

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

by
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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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About the Author

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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.

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 report⁵ 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

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:

- Radiological risk: Potential for harm resulting from unintended exposure of humans and their environment to ionizing radiation.
- Proliferation risk: Potential for diversion of fissile material or radioactive material to weapons use.
- Program risk: 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.

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.

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 $3,002 \times 384 = 1,152,768$.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: $1 \text{ PBq} = 1 \times 10^{15} \text{ Bq}$, and $1 \text{ Bq} = 1 \text{ disintegration per second}$.) The Pickering sitewide inventory of Cs-137 in 2024 would be about 10,800 PBq.

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."

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

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

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

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.

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

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

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.

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 term⁴⁹ are substantial in the areas of public health and safety, environmental integrity, security, economic viability and fairness.”

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).

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

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 = 1×10^{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.

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.”

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 switchyards⁶⁰ 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.

8. Bibliography

(Ahearne et al, 2012)

John F. Ahearne and eight other authors, with editing by Charles D. Ferguson and Frank A. Settle, *The Future of Nuclear Power in the United States* (Washington, DC: Federation of American Scientists, and Washington and Lee University, February 2012).

(Albright et al, 1997)

David Albright, Frans Berkhout, and William Walker, *Plutonium and Highly Enriched Uranium 1996: World Inventories, Capabilities and Policies* (Oxford, UK: Oxford University Press, 1997).

(Army, 1967)

Department of the Army, *Explosives and Demolitions, FM 5-25* (Washington, DC: Department of the Army, May 1967).

(Barnaby, 1992)

Frank Barnaby, "Types of Nuclear Weapon", Chapter 14 in: Frank Barnaby (editor), *Plutonium and Security: The Military Aspects of the Plutonium Economy* (London, UK: Macmillan, 1992).

(Carlsen and Raap, 2012)

Brett W. Carlsen and Michael Brady Raap, *Dry Transfer Systems for Used Nuclear Fuel, INL/EXT-12-26218* (Idaho Falls, Idaho: Idaho National Laboratory, May 2012).

(CNSC Staff, 2017)

CNSC Staff, Commission Member Document 17-H5, regarding renewal of the PWF license, 10 February 2017. (CNSC e-Doc 5186356)

(CNL, 2016)

Canadian Nuclear Laboratories, *A Feasibility Study on the Recycling of Used CANDU Fuel, Report 153-124900-REPT-002, Revision 0* (Chalk River, Ontario: Canadian Nuclear Laboratories, April 2016).

(Cochran et al, 1987)

Thomas B. Cochran and three other authors, *Nuclear Weapons Databook, Volume II, US Nuclear Warhead Production* (Cambridge, Massachusetts: Ballinger Publishing, 1987).

(Cousins and Reichmuth, 2007)

Tom Cousins and Barbara Reichmuth, "Preliminary Analysis of the Economic Impact of Selected RDD Events in Canada", presentation at the CRTI Summer Symposium 2007, Gatineau, Quebec, 11-14 June 2007. CRTI is the CBRNE Research and Technology Initiative, a program of Defence Research and Development Canada. The conference proceedings (accessed from CRTI) list the presentation as CRTI 05-0043RD, titled "Economic Impact of Radiological Terrorist Events".

(DOE, 2002)

US Department of Energy, *Final Environmental Impact Statement for a Geologic Repository for the Disposal of Spent Nuclear Fuel and High-Level Radioactive Waste at Yucca Mountain, Nye County, Nevada, DOE/EIS-0250* (Washington, DC: DOE, February 2002).

(Feiveson et al, 2011)

Harold Feiveson and three other editors, *Managing Spent Fuel from Nuclear Power Reactors: Experience and Lessons from Around the World* (Princeton, New Jersey: International Panel on Fissile Materials, Program on Science and Global Security, Princeton University, September 2011).

(FEMA, 2011/2012)

Federal Emergency Management Agency, US Department of Homeland Security, “Radiological/Nuclear WMD Response Mission, Refresher Training: Types of Radiological/Nuclear WMD”, inferred date 2011 or 2012, accessed on 7 August 2013 at: <<http://ctosnnsa.org/vtra/physicalThreats/CTOS0060V1.1211WMD-RED-RDD-IND.pdf>>.

(Frappier, 2007)

Gerry Frappier, “Enhanced Security in the Nuclear Industry”, *Frontline Security*, Spring 2007, accessed from the CNSC website, <http://www.nuclearsafety.gc.ca/eng/newsroom/articles/2007-04-18_nuclear_safety.cfm>, on 28 May 2008.

(Hare, 1988)

F. Kenneth Hare (Commissioner, Ontario Nuclear Safety Review), *The Safety of Ontario’s Nuclear Power Reactors* (Toronto: Ontario Nuclear Safety Review, 29 February 1988.)

(Mark et al, 2009)

J. Carson Mark, with an Appendix by Frank von Hippel and Edward Lyman, “Explosive Properties of Reactor-Grade Plutonium”, *Science and Global Security*, Volume 17, Number 2-3, 2009, pages 170-185.

(NRC, 2014)

US Nuclear Regulatory Commission, *Generic Environmental Impact Statement for Continued Storage of Spent Nuclear Fuel, NUREG-2157* (Washington, DC: NRC, September 2014).

(NWMO, 2005)

Nuclear Waste Management Organization, *Choosing a Way Forward: The Future Management of Canada’s Used Nuclear Fuel* (Toronto: NWMO, November 2005).

(OPG, 2018)

Ontario Power Generation website: Pickering Nuclear, accessed on 5 April 2018 at:
<https://www.opg.com/generating-power/nuclear/stations/pickering-nuclear/Pages/pickering-nuclear.aspx>

(OPG, 2016)

Ontario Power Generation, *Pickering Waste Management Facility: Application for Licence Renewal* (Toronto: OPG, October 2016).

(OPG, 2015)

Ontario Power Generation, *Repurposing Pickering: Exploring the possibilities for new uses and reuses on the Pickering Nuclear site* (Toronto: OPG, 11 December 2015).

(Seibert et al, 2013)

P. Seibert, A. Stohl, G. Wotawa, D. Arnold, J.F. Burkhart, S. Eckhardt, C. Tapia, A. Vargas, and T.J. Yasunari, "Inverse modeling of the xenon and caesium release from Fukushima," Poster T1-P35 at: Comprehensive Nuclear-Test Ban Treaty: Science and Technology Conference, 17-21 June 2013, Vienna (Austria), organized by the CTBTO Preparatory Commission.

(Stohl et al, 2012)

A. Stohl, P. Seibert, G. Wotawa, D. Arnold, J.F. Burkhart, S. Eckhardt, C. Tapia, A. Vargas, and T.J. Yasunari, "Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: determination of the source term, atmospheric dispersion, and deposition," *Atmospheric Chemistry and Physics*, Volume 12, 2012, pages 2313-2343.

(Thompson, 2014)

Gordon R. Thompson, *Darlington Refurbishment: Risk Issues Require Greater Attention* (Cambridge, Massachusetts: Institute for Resource and Security Studies, 26 February 2014).

(Thompson, 2013a)

Gordon R. Thompson, *Handbook to Support Assessment of Radiological Risk Arising from Management of Spent Nuclear Fuel* (Cambridge, Massachusetts: Institute for Resource and Security Studies, 31 January 2013).

(Thompson, 2013b)

Gordon R. Thompson, *Comments on OPG's Proposal to Develop a Deep Geologic Repository for Radioactive Waste: A Neglected Potential for Malevolent Acts* (Cambridge, Massachusetts: Institute for Resource and Security Studies, August 2013).

(Thompson, 2012)

Gordon R. Thompson, *Comments on Proposed Screening Report on Environmental Assessment of Refurbishment & Continued Operation of Darlington Nuclear Generating Station* (Cambridge, Massachusetts: Institute for Resource and Security Studies, 12 October 2012).

(Thompson, 2008)

Gordon R. Thompson, "The US Effort to Dispose of High-Level Radioactive Waste", *Energy and Environment*, Volume 19, Nos. 3+4, 2008, pp 391-412.

(Thompson, 2007)

Gordon R. Thompson, *Risk-Related Impacts from Continued Operation of the Indian Point Nuclear Power Plants* (Cambridge, Massachusetts: Institute for Resource and Security Studies, 28 November 2007).

(Thompson, 2005)

Gordon R. Thompson, *Reasonably Foreseeable Security Events: Potential threats to options for long-term management of UK radioactive waste* (Cambridge, Massachusetts: Institute for Resource and Security Studies, 2 November 2005).

(Thompson, 1987)

Gordon Thompson, "Severe Accident Potential of CANDU Reactors: A Report to the Ontario Nuclear Safety Review", 30 September 1987, contained in the volume, "Selected Consultants' Reports", that was appended to: Hare, 1988.

(Torrie and Park, 2016)

Ralph Torrie and Brian Park, *Direct Decommissioning of the Pickering Nuclear Generating Station: Economic and Other Benefits* (Toronto: Ontario Clean Air Alliance Research, March 2016).

(von Hippel and Schoeppner, 2016)

Frank N. von Hippel and Michael Schoeppner, "Reducing the Danger from Fires in Spent Fuel Pools", *Science and Global Security*, Volume 24, Number 3, 2016, pages 141-173.

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: <ul style="list-style-type: none"> • Human capital • Natural capital • Manufactured capital
#4. Create opportunities for future actions	Design the action option for: <ul style="list-style-type: none"> • Reversibility • Resilience • Flexibility • Adaptability
#5. Manage risk	Prepare for hazardous events (i.e., events that could lead to unintended, adverse outcomes) by: <ul style="list-style-type: none"> • 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: <ul style="list-style-type: none"> • 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: <ul style="list-style-type: none"> • 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: <ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Readily obtainable • Highly destructive if detonated at target 	Vehicle barriers at entry points to Protected Area
Small guided missile (anti-tank, etc.)	<ul style="list-style-type: none"> • Readily obtainable • Highly destructive at point of impact 	None if missile launched from offsite
Commercial aircraft	<ul style="list-style-type: none"> • More difficult to obtain than pre-9/11 • Can destroy larger, softer targets 	None
Explosive-laden smaller aircraft	<ul style="list-style-type: none"> • Readily obtainable • Can destroy smaller, harder targets 	None
10-kilotonne nuclear weapon	<ul style="list-style-type: none"> • 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.	<ul style="list-style-type: none"> • 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.	<ul style="list-style-type: none"> • 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.	<ul style="list-style-type: none"> • 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.	<ul style="list-style-type: none"> • 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.	<ul style="list-style-type: none"> • 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.	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • All or part of facility is vaporized or pulverized 	<ul style="list-style-type: none"> • Facility is within the fireball of a nuclear-weapon explosion 	<ul style="list-style-type: none"> • Radioactive material in facility is lofted into the atmosphere and amplifies fallout from nuc. explosion
Type 2: Rupture and Dispersal (Large)	<ul style="list-style-type: none"> • 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 	<ul style="list-style-type: none"> • Aerial bombing • Artillery, rockets, etc. • Effects of blast etc. outside the fireball of a nuclear-weapon explosion 	<ul style="list-style-type: none"> • 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)	<ul style="list-style-type: none"> • 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 	<ul style="list-style-type: none"> • Vehicle bomb • Impact by commercial aircraft • Perforation by shaped charge 	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • Facility structures are penetrated, creating a release pathway • Zirc. combustion is initiated indirectly by damage to cooling systems, or by direct ignition 	<ul style="list-style-type: none"> • Missiles (military or improvised) with tandem warheads • Close-up use of attack instruments (e.g., shaped charge, incendiary, thermic lance) 	<ul style="list-style-type: none"> • 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

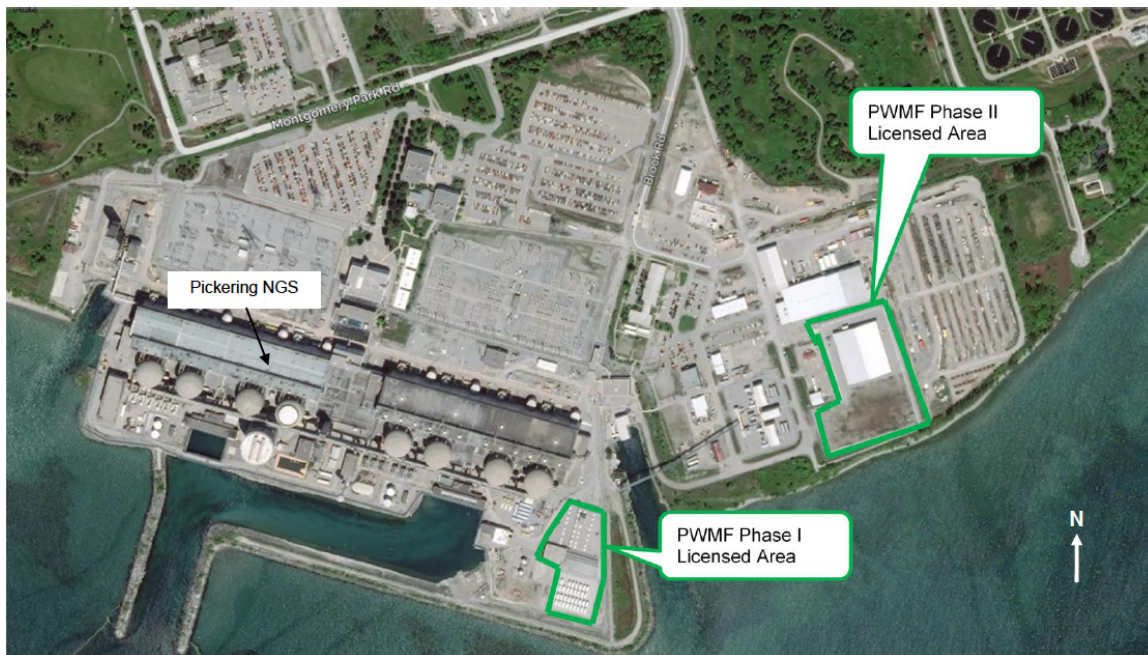
Notes:

- (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

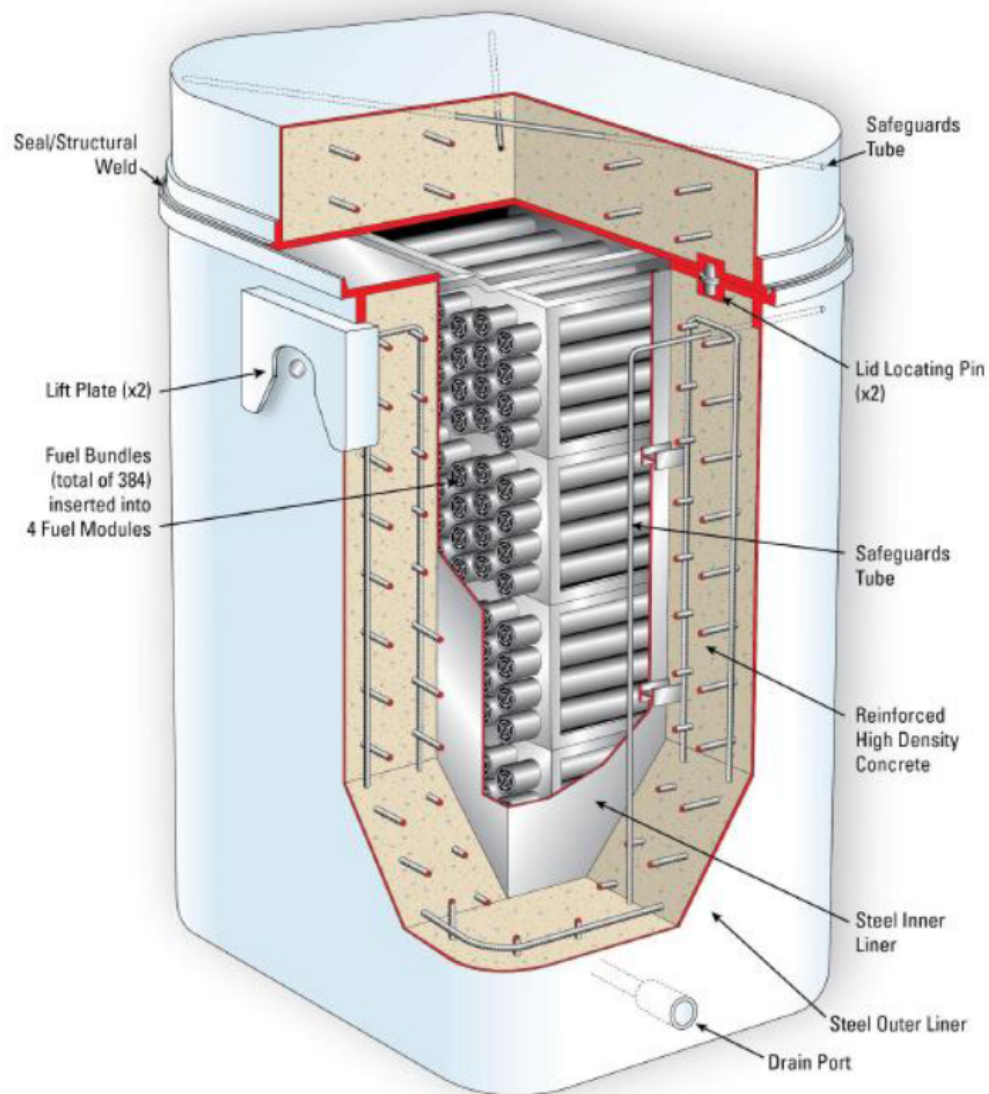
Type of Defense	General Characteristics	Illustrative Measures of Defense
Site security	The objective of site security is to prevent attackers (including insiders) or their instruments from reaching a facility.	<ul style="list-style-type: none"> • Fences, gates, vehicle barriers, defensible entry paths. • 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.	<ul style="list-style-type: none"> • 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.	<ul style="list-style-type: none"> • 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.	<ul style="list-style-type: none"> • 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



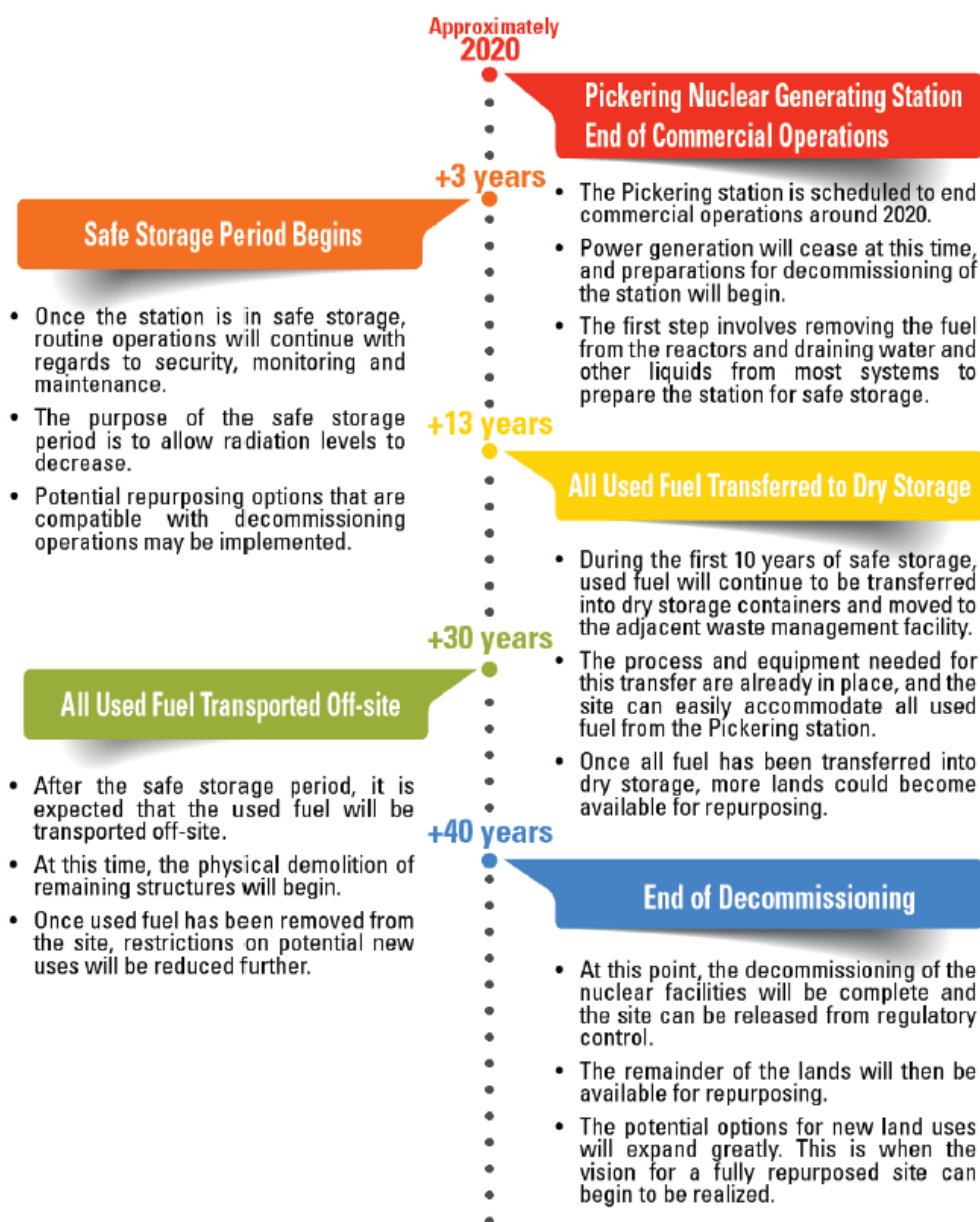
Note:
This figure reproduces Figure 1 of: OPG, 2016.

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.