
Pre-release inventory in spent-fuel pools of Fukushima #1, Units 1-4 (total for 4 pools)	2,200

Notes:
(a) This table shows estimated amounts of Cs-137 from: Stohl et al, 2012. The estimates for release from Fukushima #1 and deposition on Japan could change as new information becomes available. The cited authors subsequently stated that the Fukushima release might have been somewhat less than 37 PBq. See: Seibert et al, 2013.
(b) Stohl et al, 2012, provide the following data and estimates for Fukushima #1, Units 1-4, just prior to the March 2011 accident:

Indicator	Unit 1	Unit 2	Unit 3	Unit 4
Number of fuel assemblies in reactor core	400	548	548	0
Number of fuel assemblies in reactor spent-fuel pool	392	615	566	1,535
Cs-137 inventory in reactor core (Bq)	2.40E+17	2.59E+17	2.59E+17	0
Cs-137 inventory in reactor pool (Bq)	2.21E+17	4.49E+17	3.96E+17	1.11E+18

(The core capacity of Unit 4 was 548 assemblies. The core of Unit 3 contained some MOX fuel assemblies at the time of the accident.)
(c) For the Fukushima case, assuming a total Cs-137 release to atmosphere of 37 PBq, originating entirely from the reactor cores of Units 1, 2, and 3, which contained 760 PBq, the overall release fraction to atmosphere for Cs-137 was 37/760 = 0.049 = 4.9%.

Table 4-3
Some Potential Modes and Instruments of Attack on a Nuclear Generating Station

Attack Mode/Instrument	Characteristics	Present Defense Measures at Stations in USA
Commando-style attack	• Could involve heavy weapons and sophisticated tactics • Successful attack would require substantial planning and resources	Alarms, fences and lightly-armed guards, with offsite backup
Land-vehicle bomb	• Readily obtainable • Highly destructive if detonated at target	Vehicle barriers at entry points to Protected Area
Small guided missile (anti-tank, etc.)	• Readily obtainable • Highly destructive at point of impact	None if missile launched from offsite
Commercial aircraft	• More difficult to obtain than pre-9/11 • Can destroy larger, softer targets	None
Explosive-laden smaller aircraft	• Readily obtainable • Can destroy smaller, harder targets	None
10-kilotonne nuclear weapon	• Difficult to obtain • Assured destruction if detonated at target	None

Notes:
(a) This table is adapted from: Thompson, 2007, Table 7-4. Further citations are provided in that table and its supporting narrative. For additional, supporting information of more recent vintage, see: Ahearne et al, 2012, Chapter 5.
(b) Defenses at Canadian nuclear stations are no more robust than at US stations. See: Frappier, 2007.

Table 5.3-1
Potential Objectives of an Attack on a Radioactive-Waste Storage Facility or Transport Operation

General Purpose of Attack	Specific Objectives of Attackers	
	Functional Tasks	**Desired Impacts**
Release of radioactive material to atmosphere	Penetrate facility and storage vaults; convert contained material to small particles and promote release of particles to atmosphere (e.g., by fire or blast) OR use threat of release as a means of coercion.	• Radioactive contamination of locations downwind from facility. • Radiation exposure from dispersed material. • Adverse health effects in exposed populations. • Adverse psychological, economic and political effects in affected societies.
Misappropriation of radioactive material	Penetrate facility and storage vaults; remove contained material; use physical and chemical means to convert material to forms that can be released to atmosphere OR can be placed to irradiate persons in public places or contaminate food, etc.; release or place material OR use material as an instrument of coercion.	• Radioactive contamination of locations downwind from point of release. • Radiation exposure from dispersed material, point sources, food, etc. • Adverse health effects in exposed populations. • Adverse psychological, economic and political effects in affected societies.
Misappropriation of fissile material (primarily plutonium)	Penetrate facility and storage vaults; remove contained material; use physical and chemical means to convert material to nuclear-weapon components; construct weapon; place and detonate weapon OR use weapon as an instrument of coercion.	• Blast, thermal and direct radiation impacts on persons and structures. • Radioactive contamination (by fallout) of locations downwind from point of detonation; this impact could be greatly amplified if the weapon were detonated at a nuclear facility. • Adverse health effects in affected populations. • Adverse psychological, economic and political effects in affected societies.

Table 5.3-2
Categories of Potential Attack on a Radioactive-Waste Facility or Transport Operation

Category of Attack	General Characteristics	Illustrative Instruments and Modes of Attack
Stand-off attack	Attackers do not approach the facility. (Suicidal pilots are an exception.) Defense relies on air-defense measures (passive or active), robustness of the facility, and damage-control measures.	• Gun, rocket or mortar projectiles launched from land or sea. • Bombs or rockets launched from comparatively nearby aircraft. • Ballistic or cruise missiles launched from distant locations. • Impact by commercial or general-aviation aircraft laden with fuel or explosive.
Close-up attack	Attackers seek to penetrate the site boundary, reach the facility, and gain access to contained material. Defense relies on site-security measures, robustness of the facility, and damage-control measures.	• Commando tactics and weapons (including ultra-light aircraft, machine guns, vehicle bombs, chemical weapons, etc.) for breaching of site perimeter and neutralization of defenders. • Devices (bulk or shaped charges, thermic lances, boring machines, etc.) to penetrate a facility structure. • Methods (secondary charges, fuel-air explosives, incendiaries, etc.) to open up a penetrated facility and assist release of contained material.
Indirect attack	Attackers achieve release or misappropriation of material without major acts of violence or damage to the facility. Defense measures are bypassed or de-activated.	• Delivery of material to attackers by insiders acting voluntarily, under duress, or in response to deception. • Incorporation of vulnerability into a facility by insiders involved in its construction. • Weakening of facility-protection measures due to negligence or criminal acts by officials, or due to social breakdown.

Notes:
(a) Attackers could employ combinations of the three categories of attack shown in the table.
(b) Explosive charges could be conventional or nuclear.
(c) A close-up attack on a transport operation would typically involve actions to stop and immobilize the transport vehicle.

Table 5.3-3
Types of Potential Attack on a Nuclear Reactor or SNF-Storage Facility, Leading to Atmospheric Release of Radioactive Material

Type of Event	Facility Behavior	Some Relevant Instruments and Modes of Attack	Characteristics of Atmospheric Release
Type 1: Vaporization or Pulverization	• All or part of facility is vaporized or pulverized	• Facility is within the fireball of a nuclear-weapon explosion	• Radioactive material in facility is lofted into the atmosphere and amplifies fallout from nuc. explosion
Type 2: Rupture and Dispersal (Large)	• Facility structures are broken open • Fuel is dislodged from facility and broken apart • Some ignition of zircaloy fuel cladding may occur, typically without sustained combustion	• Aerial bombing • Artillery, rockets, etc. • Effects of blast etc. outside the fireball of a nuclear-weapon explosion	• Solid pieces of various sizes are scattered in vicinity • Gases and small particles form an aerial plume that travels downwind • Some release of volatile species (esp. Cesium-137) if zirc. combustion occurs
Type 3: Rupture and Dispersal (Small)	• Facility structures are penetrated but retain basic shape • Fuel may be damaged but most rods retain basic shape • Damage to cooling systems could lead to zirc. combustion	• Vehicle bomb • Impact by commercial aircraft • Perforation by shaped charge	• Scattering and plume formation as in Type 2 event, but involving smaller amounts of material • Substantial release of volatile species if zirc. combustion occurs
Type 4: Precise, Informed Targeting	• Facility structures are penetrated, creating a release pathway • Zirc. combustion is initiated indirectly by damage to cooling systems, or by direct ignition	• Missiles (military or improvised) with tandem warheads • Close-up use of attack instruments (e.g., shaped charge, incendiary, thermic lance)	• Scattering and plume formation as in Type 3 event • Substantial release of volatile species, potentially exceeding amount in Type 3 release

Note: This table assumes that fuel cladding is made of zircaloy.

Table 5.3-4
Performance of US Army Shaped Charges, M3 and M2A3

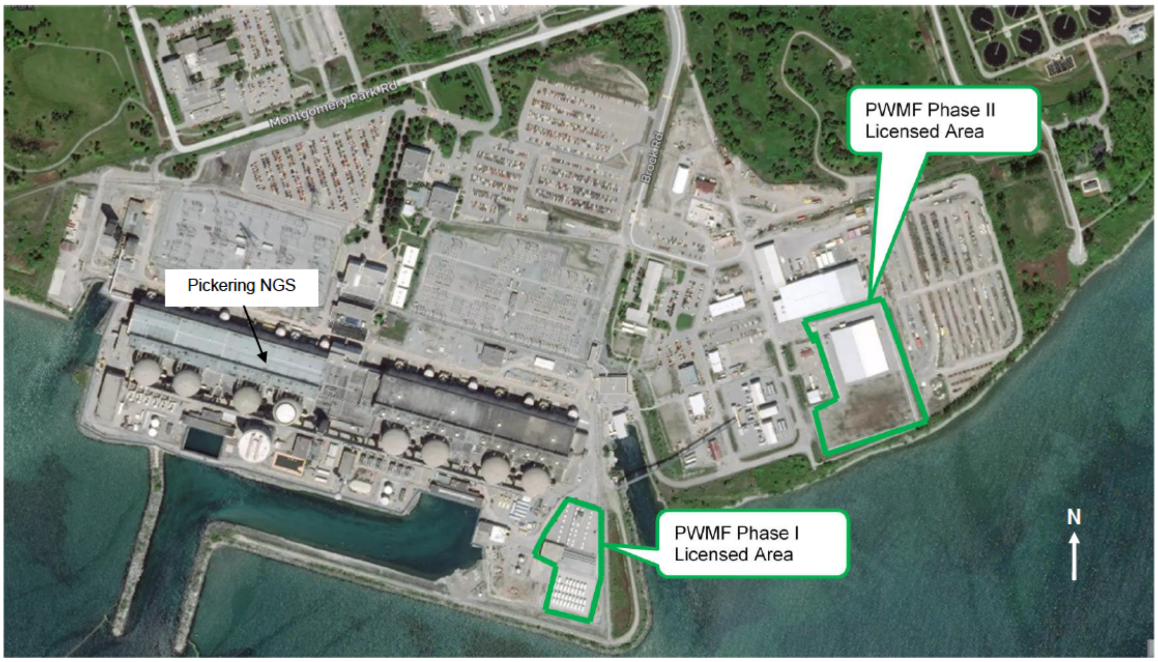
Target Material	Indicator	Value for Stated Type of Shaped Charge	
		Type: M3	**Type: M2A3**
Reinforced concrete	Maximum wall thickness that can be perforated	150 cm	90 cm
	Depth of penetration in thick walls	150 cm	75 cm
	Diameter of hole	• 13 cm at entrance • 5 cm minimum	• 9 cm at entrance • 5 cm minimum
	Depth of hole with second charge placed over first hole	210 cm	110 cm
Armor plate	Perforation	At least 50 cm	30 cm
	Average diameter of hole	6 cm	4 cm

Notes:
(a) Data are from US Army Field Manual FM 5-25: Army, 1967, pages 13-15 and page 100.
(b) The M2A3 charge has a mass of 5 kg, a maximum diameter of 18 cm, and a total length of 38 cm including the standoff ring.
(c) The M3 charge has a mass of 14 kg, a maximum diameter of 23 cm, a charge length of 39 cm, and a standoff pedestal 38 cm long.

Table 6-1
Types of Defense of a Radioactive-Waste Storage Facility or Transport Operation

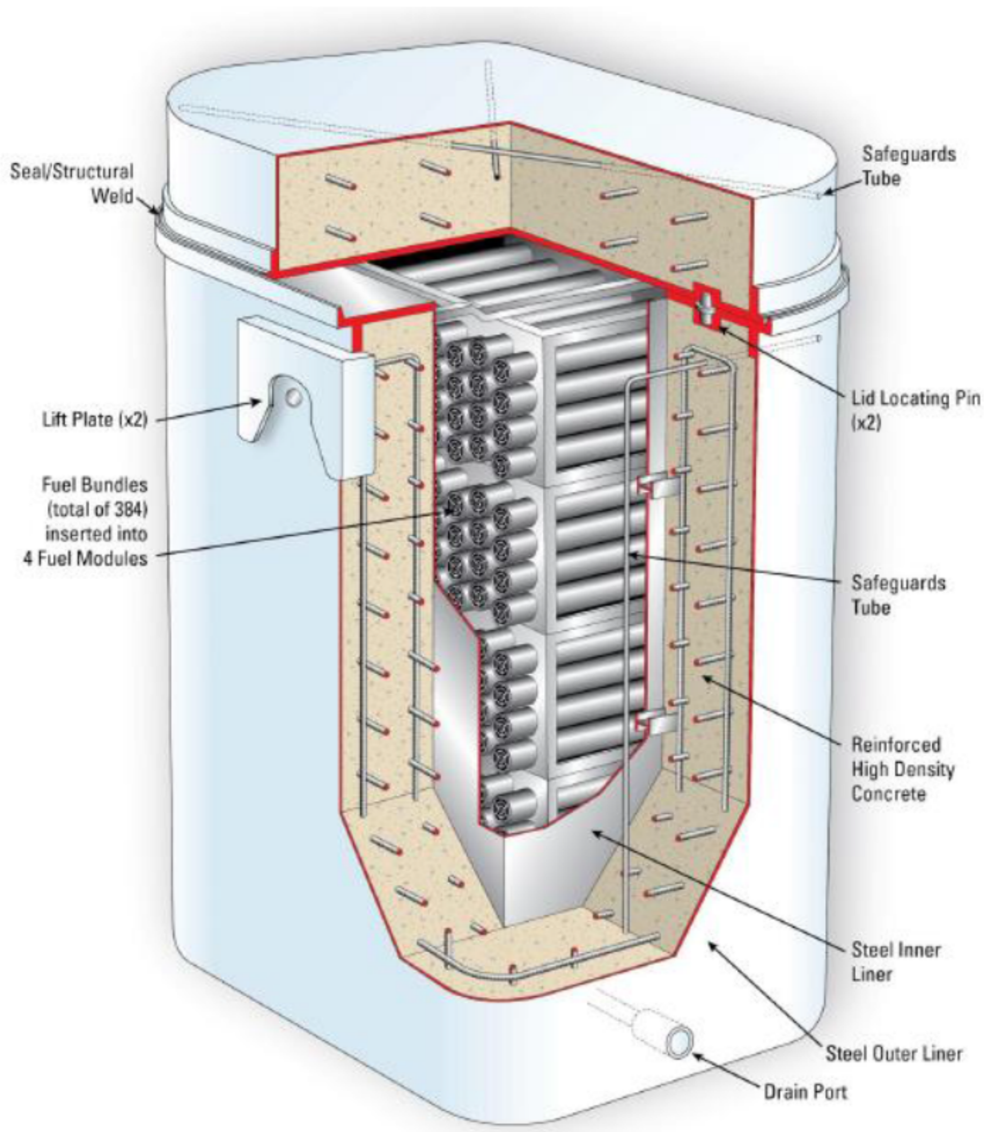
Type of Defense	General Characteristics	Illustrative Measures of Defense
Site security	The objective of site security is to prevent attackers (including insiders) or their instruments from reaching a facility.	• Fences, gates, vehicle barriers, defensible entry paths. • Intrusion detection and assessment systems. • Armed guards (onsite and backup). • Personnel vetting and oversight. • Passive air defense (e.g., poles and nets). • Active air defense (e.g., the Phalanx automated machine gun).
Facility robustness	A facility's robustness is its ability to experience attack, using stand-off or close-up instruments, without allowing a release of the contained material.	• Protection of vaults by multiple, thick layers (e.g., rubble, soil, concrete, steel) with differing properties. • Passive cooling, to prevent overheating if cooling system is damaged. • Packaging of the contained material in forms that resist fire, fragmentation, etc. • Passive measures to prevent fire and inhibit release of contained material (e.g., collapsible ceilings hold sand above the material).
Damage control	The objective of damage control is to limit the release of contained material following an attack.	• Firefighting capability (equipment and personnel). • Capability for quick repair of damaged structures and restriction or plugging of release paths. • Capability of site personnel to function in a radioactively-contaminated environment.
Offsite emergency response	Emergency-response measures seek to limit radiation exposure of members of the public in the event of a release, and seek to recover misappropriated material.	• Capability to detect, track and predict the impact of released material. • Capability to communicate information and guidance to affected persons. • Organization of protective measures (e.g., interdiction of food supply, relocation of populations). • Police capability to find and recover misappropriated material.

Figure 4-1
The Pickering Site in 2016



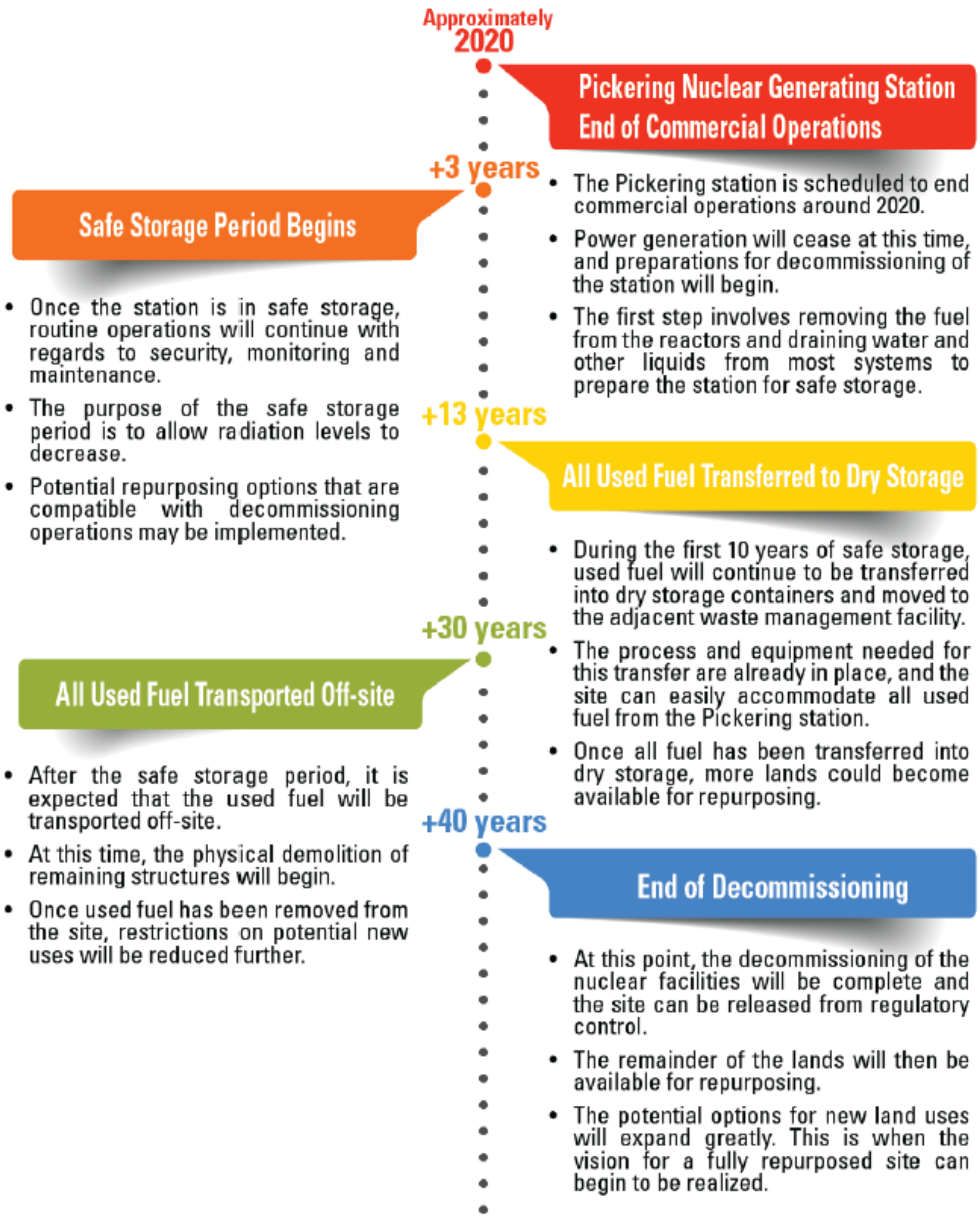
Note:
This figure reproduces Figure 1 of: OPG, 2016.

Figure 4-2
Dry Storage Container for SNF, as Used at Pickering



Note:
This figure reproduces Figure 4 of: OPG, 2016.

Figure 4-3
Timeline of Post-Shutdown Events at Pickering: An OPG Projection



Note:
This figure reproduces the figure at page 16 of: OPG, 2015.