Green Energy Coalition

EB-2007-0707
Exhibit L
Tab 8
Schedule 5

BEFORE THE ONTARIO ENERGY BOARD

IN THE MATTER OF sections 25.30 and 25.31 of the Electricity Act, 1998;

AND IN THE MATTER OF an application by the Ontario Power Authority for review and approval of the Integrated Power System Plan and proposed procurement processes.

Cost Implications of the Residual Radiological Risk of Nuclear Generation of Electricity in Ontario

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COST IMPLICATIONS OF THE RESIDUAL RADIOLOGICAL RISK OF NUCLEAR GENERATION OF ELECTRICITY IN ONTARIO

by
Gordon R. Thompson

30 July 2008

Prepared on behalf of the Green Energy Coalition, the Ontario Sustainable Energy Association, and the Pembina Institute

For submission to the Ontario Energy Board
in a Proceeding (EB-2007-0707)
Regarding an Application by the Ontario Power Authority
for Approval of an Integrated Power System Plan

Abstract

This report addresses aspects of two issues identified by the Ontario Energy Board in its proceeding EB-2007-0707. Those issues — Numbers 12 and 13 — relate to the economic prudence and cost-effectiveness of nuclear generation of electricity in Ontario. The aspects addressed here are the cost implications of the residual radiological risk posed by nuclear generation. "Radiological risk" refers to the potential for, and consequences of, unplanned releases of radioactive material to the environment or within a nuclear facility. "Residual" refers to the risk remaining after implementation of regulations regarding the safety and security of nuclear facilities. Two categories of cost are examined here. In one category are costs that arise from efforts to reduce the residual radiological risk posed by nuclear power plants. In the second category are non-insured risk costs associated with offsite and onsite impacts of potential unplanned releases of radioactive material.

About the Institute for Resource and Security Studies

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

About the Author

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

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Executive Summary

This report addresses aspects of two issues — Numbers 12 and 13 — identified by the Ontario Energy Board (OEB) in its proceeding EB-2007-0707. Those issues relate to the economic prudence and cost-effectiveness of nuclear generation of electricity in Ontario. The aspects addressed here are the cost implications of the residual radiological risk posed by the operation of nuclear power plants. "Radiological risk" refers to the potential for, and consequences of, unplanned releases of radioactive material to the environment or within a nuclear plant. "Residual" refers to the risk remaining after implementation of Canadian Nuclear Safety Commission (CNSC) regulations regarding the safety and security of nuclear power plants. The CNSC, analogous regulatory entities in other countries, and the International Atomic Energy Agency (IAEA) acknowledge the existence of a residual radiological risk of the type examined here.

The OEB proceeding is examining, among other matters, the generation of electricity by existing and new nuclear power plants in Ontario. The existing plants would be CANDU plants at the Darlington, Pickering or Bruce sites. Like most members of the present worldwide fleet of nuclear power plants, the existing Ontario plants are in the "Generation II" category. The new plants would be "Generation III" plants supplied by AREVA, Westinghouse, or Atomic Energy of Canada Ltd (AECL). The Ontario government has announced its intention to build two such plants at the Darlington site.

Two categories of future cost are examined here, for a representative existing plant and a representative new plant. In one category are costs that may arise from efforts to reduce the residual radiological risk posed by nuclear power plants. In the second category are non-insured risk costs associated with offsite and onsite impacts of potential unplanned releases of radioactive material.

Experience in the USA shows that efforts to reduce residual radiological risk were a major driver of substantial escalation during the 1970s and 1980s in capital/construction costs for new nuclear power plants and annual capital additions at existing plants. Occurrence of an accident at the Three Mile Island (TMI) Unit 2 plant in 1979 was a major, but not unique, motivator of the efforts to reduce residual radiological risk.

The nuclear industry (i.e., plant vendors and operators) and its regulators — in Canada and elsewhere — are engaged in efforts to reduce the residual radiological risk posed by future operation of new Generation III nuclear power plants, by comparison with the risk posed by the existing Generation II plants. In Canada, new plants are required to meet design criteria established by CNSC. Plants meeting those criteria could ride out a specified set of accidents and a specified set of intentional, malevolent acts.

The Generation III plants being considered for use in Ontario have some design features that could reduce residual radiological risk by comparison with Generation II plants. However, the extent of that risk reduction will be limited by the fact that the Generation III designs represent a comparatively small evolutionary step from the Generation II designs. During the 1970s and 1980s, plant vendors and other stakeholders identified innovative design options — such as the PIUS design proposed by ASEA-Atom — that could have reduced residual radiological risk to a level substantially below the level posed by the Generation II and Generation III designs. The nuclear industry did not adopt those innovative design options, choosing instead to offer the Generation III designs. Regulators, including CNSC, have adjusted their risk goals and regulations to accommodate the level of residual radiological risk posed by the Generation III designs.

Efforts to reduce residual radiological risk are influencing trends in capital/construction costs for new Generation III plants. Independent, quantitative assessment of that influence is not currently possible, because construction experience with plants of this type is limited, and relevant data are held by the plant vendors. Occurrence of a substantial unplanned release of radioactive material at any nuclear power plant worldwide would lead to public pressure on the nuclear industry and regulators to increase their efforts to reduce residual radiological risk, as occurred after the TMI accident. Enhanced efforts would follow, involving increases in capital/construction costs for new nuclear power plants and increases in annual capital additions at existing plants. Those increases would occur, to varying extents, in Ontario and elsewhere. In assessing the potential for such increases, one can reasonably assume that the probability of a substantial release from a nuclear power plant worldwide is about 4 percent per annum, and the probability of a release within a plant is significantly higher.

After efforts have been made to reduce the residual radiological risk posed by a nuclear power plant, there will remain a potential for unplanned releases of radioactive material. Such releases could cause offsite and onsite impacts. With some assumptions and caveats, the impacts of a given release can be estimated, and can be expressed in monetary terms. The probabilities of possible releases can also be estimated, again with assumptions and caveats. Taken together, these estimates yield a set of “risk costs” associated with plant operation, expressed as cent per kWh of nuclear generation. In Canada and elsewhere, only a fraction of the total risk cost is covered by payment of an insurance premium.

Table ES-1 summarizes this report’s findings of the risk costs of nuclear generation in Ontario. Also shown are the insurance premiums that are paid to provide coverage of these risk costs. Clearly, most of the risk costs are not insured. Note that the Nuclear Liability Act limits a nuclear operator’s liability to a maximum of $75 million, with an expected increase to $650 million. The costs of the offsite impacts of a radioactive release from a nuclear power plant in Ontario could far exceed $650 million.

The risk costs shown in Table ES-1 reflect "high confidence" (95th percentile) estimates of event probabilities, as estimated by CNSC, other regulators, and the nuclear industry. Practical experience, notably the TMI accident of 1979 and the Chernobyl accident of 1986, yields comparable event probabilities for Generation II plants. This report assumes that a new plant in Ontario could achieve an accident probability an order of magnitude lower than the accident probability for an existing plant. The resulting reduction in risk could be offset by the greater radioactive inventory in the new plant.

Table ES-1
Risk Costs of Nuclear Generation in Ontario: Summary of this Report's Findings

Category of Impacts from Unplanned Releases of Radioactive Material	Category of Risk Costs and the Insurance Premiums that are Paid to Provide Coverage of these Costs	Magnitude of Risk Costs and Insurance Premiums	
		For an Existing CANDU Plant	For a New Generation III Plant
Offsite Impacts	Risk Costs (2008 Can cent per kWh)	2.7 to 5.4	1.5 to 15.4
	Insurance Premiums (2008 Can cent per kWh)	0.02	As for existing CANDU plant?
Onsite Impacts	Risk Costs (2008 Can cent per kWh)	2.7 to 5.6	Smaller amount than for existing CANDU plant
	Insurance Premiums (2008 Can cent per kWh)	No explicit premium is evident	No explicit premium is evident

(This table, with notes, appears in the body of the report as Table 7-7.)

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List of Tables and Figures
(Tables and Figures appear at the end of the report.)

1. Introduction

In June 2006, the Ontario government directed the Ontario Power Authority (OPA) to create an Integrated Power System Plan (IPSP), which is currently understood to cover the period 2007-2027. As part of that order, the government directed OPA to plan for nuclear generating capacity to meet base-load electricity requirements, while limiting Ontario's total in-service nuclear capacity to 14 GWe during the IPSP period.[1]

In August 2007, OPA filed an application with the Ontario Energy Board (OEB), seeking approval of an IPSP. OEB opened a proceeding (EB-2007-0707) to consider the application. Phase 1 of the proceeding led to a March 2008 decision by OEB on the issues to be considered in the remaining phase (Phase 2) of the proceeding.[2] In that decision, OEB set forth five issues (Issues List, Nos. 10-14) that it will consider in the context of nuclear generation.[3]

Theme and scope of this report

This report addresses aspects of two of the nuclear-related issues identified by OEB. First, the report addresses aspects of Issue No. 12: “Is the IPSP’s plan to use nuclear power to meet the remaining base-load requirements economically prudent and cost effective?” Second, the report addresses aspects of Issue No. 13: “In the context of the determination of economic prudence and cost effectiveness, is the IPSP sufficiently flexible to accommodate building new nuclear plants or refurbishing existing plants or both?”

In addressing those two issues, this report focuses on the cost implications of the residual radiological risk of nuclear generation of electricity in Ontario. The phrase “residual radiological risk” refers to the potential for, and impacts of, unplanned releases of radioactive material to the environment or within a nuclear facility.[4] Such releases could occur as a result of accidents or malevolent acts, as discussed below. The releases would be “unplanned” in the sense that they would not be expected to occur during routine operation of a nuclear facility. Nevertheless, the potential for occurrence of unplanned releases is acknowledged by the nuclear industry and its regulators, in Canada and elsewhere.

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[1] Duncan, 2006.
[2] OEB, 2008.
[3] OEB, 2008, page 25 and Appendix A.
[4] The term “risk” is often used to refer to the arithmetic product of: (i) a quantitative indicator of adverse impact; and (ii) the quantitative probability that the impact will occur. In this report, the term is used in a more general sense, to encompass a range of qualitative and quantitative information about the potential for an adverse outcome.

In the phrase "residual radiological risk", the word "residual" characterizes the radiological risk that remains after the nuclear industry has complied with the requirements imposed by its regulators. In Canada, the primary regulator of the safety and security of nuclear facilities is the Canadian Nuclear Safety Commission (CNSC). This report examines radiological risk with two assumptions. First, construction and operation of nuclear facilities in Ontario consistently reflect good-faith efforts by the nuclear industry to comply with CNSC regulations. Second, CNSC personnel consistently make good-faith efforts to enforce CNSC regulations.

An unplanned release of radioactive material from a nuclear facility to the environment, or within the facility, could occur as a result of an accident or a malevolent act. The Canadian government has not yet articulated a comprehensive classification of events in these categories. An initial classification has been articulated by the Canadian Environmental Assessment Agency (CEAA) in the context of construction of nuclear power plants at the Bruce site in Ontario.[5] Bruce Power has considered the construction of new plants at the site, and pursuit of that option would require the preparation of an environmental impact statement (EIS) by Bruce Power. In April 2008, CEAA published draft guidelines for the required EIS.[6] The draft guidelines called for, among other matters, an assessment of the potential for accidents and malfunctions related to the proposed new nuclear power plants.

CEAA defined "accidents and malfunctions" as a category of events that includes accidents of a traditional type (events attributable to human error, natural phenomena, etc.) together with intentional, malevolent acts. Consideration of malevolent acts in an EIS for a commercial nuclear facility is a comparatively new development in the field of environmental assessment. CEAA's draft guidelines provided an initial classification of accidents and malfunctions.[7] That classification has been refined by the author of this report.[8] This author's classification is shown in Table 1-1.

The nuclear generating capacity envisioned in the IPSP would be provided by some combination of existing and new nuclear power plants in Ontario. To some extent, refurbishment of existing plants, to extend their operating lifetimes, could substitute for construction of new plants. The IPSP will not determine the relative contributions of refurbished and new plants to Ontario's nuclear generating capacity. Indeed, OEB has pointed out that neither OPA nor OEB will decide on the relative contributions of refurbished and new plants.[9] Accordingly, OEB has identified Issue No. 13, which asks

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[5] Throughout this report, the term "nuclear power plant" means a nuclear fission reactor and its associated equipment, including equipment to produce electricity. Future (Generation IV or later) nuclear power plants might also produce hydrogen, potable water and/or process heat.
[6] CEAA, 2008.
[7] CEAA, 2008, Section 12.
[8] Thompson, 2008, Section 3.4.
[9] OEB, 2008, page 23.

if the IPSP is sufficiently flexible to accommodate refurbished plants, new plants, or both.

Each nuclear power plant poses a unique type and level of radiological risk. Moreover, the risk posed by a particular plant can change over time, reflecting the plant's age and other factors. Those details are not addressed here. Instead, this report discusses the risks posed by a representative new plant and by a representative existing plant.

Nuclear power plants are part of a nuclear fuel cycle that begins, at the "front end", with the mining, processing and enrichment of uranium. At the "back end" of the fuel cycle, spent nuclear fuel discharged from reactors is stored or, in some countries, reprocessed. Radiological risk arises at every part of the nuclear fuel cycle. In Ontario, however, there is no enrichment of uranium and no reprocessing of spent fuel. Thus, nuclear power plants are the dominant source of the radiological risk posed by nuclear generation in Ontario. This report focuses on the radiological risk posed by nuclear power plants.

Two categories of future cost are examined here, for a representative existing nuclear power plant and a representative new plant. In one category are costs that may arise from efforts to reduce the residual radiological risk posed by nuclear power plants. In the second category are non-insured risk costs associated with offsite and onsite impacts of potential unplanned releases of radioactive material.

Structure of this report

This report begins with an Executive Summary, which contains one table. The body of the report consists of nine sections, including this Introduction (Section 1). Section headings are listed in the Table of Contents. Tables and figures are placed after the body of the report, each being numbered according to the section to which it applies. An appendix, containing one table, is placed after the tables and figures. A bibliography is provided in Section 9. Documents cited in the footnotes, tables and figures, both in the body of the report and in the Appendix, are listed in the bibliography.

2. Connections Between Radiological Risk and the Cost of Electricity

Radiological risk can affect the cost of nuclear-generated electricity through two primary pathways. First, the nuclear industry and its regulators may seek to reduce the residual radiological risk of nuclear generation by adopting measures that affect the design, construction and operation of nuclear power plants. Those measures typically involve additional costs. Second, operation of nuclear power plants poses an ongoing residual radiological risk. That risk creates costs to society that are described here as "risk costs".

Costs of measures intended to reduce the residual radiological risk

Various measures could be implemented to reduce the residual radiological risk posed by operation of nuclear power plants. Some risk-reducing options are discussed in Section 4 and the Appendix to this report. Implementation of risk-reducing options may involve increments of cost in the categories: (i) capital/construction cost; (ii) capital additions during a plant's operating lifetime; (iii) operation & maintenance costs; and (iv) revenue reduction and the cost of replacement power, if an option involves a net reduction in the amount of electricity generated by a plant. A general discussion of such cost increments appears in Section 7.2, below, and a cost estimate is provided for one risk-reducing option. Note, however, that this report does not purport to provide a comprehensive assessment of the costs that may arise from efforts to reduce residual radiological risk.

It can be difficult, especially if one is limited to publicly-available data, to discriminate between increments of cost that arise from efforts to reduce residual radiological risk, and increments of cost that arise from other influences. The nuclear industry (plant vendors and operators) possesses data relevant to this issue, but much of that information is not published. A useful body of information is publicly available regarding nuclear-power cost trends in the USA in the 1970s and 1980s, as discussed in Section 7.2. That information provides important background to the estimation of nuclear-power costs in Ontario over the coming years.

There is irreducible uncertainty in the extent to which measures to reduce residual radiological risk may be introduced in the future, either voluntarily by the nuclear industry or at the demand of a regulator. Public pressure on the industry and regulators to implement such measures would vary in response to events and trends that cannot be reliably predicted. It is clear, however, that the occurrence of a substantial, unplanned release of radioactive material from or within a nuclear power plant at any site worldwide, caused by an accident or a malevolent act, would increase public pressure for adoption of risk-reducing measures at nuclear power plants in Ontario and elsewhere.

Risk costs arising from the
residual radiological risk of plant operation

Accidents and malfunctions have arisen repeatedly during the operation of engineered systems, including energy systems. For example, a survey of accidents affecting energy systems worldwide during the period 1907-2007 identified 279 well-documented accidents that caused $41 billion in property damage and 182,000 deaths.[10] Accidents at nuclear-energy facilities accounted for 23 percent of the total number of accidents.[11] The

[10] Sovacool, 2008. Energy systems addressed by the survey were systems for production/generation, transmission or distribution of energy, or for support of those functions.
[11] Sovacool, 2008, Table 1.

number of accidents at nuclear-energy facilities is significant because these facilities are heavily regulated by entities such as CNSC. Note that this survey did not consider malevolent acts (war, sabotage, etc.) or accidents affecting military assets (ships, aircraft, bases, etc.), and consulted only English-language sources. Thus, the survey does not provide a complete historical picture of the risk associated with energy systems.

As discussed in Section 3, below, technical analysis shows that any nuclear power plant could experience an unplanned release of radioactive material, despite the existence of a regulatory regime. In other words, operation of a nuclear power plant inevitably creates the potential for a substantial radioactive release, either to the environment or within the plant. That potential can be described in terms of the probability, magnitude, isotopic composition and other characteristics of each member of a set of possible releases. For releases caused by accidents, the probability may be susceptible to quantitative estimation, with caveats as discussed in Section 3. For releases caused by malevolent acts, there is no statistical basis to support a quantitative estimate of probability.

Atmospheric releases from a plant are of particular concern from a public-health perspective, because an airborne plume of radioactive material could travel downwind for tens or hundreds of km, affecting large areas. The plume could cause adverse health effects in exposed persons, and could create lasting contamination of the environment. Computer models are available to estimate such impacts, for a given release. With various assumptions and caveats, the impacts can be translated into monetized costs. Assumptions related to monetization of impacts can be especially controversial.

An unplanned release of radioactive material at a nuclear power plant could create adverse impacts at the plant itself, whether or not the release reaches the environment. Plant personnel could receive radiation doses that yield adverse health effects, which could be translated into monetized costs. Additional costs could arise for site cleanup, repair of damaged portions of the plant, purchase of replacement power during the period when the plant is out of service, and write-off and decommissioning of the entire plant if repair is not cost-effective.

To summarize, the residual radiological risk of operating a nuclear power plant arises from the potential for unplanned releases. Potential releases can be placed in categories characterized by magnitude, probability and other parameters. The probability of each release category can, in part, be estimated quantitatively. Each release category could create costs in two categories: (i) offsite impacts; and (ii) onsite impacts.

Since the 1980s, numerous evaluations of electricity plans have considered the "externality" costs associated with options for supply and use of electricity.[12] In many of those instances, the externality costs of nuclear generation have been assessed.

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[12] Koomey and Krause, 1997; Wiel, 1995.

Typically, that assessment includes an estimate of the potential for, and impacts of, unplanned releases of radioactive material from nuclear power plants. Generally, the impacts have been monetized, and the probabilities of releases have been expressed quantitatively. With that approach, the externality costs can be expressed as cent per kWh of nuclear generation.

This report takes a somewhat different approach. Risk costs of offsite and onsite impacts of radioactive releases are estimated, using assumptions and methodology as described in Section 7, below. The insurance premiums that are paid to provide coverage of these costs are identified. Comparison of the risk costs and insurance premiums shows that most of the risk costs are non-insured. Further evidence of that finding is provided by comparing the liability limit in the Nuclear Liability Act with the monetized impacts of potential radioactive releases. In this report, risk costs, whether insured or non-insured, are expressed as cent per kWh of nuclear generation.

3. Assessing the Radiological Risk Posed by Nuclear Power Plants

There is a large body of technical literature addressing the radiological risk posed by nuclear power plants. Much of this literature assesses the potential for, and consequences of, an atmospheric release of radioactive material following accidental damage to nuclear fuel. The fuel could be in the reactor core, the spent-fuel pool, or elsewhere in the plant. Such literature typically falls under the rubric of probabilistic risk assessment (PRA).

In the PRA field, the events that initiate an accidental release are categorized as "internal" events (human error, equipment failure, etc.) or "external" events (earthquakes, fires, strong winds, etc.). PRAs typically do not consider initiating events that involve intentional, malevolent acts, although PRA techniques can be adapted to estimate the outcomes of such acts.

PRAs for nuclear power plants are conducted at Levels 1, 2 and 3, in increasing order of completeness, as discussed below. A thorough, full-scope PRA would be conducted at Level 3, and would consider internal and external initiating events. The findings of such a PRA would be expressed in terms of the magnitudes and probabilities of a set of adverse environmental impacts, and the uncertainty and variability of those indicators. The adverse impacts would include:

> (i) "early" human fatalities or morbidities (illnesses) that arise during the first several weeks after the release;
> (ii) "latent" fatalities or morbidities (e.g., cancers) that arise years after the release;
> (iii) short- or long-term abandonment of land, buildings, etc.;
> (iv) short- or long-term interruption of agriculture, water supplies, etc.; and
> (v) social and economic impacts of the above-listed consequences.

The magnitudes and probabilities of such adverse impacts would be estimated in three steps. First, a Level 1 PRA analysis would be performed. In that analysis, a set of event sequences (accident scenarios) leading to fuel damage would be identified, and the probability (frequency) of each member of the set would be estimated. The sum of those probabilities across the set would be the total estimated fuel-damage probability.[13] Second, a Level 2 PRA analysis would be performed. In that analysis, the potential for release of radioactive material to the atmosphere would be examined across the set of fuel-damage sequences. The findings would be expressed in terms of a group of release categories characterized by magnitude, probability, timing, isotopic composition, and other characteristics.

Third, a Level 3 PRA analysis would be performed, to yield the impact findings described above. In that analysis, the atmospheric dispersion, deposition and subsequent movement of the released radioactive material would be modeled for each of the release groups determined by the Level 2 analysis. The dispersion modeling would account for meteorological variation over the course of a year. Then, the adverse environmental impacts of the released material would be estimated, accounting for the material's distribution in the biosphere.

If done thoroughly, this 3-step estimation process accounts for uncertainty and variability at each stage of the process. A thorough, full-scope, Level 3 PRA is expensive and time-consuming. It yields estimated impacts expressed as statistical distributions of magnitude and probability, not as single numbers. Even after such a thorough effort, there are substantial, irreducible uncertainties in the findings.[14]

Empirical validation of PRA findings

Direct empirical evidence for the validity of PRA findings is limited. Worldwide operating experience of commercial nuclear power plants through 2007 is about 12,900 reactor-years (RY), and Canadian experience is about 560 RY.[15] Two events involving substantial damage to a reactor core have occurred worldwide while that experience was accruing. At Three Mile Island Unit 2 in 1979, the reactor core was severely damaged but there was a comparatively small radioactive release to the environment. At Chernobyl Unit 4 in 1986, a substantial fraction of the core inventory of radioactive material was released to the atmosphere. This limited experience allows one to estimate

[13] The term "core-damage frequency" (CDF) is often encountered. This term refers to the annual probability of severe damage to nuclear fuel in a reactor core.
[14] Hirsch et al, 1989.
[15] Extrapolated from Table 1 of: IAEA, 2006a. A reactor-year (RY) is equivalent to a plant-year, using this report's definition of a nuclear power plant. Both terms assume routine operation of a reactor (plant) over one calendar year.

the probability of a core-damage accident as 1.6 per 10,000 RY, and the probability of a large atmospheric release as 0.8 per 10,000 RY.[16]

NUREG-1150

The “high point” of PRA practice worldwide was reached in 1990 with publication by the US Nuclear Regulatory Commission (NRC) of its NUREG-1150 study, which examined five different nuclear power plants using a common methodology.[17] The study was well funded, involved many experts, was conducted in an open and transparent manner, was done at Level 3, considered internal and external initiating events, explicitly propagated uncertainty through its chain of analysis, was subjected to peer review, and left behind a large body of published documentation. Each of those features is necessary if the findings of a PRA are to be credible. There are deficiencies in the NUREG-1150 findings, which can be corrected by fresh analysis and the use of new information. The process of correction is possible because the NUREG-1150 study was conducted openly and left a documentary record.

PRA practice in the USA has degenerated since the NUREG-1150 study. Now, PRAs are conducted by the nuclear industry, and the only published documentation is a summary statement of findings. NRC formerly sponsored independent reviews of industry PRAs, but no longer does so. Thus, PRA findings have lacked credibility for at least a decade. In other countries, including Canada, PRA practice has experienced similar degeneration.[18]

Figures 3-1 through 3-3 show some findings from the NUREG-1150 study that are relevant to this report. The findings are for a pressurized-water-reactor (PWR) plant at the Surry site, and a boiling-water-reactor (BWR) plant at the Peach Bottom site. These plants typify many of the “Generation II” plants in the present worldwide fleet of nuclear power plants. Using the Livermore seismic estimates, the NUREG-1150 findings for these two plants are roughly comparable with the experience-derived probability estimates mentioned above — a core-damage probability of 1.6 per 10,000 RY, and a large-release probability of 0.8 per 10,000 RY.

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[16] 2/12,900 = 1.6 per 10,000; 1/12,900 = 0.8 per 10,000.
[17] NRC, 1990.
[18] In Canada, it appears that PRAs are no longer available for independent review. To illustrate, Greenpeace Canada requested a copy of the PRA for the Pickering B units. CNSC has refused to order Ontario Power Generation (OPG) to provide this PRA. In so doing, CNSC has accepted OPG's argument that the PRA should be available only to OPG personnel on a "need to know" basis. See: CNSC, 2008a. This approach, although it may be well-intentioned, will inevitably create an entrenched culture of secrecy that will suppress a clear-headed understanding of risks. A more sophisticated approach could allow independent review of the PRA without disclosing information that would assist malevolent actors.

The potential for malevolent acts at nuclear power plants

CNSC's criteria for the design of new nuclear power plants, expressed in the document RD-337, include resistance to attack as a design objective. To date, CNSC has not specified the threats that will be considered in applying the design criteria. CEAA's draft guidelines for the Bruce Power EIS require the consideration of accidents and malfunctions that include malevolent acts.[19]

A consultant to CNSC has examined potential modes and instruments of attack on a nuclear power plant, and has recommended an approach to incorporating these threats in the design criteria for new plants.[20] Among the instruments of attack considered by the consultant were a large commercial aircraft, an explosive-laden smaller aircraft, and an explosive-laden land vehicle. Table 3-1 describes some potential modes and instruments of attack on a nuclear power plant, and also describes the defenses that are now provided at US plants. There is no defense against a range of credible attacks. Defenses at Canadian plants are no more robust than at US plants.

Among the instruments of attack mentioned in Table 3-1 is a large commercial aircraft. In September 2001, aircraft of this type caused major damage to the World Trade Center and the Pentagon. However, such an aircraft would not be optimal as an instrument of attack on a nuclear power plant. Large commercial aircraft are comparatively soft objects containing a few hard structures such as turbine shafts. They can be difficult to guide precisely at low speed and altitude. A well-informed group of attackers would probably prefer to use a smaller, general-aviation aircraft laden with explosive material, perhaps in a tandem configuration in which the first stage is a shaped charge. Table 3-2 provides some information about shaped charges and their capabilities.

There is no statistical basis for a quantitative estimate of the probability that a nuclear power plant will be attacked. However, if a given attack scenario is postulated, one can apply PRA techniques to estimate the conditional probabilities of various outcomes. NRC took that approach in developing its vehicle-bomb rule of 1994.[21]

Radioactive releases from stored spent fuel

At nuclear power plants in the USA and elsewhere, large amounts of spent fuel are stored under water in pools adjacent to reactors. All US pools currently employ high-density racks, to maximize the amount of spent fuel that can be stored in each pool. This practice has been adopted because it is the cheapest mode of storage of spent fuel. Unfortunately,

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[19] The CNSC and CEAA documents discussed in this paragraph are cited and reviewed in: Thompson, 2008.
[20] Asmis and Khosla, 2007.
[21] NRC, 1994.

the high-density configuration would suppress convective cooling of fuel assemblies if water were lost from a pool.

Several reputable studies have agreed that loss of water from a pool would, across a range of water-loss scenarios, lead to spontaneous ignition of the zirconium alloy cladding of the most recently discharged fuel assemblies. The resulting fire would spread to adjacent fuel assemblies and propagate across the pool. Extinguishing the fire, once it had been initiated, would be difficult or impossible. Spraying water on the fire would feed an exothermic reaction between steam and zirconium. The fire would release a large amount of radioactive material to the atmosphere, including tens of percent of the pool's inventory of cesium-137. Large areas of land downwind of the plant would be rendered unusable for decades. Loss of water could arise in various ways as a result of an accident or an intentional, malevolent act.[22] Fortunately, measures are available for dramatically reducing the risk of a fire in a spent-fuel pool, as discussed in Section 4, below.

As discussed in Section 5, below, three designs of nuclear power plant are being considered for construction in Ontario. Two of these plant designs — the AREVA and Westinghouse designs — are PWR plants. It appears that both vendors envision the equipping of each plant’s spent-fuel pool with a set of high-density racks.[23] That practice would bring with it the potential for a large atmospheric release of radioactive material (especially cesium-137) from the pool.

This author is not aware of any study on the potential for an accidental release of radioactive material from spent fuel stored at a nuclear power plant employing a CANDU reactor. Absent such a study, the potential remains unknown.

CNSC position on residual radiological risk

CNSC has articulated safety goals for a new nuclear power plant, as shown in Table 3-3. The safety goals were first set forth in an October 2007 draft document. Revised safety goals were then set forth in a May 2008 document, and were adopted by the CNSC Commissioners at a meeting in June 2008. As shown in Table 3-3, the safety goals that were ultimately adopted by CNSC represent a significant retreat from the draft goals set forth in October 2007. A logical explanation for that retreat is a CNSC determination that compliance with the October 2007 goals could not be demonstrated for new plants of the types being considered for construction in Canada.

Thus, CNSC’s current position is that the probability of a large release of radioactive material to the environment from a new nuclear power plant in Canada “is less than” 1 per 1 million RY. Apparently, that probability does not account for malevolent acts.

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[22] Alvarez et al, 2003; National Research Council, 2006; Thompson, 2007.
[23] Thompson, 2008, Section 5.

CNSC has not specified whether the stated probability is a mean value or some other expression of the probability density function. In this report, it is assumed that CNSC's stated probability is a mean value. It would also be reasonable to assume an uncertainty factor of 10.[24] Given those assumptions, CNSC's current position would be that the 95th percentile probability of a large release from a new plant would be 1 per 100,000 RY. The 95th percentile value can be regarded as a "high confidence" estimate.

The discussion in the preceding paragraph refers to new nuclear power plants. In the context of life extension of an existing plant, CNSC requires a licensee to conduct an Integrated Safety Review, whose purposes include "determination of reasonable and practical modifications that should be made to systems, structures, and components, and to management arrangements, to enhance the safety of the facility to a level approaching that of modern nuclear power plants [emphasis added], and to allow for long term operation".[25] CNSC does not articulate numerical safety goals for existing plants.

4. Options for Reducing the Radiological Risk Posed by Nuclear Power Plants

The opportunities for reducing residual radiological risk are, in principle, substantially greater for a new nuclear power plant than for an existing plant. The design of the new plant could benefit from new technical knowledge. The safety and security criteria that the plant must meet could be more stringent than the criteria to which existing plants were designed. In practice, the new plants being considered for construction in Ontario would not pose a substantially lower risk than do the existing plants, for reasons discussed below.

Trends in construction, safety and security of nuclear power plants

Nuclear power is in a transitional phase, moving toward an uncertain future. Annual, worldwide capacity additions peaked in 1985 and have been modest since 1990.[26] If construction of nuclear power plants does not resume, total capacity will decline as plants are retired.

During the nuclear industry's start-up phase (1956-1970), capacity additions worldwide averaged about 1 GWe per year. In the decade 1971-1980, worldwide capacity increased at an average rate of about 12 GWe per year, increasing to an average rate of 20 GWe per year during the period 1981-1990. During the period 1991-present, the rate of capacity addition has been much lower, averaging about 4 GWe per year, with an even lower rate since 2000.[27]

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[24] In this report, the term "uncertainty factor" is used to designate the ratio of the 95th percentile value to the mean value of a probability density function.
[25] CNSC, 2008b, page 4.
[26] IAEA, 2006a.
[27] Keystone Center, 2007, pp 25-26.

This construction history has left the world with a fleet of existing nuclear power plants that are mostly in the "Generation II" category. The basic designs of these plants were laid down more than three decades ago. At that time, risk goals were less demanding than the goals now articulated by CNSC.[28] There was, for example, less concern by industry and regulators about the potential for malevolent acts.

During the 1970s and 1980s, plant vendors and other stakeholders identified innovative design options that could have reduced residual radiological risk to a level substantially below the level posed by the Generation II designs. Some of those options — such as ASEA-Atom's PIUS design — are discussed in the Appendix to this report.

The nuclear industry did not adopt innovative designs such as the PIUS design. Instead, the industry chose to pursue "Generation III" designs that represent a comparatively small evolutionary step from the Generation II designs. That decision has yielded a level of residual radiological risk, for new plants, that is not substantially lower than the risk posed by existing plants.[29] Regulators, including CNSC, could have sought to steer the industry toward innovative, lower-risk designs, by adopting highly stringent criteria for safety and security. Instead, regulators have accommodated the nuclear industry, by adopting criteria that are achievable by Generation III designs. The process of accommodation is clearly evident in CNSC's relaxation of its safety goals for new plants, as discussed in Section 3, above.

Risk reduction at existing nuclear power plants

At an existing nuclear power plant, efforts to reduce residual radiological risk could be made in areas including: (i) physical modification of the plant (capital additions); (ii) new procedures for operation and maintenance; (iii) personnel enhancement (training, etc.); (iv) enhanced site security (guards, gates, etc.); (v) enhanced capability for onsite damage control (firefighting, etc.); and (vi) enhanced capability for offsite emergency response.

Table 4-1 illustrates the potential for reducing residual radiological risk at an existing plant. The table shows options for reducing the risk of a fire in a spent-fuel pool equipped with high-density racks. As explained in Section 3, above, such a fire could occur if water were lost from the pool. High-density pool storage of spent fuel is standard practice at existing US plants, and could be used at new PWR plants in Ontario.

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[28] Okrent, 1981.
[29] Thompson, 2008.

5. Radiological Risk Posed by Nuclear Power Plants in Ontario

5.1 Scope of this Discussion

Sections 5.2 through 5.4, below, outline the residual radiological risk posed by operation of existing and new nuclear power plants in Ontario. A comprehensive assessment of that risk would be a major undertaking. Although some relevant studies have been done, there are major gaps in knowledge. For the purpose of estimating risk costs, this report draws from available sources to present a broad-brush picture of risk. Where possible, risk estimates developed by the nuclear industry are used here.

5.2 Types of Nuclear Power Plant that Could Operate in Ontario

The existing nuclear power plants in Ontario are CANDU plants at the Darlington, Pickering and Bruce sites. At present, 16 of these plants are operational. All of the existing plants are in the Generation II category. These plants are unusual because they share safety and support systems (e.g., a vacuum building) in 4-unit or 8-unit blocks. Most nuclear power plants in the world do not share systems to this extent.

New plants

In January 2007, one of Ontario's nuclear operators (Bruce Power) identified six types of new nuclear power plant that it was considering. This group consisted of two CANDU plants (the ACR-1000, and the Enhanced CANDU-6), two PWR plants (the AREVA US EPR, and the Westinghouse AP1000), and two BWR plants (the ESBWR, and the SWR-1000).[30]

In a March 2008 solicitation of proposals for construction of new plants, the Ontario government narrowed this list, eliminating the Enhanced CANDU-6 and the SWR-1000.[31] Subsequently, the vendor of the ESBWR withdrew from the competition. Thus, the field of contending designs in Ontario now consists of:

(i) the US EPR, a PWR plant offered by AREVA;
(ii) the AP1000, a PWR plant offered by Westinghouse; and
(iii) the ACR-1000, a CANDU plant offered by Atomic Energy of Canada Ltd (AECL).

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[30] Bruce Power, 2007, Section 4.4.
[31] Infrastructure Ontario, 2008.

Each of these plant types is in the Generation III category, as mentioned above.[32] According to Bruce Power, Generation III nuclear power plants are "safer, more efficient and easier to build" than the Generation II plants that comprise most of the world's fleet of nuclear power plants.[33] The Ontario government has announced that the first new plants would be built at the Darlington site.

There is no operational experience for any of the plant types being considered for construction in Ontario, and limited construction experience. Two EPR plants are now being built, in Finland and France. Construction of four AP1000 plants has been scheduled to commence in China during 2008. No order has been placed for an ACR-1000 plant. As a Canadian product, the ACR-1000 is a likely candidate for construction in Ontario. However, the technical competence of AECL — the vendor of the ACR-1000 plant — is under question because of AECL's experience with the MAPLE reactors. AECL built these two reactors at the Chalk River laboratories to produce medical isotopes. In May 2008 the MAPLE reactors were scrapped without ever becoming operational. AECL had concluded that the reactors were unfit to operate, and that their deficiencies could not be rectified within any reasonable budget and timeframe.[34]

The International Atomic Energy Agency (IAEA) has reviewed the plant designs being considered for use in Ontario, to compare the designs with IAEA safety standards.[35] That review was conducted at the request of the UK Health and Safety Executive. One finding of the review was that full-scope PRAs have not been completed for the EPR and ACR-1000 designs.

5.3 Potential Radioactive Releases and their Offsite Impacts

PRAs, despite their limitations, are important sources of information about the potential for, and consequences of, releases of radioactive material from nuclear power plants. For new plants that might be constructed in Ontario, PRAs are not available. For the existing plants in Ontario, there is a body of PRA-related literature, with limitations as discussed below.

Unfortunately, Canada lacks a fully developed PRA culture. PRAs performed in Canada for CANDU reactors find very low probabilities for large releases. Based on those findings, the PRAs do not estimate the radiological impacts of large releases. Yet, the low probabilities are not credible.[36] The practice of ignoring large releases deprives citizens and policy makers of needed information. For example, in a recent analysis of

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[32] Some plant designs are said to be in a Generation III+ category. That designation has no technical meaning, because it presumes a generally-accepted classification scheme that does not exist.
[33] Bruce Power, 2007, Section 4.4.
[34] Thompson, 2008, Section 5.4.
[35] IAEA, 2008. That review examined the ACR-1000, AP1000, EPR, and ESBWR designs.
[36] Thompson, 2000; IRSS, 1992.

the radiological risk of continued operation of the Pickering B station, the largest release considered included 71 TBq of Cesium-137.[37] That is a comparatively small release, and is categorized as such in Table 3-3.

The high point of PRA practice in Canada was reached by Ontario Hydro in its preparation of the Darlington Probabilistic Safety Evaluation (DPSE).[38] DPSE was conducted for internal initiating events only. It was conducted to Level 3, except that the impacts of the largest releases — in Ex-Plant Release Category 0 (EPRC0) — were not evaluated. It was not subjected to an official, independent review. Thus, DPSE did not rise to the quality of NRC's NUREG-1150 study, which is discussed in Section 3, above.

A focused review of DPSE was conducted by a team led by this author.[39] Several deficiencies were revealed. For example, DPSE had failed to identify an event sequence — involving failure of service water supply — that would be familiar to analysts conducting PRAs for PWR plants. In light of that and other deficiencies in DPSE, our team concluded that a reasonable estimate of the probability of a large, accidental radioactive release to the atmosphere from the Darlington plant would be 1 per 10,000 RY. Our value is comparable to the probability derived from occurrence of the TMI and Chernobyl accidents. (As mentioned above, those events suggest a core-damage probability of 1.6 per 10,000 RY, and a large-release probability of 0.8 per 10,000 RY.) Interestingly, our value is also comparable to the 95th percentile (high-confidence) value of DPSE's estimate of the probability of release category EPRC0, adjusted to account for external initiating events. The adjusted, 95th percentile probability of EPRC0 is 1.2 per 10,000 RY.[40]

PRAs are not available for new plants that might be built in Ontario. Lacking a PRA, one can take two approaches to estimating the probability of a large, accidental atmospheric release from a new plant. First, one can assume a 10-fold reduction in release probability for a new (Generation III) plant, by comparison with an existing (Generation II) plant. That assumption yields a release probability, for a new plant, of 1 per 100,000 RY. Second, one can rely on the CNSC safety goals, which are discussed in Table 3-3. Those goals, as now revised, state that the probability (assumed here to be the mean probability) of a large release from a new plant is 1 per 1 million RY. As discussed in Section 3, above, one can reasonably assume that CNSC's position is that the 95th percentile (high-confidence) probability of a large release is 1 per 100,000 RY.

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[37] SENES, 2007, Table B.5.3-1.
[38] Ontario Hydro, 1987.
[39] IRSS, 1992.
[40] DPSE (Ontario Hydro, 1987) states in its Table 5-6 that the probability of EPRC0 is 4.4 per 1 million RY. Applying an uncertainty factor of 14 (see Table 5-5 of DPSE), and a multiplier of 2 to account for external initiating events, one finds a 95th percentile value for EPRC0 of 1.2 per 10,000 RY.

Table 5-1 assembles a set of selected data about radioactive releases and their offsite impacts. Those data support this report's estimation, in Section 7.3, below, of the risk costs of offsite impacts. The metric used in Table 5-1 for offsite impacts is lifetime population dose. In this report, population dose is assumed to scale linearly with the amount of cesium-137 released to the atmosphere. That assumption is supported by the finding that most of the offsite population dose from the 1986 Chernobyl accident was from cesium-137.[41]

5.4 Potential Onsite Impacts of Fuel-Damage Events

As discussed in Section 2, above, a range of fuel-damage events could occur at a nuclear power plant, and the fraction of the material released from the fuel that reached the environment would vary according to the characteristics of each event. Ontario Hydro, in its DPSE study, estimated the risk of onsite economic impacts from fuel-damage events at the existing CANDU nuclear power plants at the Darlington site. That estimate considered only accidents initiated by internal events. Table 5-2 shows Ontario Hydro's findings, adjusted to 2008 Can $.

An interesting observation from Table 5-2 is that almost 90 percent of the risk of onsite economic impacts arises from fuel damage categories FDC6 through FDC9. The lowest mean probability for one of these categories is 1 per 500 RY. Thus, the overall risk is dominated by events with a comparatively high probability.

6. The Canadian Government's Consideration of Costs Related to Radiological Risk

The Canadian Government provides little information or guidance regarding: (i) the level of residual radiological risk posed by operation of nuclear power plants in Canada; and (ii) the cost implications of that risk. CNSC's safety goals for new plants, as discussed in Table 3-3, provide one source of information. The Government's perspective on radiological risk is also evident, indirectly, in the liability limit specified by the Nuclear Liability Act.

At present, the Act limits the liability of a nuclear operator to a maximum of $75 million. Legislation is pending to raise that limit to $650 million. In determining the new limit, the Government did not attempt to assess the impacts of unplanned releases of radioactive material. Instead, the Government sponsored a study to estimate the impacts of releases arising from selected design-basis accidents.[42] The assumed releases were very small by comparison with the unplanned releases that could occur.

[41] DOE, 1987.
[42] ISR, 2003.

The Canadian Government gave financial support to a study, by two UK analysts, of the implicit subsidy that arises from the provisions of the Nuclear Liability Act.[43] The concept of an "implicit subsidy" is similar to the concept of non-insured risk costs, as addressed in this report. The study sought to take an "empirical" approach to estimating the implicit subsidy. It generated a range of findings for that indicator, expressed as cent per kWh of nuclear generation. The approach taken was interesting. Unfortunately, however, the study had severe flaws as follows:

(i) the study assumed a formula, for the probability density function of monetized offsite damages, that lacked a credible rationale;
(ii) the assumed formula can, depending on the parameters chosen, yield a probability density function with a very long right-hand tail that is inconsistent with the phenomena that can cause offsite damages;
(iii) the study did not disclose the parameters used for its formula;
(iv) the analysts misunderstood expert findings regarding worst-case damages, believing (incorrectly) that these findings referred to the probability that damages would be "equal to or greater than" a particular $ value; and
(v) equation (3) of the study shows a lower bound of integration that is too high by six orders of magnitude.

7. This Report's Estimation of Costs Arising from Residual Radiological Risk

7.1 Scope of this Discussion

Drawing upon analysis in preceding sections of this report, Sections 7.2 through 7.5 address the cost implications of residual radiological risk. Section 7.2 discusses the costs of measures intended to reduce residual radiological risk. Section 7.3 provides quantitative estimates of the risk costs of offsite impacts of unplanned radioactive releases. The releases could arise from accidents or from malevolent acts. Section 7.4 provides quantitative estimates of the risk costs of onsite impacts of fuel-damage events. An overview of risk costs is provided in Section 7.5. The estimates presented here reflect assumptions and sources that are identified in the narrative of the report, and in the notes to tables and figures. A reader could repeat the analysis with different assumptions.

Relevant information was sought from OPA by submission of Interrogatories 91 through 99, by the Green Energy Coalition et al. OPA provided no information in response to these Interrogatories.

[43] Heyes and Heyes, 2000.

7.2 Costs of Measures Intended to Reduce Residual Radiological Risk

Experience in the USA during the 1970s and 1980s provides important information about the cost implications of efforts to reduce the residual radiological risk from operation of nuclear power plants. During that period there was growing awareness of safety issues, leading to actions that involved cost increments. The growth of awareness was significantly, but not exclusively, attributable to the occurrence of the TMI accident in 1979.

Charles Komanoff, in a book published in 1981, examined the escalating trends of costs associated with nuclear generation in the USA.[44] He showed that efforts to reduce residual radiological risk were a major driver of cost escalation, and he predicted that this effect would continue during the 1980s. A subsequent compilation of data showed that his prediction was correct.[45] Construction/capital costs in the 1970s averaged 1.95 cent per kWh (1990 $), but rose to an average of 3.51 cent per kWh (1990 $) in the 1980s. Annual capital additions grew from an average of 0.35 cent per kWh (1990 $) in the 1970s to 0.89 cent per kWh (1990 $) in the 1980s.[46] Efforts to reduce residual risk were a major driver of those trends.

Analysts examining the potential for a nuclear power "renaissance" are well aware of the history of cost escalation.[47] Plant vendors and other advocates of the renaissance recognize that substantial cost escalation will prevent their ambitions from being realized. They hope to curb this escalation through measures such as standardizing of designs and "streamlining" of regulation. It is not clear, however, that they fully appreciate the potential for an unplanned release, at any nuclear power plant in the world, to override those measures.[48] Such an event, whether caused by an accident or a malevolent act, would increase public pressure for adoption of risk-reducing measures at plants in Ontario and elsewhere. That pressure could become especially powerful if the public became aware that the nuclear industry had rejected innovative plant designs — such as the PIUS design — in favor of Generation III designs that pose a higher residual risk.

The potential for cost escalation to be driven by an unplanned release could be assessed through use of probabilistic cost analysis.[49] In that context, note that this report assumes

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[44] Komanoff, 1981.
[45] Komanoff and Roelofs, 1992.
[46] Komanoff and Roelofs, 1992, pp 17-20.
[47] Hultman et al, 2007.
[48] The 1986 Chernobyl accident had a less visible effect on cost trends than did the 1979 TMI accident. Two factors may explain that outcome. First, the Chernobyl accident occurred in a closed, non-Western society. Second, annual capacity additions were already beginning to decline in 1986. Those factors would not apply over the coming years.
[49] Roques et al, 2006.

that the probability of a large, unplanned release from an existing nuclear power plant is 1 per 10,000 RY. Given that 439 plants are currently operational worldwide, that assumption translates to a probability of 4.4 percent per calendar year.

If the nuclear renaissance takes hold, and cost data are published, trends in costs associated with new nuclear power plants will become evident over the coming years. The influence on costs of efforts to reduce residual risk may become discernible. At any point, however, that influence could become amplified by the occurrence of an unplanned release.

Examples of the cost of risk reduction

Table 7-1 provides an example of a capital-addition cost that would lead to risk reduction at a new or existing PWR nuclear power plant. This example would be relevant to Ontario in the future if a PWR plant were built in the province. The cost would arise from the re-equipping of the plant's spent-fuel pool with low-density racks, an option shown in the first row of Table 4-1.[50] That measure would require the transfer of spent fuel to dry storage after 5 years of storage in the pool.

Another example of a cost of risk reduction is the additional expenditures in Canada since 2001 to enhance security measures at nuclear facilities. Capital costs for these measures have totaled about $300 million, and ongoing costs are about $60 million per year.[51] Licensees are bearing the majority of these costs. It can be presumed that most of the expenditure has been at nuclear power plants.

7.3 Risk Costs of Offsite Impacts of Radioactive Releases

The potential for unplanned radioactive releases from nuclear power plants in Ontario is discussed in Section 5.3, above, with a focus on atmospheric releases. That discussion also addresses the offsite radiological impacts of releases, with a focus on lifetime population dose (collective dose commitment). Table 5-1 summarizes information that is relevant to an assessment of the risk costs of offsite impacts. Note that Table 5-1 considers the potential for releases from reactor cores and spent-fuel pools.

Monetizing radiological impacts

One of the steps in assessing the risk costs of radiological impacts is to assign a monetary value to radiation dose. Here, the relevant dose is the lifetime population dose arising from a release. That dose is statistically linked to the incidence of radiation-caused morbidity and mortality in the exposed population.

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[50] The cost estimate in Table 7-1 assumes that the pool would be re-equipped with low-density racks prior to the 11th year of plant operation.
[51] Frappier, 2007.

The potential for a population dose, as a result of an unplanned release from a nuclear power plant, would be a foreseeable outcome of a decision to operate the plant with a particular level of residual radiological risk. As discussed in Section 4, above, options are available to reduce the residual radiological risk. Implementation of those options would involve expenditures. Thus, the monetary value to be assigned to population dose should reflect the tradeoff between the cost of receiving a dose and the cost of avoiding that dose. That tradeoff is made routinely in the operation of nuclear power plants, in the context of small, routine releases of radioactive material. The tradeoff is formalized through the concept of keeping radiation exposure "as low as reasonably achievable" (ALARA).

CNSC has provided regulatory guidance for implementing the ALARA concept.[52] The CNSC guidance document notes that implementation of ALARA requires the assigning of a monetary value to population dose, and refers the reader to an IAEA report that discusses specific monetary values.[53] The IAEA report is titled, *Optimization of Radiation Protection in the Control of Occupational Exposure*.[54] Table III-2 of the IAEA report shows that owners of US nuclear power plants were, in the early 1990s, assigning an average value of US $1 million to each person-Sv of occupational exposure. The same value (in Can $) was used at the Gentilly plant in Canada.

Analysis published in 1992, by a team led by this author, noted that NRC was then recommending a value of $1,000 per person-rem ($100,000 per person-Sv) for population dose in the ALARA context. NRC also used a dose value of $1,000 per person-rem at that time to determine if a risk-reducing plant modification was economically justified. A value of $1,000 per person-rem, if updated to a 1992 value to account for inflation and new scientific information about the health effects of radiation, would amount to $1 million per person-Sv.[55]

In this report, a potential population dose is assigned a value of 1992 Can $1 million per person-Sv. That value is adjusted to 2008 Can $ by a factor of 1.36, a CPI inflator provided by Bank of Canada.

Estimating risk costs

The data in Table 5-1 are used to develop the release cases shown in Table 7-2. Application of a population-dose value of 2008 Can $1.36 million per person-Sv to those cases yields the risk costs shown in Table 7-2. In that table, the CANDU plants at the Darlington site represent the existing CANDU plants in Ontario.

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[52] CNSC, 2004.
[53] CNSC, 2004, page 3.
[54] IAEA, 2002.
[55] IRSS, 1992, Volume 2, page 22.

Table 7-3 extends Table 7-2 by showing the risk costs for specific values of: (i) the plant's capacity factor; and (ii) the probability of a release caused by malevolent action. In addition, Table 7-3 combines the risk costs for accidental and malevolent releases. The capacity factors shown in Table 7-3 and elsewhere in this report are illustrative, and do not imply that nuclear power plants in Ontario will achieve any particular capacity factor. The malevolent release probabilities (MRPs) shown in Table 7-3 are not the product of statistical analysis. Instead, they provide a range of quantitative probabilities that serves as a proxy for a qualitative assessment of the potential for malevolent action.

Table 7-3 shows some very large risk costs for releases from spent-fuel pools at new plants. In the worst instance, the risk costs for pool releases would be 99 cent per kWh.[56] That is a remarkable finding, but is a true reflection of the risk posed by storage of a large amount of spent nuclear fuel in a high-density pool.

As discussed in Section 4, above, options are available for dramatically reducing the risk of a release from a spent-fuel pool, especially by reverting to the use of low-density racks and transferring fuel to dry storage. The cost of implementing that option would be comparatively modest, as shown in Table 7-1. This report assumes implementation of that option.

Table 7-4 simplifies the findings in Table 7.3, by excluding releases from spent-fuel pools and by assuming that the capacity factor of each plant would be 0.9. Further simplification is provided in Table 7-5, which sets forth recommended risk costs of offsite impacts of radioactive releases. Table 7-5 considers releases caused by accidents and by malevolent acts, and shows risk costs for existing plants and new plants in Ontario.

7.4 Risk Costs of Onsite Impacts of Fuel-Damage Events

The potential for onsite impacts of fuel-damage events at existing CANDU plants in Ontario is discussed in Section 5.4, above. Table 5-2 shows an estimate by Ontario Hydro of the risk of such onsite impacts. The risk is expressed in 2008 Can $ per RY of plant operation.

Table 7-6 converts Ontario Hydro's findings to risk costs of onsite impacts of fuel-damage events. Ontario Hydro considered only accidents initiated by internal events. It is reasonable to double Ontario Hydro's estimate of risk to account for external initiating events and malevolent acts. It is also reasonable to use the Darlington estimate for all existing CANDU plants in Ontario.

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[56] In this instance, pool release cases 1B-H (high accidental-release probability) and 2B (high malevolent-release probability) are combined, and the plant's capacity factor is 0.8.

Note that the dominant component of the risk costs shown in Table 7-6 is the cost of replacement power due to forced outage of nuclear generating units. (See the notes to Table 5-2.) Analysts considering the economics of nuclear generation in Ontario should be wary of double counting the costs of forced outages.

7.5 An Overview of Risk Costs

The risk-cost estimates in Tables 7-5 and 7-6 are combined in Table 7-7, which summarizes this report's overall findings regarding the risk costs of nuclear generation in Ontario. Also shown in Table 7-7 are the estimated insurance premiums that are paid to provide coverage of the risk costs. Clearly, most of the risk costs are not insured.

The limited coverage provided by nuclear-facility insurance in Canada can be illustrated by comparing the anticipated liability limit ($650 million) with some costs of unplanned releases.

For an example of offsite impacts, note from the first row of Table 7-2 that an accidental release from an existing CANDU plant would yield an estimated population dose of 1.5 million person-Sv. At a dose value of $1.36 million per person-Sv, the monetized impact of the release would be $2.0 trillion.

For an example of onsite impacts, note from Table 5-2 that the onsite economic impacts of an FDC6 fuel-damage event were estimated by Ontario Hydro at $1.9 to 3.7 billion. The estimated mean probability of FDC6 is 1 per 500 RY.

8. Conclusions

C1. Future operation of the existing nuclear power plants in Ontario, and of the new plants whose construction in Ontario is now being considered, would pose a significant residual radiological risk. Any of these plants could experience an unplanned release of radioactive material to the environment or within the plant. The release could be caused by an accident or a malevolent act. The risk would be "residual" in the sense that it would persist if each plant were constructed and operated according to CNSC regulations.

C2. The residual radiological risk of operating existing (Generation II) or new (Generation III) nuclear power plants in Ontario would be generally comparable to the residual radiological risk of operating similar plants in other industrialized countries.

C3. CNSC acknowledges that an unplanned release could be caused by an accident or malevolent act beyond the design basis of existing or new nuclear power plants. IAEA and regulators in other countries have also acknowledged this potential. In response, various stakeholders have called for measures to increase the safety and security of existing and new plants.

C4. Measures are available for reducing residual radiological risk at existing or new nuclear power plants. The potential for risk reduction is greatest at new plants. During the 1970s and 1980s, plant vendors and other stakeholders identified innovative plant designs that would have posed a residual radiological risk substantially lower than is posed by existing (Generation II) plants. Those innovative designs were not adopted. The new Generation III plants, such as those whose construction in Ontario is now being considered, represent a comparatively small evolutionary step from the Generation II plants. Plant vendors claim that this step yields a significant improvement in the safety and security of a plant. The actual improvement is smaller than the vendors claim.

C5. Two of the Generation III plant designs being considered for use in Ontario currently feature high-density pool storage of spent nuclear fuel. That option would lead to very high risk costs of offsite impacts of radioactive releases. The risk of such releases could be dramatically reduced by transferring spent fuel to dry storage after 5 years of pool storage. The cost of that transfer would be modest — about 0.04 cent per kWh of nuclear generation, beginning in the 11^{th} year of plant operation. (Costs are expressed here as 2008 Can $ or cent.) This report assumes that spent fuel would be transferred to dry storage after 5 years of pool storage.

C6. In response to demand from various stakeholders, it is likely that nuclear power plant vendors, owners and regulators will engage in an ongoing pursuit of improved safety and security of existing and new plants. That pursuit would drive increases in construction/capital costs, capital additions, and operating & maintenance costs. This report does not provide a quantitative estimate of trends in those indicators.

C7. The occurrence of a substantial, unplanned release of radioactive material from or within a nuclear power plant at any location worldwide, caused by an accident or a malevolent act, would increase public pressure for adoption of risk-reducing measures at nuclear power plants in Ontario and elsewhere. Those measures could include: (i) temporary or permanent shutdown or reduction in rated power at Ontario plants, with attendant costs for replacement power and capital write-off; and (ii) other measures at Ontario plants that lead to increases in construction/capital costs, capital additions, or operating & maintenance costs. To assess this effect, it is reasonable to assume that the probability of a substantial, unplanned release is 1 per 10,000 reactor-year. Given the present size of the world fleet of nuclear power plants (439 plants), that assumption is equivalent to a probability of 4.4 percent per calendar year.

C8. From worldwide operating experience and technical analysis, one can estimate the probabilities and offsite radiological impacts of unplanned radioactive releases from nuclear power plants in Ontario, as a result of accidents or malevolent acts. Estimates of that type are performed in this report, leading to recommended values of risk costs of offsite impacts of radioactive releases, as follows (see Table 7-5): (i) 2.7 to 5.4 cent per kWh for existing CANDU plants; and (ii) 1.5 to 15.4 cent per kWh for new Generation III plants. (Costs are expressed here as 2008 Can $ or cent.) The range of risk costs for each plant type reflects, at the low end, a probability of malevolent release of 1 per 1 million reactor-year and, at the high end, a probability of malevolent release of 1 per 10,000 reactor-year. The higher values correspond to a more pessimistic, and more prudent, view of human behavior than do the lower values.

C9. Any substantial, unplanned release of radioactive material from a nuclear power plant to the environment would involve damage to nuclear fuel within or outside the reactor core, and the movement of that radioactive material through the plant to the point where the material would escape to the environment. A portion of the radioactive material released from damaged fuel would remain within the plant. In some fuel-damage events, most of the radioactive material would remain within the plant, and the release to the environment would be correspondingly small. More generally, a range of fuel-damage events could occur, and the fraction of the material released from the fuel that reached the environment would vary according to the characteristics of each event.

C10. Ontario Hydro estimated the risk of onsite economic impacts from fuel-damage events at the existing CANDU nuclear power plants at the Darlington site. That estimate considered only accidents initiated by internal events. It is reasonable to double Ontario Hydro's estimate of risk to account for external initiating events and malevolent acts. It is also reasonable to use the Darlington estimate for all existing CANDU plants in Ontario. With those assumptions, this report finds risk costs of onsite impacts of fuel-damage events at existing CANDU plants in Ontario, as follows (see Table 7-6): (i) 0.5 to 1.1 cent per kWh for Ontario Hydro's mean estimate of fuel-damage probability; and (ii) 2.7 to 5.6 cent per kWh for Ontario Hydro's 95th percentile estimate of fuel-damage probability. The 95th percentile estimate can be regarded as a "high confidence" estimate.

C11. For new nuclear power plants in Ontario, the risk costs of onsite impacts of fuel-damage events are likely to be smaller than the equivalent costs shown above for existing CANDU plants. Two factors account for this expectation. First, the Darlington CANDU plants are in a 4-plant block with shared safety and support systems. As a result, fuel damage at one plant could cause radioactive contamination of other plants. By contrast, new plants would have separate containment buildings and relatively few shared systems, thus reducing the potential for cross-contamination. Second, the probability of fuel damage is likely to be lower at new plants.

C12. Assessment of the risk costs of nuclear generation is not an exact science. The assessment process requires the development of quantitative estimates of the probabilities of unplanned radioactive releases, and of the adverse impacts of those releases. Such estimates are subject to numerous uncertainties. In the context of existing and new nuclear power plants in Ontario, much of the analytic work that could support the development of quantitative estimates has not been done. (Such work should be sponsored primarily by the nuclear industry and the regulators.) Judgment must be exercised at many points of the assessment, such as the assignation of monetary values to adverse impacts, or the representation of an uncertain indicator (e.g., by its mean value, or by its 95th percentile value). Despite these difficulties, risk costs are real and cannot be ignored. Separate efforts to assess the risk costs of nuclear generation in Ontario are likely to reach differing findings. Those differences would be a reflection of the uncertainty and controversy associated with the residual radiological risk of nuclear generation.

C13. In regard to Issue No. 12 identified by OEB ("Is the IPSP's plan to use nuclear power to meet the remaining base-load requirements economically prudent and cost effective?"), the preceding conclusions show that nuclear generation in Ontario would yield substantial, non-insured risk costs. Also, ongoing pressure from various stakeholders to reduce residual radiological risk is likely to lead to increased costs of nuclear generation. That pressure would grow if a substantial, unplanned release occurred at any nuclear power plant worldwide.

C14. In regard to Issue No. 13 identified by OEB ("In the context of the determination of economic prudence and cost effectiveness, is the IPSP sufficiently flexible to accommodate building new nuclear plants or refurbishing existing plants or both?"), the preceding conclusions show that the risk costs of nuclear generation are uncertain, and could differ significantly between existing plants and new plants. There could also be differences in the costs that arise at existing and new plants from public pressure to reduce residual radiological risk. Moreover, future expenditures for reduction of residual radiological risk cannot be reliably predicted. Thus, the IPSP would need to accommodate: (i) substantial differences between the risk-related costs of nuclear generation by existing and new plants; and (ii) substantial uncertainties in those costs.

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Table 1-1
Classification of Potential Accidents and Malfunctions at a Nuclear Power Plant

Mode of Impact of Accident or Malfunction	Type of Accident or Malfunction		
	Accidents Initiated by Internal Events	Accidents Initiated by External Events	Releases and Diversions Initiated by Intentional, Malevolent Acts
Unplanned release of radioactive material from the reactor core	X	X	X
Unplanned release of radioactive material from spent fuel, during storage or transfer to/from storage	X	X	X
Unplanned release of radioactive or hazardous chemical material from another part of the plant	X	X	X
Diversion of fissile or radioactive material for illicit use	Not applicable	Not applicable	X

Note:
The symbol X indicates that there is a potential for accidents and malfunctions in the designated category.

Table 3-1
Some Potential Modes and Instruments of Attack on a Nuclear Power Plant

Table 3.1 redacted - copies may be requested

Table 3-2
The Shaped Charge as a Potential Instrument of Attack

Table 3.2 redacted - copies may be requested

Table 3-3
Safety Goals for a New Nuclear Power Plant, as Specified in CNSC Draft Regulatory Document RD-337

Type of Outcome	**Safety Goals**	
	Sum of frequencies of all event sequences that can lead to this outcome ……..	
	Should be less than	**Shall not exceed**
Small Release to the Environment (more than 1,000 TBq of Iodine-131)	1 per 1 million plant-years	1 per 100,000 plant-years
Large Release to the Environment (more than 100 TBq of Cesium-137)	1 per 10 million plant-years	1 per 1 million plant-years
Core Damage (significant core degradation)	1 per 1 million plant-years	1 per 100,000 plant-years

Notes:
(a) The table as shown describes the safety goals set forth in the October 2007 draft of CNSC Regulatory Document RD-337, *Design of New Nuclear Power Plants*. See: CNSC, 2007a, page 5.
(b) In May 2008, the CNSC Staff completed a document (Dallaire et al, 2008) containing a revised version of RD-337, which the Staff submitted to the CNSC Commissioners for approval at their meeting of 10 June 2008. That approval was granted, and the revised version of RD-337 will be published by CNSC. At page 5 of the revised RD-337, revised safety goals are set forth, exhibiting the following changes from the table above. First, the numerical goals in the "should be less than" category are abandoned. Second, the numerical goals in the "shall not exceed" category are retained, but with different language. The revised RD-337 states that the sum of frequencies of all event sequences that can lead to a specified outcome "is less than" a numerical value. Each of these changes represents a significant retreat from the safety goals in the draft RD-337.

Table 4-1
Selected Options to Reduce the Risk of a Spent-Fuel-Pool Fire at a Nuclear Power Plant that Employs High-Density Pool Storage

Option	Passive or Active?	Does Option Address Fire Scenarios Arising From: Malevolent Acts?	Does Option Address Fire Scenarios Arising From: Other Events?	Comments
Re-equip pool with low-density, open-frame racks	Passive	Yes	Yes	• Would substantially reduce pool inventory of radioactive material • Would prevent auto-ignition of fuel in almost all cases
Install emergency water sprays above pool	Active	Yes	Yes	• Spray system must be highly robust • Spraying water on overheated fuel could feed Zr-steam reaction
Mix hotter (younger) and colder (older) fuel in pool	Passive	Yes	Yes	• Could delay or prevent auto-ignition in some cases • Would be ineffective if debris or residual water block air flow • Could promote fire propagation to older fuel
Minimize movement of spent-fuel cask over pool	Active	No (Most cases)	Yes	• Could conflict with adoption of low-density, open-frame racks
Deploy air-defense system (e.g., Sentinel and Phalanx) at plant	Active	Yes	No	• Implementation would require presence of military personnel at plant
Develop enhanced onsite capability for damage control	Active	Yes	Yes	• Would require new equipment, staff and training • Personnel must function in extreme environments

Source:
Thompson, 2007, Table 9-1. Further citations are provided in that table's supporting narrative.

Table 5-1
Radioactive Releases and Offsite Impacts for the 1986 Chernobyl Accident and Some Potential Accidents at Nuclear Power Plants: Selected Data

Accident Case	Inventory of Cesium-137 Available for Release	Probability of Release to Atmosphere	Fraction of Cesium-137 Inventory Released to Atmosphere	Lifetime Population Dose (million person-Sv)
Chernobyl Unit 4 in 1986 (capacity = 1.0 GWe)	• Reactor core: 223 PBq • Spent-fuel pool: ?	• Reactor core: 1.0 (known) • Spent-fuel pool: 0 (known)	• Reactor core: 40% (estimated from known release) • Spent fuel: 0% (known)	1.2 (estimated from known release)
Generation II plant (generic)	Varies by plant type & mode of spent-fuel storage	• Reactor core: 1/12,900 = 7.8E-05 per RY • Spent fuel: ?	Varies by plant type and scenario	Varies by plant type, scenario and site
Darlington CANDU plant (capacity = 0.88 GWe)	• Reactor core: 67 PBq • Spent-fuel pool: ?	• Reactor core: 1.0E-04 per RY (estimated) • Spent-fuel pool: 0 (assumed)	• Reactor core: 50% (est.) from each of two reactors • Spent fuel: 0% (assumed)	2.7 (estimated)
Indian Point Unit 2 PWR plant (capacity = 1.08 GWe)	• Reactor core: 420 PBq • Spent-fuel pool: 2,500 PBq	• Reactor core: 7.4E-05 per RY (estimated) • Spent-fuel pool: 2.0E-06 per RY (est.)	• Reactor core: 23% (est.) • Spent fuel: 50% (est.)	?
Generation III plant at Darlington site (amounts in this row are normalized to a plant capacity of 1.0 GWe)	• Reactor core: 390 PBq • Spent-fuel pool: 2,300 PBq	• Reactor core: 1.0E-06 per RY (CNSC goal) • Spent fuel: 1.0E-06 per RY (CNSC goal)	• Reactor core: 50% (est.) • Spent fuel: 50% (est.)	• Reactor core: 7.9 • Spent fuel: 46 (both amounts are extrapolated from the Darlington CANDU case)

(Notes are on the following page.)

Notes for Table 5-1:

(a) Actual releases would include isotopes in addition to cesium-137.

(b) RY = reactor-year

(c) "Population dose" is also known as "collective dose commitment". Lifetime dose is typically calculated for a 50-year period.

(d) Data in the first row are from: DOE, 1987; NRC, 1987; IRSS, 1992, Volume 2, Annex III. Lifetime population dose is from: DOE, 1987, Table 5.16.

(e) In the second row, the probability of a substantial reactor-core release is determined by the occurrence of one such event (at Chernobyl Unit 4) during the 12,900 RY of worldwide commercial reactor operation accrued through 2007 (see IAEA data in: Thompson, 2008, Section 4.2).

(f) Data in the third row are from: IRSS, 1992, Volume 2. The probability of a reactor-core release is an IRSS estimate for internal + external initiating events, excluding malevolent acts. The estimated lifetime population dose is a weighted average over the set of the most frequent weather conditions at Darlington, where that set accounts for 20% of the frequency of all weather conditions at the site. Dose was calculated by the MACCS code up to a distance of 1,000 km, assuming no relocation of populations. The estimated release of cesium-137 is 67 PBq for two reactors, which is equivalent to a release of 67/(2 x 0.88) = 38 PBq per GWe.

(g) Data in the fourth row are from Entergy and the author, in: Thompson, 2007. Entergy estimates a core-damage probability, accounting for internal + external initiating events + uncertainty, excluding malevolent acts, of 1.4E-04 per RY. Entergy's estimate of the conditional probability of an Early High release is adjusted here to account for containment bypass during High/Dry core-damage sequences (see: Thompson, 2007, Table 5-3). The estimated probability of a release from the spent-fuel pool is taken from the NRC study NUREG-1353 (see: Thompson, 2007, Table 6-2).

(h) In the fifth row, inventories of cesium-137 are adjusted from the Indian Point Unit 2 inventories in proportion to plant capacity. Release probabilities are set to the CNSC safety goal for a Large Release (see: CNSC, 2007a; Dallaire et al, 2008). The estimated release of cesium-137 is 0.5 x 390 = 195 PBq for the reactor core and 0.5 x 2,300 = 1,150 PBq for the spent-fuel pool. Lifetime population dose is extrapolated from the Darlington CANDU case by assuming that dose is proportional to the release of cesium-137, yielding an estimated dose of (195/67) x 2.7 = 7.9 million person-Sv for the reactor release and (1,150/67) x 2.7 = 46 million person-Sv for the spent-fuel release.

Table 5-2
Ontario Hydro Estimate of the Risk of Onsite Economic Impacts from Fuel-Damage Events at the Darlington Nuclear Power Plants (Existing CANDU Plants)

Fuel Damage Category	Est. Mean Probability (Uncertainty Factor)	Est. Onsite Economic Impacts (million 2008 Can $)	Risk of Onsite Economic Impacts (million 2008 Can $ per RY)	
			Using Mean Estimate of FDC Probability	Using 95th Percentile Estimate of FDC Probability
FDC0	3.8E-06 per RY (UF = 6)	?	?	?
FDC1	2.0E-06 per RY (UF = 6)	6,400 to 11,500	0.013 to 0.023	0.077 to 0.14
FDC2	8.0E-05 per RY (UF = 6)	5,800 to 10,200	0.46 to 0.82	2.80 to 4.90
FDC3	4.7E-04 per RY (UF = 4)	3,400 to 5,900	1.60 to 2.80	6.40 to 11.10
FDC4	3.0E-05 per RY (UF = 10)	3,400 to 6,200	0.10 to 0.19	1.02 to 1.90
FDC5	1.0E-04 per RY (UF = 10)	2,700 to 5,200	0.27 to 0.52	2.70 to 5.20
FDC6	2.0E-03 per RY (UF = 10)	1,900 to 3,700	3.80 to 7.40	38.0 to 74.0
FDC7	3.0E-03 per RY (UF = 5)	790 to 2,500	2.40 to 7.50	11.90 to 37.5
FDC8	2.0E-03 per RY (UF = 10)	120 to 600	0.24 to 1.20	2.40 to 12.0
FDC9	2.3E-02 per RY (UF = 3)	390 to 700	8.97 to 16.10	26.9 to 48.3
Total Risk			17.9 to 36.6	92.2 to 195.0

(Notes are on the following page.)

Notes for Table 5-2:

(a) Estimates are from the Darlington Probabilistic Safety Evaluation (DPSE). See: Ontario Hydro, 1987, Tables 5-2, 5-8 and 5-9. For additional data from the full version of DPSE, see: IRSS, 1992, Volume 2, Annex IV.

(b) DPSE provided cost estimates in 1985 Can $. These are adjusted here to 1991 Can $ by a multiplier of 1.25 (see: IRSS, 1992, Volume 2, Annex IV), and from 1991 Can $ to 2008 Can $ by a multiplier of 1.36 (CPI inflator from Bank of Canada). The combined multiplier is 1.70.

(c) DPSE did not estimate the risk of onsite economic impacts for FDC0.

(d) These estimates are limited to fuel damage in a reactor core or a fueling machine, caused by accidents initiated by internal events.

(e) Replacement power is the dominant component of the estimated onsite economic impacts. The other component considered by DPSE is the cost of decontamination and repair.

(f) The range of estimated onsite economic impacts is from a “best estimate” (lower bound) to a “probable maximum” (upper bound).

(g) The Darlington station has four CANDU units (plants) that share many safety and support systems (e.g., fueling duct and vacuum building), which means that a fuel-damage event at one unit could readily lead to adverse impacts on the other units. DPSE determined that accidents in categories FDC1 through FDC9 would lead to forced outage of all four units. For example, given the occurrence of an FDC1 accident, the estimated duration of the forced outage would be 45-72 months for all four units, and an additional 65-126 months for the unit that suffered fuel damage.

(h) The uncertainty factor (UF) in the second column is DPSE’s estimate of the ratio of the 95th percentile value to the mean value.

Table 7-1
Estimation of Cost to Transfer Spent Fuel from a PWR Spent-Fuel Pool to Dry Storage After 5 Years of Storage in the Pool

Estimation Step	Estimate
Average period of use of a fuel assembly in the reactor core	5 years
Period of storage of a spent-fuel assembly in the spent-fuel pool, prior to transfer to dry storage	5 years
Point in plant history when transfer of spent fuel to dry storage begins	11^{th} year of plant operation
Average annual transfer of spent fuel from pool to dry storage	36 fuel assemblies
Capital cost of transferring spent fuel from pool to dry storage (given a dry-storage cost of $200 per kgU, and a mass of 450 kgU per fuel assembly)	$3.2 million per year
Capital cost of transferring spent fuel from pool to dry storage (given a plant capacity of 1.08 GWe, and a capacity factor of 0.9)	0.04 cent per kWh of nuclear generation

Notes:
(a) This calculation employs data that apply to the Indian Point 2 nuclear power plant in New York state. Comparable data would apply to a new PWR plant in Ontario.
(b) Data in this table are from Tables 2-1 and 9-2 of: Thompson, 2007.
(c) The capital cost begins in the 11^{th} year of plant operation, and continues while the plant operates.
(d) The cost can be regarded as being in 2008 Can $.

Table 7-2
Risk Costs of Offsite Impacts of Accidental or Malevolent Releases of Radioactive Material from Nuclear Power Plants in Ontario: Selected Cases

Release Case	Lifetime Population Dose (million person-Sv)	Probability of Release	Risk Costs of Release (million 2008 Can $ per RY)	Risk Costs of Release (2008 Can cent per kWh)
Case 1A: Accidental release at existing CANDU reactor	Reactor release: 1.5	1.0E-04 per RY	Reactor release: 210	Reactor release: 2.4/C
Case 1B-L: Accidental release at new Gen III reactor or spent-fuel pool (lower probability)	• Reactor release: 7.9 • Spent-fuel release: 46	• Reactor core: 1.0E-06 per RY (CNSC goal) • Spent fuel: 1.0E-06 per RY (CNSC goal)	• Reactor release: 11 • Spent-fuel release: 63	• Reactor release: 0.13/C • Spent-fuel release: 0.72/C
Case 1B-H: Accidental release at new Gen III reactor or spent-fuel pool (higher probability)	• Reactor release: 7.9 • Spent-fuel release: 46	• Reactor core: 1.0E-05 per RY (10 x CNSC goal) • Spent fuel: 1.0E-05 per RY (10 x CNSC goal)	• Reactor release: 110 • Spent-fuel release: 630	• Reactor release: 1.3/C • Spent-fuel release: 7.2/C
Case 2A: Malevolent release at existing CANDU reactor	Reactor release: 1.5	MRP per RY	Reactor release: MRP x 2.1E+06	Reactor release: (MRP x 2.4E+04)/C
Case 2B: Malevolent release at new Gen III reactor or spent-fuel pool	• Reactor release: 7.9 • Spent-fuel release: 46	• Reactor core: MRP per RY • Spent fuel: MRP per RY	• Reactor release: MRP x 1.1E+07 • Spent-fuel release: 6.3E+07	• Reactor release: (MRP x 1.3E+05)/C • Spent-fuel release: (MRP x 7.2E+05)/C

(Notes are on the following page.)

Notes for Table 7-2:

(a) Population dose (in person-Sv) and risk costs (in $ per RY) are shown here for a 1 GWe-capacity plant, and can be scaled linearly to other capacities.

(b) C = average annual capacity factor of a plant.

(c) Malevolent release probability (MRP) = probability (per RY) that a malevolent act will yield a large atmospheric release.

(d) In this table, lifetime population dose is assigned a monetary value of 1992 Can $1 million per person-SV. That value is converted to 2008 Can $ using a CPI inflator of 1.36, from Bank of Canada.

(e) In the first and fourth rows, the release contains 38 PBq of cesium-137. Population dose is scaled linearly from the Darlington CANDU case.

(f) In the second, third and fifth rows, the reactor release contains 195 PBq of cesium-137, and the spent-fuel release contains 1,150 PBq of cesium-137. Population dose is scaled linearly from the Darlington CANDU case.

Table 7-3
Range of Risk Costs of Offsite Impacts of Accidental and Malevolent Releases of Radioactive Material from Nuclear Power Plants in Ontario: Existing or New Plants

Cases	**Risk Costs of Releases (2008 Can cent per kWh)**			
	Av. Capacity Factor (C) = 0.8		**Av. Capacity Factor (C) = 0.9**	
	Malevolent Release Prob. (MRP) = 1.0E-04 per RY	**Malevolent Release Prob. (MRP) = 1.0E-06 per RY**	**Malevolent Release Prob. (MRP) = 1.0E-04 per RY**	**Malevolent Release Prob. (MRP) = 1.0E-06 per RY**
Cases 1A & 2A: Release at existing CANDU plant	• Case 1A: 3.0 • Case 2A: 3.0 • TOTAL: 6.0	• Case 1A: 3.0 • Case 2A: 0.03 • TOTAL: 3.0	• Case 1A: 2.7 • Case 2A: 2.7 • TOTAL: 5.4	• Case 1A: 2.7 • Case 2A: 0.03 • TOTAL: 2.7
Cases 1B-L & 2B: Release at new Gen III plant (lower accident prob.)	• Case 1B-L (reactor): 0.16 • Case 1B-L (pool): 0.9 • Case 2B (reactor): 16.0 • Case 2B (pool): 90.0 • TOTAL: 107.0	• Case 1B-L (reactor): 0.16 • Case 1B-L (pool): 0.9 • Case 2B (reactor): 0.16 • Case 2B (pool): 0.9 • TOTAL: 2.1	• Case 1B-L (reactor): 0.14 • Case 1B-L (pool): 0.8 • Case 2B (reactor): 14.0 • Case 2B (pool): 80.0 • TOTAL: 95.0	• Case 1B-L (reactor): 0.14 • Case 1B-L (pool): 0.8 • Case 2B (reactor): 0.14 • Case 2B (pool): 0.8 • TOTAL: 1.9
Cases 1B-H & 2B: Release at new Gen III plant (higher accident prob.)	• Case 1B-H (reactor): 1.6 • Case 1B-H (pool): 9.0 • Case 2B (reactor): 16.0 • Case 2B (pool): 90.0 • TOTAL: 117.0	• Case 1B-H (reactor): 1.6 • Case 1B-H (pool): 9.0 • Case 2B (reactor): 0.16 • Case 2B (pool): 0.9 • TOTAL: 11.7	• Case 1B-H (reactor): 1.4 • Case 1B-H (pool): 8.0 • Case 2B (reactor): 14.0 • Case 2B (pool): 80.0 • TOTAL: 103.0	• Case 1B-H (reactor): 1.4 • Case 1B-H (pool): 8.0 • Case 2B (reactor): 0.14 • Case 2B (pool): 0.8 • TOTAL: 10.3

Note:
Amounts in this table are calculated from the formulae shown in Table 7-2.

Table 7-4
Selected Range of Risk Costs of Offsite Impacts of Accidental and Malevolent Releases of Radioactive Material from Nuclear Power Plants in Ontario: Existing or New Plants, Excluding Releases from Spent-Fuel Pools

Cases (Excluding Releases from Spent-Fuel Pools)	**Risk Costs for Accidental and Malevolent Releases, Assuming Av. Capacity Factor of 0.9 (2008 Can cent per kWh)**	
	Malevolent Release Prob. (MRP) = 1.0E-04 per RY	**Malevolent Release Prob. (MRP) = 1.0E-06 per RY**
Cases 1A & 2A: Release at existing CANDU plant	5.4	2.7
Cases 1B-L & 2B: Release at new Gen III plant (lower accident prob.)	14.1	0.28
Cases 1B-H & 2B: Release at new Gen III plant (higher accident prob.)	15.4	1.5

Notes:
(a) Amounts in this table are from Table 7-3.
(b) There are two rationales for excluding releases from spent-fuel pools when assessing risk costs. First, the potential for such releases could be greatly reduced by adopting alternative modes of storage of spent fuel. Second, the inventory of cesium-137 in a pool would grow over time, reaching its maximum value after several decades of reactor operation.

Table 7-5
Recommended Risk Costs of Offsite Impacts of Accidental or Malevolent Releases of Radioactive Material from Nuclear Power Plants in Ontario

Case	Risk Costs for Accidental or Malevolent Releases (2008 Can cent per kWh)	
	High Probability of Malevolent Release	Low Probability of Malevolent Release
Existing CANDU plant	5.4	2.7
New Generation III plant	15.4	1.5

Notes:
(a) Amounts in this table are from Table 7-4.
(b) Releases from spent-fuel pools are excluded here.
(c) The average capacity factor of the plant is assumed to be 0.9.
(d) High probability of malevolent release = 1 per 10,000 RY; low probability = 1 per 1 million RY.
(e) Here, the probability of an accidental release from an existing CANDU reactor is 1 per 10,000 RY, and the probability of an accidental release from a new Generation III reactor is 1 per 100,000 RY.

Table 7-6
Risk Costs of Onsite Impacts of Fuel-Damage Events at Existing CANDU Plants in Ontario, Using an Ontario Hydro Estimate of the Risk of Economic Impacts at the Darlington Plants

Indicator	Value of Indicator	
	Using Mean Estimate of Probabilities of Fuel Damage Categories	Using 95th Percentile Estimate of Probabilities of Fuel Damage Categories
Risk of onsite economic impacts	17.9 to 36.6 (million 2008 Can $ per RY)	92.2 to 195.0 (million 2008 Can $ per RY)
Risk costs of onsite economic impacts (OH estimate for internal initiating events only)	0.26 to 0.53 (2008 Can cent per kWh)	1.33 to 2.81 (2008 Can cent per kWh)
Risk costs of onsite economic impacts (internal initiating events + external events + malevolent acts)	0.5 to 1.1 (2008 Can cent per kWh)	2.7 to 5.6 (2008 Can cent per kWh)

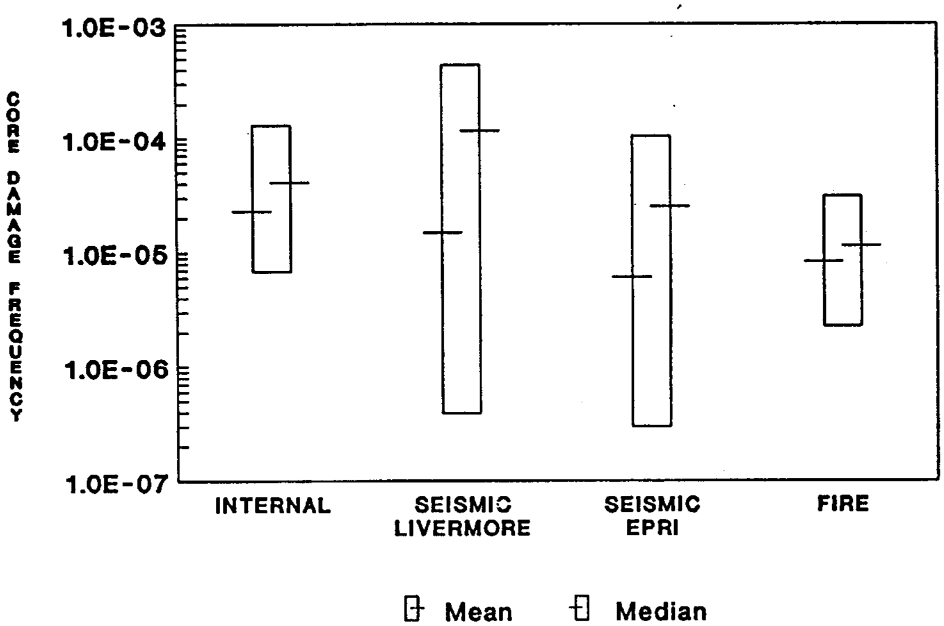
Notes:
(a) Ontario Hydro considered the occurrence of accidents involving Fuel Damage Categories FDC1 through FDC9, but not the most severe Category (FDC0).
(b) Ontario Hydro considered fuel damage in a reactor core or a fueling machine, caused by accidents initiated by internal events.
(c) Values in the first row are from Table 5-2. Values in the second row are calculated from the first row.
(d) Values in the third row are adjusted upward from values in the second row by a factor of 2, to account for accidents initiated by external events, and for malevolent acts.
(e) Each Darlington plant has a capacity of 0.88 GWe. A capacity factor of 0.9 is assumed here.

Table 7-7
Risk Costs of Nuclear Generation in Ontario: Summary of this Report's Findings

Category of Impacts from Unplanned Releases of Radioactive Material	Category of Risk Costs and the Insurance Premiums that are Paid to Provide Coverage of these Costs	Magnitude of Risk Costs and Insurance Premiums	
		For an Existing CANDU Plant	For a New Generation III Plant
Offsite Impacts	Risk Costs (2008 Can cent per kWh)	2.7 to 5.4	1.5 to 15.4
	Insurance Premiums (2008 Can cent per kWh)	0.02	As for existing CANDU plant?
Onsite Impacts	Risk Costs (2008 Can cent per kWh)	2.7 to 5.6	Smaller amount than for existing CANDU plant
	Insurance Premiums (2008 Can cent per kWh)	No explicit premium is evident	No explicit premium is evident

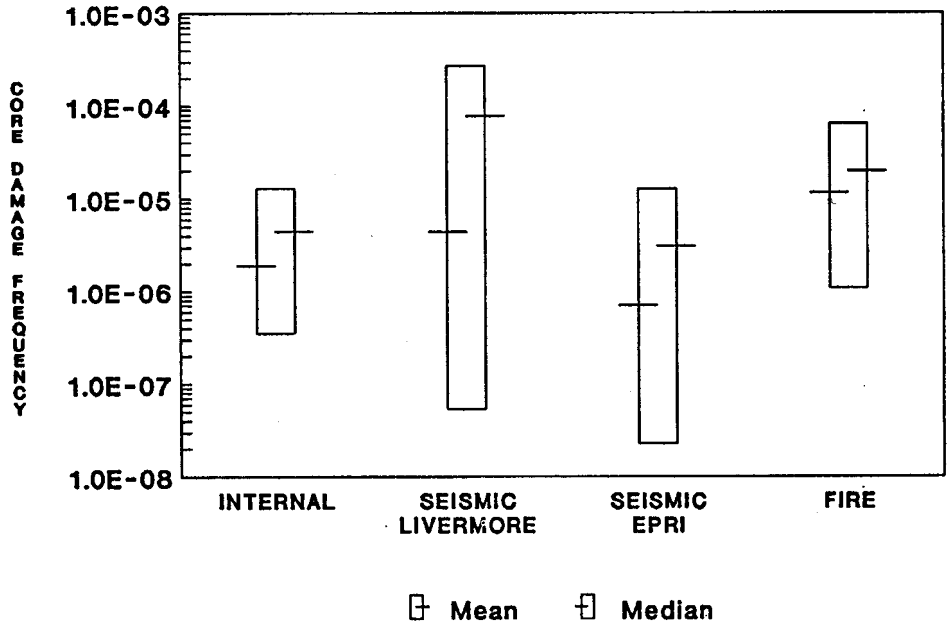
Notes:
(a) Risk costs in the first row are from Table 7-5.
(b) Risk costs in the third row are from Table 7-6, using the 95th percentile probability estimate, and considering internal events + external events + malevolent acts.
(c) Insurance premiums in the second row consider conventional insurance and "terrorist risk" insurance. For conventional insurance, a 1995 premium of $125,000 per RY for a Darlington plant is taken from: Heyes and Heyes, 2000, page 93. That premium is adjusted upward to 2008 Can $ by a factor of 1.36, and further adjusted upward by a factor of 650/75 to account for an expected increase in the NLA liability limit from $75 million to $650 million. Those adjustments yield a premium of 2008 Can $1.47 million per RY. For "terrorist risk" insurance, note that in 2006 the Government of Canada provided 80% of the coverage for Canada's 18 operating nuclear power plants for an aggregate premium of $280,000. See: Lunn, 2007. That yields a total premium of 2008 Can $280,000/(18 x 0.8) = $19,400 per RY, which is adjusted upward by a factor of 650/75 to account for the expected increase in the NLA liability limit, resulting in a premium of 2008 Can $0.17 million per RY. The combined premiums of 2008 Can $1.64 million per RY translate, assuming a plant capacity of 0.88 GWe and a capacity factor of 0.9, to an amount, in 2008 Can cent, of 0.024 cent per kWh.

Figure 3-1
Core Damage Frequency for Accidents at a Surry PWR Nuclear Power Plant, as Estimated in the NRC Study NUREG-1150



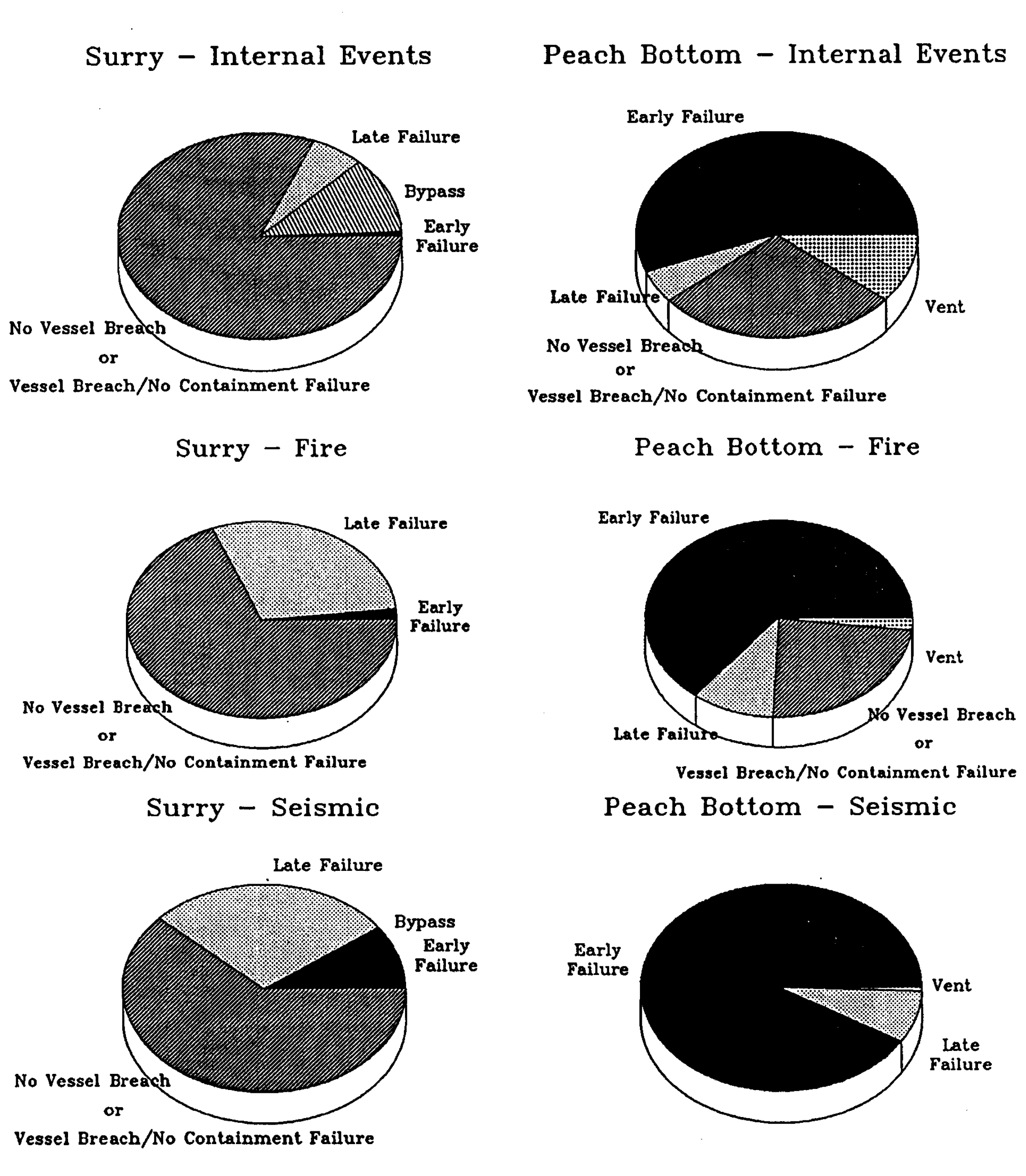
Notes:
(a) This figure is adapted from Figure 8.7 of: NRC, 1990.
(b) The bars range from the 5th percentile (lower bound) to the 95th percentile (upper bound) of the estimated CDF.
(c) Two estimates are shown for the CDF from earthquakes (seismic effects). One is from Lawrence Livermore National Laboratory (Livermore), the other is from the Electric Power Research Institute (EPRI).
(d) CDFs are not estimated for external initiating events other than earthquakes and fires.
(e) Malevolent acts are not considered.

Figure 3-2
Core Damage Frequency for Accidents at a Peach Bottom BWR Nuclear Power Plant, as Estimated in the NRC Study NUREG-1150



Notes:
(a) This figure is adapted from Figure 8.8 of: NRC, 1990.
(b) The bars range from the 5th percentile (lower bound) to the 95th percentile (upper bound) of the estimated CDF.
(c) Two estimates are shown for the CDF from earthquakes (seismic effects). One is from Lawrence Livermore National Laboratory (Livermore), the other is from the Electric Power Research Institute (EPRI).
(d) CDFs are not estimated for external initiating events other than earthquakes and fires.
(e) Malevolent acts are not considered.

Figure 3-3
Conditional Probability of Containment Failure Following a Core-Damage Accident at a Surry PWR or Peach Bottom BWR Nuclear Power Plant, as Estimated in the NRC Study NUREG-1150



Note:
This figure is adapted from Figure 9.5 of: NRC, 1990.

Appendix A:
Designing Nuclear Power Plants to Pose a Low Level of Residual Radiological Risk[57]

The most reliable option for reducing the residual radiological risk posed by a nuclear power plant would be to design the plant according to highly stringent criteria of safety and security. During the 1970s and 1980s, some plant vendors and other stakeholders sought to develop designs that could meet such criteria. One design approach was to provide a highly robust containment — which might be an underground cavity — to separate nuclear fuel from the environment. Another approach was to incorporate principles of "inherent" or "intrinsic" safety into the design. The two approaches could be complementary.

Underground siting

In the 1970s, there were several studies on constructing nuclear power plants underground. Those studies are exemplified by a report published in 1972 under the auspices of the California Institute of Technology (Caltech).[58] The report identified a number of advantages of underground siting. Those advantages included highly-effective confinement of radioactive material in the event of a core-damage accident, isolation from falling objects such as aircraft, and protection against malevolent acts. Based on experience with underground testing of nuclear weapons, the report concluded that an appropriately designed plant would provide essentially complete containment of the radioactive material liberated from a reactor core during a core-damage event.

The Caltech report described a preliminary design study for underground construction of a light-water-reactor power plant with a capacity of 1,000 MWe. The minimum depth of the underground cavities containing the plant components would be 150 to 200 feet. The estimated cost penalty for underground siting would be less than 10 percent of the total plant cost.

In an appendix, the Caltech report described four underground nuclear reactors that had been constructed and operated in Europe. Three of those reactors supplied steam to turbo-generators, above or below ground. The largest of those reactors and its above-ground turbo-generator made up the Chooz plant in France, which had a capacity of 270 MWe. In describing the European reactors, the report noted:[59]

> "The motivation for undergrounding the plant appears to be insurance of containment of accidentally released radioactivity and also physical protection from damage due to hostile military action."

[57] A lengthier version of this discussion is provided in: Thompson, 2008.
[58] Watson et al, 1972.
[59] Watson et al, 1972, Appendix I.

Since the 1970s, underground siting of nuclear power plants has been considered by various groups. For example, in 2002 a workshop was held under the auspices of the University of Illinois to discuss a proposed US-wide "supergrid". That grid would transmit electricity — via superconducting DC cables — and liquid hydrogen, which would provide cooling to the DC cables and be distributed as fuel. Much of the energy fed to the grid would be supplied by nuclear power plants, which could be constructed underground. Motives for placing those plants underground would include "reduced vulnerability to attack by nature, man or weather" and "real and perceived reduced public exposure to real or hypothetical accidents".[60]

The PIUS reactor

In the 1980s the reactor vendor ASEA-Atom developed a preliminary design for an "intrinsically safe" commercial reactor known as the Process Inherent Ultimate Safety (PIUS) reactor. An ASEA-Atom official described the company's motives for developing the reactor as follows:[61]

> "The basic designs of today's light water reactors evolved during the 1950s when there was much less emphasis on safety. Those basic designs held certain risks, and the control of those risks led to an increasing proliferation of add-on systems and equipment ending up in the present complex plant designs, the safety of which is nevertheless being questioned. Rather than to continue into this 'blind alley', it is now time to design a truly 'forgiving' light water reactor in which ultimate safety is embodied in the primary heat extraction process itself rather than achieved by add-on systems that have to be activated in emergencies. With such a design, system safety would be completely independent of operator actions and immune to malicious human intervention."

The central goal of the PIUS design was to preserve fuel integrity "under all conceivable conditions". That goal translated to a design specification of "complete protection against core melting or overheating in case of:

- any credible equipment failures;
- natural events, such as earthquakes and tornadoes;
- reasonably credible operator mistakes; and
- combinations of the above;

<u>and</u> against:

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[60] Overbye et al, 2002.
[61] Hannerz, 1983, pp 1-2.

- inside sabotage by plant personnel, completely knowledgeable of reactor design (this can be considered an envelope covering all possible mistakes);
- terrorist attacks in collaboration with insiders;
- military attack (e.g., by aircraft with 'off-the-shelf' non-nuclear weapons); and
- abandonment of the plant by the operating personnel".[62]

To meet those requirements, ASEA-Atom designed a light-water reactor — the PIUS reactor — with novel features. The reactor pressure vessel would contain sufficient water to cool the core for at least one week after reactor shut-down. Most of that water would contain dissolved boron, so that its entry into the core would inherently shut down the reactor. The borated water would not enter the core during normal operation, but would enter through inherent mechanisms during off-normal conditions. The reactor pressure vessel would be made of pre-stressed concrete with a thickness of 25 feet. That vessel could withstand an attack using 1,000-pound bombs. About two-thirds of the vessel would be below ground.

ASEA-Atom estimated that the construction cost of a four-unit PIUS station with a total capacity of 2,000 MWe would be about the same as the cost of a station equipped with two 1,000 MWe "conventional" light-water reactors. The PIUS station could be constructed more rapidly, which would offset its slightly lower thermal efficiency. Thus, the total generating cost would be about the same for the two stations. ASEA-Atom estimated (in 1983) that the first commercial PIUS plant could enter service in the early 1990s, if a market existed.[63] To date, no PIUS plant has been ordered.

Design criteria for reducing residual radiological risk

Table App-1 sets forth criteria for designing and siting a nuclear power plant that would pose a residual radiological risk substantially lower than is posed by the Generation II plants that are now in use worldwide, and by the Generation III plants whose construction in Ontario is being considered. These criteria are similar to ASEA-Atom's design specification for the PIUS plant. Thus, there is evidence that the criteria set forth in Table App-1 are achievable. If ASEA-Atom's cost projections were accurate, there would be no overall cost premium for complying with such criteria.

An initial review of the three types of Generation III plants whose construction in Ontario is being considered shows that none of the three designs could meet the criteria in Table App-1.[64]

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[62] Hannerz, 1983, page 3.
[63] Hannerz, 1983, pp 73-76.
[64] Thompson, 2008, Section 5.

Table App-1
Criteria for Design and Siting of a New Nuclear Power Plant that Poses a Residual Radiological Risk Substantially Lower than is Posed by Generation II or III Plants

Application of Criteria	Criteria
Safety performance of the plant during reactor operation (design-basis criteria)	<u>No significant damage of the reactor core or adjacent stored spent fuel in the event of</u>: • Loss of all electrical power (AC & DC), compressed air, other power sources, and normal heat sinks for an extended period (e.g., 1 week); • Abandonment of the plant by operating personnel for an extended period (e.g., 1 week); • Takeover of the plant by hostile, knowledgeable persons who are equipped with specified explosive devices, for a specified period (e.g., 8 hours); • Military attack by specified means (e.g., 1,000-pound air-dropped bombs); • An extreme, specified earthquake; • Conceivable erroneous operator actions that could be accomplished in a specified period (e.g., 8 hours); or • Any combination of the above.
Safety performance of the plant during reactor refueling (design-basis criteria)	<u>A specified maximum release of radioactive material to the accessible environment in the event of</u>: • Loss of reactor coolant at a specified time after reactor shut-down, with replacement of the coolant by fluid (e.g., air, steam, or unborated water) creating the chemical and nuclear reactivity that would maximize the release of radioactive material, at a time when the plant's containment is most compromised; and • Any combination of the events specified above, in the context of reactor operation.
Site specification (radiological-impact criteria)	<u>In the event of the maximum release of radioactive material specified above, in the context of reactor refueling, radiological impacts would not exceed specified values regarding</u>: • Individual dose; • Population dose; and • Land areas in various usage categories that would be contaminated above specified levels.

Notes:
(a) The criteria in the first two rows of this table would apply to spent fuel stored adjacent to the reactor core. Separate criteria would apply to an independent facility for storing spent fuel, whether onsite or offsite.
(b) For a more detailed discussion, see: Thompson, 2008, Section 4.3.

Curriculum Vitae for Gordon R. Thompson
October 2007

Professional expertise

• Technical and policy analysis in the fields of energy, environment, sustainable development, human security, and international security.

Current appointments

• Executive director, Institute for Resource & Security Studies (IRSS), Cambridge, Massachusetts (since 1984).
• Research Professor, George Perkins Marsh Institute, Clark University, Worcester, Massachusetts (since 2002).

Education

• D.Phil., applied mathematics, Oxford University (Balliol College), 1973.
• B.E., mechanical engineering, Univ. of New South Wales, Sydney, Australia, 1967.
• B.Sc., mathematics & physics, Univ. of New South Wales, 1966.

Project sponsors and tasks (selected)

• World Health Organization, 2006-2007: conducted policy analysis on the potential for "health-bridge" programs to improve cooperation within and between nations.
• Various sponsors, 2005-2007: co-convened the Working Group on US-Iran Health Science Cooperation.
• Sierra Club of Canada, 2006-2007: prepared a strategy for development of planning and public-engagement tools to facilitate action on climate change.
• Mothers for Peace, California, 2002-2007: analyzed risk issues and prepared expert testimony associated with the Diablo Canyon nuclear power plants.
• Riverkeeper, New York, 2007: analyzed risk issues and prepared expert testimony associated with the Indian Point nuclear power plants.
• Attorney General of Massachusetts, 2006-2007: analyzed risk issues and prepared expert testimony associated with the Pilgrim and Vermont Yankee nuclear plants.
• Minnesota Center for Environmental Advocacy, and Minnesotans for an Energy Efficient Economy, 2005-2006: conducted technical analysis and provided expert testimony regarding management of spent fuel from the Monticello nuclear power plant.
• California Energy Commission, 2005: conducted technical analysis and participated in an expert workshop regarding safety and security of commercial nuclear facilities.
• Committee on Radioactive Waste Management (a committee appointed by the UK government), 2005: provided expert advice and technical analysis on long-term safety and security of radioactive waste management.

• Legal Resources Centre, Cape Town, South Africa, 2004-2007: conducted technical analysis regarding the proposed South African pebble bed modular nuclear reactor.
• STAR Foundation, New York, 2002-2004: reviewed planning and actions for decommissioning of research reactors at Brookhaven National Laboratory.
• Attorney General of Utah, 2003: conducted technical analysis and provided expert testimony regarding a proposed national storage facility for spent nuclear fuel.
• Citizens Awareness Network, Massachusetts, 2002-2003: conducted analysis on robust storage of spent nuclear fuel.
• Tides Center, California, 2002-2004: conducted analysis for the Santa Susana Field Laboratory (SSFL) Advisory Panel regarding the history of releases of radioactive material from the SSFL.
• Orange County, North Carolina, 1999-2002: assessed risk issues associated with the Harris nuclear power plant, identified risk-reduction options, and prepared expert testimony.
• William and Flora Hewlett Foundation and other sponsors, 1999-2007: performed research and project development for conflict-management projects, through IRSS's International Conflict Management Program.
• STAR Foundation, New York, 2000-2001: assessed risk issues associated with the Millstone nuclear power plant, identified risk-reduction options, and prepared expert testimony.
• Massachusetts Water Resources Authority, 2000: evaluated risks associated with water supply and wastewater systems that serve greater Boston.
• Canadian Senate, Energy & Environment Committee, 2000: reviewed risk issues associated with the Pickering Nuclear Generating Station.
• Greenpeace International, Amsterdam, 2000: reviewed impacts associated with the La Hague nuclear complex in France.
• Government of Ireland, 1998-2001: developed framework for assessment of impacts and alternative options associated with the Sellafield nuclear complex in the UK.
• Clark University, Worcester, Massachusetts, 1998-1999: participated in confidential review of outcomes of a major foundation's grants related to climate change.
• UN High Commissioner for Refugees, 1998: developed a strategy for conflict management in the CIS region.
• General Council of County Councils (Ireland), W. Alton Jones Foundation (USA), and Nuclear Free Local Authorities (UK), 1996-2000: assessed environmental and economic issues of nuclear fuel reprocessing in the UK; assessed alternative options.
• Environmental School, Clark University, Worcester, Massachusetts, 1996: session leader at the Summer Institute, "Local Perspectives on a Global Environment".
• Greenpeace Germany, Hamburg, 1995-1996: a study on war, terrorism and nuclear power plants.
• HKH Foundation, New York, and Winston Foundation for World Peace, Washington, DC, 1994-1996: studies and workshops on preventive action and its role in US national security planning.
• Carnegie Corporation of New York, Winston Foundation for World Peace, Washington, DC, and others, 1995: collaboration with the Organization for Security and Cooperation

in Europe to facilitate improved coordination of activities and exchange of knowledge in the field of conflict management.

• World Bank, 1993-1994: a study on management of data describing the performance of projects funded by the Global Environment Facility (joint project of IRSS and Clark University).

• International Physicians for the Prevention of Nuclear War, 1993-1994: a study on the international control of weapons-usable fissile material.

• Government of Lower Saxony, Hannover, Germany, 1993: analysis of standards for radioactive waste disposal.

• University of Vienna (using funds supplied by the Austrian government), 1992: review of radioactive waste management at the Dukovany nuclear power plant, Czech Republic.

• Sandia National Laboratories, 1992-1993: advice to the US Department of Energy's Office of Foreign Intelligence.

• US Department of Energy and Battelle Pacific Northwest Laboratories, 1991-1992: advice for the Intergovernmental Panel on Climate Change regarding the design of an information system on technologies that can limit greenhouse gas emissions (joint project of IRSS, Clark University and the Center for Strategic and International Studies).

• Winston Foundation for World Peace, Boston, Massachusetts, and other funding sources, 1992-1993: development and publication of recommendations for strengthening the International Atomic Energy Agency.

• MacArthur Foundation, Chicago, Illinois, W. Alton Jones Foundation, Charlottesville, Virginia, and other funding sources, 1984-1993: policy analysis and public education on a "global approach" to arms control and disarmament.

• Energy Research Foundation, Columbia, South Carolina, and Peace Development Fund, Amherst, Massachusetts, 1988-1992: review of the US government's tritium production (for nuclear weapons) and its implications.

• Coalition of Environmental Groups, Toronto, Ontario (using funds supplied by Ontario Hydro under the direction of the Ontario government), 1990-1993: coordination and conduct of analysis and preparation of testimony on accident risk of nuclear power plants.

• Greenpeace International, Amsterdam, Netherlands, 1988-1990: review of probabilistic risk assessment for nuclear power plants.

• Bellerive Foundation, Geneva, Switzerland, 1989-1990: planning for a June 1990 colloquium on disarmament and editing of proceedings.

• Iler Research Institute, Harrow, Ontario, 1989-1990: analysis of regulatory response to boiling-water reactor accident potential.

• Winston Foundation for World Peace, Boston, Massachusetts, and other funding sources, 1988-1989: analysis of future options for NATO (joint project of IRSS and the Institute for Peace and International Security).

• Nevada Nuclear Waste Project Office, Carson City, Nevada (via Clark University), 1989-1990: analyses of risk aspects of radioactive waste management and disposal.

• Ontario Nuclear Safety Review (conducted by the Ontario government), Toronto, Ontario, 1987: review of safety aspects of CANDU reactors.

• Washington Department of Ecology, Olympia, Washington, 1987: analyses of risk aspects of a proposed radioactive waste repository at Hanford.

• Natural Resources Defense Council, Washington, DC, 1986-1987: preparation of expert testimony on hazards of the Savannah River Plant, South Carolina.
• Lakes Environmental Association, Bridgton, Maine, 1986: analysis of federal regulations for disposal of radioactive waste.
• Greenpeace Germany, Hamburg, 1986: participation in an international study on the hazards of nuclear power plants.
• Three Mile Island Public Health Fund, Philadelphia, Pennsylvania, 1983-1989: studies related to the Three Mile Island nuclear power plant and emergency response planning.
• Attorney General, Commonwealth of Massachusetts, 1984-1989: analyses of the safety of the Seabrook nuclear power plant, preparation of expert testimony.
• Union of Concerned Scientists, Cambridge, Massachusetts, 1980-1985: studies on energy demand and supply, nuclear arms control, and the safety of nuclear installations.
• Conservation Law Foundation of New England, Boston, Massachusetts, 1985: preparation of expert testimony on cogeneration potential at a Maine paper mill.
• Town & Country Planning Association, London, UK, 1982-1984: coordination and conduct of a study on safety and radioactive waste implications of the proposed Sizewell nuclear power plant, testimony to the Sizewell Public Inquiry.
• US Environmental Protection Agency, Washington, DC, 1980-1981: assessment of the cleanup of Three Mile Island Unit 2 nuclear power plant.
• Center for Energy & Environmental Studies, Princeton University, Princeton, New Jersey, and Solar Energy Research Institute, Golden, Colorado, 1979-1980: studies on the potentials of renewable energy sources.
• Government of Lower Saxony, Hannover, Federal Republic of Germany, 1978-1979: coordination and conduct of studies on safety and security aspects of the proposed Gorleben nuclear fuel cycle center.

<u>Other experience (selected)</u>

• Principal investigator, project on "Exploring the Role of 'Sustainable Cities' in Preventing Climate Disruption", involving IRSS and three other organizations, 1990-1991.
• Visiting fellow, Peace Research Centre, Australian National University, 1989.
• Principal investigator, Three Mile Island emergency planning study, involving IRSS, Clark University and other partners, 1987-1989.
• Co-leadership (with Paul Walker) of a study group on nuclear weapons proliferation, Institute of Politics, Harvard University, 1981.
• Foundation (with others) of an ecological political movement in Oxford, UK, which contested the 1979 Parliamentary election.
• Conduct of cross-examination and presentation of expert testimony, on behalf of the Political Ecology Research Group, at the 1977 Public Inquiry into proposed expansion of reprocessing capacity at Windscale, UK.
• Conduct of research on plasma theory (while a D.Phil candidate), as an associate staff member, Culham Laboratory, UK Atomic Energy Authority, 1969-1973.

• Service as a design engineer on coal-fired power plants, New South Wales Electricity Commission, Sydney, Australia, 1968.

<u>Publications (selected)</u>

• *Assessing Risks of Potential Malicious Actions at Commercial Nuclear Facilities: The Case of a Proposed Independent Spent Fuel Storage Installation at the Diablo Canyon Site*, a report for San Luis Obispo Mothers for Peace, 27 June 2007.
• *Health as a Bridge for Peace: Achievements, Challenges, and Opportunities for Action by WHO* (with Paula Gutlove), a report for the Department for Health Action in Crises, World Health Organization, 31 December 2006.
• "Using Psychosocial Healing in Postconflict Reconstruction" (with Paula Gutlove), in Mari Fitzduff and Chris E. Stout (eds), *The Psychology of Resolving Global Conflicts: From War to Peace*, Praeger Security International, 2006.
• "What Role for Nuclear Power in a Sustainable Civilization?", *The Green Cross Optimist*, Spring 2006, pp 28-30.
• *Radiological Risk of Homeport Basing of a Nuclear-Propelled Aircraft Carrier in Yokosuka, Japan*, a report for the Citizens Coalition Concerning the Homeporting of a CVN in Yokosuka, 29 June 2006.
• *Risks and Risk-Reducing Options Associated with Pool Storage of Spent Nuclear Fuel at the Pilgrim and Vermont Yankee Nuclear Power Plants*, a report for the Attorney General, Commonwealth of Massachusetts, 25 May 2006.
• *Reasonably Foreseeable Security Events: Potential threats to options for long-term management of UK radioactive waste*, a report for the UK Committee on Radioactive Waste Management, 2 November 2005.
• "Plasma, policy and progress", *The Australian Mathematical Society Gazette*, Volume 32, Number 3, 2005, pp 162-168.
• "A Psychosocial-Healing Approach to Post-Conflict Reconstruction" (with Paula Gutlove), *Mind & Human Interaction*, Volume 14, Number 1, 2005, pp 35-63.
• "Designing Infrastructure for New Goals and Constraints", Proceedings of the conference, *Working Together: R&D Partnerships in Homeland Security*, Boston, Massachusetts, 27-28 April 2005, sponsored by the US Department of Homeland Security. (A version of this paper has also been published as CRS Discussion Paper 2005-02, Center for Risk and Security, George Perkins Marsh Institute, Clark University, Worcester, Massachusetts.)
• "Potential Radioactive Releases from Commercial Reactors and Spent Fuel", Proceedings of the conference, *Working Together: R&D Partnerships in Homeland Security*, Boston, Massachusetts, 27-28 April 2005, sponsored by the US Department of Homeland Security. (A version of this paper has also been published as CRS Discussion Paper 2005-03, Center for Risk and Security, George Perkins Marsh Institute, Clark University, Worcester, Massachusetts.)
• *Safety of the Proposed South African Pebble Bed Modular Reactor*, a report for the Legal Resources Centre, Cape Town, South Africa, 12 January 2005.

• *Decommissioning of Research Reactors at Brookhaven National Laboratory: Status, Future Options and Hazards*, a report for STAR Foundation, East Hampton, New York, April 2004.
• "Psychosocial Healing and Post-Conflict Social reconstruction in the Former Yugoslavia" (with Paula Gutlove), *Medicine*, *Conflict and Survival*, Volume 20, Number 2, April-June 2004, pp 136-150.
• "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States" (with Robert Alvarez, Jan Beyea, Klaus Janberg, Jungmin Kang, Ed Lyman, Allison Macfarlane and Frank N. von Hippel), *Science and Global Security*, Volume 11, 2003, pp 1-51.
• "Health, Human Security, and Social Reconstruction in Afghanistan" (with Paula Gutlove and Jacob Hale Russell), in John D. Montgomery and Dennis A. Rondinelli (eds), *Beyond Reconstruction in Afghanistan*, Palgrave Macmillan, 2004.
• *Psychosocial Healing: A Guide for Practitioners, based on programs of the Medical Network for Social Reconstruction in the Former Yugoslavia* (with Paula Gutlove), IRSS, Cambridge, Massachusetts and OMEGA Health Care Center, Graz, Austria, May 2003.
• *A Call for Action to Protect the Nation Against Enemy Attack on Nuclear Power Plants and Spent Fuel*, and a Supporting Document, Mothers for Peace, San Luis Obispo, California, April 2003 and May 2003.
• "Human Security: Expanding the Scope of Public Health" (with Paula Gutlove), *Medicine, Conflict and Survival*, Volume 19, 2003, pp 17-34.
• *Social Reconstruction in Afghanistan through the Lens of Health and Human Security* (with Paula Gutlove and Jacob Hale Russell), IRSS, Cambridge, Massachusetts, May 2003.
• *Robust Storage of Spent Nuclear Fuel: A Neglected Issue of Homeland Security*, a report for Citizens Awareness Network, Shelburne Falls, Massachusetts, January 2003.
• *Medical Network for Social Reconstruction in the Former Yugoslavia: A Survey of Participants' Views on the Network's Goals and Achievements*, IRSS, Cambridge, Massachusetts, September 2001.
• *The Potential for a Large, Atmospheric Release of Radioactive Material from Spent Fuel Pools at the Harris Nuclear Power Plant: The Case of a Pool Release Initiated by a Severe Reactor Accident*, a report for Orange County, North Carolina, 20 November 2000.
• *A Review of the Accident Risk Posed by the Pickering 'A' Nuclear Generating Station*, a report for the Standing Committee on Energy, Environment and Natural Resources, Canadian Senate, August 2000.
• *High-Level Radioactive Liquid Waste at Sellafield: An Updated Review*, a report for the UK Nuclear Free Local Authorities, June 2000.
• *Hazard Potential of the La Hague Site: An Initial Review*, a report for Greenpeace International, May 2000.
• *A Strategy for Conflict Management: Integrated Action in Theory and Practice* (with Paula Gutlove), IRSS, Cambridge, Massachusetts, March 1999.
• *Risks and Alternative Options Associated with Spent Fuel Storage at the Shearon Harris Nuclear Power Plant*, a report for Orange County, North Carolina, February 1999.

• *High Level Radioactive Liquid Waste at Sellafield: Risks, Alternative Options and Lessons for Policy*, IRSS, Cambridge, Massachusetts, June 1998.
• "Science, democracy and safety: why public accountability matters", in F. Barker (ed), *Management of Radioactive Wastes: Issues for local authorities,* Thomas Telford, London, 1998.
• "Conflict Management and the OSCE" (with Paula Gutlove), *OSCE/ODIHR Bulletin*, Volume 5, Number 3, Fall 1997.
• *Safety of the Storage of Liquid High-Level Waste at Sellafield* (with Peter Taylor), Nuclear Free Local Authorities, UK, November 1996.
• *Assembling Evidence on the Effectiveness of Preventive Actions, their Benefits, and their Costs: A Guide for Preparation of Evidence*, IRSS, Cambridge, Massachusetts, August 1996.
• *War, Terrorism and Nuclear Power Plants,* Peace Research Centre, Australian National University, Canberra, October 1996.
• "The Potential for Cooperation by the OSCE and Non-Governmental Actors on Conflict Management" (with Paula Gutlove), *Helsinki Monitor*, Volume 6 (1995), Number 3.
• "Potential Characteristics of Severe Reactor Accidents at Nuclear Plants", "Monitoring and Modelling Atmospheric Dispersion of Radioactivity Following a Reactor Accident" (with Richard Sclove, Ulrike Fink and Peter Taylor), "Safety Status of Nuclear Reactors and Classification of Emergency Action Levels", and "The Use of Probabilistic Risk Assessment in Emergency Response Planning for Nuclear Power Plant Accidents" (with Robert Goble), in D. Golding, J. X. Kasperson and R. E. Kasperson (eds), *Preparing for Nuclear Power Plant Accidents*, Westview Press, Boulder, Colorado, 1995.
• *A Data Manager for the Global Environment Facility* (with Robert Goble), Environment Department, The World Bank, June 1994.
• *Preventive Diplomacy and National Security* (with Paula Gutlove), Winston Foundation for World Peace, Washington, DC, May 1994.
• *Opportunities for International Control of Weapons-Usable Fissile Material,* International Physicians for the Prevention of Nuclear War, Cambridge, Massachusetts, January 1994.
• "Article III and IAEA Safeguards", in F. Barnaby and P. Ingram (eds), *Strengthening the Non-Proliferation Regime*, Oxford Research Group, Oxford, UK, December 1993.
• *Risk Implications of Potential New Nuclear Plants in Ontario* (prepared with the help of eight consultants), a report for the Coalition of Environmental Groups, Toronto, submitted to the Ontario Environmental Assessment Board, November 1992 (3 volumes).
• *Strengthening the International Atomic Energy Agency*, IRSS, Cambridge, Massachusetts, September 1992.
• *Design of an Information System on Technologies that can Limit Greenhouse Gas Emissions* (with Robert Goble and F. Scott Bush), Center for Strategic and International Studies, Washington, DC, May 1992.
• *Managing Nuclear Accidents: A Model Emergency Response Plan for Power Plants and Communities* (with six other authors), Westview Press, Boulder, CO, 1992.
• "Let's X-out the K" (with Steven C. Sholly), *Bulletin of the Atomic Scientists*, March 1992, pp 14-15.

• "A Worldwide Programme for Controlling Fissile Material", and "A Global Strategy for Nuclear Arms Control", in F. Barnaby (ed), *Plutonium and Security*, Macmillan Press, UK, 1992.
• *No Restart for K Reactor* (with Steven C. Sholly), IRSS, Cambridge, Massachusetts, October 1991.
• *Regulatory Response to the Potential for Reactor Accidents: The Example of Boiling-Water Reactors*, IRSS, Cambridge, Massachusetts, February 1991.
• *Peace by Piece: New Options for International Arms Control and Disarmament*, IRSS, Cambridge, Massachusetts, January 1991.
• *Developing Practical Measures to Prevent Climate Disruption* (with Robert Goble), CENTED Research Report No. 6, Clark University, Worcester, Massachusetts, August 1990.
• "Treaty a Useful Relic", *Bulletin of the Atomic Scientists*, July/August 1990, pp 32-33.
• "Practical Steps for the 1990s", in Sadruddin Aga Khan (ed), *Non-Proliferation in a Disarming World*, Proceedings of the Groupe de Bellerive's 6th International Colloquium, Bellerive Foundation, Geneva, Switzerland, 1990.
• *A Global Approach to Controlling Nuclear Weapons*, IRSS, Cambridge, Massachusetts, October 1989.
• *IAEA Safety Targets and Probabilistic Risk Assessment* (with three other authors), Greenpeace International, Amsterdam, August 1989.
• *New Directions for NATO* (with Paul Walker and Pam Solo), published jointly by IRSS and the Institute for Peace and International Security (both of Cambridge, Massachusetts), December 1988.
• "Verifying a Halt to the Nuclear Arms Race", in F. Barnaby (ed), *A Handbook of Verification Procedures*, Macmillan Press, UK, 1990.
• "Verification of a Cutoff in the Production of Fissile Material", in F.Barnaby (ed), *A Handbook of Verification Procedures*, Macmillan Press, UK, 1990.
• "Severe Accident Potential of CANDU Reactors," Consultant's Report in *The Safety of Ontario's Nuclear Power Reactors*, Ontario Nuclear Safety Review, Toronto, February 1988.
• *Nuclear-Free Zones* (edited with David Pitt), Croom Helm Ltd, Beckenham, UK, 1987.
• *Risk Assessment Review For the Socioeconomic Impact Assessment of the Proposed High-Level Nuclear Waste Repository at Hanford Site, Washington* (edited; written with five other authors), prepared for the Washington Department of Ecology, December 1987.
• *The Nuclear Freeze Revisited* (with Andrew Haines), Nuclear Freeze and Arms Control Research Project, Bristol, UK, November 1986. Variants of the same paper have appeared as Working Paper No. 18, Peace Research Centre, Australian National University, Canberra, February 1987, and in *ADIU Report*, University of Sussex, Brighton, UK, Jan/Feb 1987, pp 6-9.
• *International Nuclear Reactor Hazard Study* (with fifteen other authors), Greenpeace, Hamburg, Federal Republic of Germany (2 volumes), September 1986.
• "What happened at Reactor Four" (the Chernobyl reactor accident), *Bulletin of the Atomic Scientists*, August/September 1986, pp 26-31.

• *The Source Term Debate: A Report by the Union of Concerned Scientists* (with Steven C. Sholly), Union of Concerned Scientists, Cambridge, Massachusetts, January 1986.
• "Checks on the spread" (a review of three books on nuclear proliferation), *Nature*, 14 November 1985, pp 127-128.
• Editing of *Perspectives on Proliferation*, August 1985, published by the Proliferation Reform Project, IRSS.
• "A Turning Point for the NPT ?", *ADIU Report*, University of Sussex, Brighton, UK, Nov/Dec 1984, pp 1-4.
• "Energy Economics", in J. Dennis (ed), *The Nuclear Almanac*, Addison-Wesley, Reading, Massachusetts, 1984.
• "The Genesis of Nuclear Power", in J. Tirman (ed), *The Militarization of High Technology*, Ballinger, Cambridge, Massachusetts, 1984.
• *A Second Chance: New Hampshire's Electricity Future as a Model for the Nation* (with Linzee Weld), Union of Concerned Scientists, Cambridge, Massachusetts, 1983.
• *Safety and Waste Management Implications of the Sizewell PWR* (prepared with the help of six consultants), a report to the Town & Country Planning Association, London, UK, 1983.
• *Utility-Scale Electrical Storage in the USA: The Prospects of Pumped Hydro, Compressed Air, and Batteries*, Princeton University report PU/CEES #120, 1981.
• *The Prospects for Wind and Wave Power in North America*, Princeton University report PU/CEES # 117, 1981.
• *Hydroelectric Power in the USA: Evolving to Meet New Needs*, Princeton University report PU/CEES # 115, 1981.
• Editing and part authorship of "Potential Accidents & Their Effects", Chapter III of *Report of the Gorleben International Review*, published in German by the Government of Lower Saxony, FRG, 1979; Chapter III published in English by the Political Ecology Research Group, Oxford, UK.
• *A Study of the Consequences to the Public of a Severe Accident at a Commercial FBR located at Kalkar, West Germany*, Political Ecology Research Group, 1978.

Expert presentations and testimony (selected)

• Abt Associates, Cambridge, Massachusetts, 2007: presentation, "Creating Informed Action on Climate Change".
• Universities of Medical Science in Tabriz and Isfahan, Iran, 2007: presentation, "Healthy Design of the Built Environment".
• Minnesota Public Utilities Commission, 2006: testimony regarding trends, risks and costs associated with management of spent fuel from the Monticello nuclear power plant.
• Presentation, "Are Nuclear Installations Terrorist Targets?", at the conference, *Nuclear Energy: Does it Have a Future?*, Drogheda, County Louth, Ireland, 10-11 March 2005.
• Presentation at the session, "UN Security Council Resolution 1244 and Final Status for Kosovo", at the conference, *Lessons Learned from the Balkan Conflicts*, Boston College, Chestnut Hill, Massachusetts, 16-17 October 2004.

• California Public Utilities Commission, 2004: testimony regarding the nature and cost of potential measures for enhanced defense of the Diablo Canyon nuclear power plant.
• European Parliament, 2003: invited presentation to EP members regarding safety and security issues at the Sellafield nuclear site in the UK, and broader implications.
• US Congress, 2002 and 2003: invited presentations at member-sponsored staff briefings on vulnerabilities of nuclear-power facilities to attack and options for improved defenses.
• Numerous public forums in the USA, 2001-2006: invited presentations to public officials and general audiences regarding vulnerabilities of nuclear-power facilities to attack and options for improved defenses.
• UK Consensus Conference on Radioactive Waste Management, 1999: invited testimony on information and decision-making.
• Joint Committee on Public Enterprise and Transport, Irish Parliament, 1999: invited testimony on nuclear fuel reprocessing and international security.
• UK and Irish Parliaments, 1998: invited presentations to members on risks and alternative options associated with nuclear fuel reprocessing in the UK.
• Center for Russian Environmental Policy, Moscow, 1996: invited presentation at a forum in parallel with the G-7 Nuclear Safety Summit.
• Lacey Township Zoning Board, New Jersey, 1995: testimony regarding radioactive waste management.
• Ontario Court of Justice, Toronto, Ontario, 1993: testimony regarding Canada's Nuclear Liability Act.
• Oxford Research Group, seminar on "The Plutonium Legacy", Rhodes House, Oxford, UK, 1993: invited presentation on nuclear safeguards.
• Defense Nuclear Facilities Safety Board, Washington, DC, 1991: testimony regarding the proposed restart of K-reactor, Savannah River Site.
• Conference to consider amending the Partial Test Ban Treaty, United Nations, New York, 1991: presentation on a global approach to arms control and disarmament.
• US Department of Energy, hearing on draft EIS for new production reactor capacity, Columbia, South Carolina, 1991: testimony on tritium need and implications of tritium production options.
• Society for Risk Analysis, 1990 annual meeting, New Orleans, special session on nuclear emergency planning: presentation on real-time techniques for anticipating emergencies.
• Parliamentarians' Global Action, 11th Annual Parliamentary Forum, United Nations, Geneva, 1990: invited presentation on the potential for multilateral nuclear arms control.
• Advisory Committee on Nuclear Facility Safety, Washington, DC, 1989: testimony on public access to information and on government accountability.
• Peace Research Centre, Australian National University, seminar on "Australia and the Fourth NPT Review Conference", Canberra, 1989: invited presentation regarding a universal nuclear weapons non-proliferation regime.
• Carnegie Endowment for International Peace, Conference on "Nuclear Non-Proliferation and the Role of Private Organizations", Washington, DC, 1989: invited presentation on options for reform of the non-proliferation regime.

• US Department of Energy, EIS scoping hearing, Columbia, South Carolina, 1988: testimony on appropriate scope of an EIS for new production reactor capacity.
• International Physicians for the Prevention of Nuclear War, 6th and 7th Annual Congresses, Koln, FRG, 1986 and Moscow, USSR, 1987: invited presentations on relationships between nuclear power and the threat of nuclear war.
• County Council, Richland County, South Carolina, 1987: testimony on implications of severe reactor accidents at the Savannah River Plant.
• Maine Land Use Regulation Commission, 1985: testimony on cogeneration potential at facilities of Great Northern Paper Company.
• Interfaith Hearings on Nuclear Issues, Toronto, Ontario, 1984: invited presentations on options for Canada's nuclear trade and Canada's involvement in nuclear arms control.
• Sizewell Public Inquiry, UK, 1984: testimony on safety and radioactive waste implications of the proposed Sizewell nuclear power plant.
• New Hampshire Public Utilities Commission, 1983: testimony on electricity demand and supply options for New Hampshire.
• Atomic Safety & Licensing Board, US Nuclear Regulatory Commission, 1983: testimony on use of filtered venting at the Indian Point nuclear power plant.
• US National Advisory Committee on Oceans and Atmosphere, 1982: testimony on implications of ocean disposal of radioactive waste.
• Environmental & Energy Study Conference, US Congress, 1982: invited presentation on implications of radioactive waste management.

<u>Miscellaneous</u>

• Married, two children.
• Extensive experience in public speaking and interviews by representatives of print and electronic media.
• Author of numerous essays and letters in newspapers and magazines.

<u>Contact information</u>

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