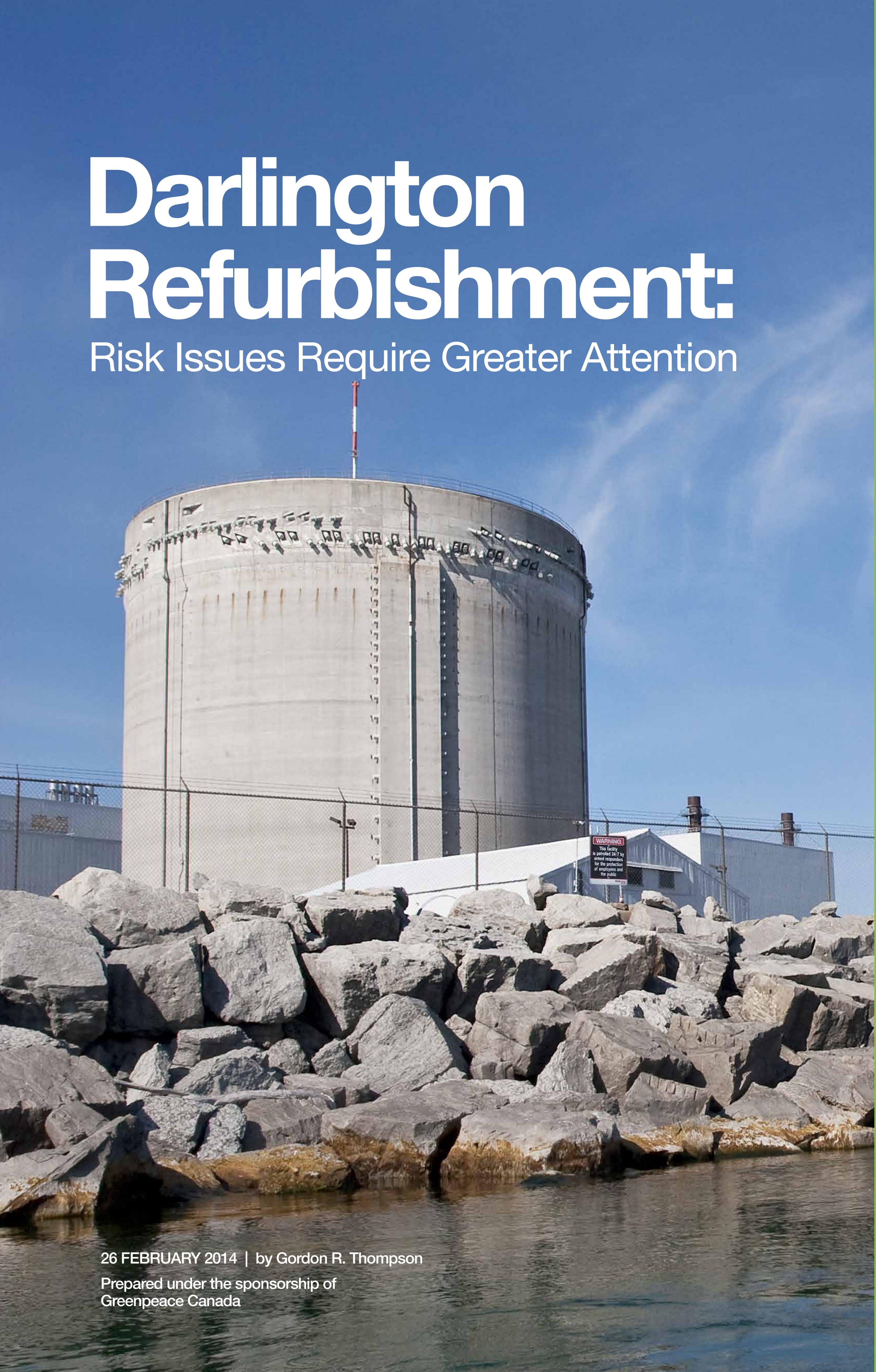
Darlington Refurbishment:

Risk Issues Require Greater Attention



26 FEBRUARY 2014 | by Gordon R. Thompson

Prepared under the sponsorship of
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GREENPEACE

ABSTRACT

The Ontario government currently envisions that ten existing nuclear reactors at the Darlington and Bruce sites will be refurbished during the next two decades and then operated until mid-century, providing a substantial fraction of the province's electricity. The government acknowledges that refurbishment could turn out to be economically less attractive than it now appears. Accordingly, the government has established policy "off-ramps" that would allow it to withdraw from its present commitment to refurbishment. This report shows that decision making about reactor refurbishment has been conducted without full information about risks. It further shows that a thorough, independent assessment of radiological risk and program risk would almost certainly identify large costs and impacts of reactor refurbishment and continued operation that have not yet been recognized by decision makers. The report reaches these findings by focusing on the Darlington reactors, but the findings also apply to the Bruce reactors. Also, these findings are relevant to the remaining years of operation of reactors at the Pickering site. Moreover, these findings have important Canada-wide implications regarding the adequacy of emergency response planning for nuclear incidents, the need for upgrading of Canada's *Nuclear Liability Act,* the need to enhance the safety and security of reactors, and Canada's national security.

INSTITUTE FOR RESOURCE AND SECURITY STUDIES

27 Ellsworth Avenue, Cambridge, Massachusetts 02139, USA

Web: http://www.irss-usa.org

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

ACKNOWLEDGEMENTS

This report was prepared by IRSS under the sponsorship of Greenpeace Canada. Shawn-Patrick Stensil generously assisted the author by obtaining information that was used during preparation of the report. The author, Gordon R. Thompson, is solely responsible for the content of the report.

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1. Introduction

In recent decades, nuclear power – generated at the Darlington, Pickering, and Bruce sites – has provided about half of Ontario's electricity supply. The Ontario government currently envisions that the nuclear power sector will continue to be a major supplier of electricity to the province. However, the government has shelved a previous plan to build new nuclear reactors at the Darlington site. Instead, the government envisions that nuclear power will be generated exclusively by existing nuclear reactors. Specifically, the government envisions that ten existing reactors at the Darlington and Bruce sites will be refurbished and then operated until mid-century. Also, two previously refurbished reactors at the Bruce site will continue operating. The six reactors now operating at the Pickering site will be permanently shut down by 2020 or earlier.[1]

The Ontario government promises to proceed cautiously with the Darlington and Bruce refurbishment projects, taking account of two trends. One trend is the evolution of Ontario's electricity demand over coming years. The second trend is the economics of reactor refurbishment. In regard to the second trend, the government is aware that current budgets and schedules for refurbishment could be exceeded, and that refurbished reactors might not perform as well as expected. In light of both trends, says the government, it has established policy "off-ramps" that would allow it to withdraw from its present commitment to refurbishment.[2]

This report addresses risk issues as factors in the making of decisions about Ontario's reactors. Two categories of risk are considered here. Full definitions of these categories of risk are provided in Section 3, below. In brief, in the context of this report:

- **Radiological risk** is the potential for harm arising from an unplanned release of radioactive material from one or more reactors.
- **Program risk** is the potential for refurbishment or operational performance of reactors to diverge substantially from the planned outcome.

In addressing these risks, this report focuses on the Darlington reactors. However, its findings have wider applicability, as discussed below. There are two major findings:

1. Decision making about reactor refurbishment and continued operation has been conducted without full information about the associated radiological risk and program risk.
2. A thorough, independent assessment of radiological risk and program risk would almost certainly identify large costs and impacts of reactor refurbishment and continued operation that have not yet been recognized by decision makers.

These findings apply equally to the Bruce reactors, including the two previously-refurbished Bruce reactors. Also, they are relevant to the remaining years of operation of the Pickering reactors. Moreover, these findings have important Canada-wide implications regarding the adequacy of emergency response planning for nuclear incidents, the need for upgrading of Canada's *Nuclear Liability Act*, the need to enhance the safety and security of reactors, and Canada's national security.

In light of these findings and their implications, the governments of Ontario and Canada have important responsibilities. As a first step, each government has a duty to ensure that the radiological risk and program risk associated with reactor refurbishment and operation are assessed more thoroughly than has been done to date. This duty reflects somewhat different considerations for each government. The Ontario government's formal responsibilities are weighted more toward the economic implications of risk, while the Canadian government's formal responsibilities are weighted more toward public-safety and national-security implications.

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[1] Ontario Ministry of Energy, 2013.

[2] Ontario Ministry of Energy, 2013.

ECONOMIC IMPLICATIONS OF RISK

This report shows that a thorough, independent assessment of radiological risk and program risk, if properly translated into policy, would almost certainly alter the economics of refurbishment and continued operation of Ontario's nuclear reactors. The electricity these reactors are expected to produce could become significantly more expensive than is now apparent. That outcome could tip the balance of choice in favor of non-nuclear options for meeting Ontario's electricity needs. Therefore, the Ontario government has a special responsibility to ensure that program risk and the economic implications of radiological risk are properly assessed. The nuclear industry shares that responsibility.

PUBLIC-SAFETY AND NATIONAL-SECURITY IMPLICATIONS OF RISK

This report shows that a thorough, independent assessment of radiological risk would almost certainly determine that the potential for an unplanned radioactive release from one or more of Ontario's nuclear reactors, and the potential for harm from such a release, are significantly greater than is now claimed by the nuclear industry. That determination would have at least four Canada-wide implications:

1. There should be improvements in national and provincial capabilities for emergency response to nuclear incidents;
2. Canada's *Nuclear Liability Act* should be upgraded to reflect the true radiological risk associated with nuclear reactors;
3. There should be fresh examination of options to enhance the safety and security of nuclear reactors; and
4. There should be a broad public debate about nuclear reactor operation as a factor in Canada's national security.

Given the national scope of these implications, the Canadian government has a special responsibility to ensure that radiological risk is properly assessed. The nuclear industry shares that responsibility. Also, the Ontario government has an important role in emergency response planning. Accordingly, the Ontario government has a responsibility to ensure that emergency planning reflects the true radiological risk.

THE DARLINGTON REFURBISHMENT PROJECT

Darlington Nuclear Generating Station (DNGS) is a four-unit nuclear power facility that is owned and operated by Ontario Power Generation (OPG). In turn, OPG is wholly owned by the Province of Ontario. The DNGS site is on the north shore of Lake Ontario, approximately 70 km east of Toronto. Figure 1-1 shows an aerial view of DNGS.

Each of the four units at DNGS employs a CANDU fission reactor fueled by natural uranium, and has a net generating capacity of 881 MWe. The units entered commercial service in the period 1990-1993.[3]

OPG intends to refurbish the four reactors at DNGS during the period 2016-2025, and to operate them thereafter. Refurbishment of each reactor could occur over a period of about three years. Figure 1-2 shows an anticipated refurbishment schedule for the four Darlington reactors and six of the eight Bruce reactors. Two of the Bruce reactors have already been refurbished. After refurbishment, each Darlington reactor could operate for about thirty years. Thus, at least one reactor could operate at DNGS until about 2055.[4]

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[3] SENES, 2011, Section 1.1.

[4] SENES, 2011, Section 1.1.

THEME, PURPOSES, AND SCOPE OF THIS REPORT

The broad theme of this report is the state of knowledge about the risks (i.e., radiological risk and program risk) associated with the future of Ontario's nuclear reactors. That broad theme is addressed through a focused examination of the risks associated with refurbishment and continued operation of the Darlington reactors. Through that examination, this report pursues three major purposes:

1. Determine if decision making about the future of Ontario's reactors has been informed by a thorough assessment of risks;
2. If risks have not been thoroughly assessed, estimate the extent to which they have been under-estimated; and
3. Identify the implications, for Ontario and Canada, of the findings that result from pursuing the preceding two purposes.

In pursuing these three purposes, this report reviews a broad literature. That literature includes risk-related studies by the nuclear industry and its regulators, in Canada and the USA. This report also presents its own illustrative analyses of selected issues, based on studies by the author and his colleagues.

In regard to the first purpose, this report is able to make a definitive finding. Review of publicly available information shows unequivocally that neither the radiological risk nor the program risk associated with the future of Ontario's reactors has been thoroughly assessed.

In regard to the second purpose, this report can make a more limited finding. The illustrative analyses presented here do not purport to provide a thorough and comprehensive assessment of radiological risk and program risk. Such an assessment would require substantial funding that would support, among other functions, the involvement of numerous analysts with diverse expertise. Funding at that level is far beyond the capacity of Greenpeace Canada, the sponsor of this report. Also, a thorough assessment would require access to information that is not, at present, publicly available.

This report recommends the conduct of a thorough, independent assessment of radiological risk and program risk. The report finds that such an assessment would "almost certainly" identify large costs and impacts of reactor refurbishment and continued operation that have not yet been recognized by decision makers. That outcome cannot, of course, be guaranteed. By its nature, an independent assessment would follow its own course. However, there is compelling evidence that the risks associated with the future of Ontario's reactors have been substantially under-estimated, and that the illustrative analyses presented here are reasonable.

In regard to the third purpose, this report is again able to reach definitive conclusions. If risks have indeed been substantially under-estimated, there are major implications as outlined above.

RELATED ANALYSES BY THIS AUTHOR

The author of this report, Gordon Thompson, has conducted a number of studies that addressed, in various ways, the risks posed by Ontario's nuclear reactors and by CANDU reactors in other contexts. Statements made in this report reflect that experience. Some of the studies are discussed briefly in the following paragraphs, with citations to some relevant reports. The findings of those reports are incorporated into the present report by reference.

In December 1986, the Ontario government commissioned Professor Kenneth Hare to conduct the Ontario Nuclear Safety Review. Professor Hare prepared a report on the Review, which he submitted to the Ontario government in February 1988.[5] Gordon Thompson was a consultant to the Review, and in that capacity prepared a September 1987 report titled *Severe Accident Potential of CANDU Reactors*, which is appended to Professor Hare's report.[6] Thompson's report identified six salient areas of concern about the accident potential of CANDUreactors, with particular attention to the unusual Ontario practice of building CANDU reactors in clusters of four or eight units that share a single safety system. The six areas of concern were:

- Containment bypass or isolation failure
- High pressure sequences
- Pressure tube failure
- Hydrogen burns
- Earthquake effects
- Multiple reactor accidents

During the years since the author identified these areas of concern in 1987, some areas have received some attention from the responsible authorities. However, at the time of completion of this report in February 2014, no entity in Canada had done a systematic assessment of the radiological risk associated with multiple reactor accidents. Canada's nuclear industry and its regulator – the Canadian Nuclear Safety Commission (CNSC) – had just begun to explore the conduct of such an assessment. The stimulus for their exploration was the occurrence of three concurrent reactor accidents at the Fukushima #1 site in Japan in March 2011. Industry and the CNSC do not seem to view their exploration as an urgent task. Such a dilatory approach to risk issues is regrettably common in the nuclear sector, in Canada and in other countries.

In November 1992, the Institute for Resource and Security Studies (IRSS) completed a study titled *Risk Implications of Potential New Nuclear Plants in Ontario*.[7] That study was commissioned by the Coalition of Environmental Groups for a Sustainable Energy Future. Gordon Thompson was the coordinator and lead author of the study. One of the issues addressed by the study was the radiological risk of operating DNGS, which was then under construction. In addressing that issue, the IRSS study examined a risk assessment known as the *Darlington Probabilistic Safety Evaluation* (DPSE).[8] The DPSE assessment was conducted by Ontario Hydro, the predecessor of OPG. DPSE's summary report was published in December 1987. The IRSS study concluded that DPSE did not provide a credible assessment of the risk posed by the Darlington reactors.

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[5] Hare, 1988.
[6] Thompson, 1987.
[7] IRSS, 1992.
[8] Ontario Hydro, 1987.

Other, relevant studies authored by Gordon Thompson have included:

- *A Review of the Accident Risk Posed by the Pickering 'A' Nuclear Generating Station*, August 2000, commissioned by the Canadian Senate's Standing Committee on Energy, Environment and Natural Resources.[9]
- *Design and Siting Criteria for Nuclear Power Plants in the 21st Century*, January 2008, commissioned by Greenpeace Canada.[10]
- *Risks of Operating CANDU 6 Nuclear Power Plants: Gentilly Unit 2 Refurbishment and its Global Implications*, October 2008, commissioned by Greenpeace Canada.[11]
- *Scope of the EIS for New Nuclear Power Plants at the Darlington Site in Ontario: Accidents, Malfunctions and The Precautionary Approach*, November 2008, commissioned by Greenpeace Canada.[12]
- *The Nuclear Liability and Compensation Act: Is it Appropriate for the 21st Century?*, 30 October 2009, commissioned by Greenpeace Canada.[13]
- *Comments on Proposed Screening Report on Environmental Assessment of Refurbishment & Continued Operation of Darlington Nuclear Generating Station*, 12 October 2012, commissioned by Northwatch, scope limited to onsite management and storage of spent nuclear fuel.[14]

STRUCTURE OF THIS REPORT

After this Introduction, this report has the following substantive sections:

Section 2: Status and Characteristics of Darlington Refurbishment

Section 3: Definition of Risk, and the Role of Risk in Decision Making

Section 4: The Risk Environment

Section 5: Assessing Radiological Risk, Generically and at DNGS

Section 6: Assessing Program Risk at DNGS

Section 7: An Overview of Risk at DNGS, and its Implications

Section 8: Conclusions and Recommendations

Section 5 has eight sub-Sections. These contain the bulk of this report's discussion of radiological risk.

A bibliography is provided in Section 9. Tables and Figures appear after Section 9. All documents cited in the main text (where they are identified in footnotes), or in the Tables and Figures, are listed in the bibliography unless identified directly.

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[9] Thompson, 2000.

[10] Thompson, 2008c.

[11] Thompson, 2008b.

[12] Thompson, 2008a.

[13] Thompson, 2009.

[14] Thompson, 2012.

2. Status and Characteristics of Darlington Refurbishment

Refurbishment of DNGS would be comparable, in terms of schedule and cost, to the construction of a new facility to generate electricity. In regard to schedule, Figure 1-2 shows that the Darlington reactors could potentially be refurbished between 2016 and 2025. After refurbishment, each reactor could operate for three decades. In regard to cost, Figure 2-1 shows that, in OPG's estimation, the life-cycle cost (i.e., levelized unit energy cost, or LUEC) of electricity from a refurbished DNGS would be comparable to the cost of electricity from a new, combined-cycle gas turbine (CCGT) unit fueled by natural gas.

Given the threat of climate change, construction of new CCGT units may not be the best alternative to refurbishment of DNGS. CCGT units would emit carbon dioxide, a powerful greenhouse gas (GHG). Also, the natural gas (i.e., methane) that would fuel a CCGT unit is a potent GHG, and there is concern about its leakage to atmosphere between the points of extraction and combustion. Figure 2-1 includes a case in which the carbon dioxide effluent from a CCGT unit would be sequestered rather than emitted to atmosphere. That option might be an appropriate alternative to refurbishment of DNGS, if leakage of natural gas could be controlled.

A full menu of alternatives to refurbishment of DNGS would include measures to improve the efficiency with which electricity services (e.g., lighting) are delivered, and options for renewable supply of electricity (e.g., photovoltaic panels, wind turbines). Renewable-supply options would be accompanied by "smart-grid" demand-management measures or storage devices to accommodate mismatch between electricity supply and demand over time.

The Ontario government recognizes the need to reduce the province's GHG emissions. However, Figure 2-2 shows that, according to the Ontario Power Authority, refurbishment of Ontario's nuclear reactors will not reduce GHG emissions from electricity generation in Ontario during the period 2013-2032. Indeed, unavailability of reactors during their refurbishment could cause a spike in GHG emissions in the years around 2021. That spike would be prolonged if refurbishments were not completed on schedule. Thus, if rapid reduction of Ontario's GHG emissions were assigned a high priority, reactor refurbishment might become less attractive in the eyes of the Ontario government than it now appears.

Development of an optimal energy strategy for Ontario is a matter beyond the scope of this report. However, the findings of this report are highly relevant to such a strategy. Figure 2-1 illustrates that relevance, from two perspectives. First, OPG's estimate of LUEC for the Darlington refurbishment takes no account of radiological-risk costs. Yet, as shown in this report, those costs could be substantial. Second, it appears that OPG's estimate of LUEC for the Darlington refurbishment excludes interest and escalation. These excluded components of cost could be significant.[15] Moreover, these components could increase substantially if program risk is properly considered.[16] Combining both perspectives, one sees that full consideration of radiological risk and program risk could tip the economic balance in favor of non-nuclear options for meeting Ontario's electricity needs.

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[15] The interest and escalation components of LUEC could be substantially lower for non-nuclear options than for DNGS refurbishment.

[16] Program risk could be manifested, during refurbishment, by cost or schedule overruns. These outcomes would increase the interest and escalation components of LUEC. Also, program risk could be manifested, after refurbishment, by failure of reactors to perform as expected or by the incurring of unexpected costs. These outcomes would increase LUEC.

REFURBISHMENT COST AND SCHEDULE

The OPG website makes the following statement about the timeline and cost of refurbishing DNGS:[17]

> "The final timeline and cost will not be known until the regulatory and technical scope is determined, engineering is completed, construction contracts are signed, and a release quality cost and schedule is developed. This should be completed by 2015.
>
> It would not be prudent to speculate on a potential cost when construction is many years away and so many variables, outside of OPG control, might impact that estimate.
>
> The Ontario Minister of Energy approximates refurbishment costs in the range of $6-10 billion as a preliminary bounding estimate."

As shown in the notes to Figure 2-1, OPG currently (i.e., in February 2014) estimates that the cost of DNGS refurbishment will not exceed $12.9 billion, including interest and escalation. That estimate reflects a reduction of $0.8 billion, between November 2012 and February 2014, of the estimated maximum cost without interest and escalation. Many of the assumptions underlying OPG's cost estimates are not discussed in published documents or are redacted from those documents.[18]

Preparations for DNGS refurbishment are consuming substantial OPG funds. Cumulative expenditure on these preparations through 2013 was $0.9 billion. OPG expects the cumulative expenditure through 2014 to be $1.6 billion, and through 2015 to be $2.4 billion. OPG anticipates that a detailed schedule and budget for the refurbishment will be developed by October 2015 and that refurbishment of the first DNGS unit will commence in October 2016.[19] Thus, the refurbishment project involves a large, initial commitment of funds by OPG before detailed predictions of schedule and budget are available. This commitment could bias decision making by OPG and the Ontario government if future developments reveal that DNGS refurbishment is a less attractive option than it now appears, because these entities could be reluctant to admit that previous expenditures (i.e., sunk costs) had been wasted.

Experience with refurbishment of CANDU reactors, in Ontario and elsewhere, suggests that OPG's schedule and budget targets for DNGS refurbishment will be exceeded. Aspects of this experience include:

- The cost of refurbishing Bruce A Units 1 and 2 in Ontario rose from an estimated $2.8 billion to an actual value of $4.8 billion, and the duration of refurbishment rose from an estimated 25 months to an actual value of 84 months. This refurbishment began in October 2005.[20]
- The schedule for refurbishing a CANDU 6 reactor at Wolsong, in South Korea, rose from an estimated 22 months to an actual value of 28 months. Cost information is not available. This refurbishment began in April 2009.[21]
- The cost of refurbishing a CANDU 6 reactor at Point Lepreau, in New Brunswick, rose from an estimated $1.4 billion to an actual value of $2.4 billion, and the duration of refurbishment rose from an estimated 18 months to an actual value of 55 months. This refurbishment began in March 2008. The New Brunswick Auditor General has determined that the program risk of this refurbishment project was not thoroughly assessed before the project began.[22]
- According to a press report, the cost of a project to refurbish four reactors at the Pickering A station in Ontario was estimated at $1.3 billion, but when the project was completed only two reactors had been refurbished at a cost of $2.6 billion.[23] The four reactors at Pickering A were laid up in 1997. Unit 4 returned to service in September 2003, and Unit 1 returned to service in November 2005.[24]

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[17] OPG website, "Darlington Refurbishment – How much will refurbishment cost?", accessed on 6 February 2014 at: http://www.opg.com/power/nuclear/refurbishment/dn_factsheets.asp

[18] Robinson et al, 2014; Sweetnam and Mitchell, 2012.

[19] Robinson et al, 2014.

[20] Robinson et al, 2014, Table C2.

[21] Robinson et al, 2014, Table C2.

[22] Robinson et al, 2014, Table C2; New Brunswick Auditor General, 2013.

[23] Spears, 2014.

[24] OPG website, "Pickering Nuclear", accessed on 11 February 2014 at: http://www.opg.com/power/nuclear/pickering/

RELATED POLICY ISSUES

The merit of DNGS refurbishment is entangled with Ontario's response to the threat of climate change, as discussed above. Other policy issues are also relevant to decisions about DNGS refurbishment. Some examples are briefly discussed here. This report does not make findings about these issues.

One issue is the ability of OPG to recover its investment in DNGS refurbishment through electricity sales. OPG says that currently approved electricity rates in Ontario are not sufficient for cost recovery, and that it has suggested regulatory changes to provide it with greater assurance of cost recovery in the future. OPG acknowledges a risk that full recovery of DNGS refurbishment cost may not occur.[25]

Another issue is the employment created by refurbishment and continued operation of DNGS. OPG says that refurbishment would create about 2,000 direct jobs, while continued operation after refurbishment would result in about 5,700 jobs (direct, indirect, and induced) in Durham Region.[26] OPG does not compare these anticipated economic outcomes with the outcomes if alternative, non-nuclear options were used to meet Ontario's electricity needs.

A third issue, which also has employment implications, is the connection between reactor refurbishment and the international marketing of Ontario's nuclear expertise. The Ontario government has discussed this connection in the following terms:[27]

> "The refurbishment of Ontario's nuclear fleet represents a multi-billion dollar investment and continued support of the province's nuclear supply chain and operations for decades to come. This will create a strong foundation where Ontario's nuclear suppliers can market their products and services to a global nuclear industry that could reach over 500 reactors by 2030. By working with Ontario's nuclear operators, Bruce Power and OPG, these suppliers will demonstrate their capability to deliver domestically and internationally, creating jobs and economic opportunities for the province. The province will encourage operators to compete internationally and consider opportunities and partnerships."

It is appropriate for the Ontario government to seek export opportunities for the province's industries. However, it is not obvious that the international market for Ontario's nuclear expertise is sufficient to be a factor in decision making about refurbishment of Ontario's reactors. Consider three issues. First, the global nuclear industry is not growing at present, and may be poised for substantial decline over the coming decades.[28] Second, Ontario's nuclear expertise is centered on the CANDU reactor, which plays a comparatively small role in the nuclear arena worldwide. Third, the only reactor that Canada can offer to the world market is the CANDU 6, which is an old design with questionable characteristics from the perspectives of radiological risk and proliferation risk.[29]

OBTAINING REGULATORY APPROVAL FROM THE CANADIAN GOVERNMENT

The DNGS refurbishment project has passed through part of the process of obtaining regulatory approval from the Canadian government. Specifically, CNSC has conducted a screening-level environmental assessment (EA) of the project. As part of that exercise, staff of CNSC and Fisheries and Oceans Canada published a proposed EA Screening Report in September 2012.[30] Also, a public hearing was held in December 2012. In March 2013, CNSC announced:[31]

> "The Commission [CNSC] concludes that the project, taking into account the appropriate mitigation measures identified in the Screening Report, is not likely to cause significant adverse environmental effects".

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[25] Robinson et al, 2014, page 9.

[26] Robinson et al, 2014, page 3.

[27] Ontario Ministry of Energy, 2013, page 32.

[28] Schneider et al, 2013.

[29] Thompson, 2008b.

[30] CNSC and DFO, 2012.

[31] CNSC, 2013b, paragraph 221.

CNSC further concluded that it would not refer the project for additional review or mediation, and that it could proceed with consideration of a license amendment that, if approved, would allow the project to be implemented.[32]

Consideration of a license amendment is supposed to conform to CNSC's Regulatory Document RD-360, titled *Life Extension of Nuclear Power Plants*.[33] Also, interpretation of RD-360 is supposed to conform to the *Nuclear Safety and Control Act*, whose Section 3 provides for:[34]

> "the limitation, to a reasonable level and in a manner that is consistent with Canada's international obligations, of the risks to national security, the health and safety of persons and the environment that are associated with the development, production and use of nuclear energy……"

That language sets a clear standard for CNSC's consideration of a license amendment. It says that CNSC should ensure, prior to allowing DNGS refurbishment to proceed, that it has received and considered a rigorous assessment of "the risks to national security, the health and safety of persons and the environment" that would arise from this action. CNSC could perform all of the assessment itself, or could require OPG to perform parts of the assessment. In either case, CNSC has an obligation to ensure that the assessment satisfies the principles of scientific inquiry, including completeness, objectivity, transparency, accountability, and response to critical review.

According to RD-360, a licensee that receives a positive EA decision must then complete an Integrated Safety Review (ISR). The findings of the EA process and the ISR are then incorporated into a Global Assessment Report (GAR) that includes an Integrated Implementation Plan (IIP). If CNSC accepts the GAR, the license is amended. The findings of the ISR are expressed in ISR Safety Factor Reports that are reviewed by CNSC to determine if they are acceptable.

CNSC stated, in its March 2013 EA decision, that it expected a license-amendment hearing to occur in 2014. In addition, CNSC stated that it would require OPG to consider, in its ISR, severe accident and malfunction scenarios with an alleged probability of occurrence lower than the probability considered in the EA process.[35] Also, CNSC stated that the CNSC staff would make a presentation to the Commission in 2014 regarding the treatment of such allegedly lower-probability scenarios in the IIP.[36]

CNSC further stated that the CNSC staff would provide an update to the Commission in September 2013 on the estimated health and environmental consequences of severe accident scenarios.[37] These scenarios would be more severe than the scenarios considered in the EA. CNSC stated:[38]

> "CNSC staff, because of public concern, agreed to provide an information document or equivalent assessing health and environmental consequences of more severe accident scenarios discussed by intervenors and intends on updating the Commission on this topic in fall 2013."

As far as this author can determine, the CNSC staff had not published any such document prior to completion of this report in February 2014. In December 2013, OPG submitted an application to CNSC for renewal of the DNGS licence, accounting for the planned refurbishment.[39] OPG's application refers to the ISR, IIP, and GAR that are mentioned above. From the EA process, from OPG's licence renewal application and related documents, and in view of the lack of the CNSC staff document that was promised for September 2013, it appears that only one significant document has been published by either OPG or CNSC that examines the radiological risk posed by operation of DNGS. That document is the summary report of an OPG study titled the *Darlington NGS Risk Assessment* (DARA). The DARA summary report was published in May 2012.[40] DARA is an update of Ontario Hydro's *Darlington Probabilistic Safety Evaluation*, whose summary report was published in December 1987.[41]

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[32] CNSC, 2013b, paragraphs 222 and 223.
[33] CNSC, 2008.
[34] CNSC, 2008, Section 3.0.
[35] CNSC, 2013b, paragraph 147.
[36] CNSC, 2013b, paragraph 14.
[37] CNSC, 2013b, paragraph 14.
[38] CNSC, 2013b, paragraph 153.
[39] OPG, 2013a.
[40] OPG, 2012.
[41] Ontario Hydro, 1987.

Thus, at this time, DARA is the only document OPG has proffered to CNSC that might support a rigorous assessment of "the risks to national security, the health and safety of persons and the environment" that would arise from refurbishment and continued operation of DNGS. Accordingly, this report focuses much of its attention on DARA. In doing so, this report compares the findings of DARA with the findings of DPSE and other studies.

SAFETY IMPROVEMENTS AT DNGS

OPG is implementing a variety of new measures that are intended to reduce the radiological risk posed by the operation of DNGS.[42] This action is a response to the Fukushima accident in 2011. The new measures were developed through a collaboration involving CNSC staff, OPG, and other nuclear-industry actors such as Bruce Power.

Many of the new measures are procedural in nature. Some measures involve the acquisition of "emergency mitigating equipment" (EME) that could be deployed during an incident. EME items include portable generators that could substitute for normal means of supplying electricity, and portable pumps that could substitute for normal means of supplying water for cooling and makeup.

Some of the new measures involve plant modifications at DNGS. Four of the larger modifications have been designated as Safety Improvement Opportunities (SIOs), and their radiological-risk implications were partially considered in DARA. OPG intends to implement these SIOs before refurbishment of DNGS begins in late 2016. The SIOs are:[43]

- Installation of a third Emergency Power Generator (EPG) qualified for a higher seismic load than are the two existing EPGs.
- Installation of a Containment Filtered Venting System and a Shield Tank Overpressure Relief System.
- Duplication of the controller for the Powerhouse Steam Venting System, to improve its reliability.
- Provision of an Emergency Heat Sink in the form of an alternate and independent supply of water.

According to OPG's chief nuclear engineer, the various new measures seek to:[44]

> "Practically eliminate the potential for societal disruption due to a nuclear incident by maintaining multiple and flexible barriers to severe event progression".

The new measures would undoubtedly be useful in some emergency situations. They will somewhat reduce the radiological risk posed by operation of DNGS. However, they will not overcome fundamental vulnerabilities in the design of DNGS. They are comparatively cheap measures that will not involve substantial modification of DNGS systems or structures. They will have little effect on the radiological risk associated with malevolent acts.

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[42] OPG, 2013a, Section 18.0; Elliott, 2013.

[43] OPG, 2012, Sections 7.1 and 7.2; Robinson et al, 2014, pp 14-15; OPG, 2013a, pp 13-14.

[44] Elliott, 2013.

3. Definition of Risk, and the Role of Risk in Decision Making

In this report, the term "risk" refers to the potential for an unplanned, undesired outcome. This report addresses aspects of two types of risk – radiological risk, and program risk. These types of risk are defined below.

THE IMPORTANCE OF CAREFUL DEFINITION

Definition of risk might appear to be an academic or arcane matter, but that perception is mistaken. In fact, the definition of risk has profound implications for policy. Regrettably, the nuclear industry and its regulators have not developed a consistent, well-founded definition of risk. For example, this author could not find any formal definition of risk by CNSC.

The author searched for definitions of risk by branches of the Canadian government. That search led to a "Framework for the Management of Risk", articulated by the Treasury Board of Canada Secretariat.[45] The Framework includes definitions of several terms, including the following:

- "**Risk** refers to the effect of uncertainty on objectives. It is the expression of the likelihood and impact of an event with the potential to affect the achievement of an organization's objectives."
- "**Residual risk** is the remaining level of risk after taking into consideration risk mitigation measures and controls in place."
- "**Risk management** is a systematic approach to setting the best course of action under uncertainty by identifying, assessing, understanding, making decisions on and communicating risk issues."
- "**Risk tolerance** is the willingness of an organization to accept or reject a given level of residual risk (exposure). Risk tolerance may differ across the organization, but must be clearly understood by the individuals making risk-related decisions on a given issue. Clarity on risk tolerance at all levels of the organization is necessary to support risk-informed decision-making and foster risk-informed approaches."
- "**Uncertainty** is the state, even partial, of deficiency of information related to understanding or knowledge of an event, its consequence, or likelihood."

These definitions were not designed for use in the context of an investment in nuclear infrastructure, such as refurbishment of Ontario's nuclear reactors. Nevertheless, these definitions, as they stand, provide reasonable guidance and are consistent with this report's definition of risk.

Risk is an inevitable part of human existence. Thus, risk management should be a major element in the planning and implementation of any large investment in infrastructure. Table 3-1 outlines a framework of principles for design and appraisal of infrastructure investments, with special attention to the imperatives of sustainable development. Those imperatives will be increasingly evident as the 21st century unfolds. Table 3-1 shows how risk management should relate to other considerations.

RADIOLOGICAL RISK AND PROGRAM RISK

Table 3-2 provides definitions of radiological risk and program risk. The table also provides a definition of proliferation risk, but this report does not address that category of risk. Proliferation risk was addressed in a 2008 report by this author that examined the risks associated with CANDU 6 reactors.[46]

As shown in Table 3-2, **radiological risk** is defined in this report as the potential for harm resulting from unplanned exposure of humans and their environment to ionizing radiation. The unplanned exposure could arise from a release of radioactive material via air or water pathways, or from line-of-sight exposure to unshielded radioactive material or a criticality event. This report focuses on exposure arising from a release of radioactive material, especially an atmospheric release.

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[45] Treasury Board of Canada Secretariat, "Framework for the Management of Risk", accessed on 25 January 2014 at: http://www.tbs-sct.gc.ca/pol/doc-eng.aspx?id=19422&section=text

[46] Thompson, 2008b.

The events leading to an unplanned release of radioactive material could be accidents or attacks. Here, the term “accidents” encompasses events such as random failure of equipment, random human error, or natural forces such as earthquakes. This category of events has been extensively studied in the context of commercial nuclear facilities. An accident would not involve malevolent action as a significant factor. By contrast, the term “attacks” encompasses events in which deliberate, malevolent action is a major factor.[47] An attack could involve non-State actors or a State. The persons involved in an attack could be insiders (i.e., persons who work at the attacked facility) and/or outsiders. Attackers could have a clearly defined purpose, could be insane, or could exhibit both characteristics.[48]

An unplanned release of radioactive material could lead to direct exposure of humans to ionizing radiation. The exposure could be transient (e.g., external exposure from a passing radioactive plume) or lasting (e.g., inhalation of radioactive particles that become lodged in tissue). Also, an unplanned release would inevitably lead to some exposure of the environment and could cause lasting contamination of parts of the environment (e.g., soil or water). Harm to a particular person could occur in a variety of ways, whether or not that person is directly irradiated. The magnitude of a radioactive release from a commercial reactor could be such that millions of people are harmed, directly or indirectly, in a variety of ways.

As shown in Table 3-2, **program risk** is defined in this report as the potential for the functioning of a facility to diverge substantially from the original design objectives. In the context of refurbishment and continued operation of Ontario’s reactors, this definition can be re-stated as follows: Program risk is the potential for refurbishment or operational performance of the reactors to diverge substantially from the planned outcome. The word “program” in program risk is particularly appropriate in this instance, because refurbishment and continued operation of Ontario’s reactors would involve numerous, coordinated activities occurring in a sequence of phases. The sum of these activities is probably best described as a program.

At a nuclear power facility such as DNGS, radiological risk and program risk are intertwined. For example, an accident or attack could disable the facility for a long period, whether or not there is a large release of radioactive material to the environment. Disabling of the facility in this manner would be a manifestation of program risk. If there is an accompanying release, that outcome would be a manifestation of radiological risk. Also, an accident or attack at one facility could affect the operation of other facilities, including facilities at other sites. For example, the Fukushima accident in 2011 was a manifestation of radiological risk. Among other outcomes, that accident catalyzed a political decision in Germany to accelerate the phase-out of nuclear power, while in Japan it led to suspended operation of the country’s commercial reactors. Both outcomes are manifestations of program risk.

WAYS OF DESCRIBING AND MEASURING RISK

Defining risk as the potential for an unplanned, undesired outcome does not imply that any single indicator can adequately describe a particular risk. To the contrary, assessment of risk requires the compiling of a set of qualitative and quantitative information about the likelihood (i.e., frequency, or probability) and characteristics (i.e., impacts, or consequences) of the undesired outcome.

Quantitative analysis is essential to science, engineering, and other fields. Yet, the limitations of quantitative analysis should be recognized. These limitations can be important in risk assessment, and can be especially important in risk assessment in the nuclear sector. Regrettably, assessors of nuclear risk often fail to recognize the limitations of quantitative analysis. As a result, they tend to fall into two intellectual traps that have substantial, adverse implications for policy. These traps are discussed in the following two paragraphs.

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[47] The term “attacks”, as used in this report, encompasses an array of possible events that may be given labels such as “sabotage”, “terrorism”, or “acts of war”. Often, these labels have subjective overtones that hinder a clear-headed discussion of radiological risk. Use of the term “attacks” is intended to focus attention on a shared characteristic of these events – the application of human intellect guided by malevolent intent.

[48] Given large-scale violence (i.e., war), a nuclear facility might be targeted inadvertently, or might suffer collateral damage from an attack on a nearby target. In such an event, damage to the facility would be, in a sense, “accidental”. As a practical matter, however, the damage would be attributable to malevolent action.

The first intellectual trap is to ignore risk factors that are difficult to quantify. In the context of radiological risk assessment, prominent examples of such factors are: (i) malevolent acts; (ii) gross errors in design, construction, or operation of facilities; and (iii) institutional or cultural factors that inhibit recognition of threats. These factors could have a substantial, perhaps dominant, role in determining the likelihood of an unplanned radioactive release from a particular facility. Yet, because these factors are difficult or impossible to quantify, they are routinely ignored in radiological risk assessments for nuclear facilities. Similarly, radiological risk assessments routinely ignore potential undesired outcomes that are not readily quantifiable.

The second intellectual trap is the belief that severe, undesired outcomes are insignificant if their supposed frequency (i.e., likelihood, or probability) is very low. An individual is entitled to hold that belief in the context of the individual's personal choices. Regrettably, however, many radiological risk assessors seek to impose this belief on society at large. Typically, they seek to justify this imposition by characterizing their belief as "scientific". To the contrary, their belief is a manifestation of ideology, reflecting subjective values and interests.

THE "ARITHMETIC" DEFINITION OF RISK, AND ITS DEFICIENCIES

The road to both intellectual traps is paved by the adoption of a particular definition of risk. That definition is widely used in the nuclear industry and its regulators. In that definition, risk is the arithmetic product of a numerical indicator of harmful impacts and a numerical indicator of the frequency of occurrence of those impacts.[49] That definition is hereafter designated as the "arithmetic" definition of risk.

In the context of the radiological risk posed by commercial nuclear facilities, the "arithmetic" definition of risk is flawed from at least four overlapping perspectives:

- First, numerical estimates of impacts and their frequencies are typically incomplete and highly uncertain.
- Second, significant aspects of impact and frequency are not susceptible to numerical estimation.
- Third, larger impacts can be qualitatively different than smaller impacts.
- Fourth, devotees of the arithmetic definition typically argue that equal levels of "risk", as they define it, should be equally acceptable to citizens. That argument may be given a scientific gloss, but is actually a statement laden with subjective values and interests. An informed citizen could reject that argument on reasonable grounds.

This report provides a variety of evidence to support these four statements. That evidence can be found at various points in the report. The fourth statement also relies upon basic principles that are supposed to underlie a democratic society.

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

Both practices are common in the nuclear sector. In the context of radiological risk, a nuclear facility – such as DNGS – typically has the potential to experience unplanned releases of radioactive material across a spectrum ranging from small releases to large releases. Risk assessors working for the nuclear industry and its regulators typically conclude that small releases have a higher frequency than do large releases. That conclusion might be technically accurate. However, these assessors typically take another step, into the realm of ideology. They apply an "arithmetic" definition of risk, in which impacts are multiplied by frequency. Then, it appears that large releases with low frequency are equivalent to small releases with high frequency.

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

In a further step, radiological risk assessors commonly assert or imply that the apparent equivalence of these two types of release is “scientific”. Thus, they argue, equal levels of the numerically-estimated risk should be equally acceptable to citizens. Moreover, they often allege that citizens who reject their argument are ignorant or irrational.

In fact, the assumption of equivalence lacks a scientific basis. It is a subjective statement that reflects a particular set of values and interests. From the perspective of a citizen, the potential for a large release may be much less acceptable than the potential for a small release, regardless of frequency. That perspective could have a solid, rational basis, because a large release could have effects that are qualitatively different from the effects of a small release. Moreover, a prudent citizen will be skeptical of the frequency findings generated by risk assessors of an “arithmetic” persuasion, given the propensity of these assessors to ignore important risk factors.

Devotees of the “arithmetic” definition sometimes justify their position by pointing to the public’s apparent tolerance of natural events that could have high impacts but, in human experience, have low frequency. Examples include severe earthquakes, volcano eruptions, and meteorite landings. People do appear to tolerate these threats, even to the extent of living in areas with a comparatively high potential for earthquakes. However, these threats are not of human origin. By contrast, the radiological risk associated with a nuclear power facility – such as DNGS – arises from a decision by industry and government to use this technology to produce electricity. There are other ways of generating electricity, or of providing equivalent electricity services through enhancement of end-use efficiency. Thus, the tolerability of this radiological risk inevitably reflects a range of socio-political factors, including citizens’ trust in the nuclear industry and its regulators.

A further consideration is that the radiological risk posed by a facility such as DNGS reflects decisions in which cost is a major factor. These decisions begin with the selection of a site and a facility design. Some sites or designs might pose a lower risk than others, but might be more expensive. Then, over the years of operation, further decisions are made in which the benefit of a risk-reduction measure (e.g., installation of a new safety feature) is weighed against its cost. The Ontario government, in supporting refurbishment and continued operation of the Darlington and Bruce reactors, implicitly accepts the associated radiological risk. The government justifies this position by arguing that the refurbished reactors will produce electricity at a competitive cost. Yet, as shown in this report, the government has not been fully informed about the radiological risk, or the program risk, associated with refurbishment.

In decision-making contexts where cost is important, there is a clear incentive for some of the interested parties to reduce the apparent significance of potential radioactive releases. The “arithmetic” definition of risk provides a convenient way of responding to that incentive.

QUALITATIVE DIFFERENCES BETWEEN SMALL AND LARGE IMPACTS

As stated above, the impacts of a larger radioactive release can be qualitatively different than the impacts of a smaller release. There is ample evidence to support this proposition. For example, analysts at the French government’s Institut de Radioprotection et de Surete Nucleaire (IRSN) have found such a qualitative difference. The IRSN analysts estimated the costs (i.e., economic damage) that would arise from an accidental, atmospheric release of radioactive material from the Dampierre nuclear generating station in France. They considered two types of release – a “controlled” (smaller) and a “massive” (larger) release. A paper summarizing their findings was presented at the 2012 Eurosafe conference.[50]

The IRSN analysts concluded that the costs arising from a massive release would differ “profoundly” from the costs arising from a controlled release, in terms of both qualitative and quantitative factors. Indeed, they described the massive release as “an unmanageable European catastrophe”. Their paper concluded with the statement: [51]

> “Safety decisions may also be informed by this picture, in particular if it is realized that the most severe cases actually carry huge stakes for the nation and therefore that their lower probability may not balance their catastrophic potential.”

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[50] Pascucci-Cahen and Patrick, 2012.

[51] Pascucci-Cahen and Patrick, 2012.

To illustrate the potential for qualitative difference between larger and smaller impacts, consider the IRSN description of a massive release as "an unmanageable European catastrophe". Underlying that description is the potential for major socio-political consequences that would, in Europe, have substantial trans-boundary dimensions. The European Union might not survive the political stress arising from this event.

There is strong evidence that the 1986 Chernobyl accident was a principal cause of the dissolution of the Soviet Union. Political unrest related to the accident was noted in a 1987 paper by the US Central Intelligence Agency. The paper's concluding statement was:[52]

> "As public dissatisfaction grows, the Chernobyl' accident may provide a focal point around which disgruntled citizens can organize, and Moscow may discover that Chernobyl' is a continuing irritant with a potential for social and ethnic tensions for years to come."

Public dissatisfaction did indeed grow, and the Warsaw Pact and the Soviet Union dissolved in 1991. Mikhail Gorbachev, the last head of state of the Soviet Union, confirmed in a 2006 essay that the Chernobyl accident was a principal cause of the Union's dissolution. Gorbachev's essay began with the statement:[53]

> "The nuclear meltdown at Chernobyl 20 years ago this month, even more than my launch of *perestroika*, was perhaps the real cause of the collapse of the Soviet Union five years later. Indeed, the Chernobyl catastrophe was an historic turning point: there was the era before the disaster, and there is the very different era that has followed."

The full array of impacts of a large, atmospheric release of radioactive material from a nuclear facility in Ontario is difficult to predict. The nature and scale of those impacts would vary according to the characteristics of the release, the weather at the time, and other factors. Substantial radiological harm could extend across other provinces of Canada and deep into the USA. Impacts could include substantial political stress. It is unlikely that aggrieved citizens in Canada and the USA would be comforted if they learned that Ontario's nuclear industry had determined, at a prior time, that the release was a low-risk event.

SPATIAL AND TEMPORAL SCOPE OF RADIOLOGICAL RISK

When analysts working for the nuclear industry and its regulators discuss radiological risk, they usually do so in the context of a single facility, such as one of the reactors at DNGS. Also, they typically discuss the likelihood of an adverse impact in terms of the frequency of that impact on an annual basis. In addition, they typically limit their consideration of impacts to the impacts that occur within a comparatively small geographic area. Each of these choices about the framing of radiological risk tends to reduce the apparent significance of the risk.

Some risk analysts take a broader view. For example, three European analysts – referred to here as Lelieveld et al – have examined the "global" risk of radioactive fallout from reactor accidents.[54] They estimate the worldwide risk of fallout from all commercial reactors operating in the world. Some of their findings are presented here, focusing on potential fallout of the radio-isotope Cs-137. That isotope would be a major contributor to the radiological impacts of an accident or attack that causes a substantial atmospheric release from a reactor.

Lelieveld et al find that Cs-137 released from a reactor would be widely distributed. They say:[55]

> "Using a global model of the atmosphere we compute that on average, in the event of a major reactor accident of any nuclear power plant worldwide, more than 90% of emitted Cs-137 would be transported beyond 50 km and about 50% beyond 1,000 km distance before being deposited. This corroborates that such accidents have large-scale and transboundary impacts."

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[52] CIA, 1987.

[53] Gorbachev, 2006.

[54] Lelieveld et al, 2012.

[55] Lelieveld et al, 2012, Abstract.

Figure 3-1 illustrates their findings. That figure shows the risk of land contamination by Cs-137 at locations across the world. Three large concentrations of risk are evident. Ontario falls within the North American concentration. Figure 3-1 shows that the risk of land contamination above the specified level exceeds 2% per year at some locations. That risk would accumulate over the decades during which reactors continue to operate.

DEFINITION AND TOLERABILITY OF RADIOLOGICAL RISK – CANADIAN PERSPECTIVES

A number of Canadian experts have expressed views about radiological risk that challenge the paradigm which prevails in Canada's nuclear industry and the CNSC. The views of two experts are summarized here.

Professor John Luxat holds a research chair in nuclear safety analysis at McMaster University in Ontario. In a paper presented at the 2013 annual conference of the Canadian Nuclear Society, Luxat rejected the use of the traditional (i.e., "arithmetic") definition of risk to address "black swan" events that combine very low frequency with high consequences. He further rejected the notion that high-consequence events with a supposedly very low frequency should be regarded as "incredible" and therefore not worthy of consideration. Instead, he proposed that "black swan" events in the nuclear sector should be addressed through "threat-risk assessment methods which are not probabilistically based". He said that threat-risk assessment "does not attempt to rank threats by their likelihood". Instead, it postulates the occurrence of an event, assesses the consequences that may result, and then identifies options to mitigate the consequences and stabilize the event.[56]

Romney Duffey is a physicist who retired from Atomic Energy of Canada Limited as a principal scientist, and who is a former chair of ASME's Nuclear Engineering Division. In July 2012 he published a journal article on risk, including radiological risk in the nuclear sector. In that article he rejected the traditional (i.e., "arithmetic") definition of risk, saying:[57]

> "The uncertainty of an extreme event happening – and its fiscal costs, political damage, and social consequences – can be defined using probability and consequence measures. But the risk of such an event is not given by the often-used formula, probability times consequence. Nor is it found via the more sophisticated means of defining a negatively sloped risk boundary between acceptable and unacceptable risks. Instead, the best method for finding this risk is by calculating the total integral risk due to all possible exposure to releases, fears, damages, and social and political disruption. We can also derive the exact expression for relative social risk using a social damage relation.
>
> How does changing the way we calculate risk affect the design and operation of nuclear power plants in particular? First, and perhaps most critically, we ought to preclude by design measures and margins the potential consequences of extreme events that lead to severe damage. Designs, policies, and safety management must address extreme and rare events that may almost defy our imagination."

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[56] Luxat, 2013.

[57] Duffey, 2012.

4. The Risk Environment

Radiological risk and program risk in the nuclear sector do not exist in a vacuum. They are determined by an array of influences that are specific to a particular context (i.e., a particular nuclear activity, at a particular time and place). Risk-related characteristics of that context could include: (i) institutional arrangements and culture; (ii) laws and regulations; (iii) available technology; (iv) management, workforce, and supplier capabilities; (v) site characteristics (e.g., seismic potential, vulnerability to flooding, distance from population centers); (vi) economic conditions – regional, national, and global; (vii) potential for localized violence (e.g., an attack on a reactor); and (viii) potential for societal disorder or violent conflict. Taken together, these characteristics can be thought of as the "risk environment" in a particular context.

The risk environment typically has dynamic aspects. For example, the population living near a nuclear facility might grow substantially over a period of decades. As another example, on a shorter timescale, a group committed to political violence might decide to attack a particular nuclear facility. In that case, the time interval between the decision and the attack might be measured in months.

THE RISK ENVIRONMENT IN CANADA

Ontario, and Canada as a whole, are fortunate to have a comparatively stable risk environment. Also, in terms of some characteristics – such as the potential for societal disorder or violent conflict – the Canadian risk environment is comparatively benign at present. However, DNGS refurbishment is predicated on the idea that the refurbished reactors will operate until the middle of the 21st century. Looking at that timeframe, it would be imprudent to assume that the risk environment will remain stable. Canada is embedded in a world that features some disturbing trends, as discussed below.

Although Canada currently has a comparatively benign risk environment in terms of some characteristics, other characteristics provide cause for concern. In Section 5, below, this report shows that deficiencies in institutional arrangements and culture, compounded by weaknesses in regulation, have been major contributors to the occurrence of reactor accidents in the USA, USSR, and Japan. This report finds that radiological risk and program risk associated with DNGS have not been adequately assessed. That finding is indicative of deficiencies in institutional arrangements and culture, and in regulation, in Canada's nuclear sector.

SOME DISTURBING GLOBAL TRENDS

Science and direct observation provide ever more compelling evidence that we must change our practices if human civilization is to be sustainable. For example, a group of scientists examining the "safe operating space for humanity" has said: [58]

> "The exponential growth of human activities is raising concern that further pressure on the Earth System could destabilize critical biophysical systems and trigger abrupt or irreversible environmental changes that would be deleterious or even catastrophic for human well-being. This is a profound dilemma because the predominant paradigm of social and economic development remains largely oblivious to the risk of human-induced environmental disasters at continental to planetary scales."

Figure 4-1, which was prepared by the same group of scientists, illustrates our assault on the boundaries of Earth's safe operating space. We have already gone beyond the safe boundaries of three systems (rate of biodiversity loss, climate change, and human interference with the nitrogen cycle), and are approaching other boundaries.

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[58] Rockstrom et al, 2009a.

Societal response to the threat illustrated by Figure 4-1 is inhibited by a number of factors, including a widespread lack of recognition of the rapidity of action that is needed to prevent adverse outcomes. For example, government leaders meeting in Copenhagen in 2009 committed their countries to holding the human-caused increase in average global temperature below 2°C. Yet, although accumulating scientific knowledge indicates that a 2°C increase may be dangerously high, current trends in GHG emissions make it unlikely that the increase can be held below 2°C.[59] Correcting those trends to achieve a 2°C limit would, according to analysis published in November 2012 by Pricewaterhouse Coopers, require an unprecedented reduction in global carbon intensity (CO_2 emissions per unit of economic product) averaging 5.1% per year throughout the period from the present until 2050.[60] There is no international agreement or plan to achieve such reduction.

Adverse outcomes for human welfare, as a result of our abuse of natural resources, could include direct effects, such as reduced agricultural yields and increased incidence of infectious diseases. These direct effects could be accompanied and amplified by indirect effects, with the potential for a descending spiral in the human condition. Many analysts have noted that indirect effects could include an increase in violent conflict. For example, the Defense Science Board in the USA has examined the implications of climate change for national and international security, and has stated:[61]

> "Climate change is likely to have the greatest impact on security through its indirect effects on conflict and vulnerability."

As natural-resource constraints tighten over the coming decades, the choice facing humanity will become ever starker. Continued pursuit of the currently predominant, but now obsolete, economic paradigm would degrade our life-support systems, widen gaps between rich and poor, and promote conflict within and between nations, potentially leading to a retrograde civilization that has been dubbed "Fortress World".[62] Table 4-1 outlines the features of Fortress World and other future world scenarios identified by the Stockholm Environment Institute.

A trend toward Fortress World would inevitably have adverse effects on the risk environment affecting the nuclear sector in Canada. Thus, given the present likelihood of such a trend, it would be prudent for the Ontario and Canadian governments, and Canada's nuclear industry, to prepare for a more adverse risk environment in the coming decades. One manifestation of that changed risk environment would be an increased potential for an attack on DNGS.

Table 4-1 outlines, as an alternative to Fortress World, a scenario dubbed "New Sustainability Paradigm". That scenario offers a bright future for humanity. If humanity achieves such a scenario, it will do so through a host of decisions. The Ontario government could contribute to such an outcome by making wise decisions about the province's energy systems.

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[59] Anderson and Bows, 2011.

[60] PwC, 2012.

[61] Defense Science Board, 2011, page xi.

[62] Raskin et al, 2002.

5. Assessing Radiological Risk, Generically and at DNGS

5.1 Probabilistic Risk Assessment: History, Strengths, and Limitations

Beginning in the 1970s, the nuclear industry and its regulators have developed an analytic art to examine the radiological risk posed by nuclear facilities. This art is known as probabilistic risk assessment (PRA). Sometimes, this art is referred to as probabilistic "safety assessment", but "risk assessment" is a more honest description. Much of the early work on PRA development was done by the US Atomic Energy Commission (AEC) and by the US Nuclear Regulatory Commission (NRC), which took over AEC's regulatory function in 1975.

Analysts have developed an array of PRA techniques to estimate the frequencies and impacts of potential unplanned releases of radioactive material from a nuclear facility. Most of this work has focused on commercial nuclear reactors. However, PRA techniques can be applied to nuclear facilities other than reactors. Similar techniques can be used to estimate the frequencies and impacts of unplanned releases from chemical plants. Also, PRA techniques can contribute to aspects of program risk assessment. Overall, PRA can be a useful art, provided that its limitations are kept firmly in mind.

Here, in Section 5.1, this report provides a general discussion of PRA in the context of reactors. In Section 5.2, the findings of reactor PRAs are compared with lessons from experience. Then, in Section 5.3, this report discusses applications of PRA to Canadian reactors, especially the DNGS reactors. Other perspectives on radiological risk are discussed in Sections 5.4 through 5.7. Drawing upon all of these discussions, Section 5.8 sets forth a prudent assessment of radiological risk at DNGS.

BACKGROUND TO DEVELOPMENT OF PRA

The basic designs of the commercial reactors now operating around the world were established in the 1960s. At that time, incidents involving substantial melting of fuel in a reactor core had occurred in prototypical power reactors, research reactors, and military reactors. Canada's NRX research reactor experienced such an incident in 1952. Yet, the designers of the present worldwide fleet of commercial reactors, and the regulators who accepted their designs, decided that fuel melting was no longer a credible event. Accordingly, the containments of these reactors were not specifically designed to contain radioactive material released from melting fuel. To varying degrees, the containments have some capability of this kind, as a byproduct of design for other threats. Also, plant modifications over the years have somewhat improved that capability. Nevertheless, all containments remain vulnerable, as discussed below.

The primary goal of containment design was to accommodate a loss-of-coolant accident (LOCA).[63] In the hypothesized LOCA, water would escape from the reactor coolant system via a pipe break, but emergency core cooling systems would ensure that fuel in the core did not experience substantial melting. Thus, the containment was designed to accommodate a comparatively light loading of steam and gases. That design goal was pursued in various ways. For example, boiling-water reactor (BWR) containments employ pools of water to condense steam released during a LOCA. Some pressurized-water reactor (PWR) containments employ baskets of ice to serve the same purpose. The remaining PWR containments employ large, dry containment buildings. The CANDU reactors now operating in Ontario have a containment system involving a vacuum building that is shared by several reactors. Also, Ontario's CANDU reactors employ an emergency core cooling system that is shared by several reactors. The Ontario practice of sharing safety systems reflects an assumption that the major safety threat – presumed to be a LOCA – is a random event that could affect only one reactor at a given time.

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[63] Ford, 1982; Okrent, 1981.

At DNGS, four reactors share one containment system and one emergency cooling system. The same arrangement exists at the Bruce A and Bruce B stations. Each of those stations has four reactors, and the stations are located in different portions of the Bruce site. At the Pickering site, eight reactors – four at Pickering A plus four at Pickering B – share one containment system and one emergency cooling system. For each of these clusters of reactors, the shared safety system is designed to accommodate an incident at a single reactor. Presumably, sharing of safety systems in this manner led to substantial reductions in the initial capital costs of Ontario's nuclear stations. However, that unusual design choice increased Ontario's burden of radiological risk, as discussed in this report.

Even while the designs of the present fleet of reactors were being fixed, evidence was emerging that core-melt accidents at these reactors are credible events. That evidence became definitive when a core-melt accident occurred at the Three Mile Island (TMI) site in 1979. Fortunately, the large, dry containment of the affected reactor – a PWR – was able to withstand a hydrogen explosion that occurred inside the containment. It soon became obvious, however, that other containment designs are more vulnerable and, more generally, that the hypothesized LOCA did not provide a sufficient basis for containment design.

In light of the TMI experience, regulators ordered changes in the hardware and modes of operation of commercial reactors. For example, NRC required that BWR containments be filled with nitrogen during reactor operation, to suppress a hydrogen explosion arising from a core melt. However, the measures required by regulators were unable to overcome the fundamental fact that no reactor in the worldwide fleet has a containment that was specifically designed to withstand the loading created by a core melt. The new measures could reduce, but not eliminate, the potential for containment failure.

When it became clear that any commercial reactor could experience a core melt, potentially followed by containment failure, regulators opened up a new arena of regulation. Previously, regulation had centered on "design-basis" events such as the hypothesized LOCA mentioned above. Regulations had required that a reactor be designed to withstand such events, regardless of their probability. That arena of regulation continues to function today, but has been supplemented by a new arena centered on the probability of events beyond the design basis. PRA plays a central role in the new arena of regulation. Specific aspects of that role vary by country.

PURPOSE AND SCOPE OF A REACTOR PRA

The first PRA for a commercial reactor was known as the Reactor Safety Study, and was published by NRC in 1975.[64] A PRA for a commercial reactor considers a range of scenarios (event sequences) that involve damage to the reactor core. The initiating events are categorized as "internal" events (human error, equipment failure, etc.) or "external" events (earthquakes, fires, strong winds, etc.). The core-damage scenarios that arise from these events are termed "accidents".

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. For example, NRC adapted PRA techniques in developing its 1994 rule requiring protection of a nuclear power plant against attack using a vehicle bomb.[65]

PRAs for commercial reactors 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 (i.e., frequencies) of a set of adverse impacts, and the uncertainty and variability of those indicators. Typically, PRAs focus on atmospheric releases of radioactive material originating in the reactor core.[66] The adverse impacts of such releases at downwind locations would include:

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[64] NRC, 1975.

[65] NRC, 1994.

[66] A release could also occur to ground water or surface water (e.g., river, lake, or ocean). For a given size and composition of release, human exposure to radiation would typically be much larger for an atmospheric release than for a water release.

(i) “early” human fatalities or morbidities (illnesses) that arise during the first weeks and months 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 damage to the reactor core would be identified, and the probability (i.e., frequency) of each member of the set would be estimated. The sum of those probabilities across the set would be the total estimated core-damage probability. That indicator is commonly known as core-damage frequency (CDF), typically expressed as a number per reactor-year (RY) of reactor operation.

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 core-damage sequences. The findings would be expressed in terms of a group of release categories characterized by magnitude, frequency, timing, isotopic composition, and other characteristics.

Third, a Level 3 PRA analysis would be performed, to yield the 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 impacts of the released material would be estimated, accounting for the material’s distribution in the biosphere. As mentioned above, the impacts would include adverse health effects and socio-economic impacts.

If done thoroughly, this three-step estimation process would account 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 frequency, not as single numbers. Even after such a thorough effort, there are substantial, irreducible uncertainties in the findings.[67] PRA findings rely on numerous assumptions and judgments. There is no certainty that all of the relevant factors are captured. Findings of very low frequency cannot be validated by direct experience. Moreover, a PRA cannot estimate the frequencies of event sequences initiated by malevolent acts, because there is no statistical basis for doing so. A PRA that considered malevolent acts would have to postulate the occurrence of a set of such acts and then estimate their impacts, accounting for variable factors such as wind speed and direction.

NUREG-1150

The high point of PRA practice worldwide was reached in 1990 with publication by NRC of its NUREG-1150 study, which examined five different US nuclear power plants using a common methodology.[68] 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 almost entirely 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, contemporary PRA findings have limited credibility. Outside the USA, PRA practice never attained the combined scope and transparency of NUREG-1150.

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[67] Hirsch et al, 1989.
[68] NRC, 1990.

Figures 5.1-1 through 5.1-3 show some findings from the NUREG-1150 study that are relevant to this report. The findings are for a PWR at the Surry site (Virginia, USA), and a BWR at the Peach Bottom site (Pennsylvania, USA). Those reactors typify many of the Generation II commercial reactors in the present worldwide fleet. In viewing the CDF findings in Figures 5.1-1 and 5.1-2, it should be noted that NUREG-1150 itself warns that estimated core-damage frequencies lower than 1 per 100,000 RY should be viewed with caution because of limitations in PRA.

Figures 5.1-1 and 5.1-2 show estimated CDF for internal events and two types of external event – earthquake, and fire. Other types of external event could be significant for a particular reactor. For example, experience in 2011 showed that tsunami was a significant external event for reactors at the Fukushima #1 site in Japan.

The categories of initiating event shown in Figures 5.1-1 and 5.1-2 are independent. There is no double counting of event sequences across these categories. Thus, CDF should be summed across the categories. For example, the mean values shown in Figures 5.1-1 and 5.1-2 for CDF arising from internal, seismic, and fire initiators could be added to yield an overall mean CDF.[69] If another category of initiating event (e.g., strong wind) was also determined to be significant, the mean CDF for that category should be added to the overall sum.

Figure 5.1-3 shows the estimated conditional probability of containment failure, given substantial melting of fuel in a reactor core. Various modes of containment failure – including no failure – are presented. One sees that the conditional probabilities of containment-failure modes vary substantially according to the initiating event. Thus, conditional probabilities cannot be simply summed across categories of initiating event, as can be done for CDF. However, an overall conditional probability of a particular mode of containment failure can be calculated, by summing the release frequencies for that mode across all relevant categories of initiating event. .

FACTORS THAT ARE NOT ADDRESSED BY PRA

Malevolent acts are not addressed in PRAs for commercial reactors. Similarly, PRAs do not address the potential for gross errors in design, construction, or operation of a reactor. Also, PRAs do not address institutional or cultural factors that inhibit recognition of threats. Yet, in each of these areas, the potential for harm is real. Indeed, factors of this type may be major, or even dominant, sources of risk at a facility.

PRA analysts routinely ignore risk factors of this type, effectively assigning their impacts a probability of zero. After making this convenient but highly questionable assumption, PRA analysts focus their attention on a sub-set of risk factors, namely those that are easy to quantify. The findings generated by that work can have value for certain, limited purposes, but do not constitute a complete, objective assessment of risk.

The importance of risk factors that are not readily quantifiable is illustrated by each of the core-melt accidents that has occurred at a Generation II commercial reactor – at Three Mile Island in 1979, Chernobyl in 1986, and the Fukushima #1 site in 2011. In each instance, retrospective investigations identified dominant risk factors that were not readily quantifiable. These instances are discussed in the following paragraphs.

A commission established by the US President to investigate the TMI accident concluded that systemic deficiencies in human behavior and organization were the dominant causes of the accident. To illustrate, their report included the statement:[70]

> "We are convinced that if the only problems were equipment problems, this Presidential Commission would never have been created. The equipment was sufficiently good that, except for human failures, the major accident at Three Mile Island would have been a minor incident. But, wherever we looked, we found problems with the human beings who operate the plant, with the management that runs the key organization, and with the agency that is charged with assuring the safety of nuclear power plants."

Two Harvard University physicists, one of whom had previously worked in a reactor physics group in the USSR, published a paper in 1992 that examined the Chernobyl accident. The abstract of their paper stated:[71]

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[69] Note that overall CDF, on a reactor-year basis, could, in principle, be greater than 1. In practice, values greater than 1 are not supported by experience.

[70] Kemeny et al, 1979, page 8.

[71] Shlyakhter and Wilson, 1992.

> “The Chernobyl accident was the inevitable outcome of a combination of bad design, bad management and bad communication practices in the Soviet nuclear industry. We review the causes of the accident, its impact on Soviet society, and its effects on the health of the population in the surrounding areas. It appears that the secrecy that was endemic in the USSR has had profound negative effects on both technological safety and public health.”

The National Diet of Japan established an independent commission to investigate the Fukushima accident. The commission’s principal conclusion was:[72]

> “The TEPCO Fukushima Nuclear Power Plant accident was the result of collusion between the government, the regulators and TEPCO, and the lack of governance by said parties. They effectively betrayed the nation’s right to be safe from nuclear accidents. Therefore, we conclude that the accident was clearly “manmade”. We believe that the root causes were the organizational and regulatory systems that supported faulty rationales for decisions and actions, rather than issues related to the competency of any specific individual.”

Other analysts have reached similar conclusions about the Fukushima accident. For example, three analysts based in China and Australia examined a regulatory history in which, for example, TEPCO management ignored warnings from its own staff in 2008 that a tsunami with wave height exceeding 10 m could strike the Fukushima #1 site. These three analysts concluded that institutional failure, involving complacency and laxity, was the root cause of the accident. They said:[73]

> “We argue that the root cause of the problems is the failure of the Japan’s nuclear regulatory system. This argument is in line with those who believe the Japan’s nuclear regulatory failures contributed to the Fukushima nuclear accident.
>
> Both nuclear regulators and nuclear operators were far too lax with the regulations on operation and development of nuclear facilities and complacent with the safety record of nuclear power plants. For example, when asked why the government failed to act on tsunami warnings, Mr. Banri Kaieda, the minister of METI, said his ministry had blindly believed Japan’s nuclear plants “were the safest in the world”.”

The combined experience of the TMI, Chernobyl, and Fukushima accidents strongly suggests that a non-quantifiable factor will be a major or dominant risk factor underlying the next core-melt accident at a commercial nuclear reactor. Thus, reliance on PRA to estimate the likelihood of the next accident would be neither reasonable nor prudent.

MULTI-UNIT INCIDENTS

Reactor PRAs have, with a few exceptions, focused on potential accidents affecting a single reactor. Yet, many sites have more than one reactor. Thus, when three concurrent reactor accidents occurred at the Fukushima #1 site in 2011, it became difficult to deny that a single-unit PRA is an inadequate instrument for examining radiological risk at a multi-unit site. That finding is particularly significant for Ontario’s nuclear stations, in view of their use of shared safety systems. Section 5.5 of this report discusses multi-unit incidents.

LEGITIMATE USES OF PRA

PRA studies can be valuable for various purposes, provided that their limitations are recognized. For example, during the past three decades PRA studies have helped to identify numerous points of vulnerability in the design and operation of commercial reactors. Some of these vulnerabilities could be addressed by comparatively low-cost measures that have reduced the probability of a core-melt accident.

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[72] Diet, 2012, page 16.

[73] Wang et al 2013, page 139.

In illustration, PRA studies and operating experience have shown that maintenance errors could lead to simultaneous, common-mode failure of safety systems that are nominally independent and redundant. When this problem was recognized, maintenance schedules and procedures were changed so that redundant systems receive maintenance service at different times and in different ways.

These successes involved the application of PRA techniques in conjunction with the systematic collection of relevant operating experience. Notably, NRC has operated its Accident Sequence Precursor (ASP) program since 1979. That program has identified and analyzed numerous sequences of events, during the operation of commercial reactors, that were "precursors" to a core-melt accident. A sequence of events (e.g., equipment failure, human error) is categorized as a significant precursor if the occurrence of a plausible set of additional events would have led to core melt. Programs similar to the ASP program operate in the aviation industry and other industries.[74]

5.2 Lessons from Experience

The ASP program provides useful lessons from experience. These lessons reflect, however, the potential occurrence of a core-melt accident rather than the actual occurrence of such an accident. Also, the ASP program is mostly relevant to accidents in which a chain of events, each comparatively minor, could lead ultimately to a core melt. PRA techniques are particularly suited to accidents of that type. Many potential accidents are different, however, in that they would involve common-mode failures (e.g., in response to an earthquake) or one or two major failures (e.g., a burst pressure vessel). A core melt caused by attack would be different again, because it would involve the focused application of intellect.

IMPEDIMENTS TO LEARNING

Learning from experience is widely regarded as a laudable activity. Yet, in many institutional settings, there can be substantial impediments to learning. Regrettably, such impediments are common in the nuclear industry and its regulators.

As mentioned above, the combined experience of the TMI, Chernobyl, and Fukushima accidents strongly suggests that a non-quantifiable factor will be a major or dominant risk factor underlying the next core-melt accident. Thus, one might expect that responsible authorities would learn from these three accidents, and ensure that hitherto neglected risk factors are considered in future assessments of radiological risk. However, a 2013 paper by the sociologist John Downer shows that entrenched institutional cultures in the nuclear industry can suppress learning and promote the continuation of favored narratives. The paper's conclusion begins with the statement:[75]

> "The disaster-punctuated history of nuclear power ought to speak for itself about the limitations of risk assessments, but our narratives obfuscate that history by rationalizing it away. For experience can only "show" if we are willing to "see," and the lessons of Fukushima, like those of the accidents that preceded it, will always be opaque to us if our narratives consistently interpret it as exceptional. So it is that even as the dramas of Fukushima linger, and in some ways intensify, the Ideal of Mechanical Objectivity survives with its misleading impression that expert calculations can objectively and precisely reveal the "truth" of nuclear risks. This has critical policy implications."

John Waddington provided an illuminating perspective on impediments to learning, in a paper he presented at the Nuclear Inter Jura Congress that was held in Toronto in October 2009.[76] Waddington was Director General of CNSC and its predecessor, the Atomic Energy Control Board (AECB), from 1991 to 2002.

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[74] Phimister et al, 2004.

[75] Downer, 2013, page 17.

[76] Waddington, 2009.

Waddington noted in his paper that human errors are the dominant causes of accidents in "high reliability" industries such as commercial aviation, the chemical industry, and nuclear power. He went on to say that these errors are typically not random, independent events, but are embedded in institutional cultures. He said:[77]

> "When a serious accident or a near miss occurs, it usually appears at first that human error on the part of control room operators or maintainers (or pilots in the aviation business) – that is, the people at "the sharp end" of operations – played a large part in causing the accident. But closer inspection and analysis shows that most of the root causes of the accident arise from failings in the way in which complex technological organizations such as airlines or electrical utilities organize themselves. The errors are still human errors, but they arise from latent weaknesses in the way the organization runs, rather than individual error. The usual term for these weaknesses is "Institutional Failure." It is this type of failure that provides the greatest contributor to real accidents and near misses."

Having identified the key role of institutional failure as a risk factor, Waddington considered various options for reducing the incidence of institutional failure in the nuclear industry. In doing so, he considered impediments to learning and, in that context, compared practices in the commercial aviation and nuclear industries. He noted that, in the aviation industry, designers and manufacturers have major responsibilities in regard to risk. Thus, a "Type Certificate" is issued to the designer or manufacturer of an aircraft or aircraft product, followed by "Production Approval" and an "Air Worthiness Certificate" for each individual aircraft. These three processes never end, and promote continuous learning. By contrast, in the nuclear industry, designers and manufacturers are shielded from responsibility for harmful outcomes. Waddington described this situation as follows:[78]

> "From a safety point of view, the lack of a formal role for designers in operation is a very unhealthy state of affairs, but the assumption that only the operator is responsible for nuclear safety, and that the designer has no formal role, has been an almost unchallengeable (and certainly unchallenged) mantra from the beginnings of the industry. This lack of recognition is unhealthy because there has been no systematic, legally enforceable way for designers to ensure they have been learning the lessons that operation of their products brings, to ensure that any design changes that should be made to a fleet of like designs from a safety point of view have been identified and passed on to the fleet of stations throughout operating life, and to ensure that they are held to these responsibilities for as long as the fleet of stations keeps operating."

Channeling liability for offsite harm exclusively to the operator – OPG in the case of DNGS – is a fundamental provision of Canada's *Nuclear Liability Act* and of its currently-proposed replacement, the *Nuclear Liability and Compensation Act*. Waddington has shown us that this provision is a powerful impediment to risk-related learning in Canada's nuclear sector. Moreover, Waddington has also pointed out that OPG has closed down and privatized its design and development organization, so that OPG no longer has an in-house capability to learn from experience in a systematic manner.[79] CNSC also lacks that capability.

The commercial aviation industry has achieved a substantial reduction of risk over recent decades, as illustrated by Figure 5.2-1. The learning processes outlined by Waddington have been major contributors to this outcome. Yet, as Figure 5.2-1 shows, aircraft accidents involving fatality have not been reduced to zero. If non-fatal accidents and near misses are included, the aviation industry continues to generate a comparatively rich flow of data on actual, severe incidents. By comparison, the nuclear industry promotes the idea that a severe reactor accident is so unlikely that, as a practical matter, it is almost impossible. The core-melt accidents at TMI, Chernobyl, and Fukushima reveal the falsity of that idea. Nevertheless, there is a comparatively sparse body of data on actual, core-melt accidents.

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[77] Waddington, 2009.

[78] Waddington, 2009.

[79] Waddington, 2009.

A task force of the American Society of Mechanical Engineers (ASME) has acknowledged that the sparsity of data on core-melt accidents inhibits learning about these accidents. The task force said that reactor operating experience over several decades has led to substantial improvements in what the task force termed "operational safety". Those improvements would be manifested through indicators such as reactor capacity factor or radiation dose to workers. By contrast, the task force used the term "nuclear safety" to encompass severe accidents, and said:[80]

> "To some degree, the industry attention to, and resultant improvement in, plant operations is a consequence of the relative infrequency of serious nuclear safety events in that time frame – itself an indicator of a safe technology, but also a circumstance that inherently limits the learning experience afforded by safety events."

ESTIMATING CORE-DAMAGE FREQUENCY FROM EXPERIENCE

Severe fuel damage or core melt at a commercial reactor is often thought of as a rare event. Yet, a post-Fukushima inventory lists twelve events involving severe damage to fuel in the core of a power reactor.[81] This inventory excludes similar events at non-power reactors. For example, it excludes the core fire and radioactive release experienced in 1957 by a reactor at the Windscale site in the UK. That reactor was used to produce plutonium and other materials for nuclear weapons.

Of the twelve core-damage events at power reactors, five have both: (i) occurred at a Generation II commercial reactor; and (ii) involved substantial fuel melting. These five events were at Three Mile Island Unit 2 (a PWR plant) in 1979, Chernobyl Unit 4 (an RBMK plant) in 1986, and Fukushima #1 Units 1 through 3 (BWR plants) in 2011.

These five events occurred in a worldwide fleet of nuclear power plants. About 430 plants are currently operable, although none of Japan's 50 nominally operable plants is actually operating at present. Currently operating plants and previous plants in the worldwide fleet had accrued 14,760 RY of operating experience as of February 2012.[82] Thus, about 15,500 RY of experience were accrued through 2013.

The five core-melt events provide a data set that is comparatively sparse and therefore does not provide a statistical basis for a high-confidence estimate of CDF. Nevertheless, this data set does provide a reality check for PRA estimates of CDF. From this data set – five core-damage events over a worldwide experience base of about 15,500 RY – one obtains a "simple" CDF estimate of 3.2×10^{-4} per RY (i.e., 1 event per 3,100 RY).[83]

Confidence in this reality check is enhanced by noting that the five events occurred in three different countries at three different types of reactor, involved differing initiating events, and happened on three distinct occasions over a period of 32 calendar years. This spread of accident characteristics is consistent with the diversity of circumstances that PRA analysis seeks to address.

A PRA analyst employed by NRC, Raymond Gallucci, has written a paper that develops CDF estimates based on direct experience. [84] Gallucci's paper considers the experience of actual core melts and their precursors, leading to a "simple" CDF estimate of 6.0×10^{-4} per RY (i.e., 1 event per 1,700 RY). The paper does not adopt that estimate. Instead, it makes some analytic assumptions, and ultimately concludes that CDF, worldwide and in the USA, is in the range 0.7×10^{-4} to 4.0×10^{-4} per RY (i.e., between 1 event per 14,300 RY and 1 event per 2,500 RY). The assumptions underlying this downward adjustment of the "simple" CDF estimate can be questioned. However, Gallucci's analysis deserves consideration in view of his professional expertise. On another note, Gallucci ends his paper by expressing his personal willingness to tolerate a CDF of the level that he has identified. On that matter, his opinion has no more weight than the opinion of any citizen.

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[80] ASME, 2012, page 11.

[81] Cochran, 2011.

[82] See: World Nuclear Association (WNA) website, http://www.world-nuclear.org/. Data on cumulative reactor-years worldwide were obtained from the WNA website on 17 February 2012. The WNA website no longer provides such data.

[83] This "simple" estimate of CDF might be criticized because the three core-damage events at Fukushima #1 had a common cause. However, there are some design differences between the three affected reactors at Fukushima #1, and it appears that there were differences in the accident sequences at these reactors. Also, multiple core-damage events with a common cause could occur in the future, potentially involving reactors at single-unit sites.

[84] Gallucci, 2012.

Some analysts have sought to apply statistical models to the body of reactor-accident experience. For example, two French analysts applied four variants of a Poisson model to the worldwide record of core melts and related reactor accidents between 1952 and 2012.[85] For each of the four model variants, they calculated the “arrival rate” of a Poisson distribution, which corresponds to the expected frequency of an accident (per RY). They found that the arrival rate of a core-melt accident would increase if it were computed after the Fukushima accident instead of before, by an amount depending on the model used. That finding is not particularly helpful. The main value of this exercise was to demonstrate that the record of core-melt experience is too sparse for statistical analysis.

After the Fukushima accident, the members of a subcommittee of the Japan Atomic Energy Commission (JAEC) sought consensus on an appropriate assumption for the frequency of a severe reactor accident.[86] They could not reach consensus. Instead, they expressed the range of views that is presented in Table 5.2-1. Their proposed assumptions of accident frequency ranged from $1.0\text{x}10^{-5}$ per RY to $2.0\text{x}10^{-3}$ per RY. This broad range (a factor of 200) illustrates the difficulty of interpreting severe-accident experience.

ESTIMATING RELEASE MAGNITUDE AND DIRECT RADIOLOGICAL IMPACT, FROM EXPERIENCE

The five core-melt accidents at TMI, Chernobyl, and Fukushima had differing outcomes in terms of the amount of radioactive material that was released to the atmosphere, and the direct radiological impact of the release. These outcomes provide a partial illustration of the spectrum of potential releases and resulting radiological impacts associated with accidents or attacks at nuclear stations.

The radio-isotope Cs-137 is a useful indicator of radioactive release. The atmospheric release of this isotope during the TMI accident was small. However, the releases during the Chernobyl and Fukushima accidents were substantial. Estimates in Table 5.2-2 show that the Chernobyl accident released about 85 PBq of Cs-137, representing about 40 percent of the reactor core inventory, while the Fukushima accident released about 37 PBq of Cs-137, representing about 5 percent of the combined core inventories of the three affected reactors. About one-sixth of the Fukushima release (i.e., 6.4 PBq of Cs-137) was deposited on the territory of Japan. Figure 5.2-2 shows the spatial distribution of the deposited material. Various effects of this contamination – such as displacement of residents, and limits on the use of land for agriculture – will be evident to Japanese citizens for decades to come.

Japanese officials have conceded that the release of radioactive Cesium would have been substantially greater if water had been lost from spent-fuel pools at Fukushima, causing exposed spent fuel to burn (i.e., react exothermically with steam or air). In a February 2012 interview, Japan Atomic Energy Commission chair Shunsuke Kondo described a “worst-case” release scenario that he delivered to the Japanese government on 25 March 2011. The scenario envisioned an atmospheric release from burning spent fuel that would be “the radiation equivalent of two reactor cores”.[87]

Table 5.2-3 shows the estimated collective dose of radiation from the Chernobyl release, in various regions. The total collective dose, which is predominantly accrued across the territories of the USSR and Europe, and is mostly attributable to Cs-137, is about 1.2 million person-Sv. According to the US National Research Council’s BEIR VII study, each person-Sv of collective dose is expected to yield 0.051 excess (i.e., premature) deaths from solid cancer.[88] Further background is provided in Table 5.2-4. Thus, a collective dose of 1.2 million person-Sv is expected to yield $(1.2\text{x}10^{6})\text{x}(0.051) = 61{,}200$ premature deaths. Those deaths will occur in parallel with a much larger number of deaths from solid cancer that has other causes. In other words, the number of cancer deaths attributable to the Chernobyl release will be substantial, but will be masked by cancer deaths of other origin.

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[85] Rangel and Leveque, 2014.

[86] JAEC Subcommittee, 2011.

[87] Associated Press, 2012.

[88] BEIR VII, 2006.

The experience outlined in the preceding paragraphs provides a partial illustration of potential atmospheric releases and the resulting radiological impacts. It shows that releases and their impacts can be substantial. It does not, however, provide a basis for predicting the characteristics of the release from the next core-melt incident. That release will depend upon the particular circumstances of the incident, and upon the design of the affected reactor(s). The resulting radiological impact will depend upon wind velocity and other weather characteristics at the time of the release, and upon features of the site such as the size and spatial distribution of the surrounding population.

ESTIMATING SOCIAL AND ECONOMIC IMPACTS OF AN ACCIDENT, FROM EXPERIENCE

An ASME task force, mentioned above, compiled estimates of social and economic impacts of the Chernobyl accident, as follows:[89]

- Worldwide economic impact on the nuclear power industry, especially in Europe, was in the range US$250 billion to US$500 billion over 25 years.
- There were major psychological and sociological impacts on millions of people, with over 300,000 people resettled.
- There was major disruption of land, habitat, and workplaces – about 150,000 square km in Belarus, Russia, and Ukraine were contaminated, and an area within 30 km of the plant was declared an exclusion zone.
- About 7 million people in the most affected regions still receive compensation or allowances related to their role in recovering from or being affected by the Chernobyl accident.

Thorough assessment of the Chernobyl accident's social and economic impacts was impeded by its context. The accident occurred during the Cold War, when the USSR had a highly secretive government and its economy and society were opaque to Western analysts. The magnitude of the social impacts became clearer in retrospect. As discussed in Section 3, above, there is strong evidence that the accident was a principal cause of the dissolution of the USSR.

The ASME task force also compiled estimates of economic damage attributable to the Fukushima accident. That work was done in early May 2012, 14 months after the accident. The task force compiled estimates, from various sources, of the following components of economic damage:[90]

- Replacement power cost: US$55 billion for increased import of fossil fuel through the final 9 months of 2011.
- Direct cleanup and decommissioning cost for Units 1-4 at Fukushima #1: In excess of US$250 billion.
- Cost of cleanup of contaminated land (offsite): In October 2011, Prime Minister Noda estimated a cost of US$13 billion; the actual cost will depend on cleanup standards.
- Compensation of displaced citizens: The Japanese government set aside an initial amount of US$65 billion to cover this cost.
- Lost capitalization of TEPCO: $30 billion.
- Lost commerce: Not estimated.

The ASME task force went on to say:[91]

> "The estimated total cost of the Fukushima Dai-ichi accident is therefore currently approaching $500 billion U.S. dollars. This can only increase in the future because of the additional imported LNG to replace the power from the shuttered nuclear power plants and from other losses of commerce. As of May 5, 2012, all Japanese nuclear power plants are shut down for an undefined period while safety assessments and improvements are being made. The local prefectures have the final approval authority once the Government of Japan approves restart. It is not known at this time when or if the local prefectures will allow restart of the plants in their regions

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[89] ASME, 2012, page 88.
[90] ASME, 2012, pp 86-87.
[91] ASME, 2012, page 87.

> or if the Japanese government will decide to phase out nuclear power in the country. If Japan abandons nuclear power, there will be staggering economic and environmental impacts, including shutdown of much of the Japanese nuclear infrastructure and potential loss of nuclear power technology export business."

This report was completed in February 2014. At that point, 21 months after the cutoff date for the ASME task force's estimate, the total cost of the Fukushima accident was continuing to rise. All of Japan's commercial reactors were still shut down. Presumably, therefore, the total cost as of February 2014 was substantially in excess of US$500 billion. The ultimate total cost, whatever its value will be, will reflect both radiological risk and program risk.

ESTIMATING THE FREQUENCY OF ECONOMIC DAMAGE, FROM EXPERIENCE

Three analysts based in Switzerland – Sornette et al – have written an illuminating paper that compares PRA findings with lessons from experience.[92] The paper considers monetized losses from nuclear-facility incidents, using two sources of information. One source is a reactor PRA. The other source is a compilation of data on actual incidents at nuclear facilities. Figure 5.2-3 reproduces a figure from Sornette et al. That figure shows that the PRA substantially under-estimates the probability of a monetized loss. The under-estimation grows as losses become larger. In other words, the PRA findings show a thin-tail probability distribution, whereas the empirical data show a fat-tail distribution.

SUMMARY

Gallucci's analysis of accident experience suggests a CDF as high as $6.0\text{x}10^{-4}$ per RY. The lowest value in the range suggested by Gallucci is $0.7\text{x}10^{-4}$ per RY. It is instructive to compare these numbers with the CDF estimates from NUREG-1150 that are shown in Figures 5.1-1 and 5.1-2. The only CDF estimates in those figures that approach experience levels are the upper-bound (95th percentile) levels of earthquake-caused CDF using Livermore seismic estimates. Thus, experience indicates that NUREG-1150 substantially under-estimated CDF. This finding does not mean that NUREG-1150 was a bad study. On the contrary, as stated above, NUREG-1150 was the high point of PRA practice. This finding simply confirms that PRA cannot account for all of the factors that determine the probability component of radiological risk.

Experience also shows that a reactor accident can have substantial and diverse consequences. These consequences can include fatal cancers, contamination of land, displacement of populations, societal stress, political disruption, and economic damage measured in hundreds of billions of dollars.

5.3 PRA Findings for Darlington: DPSE, DARA, and Related Studies

Preceding parts of this report provide background information that can help to guide a critical review of the PRA studies that have been done for DNGS. In turn, that critical review can shed light on the radiological risk posed by the Pickering and Bruce stations, and by CANDU reactors elsewhere.

This section (i.e., Section 5.3) of this report begins with brief discussion of some issues that provide a context for reviewing the PRA studies done for DNGS. Then, this section examines those studies and some related studies that address other CANDU stations.

COMPARING RADIOLOGICAL RISK POSED BY A CANDU REACTOR AND BY OTHER TYPES OF REACTOR

The NUREG-1150 study was done for PWRs and BWRs, which together constitute about 80% of the worldwide fleet of commercial reactors. PWRs and BWRs have some design features in common with CANDU reactors. For example, each type employs fuel assemblies made up of uranium oxide pellets stacked inside zirconium alloy (i.e., zircaloy) tubes. There are also many differences in design.

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[92] Sornette et al, 2013.

Table 5.3-1 compares the inventories of two, representative radio-isotopes in the core of a Darlington reactor and the core of the Indian Point 2 reactor, which is a PWR located in New York state. I-131, whose half-life is 8 days, represents the shorter-lived isotopes in each reactor core, while Cs-137, whose half-life is 30 years, represents the longer-lived isotopes. One sees that the two reactors have comparable inventories of I-131, while the Darlington reactor has a significantly smaller inventory of Cs-137.

The smaller inventory of Cs-137 in the Darlington reactor reflects the fact that CANDU fuel is driven to a lower burnup than is PWR fuel. That difference means that the Darlington reactor would pose a lower radiological risk than would the Indian Point 2 reactor, if all other factors were equal. However, other factors are not equal. Notably, at Darlington and other nuclear stations in Ontario, one safety system is shared among several reactors. The adverse implications of that arrangement for radiological risk are discussed in Section 5.5, below.

CONTRIBUTION OF STORED SPENT FUEL TO RADIOLOGICAL RISK

One sees from Table 5.3-1, Note (f), that a spent-fuel pool adjacent to the Indian Point 2 reactor contains a large inventory of Cs-137. That pool contains 2,300 PBq of Cs-137 while the reactor core contains 420 PBq of Cs-137. At DNGS, spent fuel discharged from the four reactors is stored in two irradiated fuel bays (IFBs). These IFBs contain an inventory of Cs-137 that must be substantially larger than the inventory in the reactor cores.

If water is lost from the spent-fuel pool at Indian Point 2, the temperature of the spent fuel could rise to the point where a self-propagating exothermic reaction between zircaloy cladding and steam or air begins. That potential event, often termed a “pool fire”, could release to the atmosphere a substantial amount of radioactive material, including a substantial fraction of the Cs-137 inventory in the pool.[93]

OPG and CNSC are aware that loss of water from an IFB at DNGS is an event to be feared. However, neither entity has performed the investigation needed to determine if a pool fire could occur at DNGS or another CANDU station. Thus, neither entity knows the contribution of spent-fuel storage to the radiological risk posed by DNGS. In 2012 this author recommended that OPG and CNSC rectify this deficiency in their knowledge prior to completion of the EA process for refurbishment and continued operation of DNGS.[94] That work was not done.

CRITERIA FOR JUDGING A PRA

This report shows that a PRA cannot provide a comprehensive, objective assessment of the radiological risk posed by a commercial reactor. Nevertheless, a PRA can provide valuable information about that risk, if the limitations of PRA are kept firmly in mind. Thus, it is important to establish high standards for the conduct of PRAs. Appropriate criteria for judging a PRA include:

- **Scope and completeness**: A PRA should be done at Levels 1, 2, and 3, with full consideration of internal and external initiating events.
- **Uncertainty and variability**: Sources of uncertainty and variability should be identified, and their effects should be systematically propagated through each phase of the analysis.
- **Openness and transparency**: Assumptions, supporting data, analytic methods, and analytic findings should be fully and clearly described in published documents.
- **Peer review**: The PRA should be subjected to thorough, independent, open peer review, and revised to reflect the findings of that review.

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[93] Thompson, 2012.

[94] Thompson, 2012.

ROLES OF DPSE AND DARA

OPG published the summary report of the *Darlington NGS Risk Assessment* (DARA) in May 2012.[95] DARA is an update of Ontario Hydro's *Darlington Probabilistic Safety Evaluation* (DPSE), whose summary report was published in December 1987.[96] At this time, DARA is the only document OPG has proffered to CNSC that might support a rigorous assessment of "the risks to national security, the health and safety of persons and the environment" that would arise from refurbishment and continued operation of DNGS.

This author coordinated a study, titled *Risk Implications of Potential New Nuclear Plants in Ontario*, that was published in November 1992.[97] One of the issues addressed by the study was the radiological risk of operating DNGS, which was then under construction. In addressing that issue, the study conducted a focused review of DPSE. Initially, Ontario Hydro provided only the summary report of DPSE. Eventually, with some reluctance, Ontario Hydro provided the full version of DPSE. Also, Ontario Hydro arranged an extensive tour of DNGS by the author and his colleagues, while they were conducting their study.

To the author's knowledge, release of the full version of DPSE in 1992 was the only occasion on which the full version of a Canadian PRA for a CANDU station has been published. In other instances, only summary documents have been published. Also, the focused review of DPSE by the author and his colleagues was the only occasion on which a Canadian PRA for a CANDU station has been subjected to open, independent peer review. Our group was obliged to conduct a focused review, rather than a comprehensive review, because our funding was limited. Nevertheless, we identified substantial deficiencies in DPSE.

FINDINGS OF DPSE AND DARA

Table 5.3-2 shows DPSE and DARA estimates of the frequencies of various fuel damage categories (FDCs) for accidents initiated by internal events. Only a few of the FDCs would involve severe core damage (i.e., "loss of core structural integrity"), which is analogous to the partial or total core melting that is considered in a PRA for a PWR or BWR. The potential occurrence at DNGS of fuel damage in categories across a spectrum of severity reflects the division of a CANDU reactor core into multiple fuel channels. By contrast, a PWR or BWR core is more compact, and does not have separate fuel channels.

DPSE found that only one fuel damage category – FDC0 – would involve severe core damage. As shown in Table 5.3-2, DPSE estimated that the mean frequency of FDC0, accounting only for internal initiating events, would be $3.8\text{x}10^{-6}$ per RY. According to DPSE, this mean value would feature an uncertainty factor of 6, where that factor would be the ratio of the 95th percentile frequency to the mean frequency.[98] In other words, the 95th percentile value of the internal-events FDC0 frequency would be $6\text{x}3.8\text{x}10^{-6} = 2.3\text{x}10^{-5}$ per RY.

DARA found that two fuel damage categories – FDC1 and FDC2 – would involve severe core damage. As shown in Table 5.3-2, DARA estimated that their combined frequency, accounting only for internal initiating events, would be $7.9\text{x}10^{-6}$ per RY. DARA did not say if this estimate was a mean value, and did not provide an uncertainty factor. Interestingly, DARA's estimate – after two decades of DNGS operation – was more than twice DPSE's mean estimate. All of this increase was attributable to event sequences not involving failure to shut down the fission reaction.

Table 5.3-3 shows DPSE estimates of the frequencies and collective-dose impacts of various ex-plant release categories (EPRCs) at DNGS, for internal initiating events. The largest release – EPRC0 – had an estimated mean frequency of $4.4\text{x}10^{-6}$ per RY. No uncertainty factor was provided. The collective-dose impact of this release was not calculated. In Table 5.3-3 and elsewhere in this report, the monetary equivalent of collective dose is shown, assuming a value of $1 million per person-Sv. That value is shown for illustrative purposes.

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[95] OPG, 2012.

[96] Ontario Hydro, 1987.

[97] IRSS, 1992.

[98] Ontario Hydro, 1987, Table 5-2 and Section 5.4.

Table 5.3-4 shows DPSE estimates of the magnitudes of atmospheric, radioactive release associated with various EPRCs. This table focuses on two isotopes, namely I-131 and Cs-137. Many analysts refer to the magnitude and other characteristics of a particular estimated release as the "source term" for that release. One sees from Table 5.3-4 that DPSE did not provide a source term for EPRC0.

DARA did not use EPRCs. Instead, it used release categories (RCs) as shown in Table 5.3-5. According to OPG, "large" atmospheric releases would be in categories RC1 through RC3. CNSC has defined a large, atmospheric release as one containing an amount of Cs-137 exceeding 0.1 PBq ($1x10^{14}$ Bq). One sees from Table 5.3-5 that DARA yielded estimates of mean frequencies for RC1 and RC2, while concluding that the frequency of RC3 is zero. No uncertainty factor was provided. Collective-dose impacts – which might be mean values, but were not stated as such – were estimated in DARA for RC1, RC2, and some other release categories. DARA did not provide a source term for any of the releases that it considered.

DPSE considered only internal initiating events. By contrast, DARA also considered external initiating events of three types – fire, seismic, and flooding events. Table 5.3-6 shows DARA's estimate of severe-core-damage frequency for these external events and for internal events. Also shown, for each event type, is the estimated frequency of a large release. Severe-core-damage and large-release frequencies might be mean values, but were not stated as such. No uncertainty factor was provided.

DARA repeated its internal-events analysis in two iterations. In the first iteration, DARA made different assumptions, in a so-called "enhanced model". In the second iteration, DARA also assumed the future implementation of four Safety Improvement Opportunities (SIOs) at DNGS. From Table 5.3-6, Note (c), one sees that the original DARA analysis and its two subsequent iterations yielded severe-core-damage and large-release frequencies as follows, with OPG safety-goal targets and limits being shown for comparison:

Version of DARA Study	Severe Core Damage Frequency (per RY)	Large Release Frequency (per RY)
Baseline study	$1.4x10^{-5}$	$9.5x10^{-6}$
Enhanced model	$9.4x10^{-6}$	$5.6x10^{-6}$
Enhanced model + SIOs	$8.2x10^{-6}$	$4.7x10^{-6}$
OPG Safety Goal Target	$1.0x10^{-5}$	$1.0x10^{-6}$
OPG Safety Goal Limit	$1.0x10^{-4}$	$1.0x10^{-5}$

One sees that OPG's alteration of the analytic assumptions in DARA drove the frequency of severe core damage to just below OPG's safety-goal target, while the frequency of large release remained above that target. If these estimated frequencies were multiplied by an uncertainty factor – say, for example, the value of 6 provided in DPSE for FDC0 – one sees that all values of severe-core-damage frequency would exceed the OPG safety-goal target, while all values of large-release frequency would exceed the OPG safety-goal limit.

For a given category of initiating events, estimates of severe-core-damage frequency and large-release frequency can be translated into a conditional probability of large release, given severe core damage. Table 5.3-7 shows values of this conditional probability, derived from DPSE and DARA estimates of frequency. One sees that DPSE and DARA found a conditional probability of large release of 22% and 66% respectively, for internal events. It is interesting that this conditional probability rose by a factor of 3 when DPSE's 1987 analysis was updated by DARA in 2012. Note that DARA found an overall conditional probability of large release, across all categories of initiating event, of 68%. For comparison, OPG's safety-goal targets and limits call for a conditional probability below 10%.

PRA FINDINGS FOR PICKERING B

This report focuses on the Darlington station. Nevertheless, it is instructive to examine OPG's most recent estimates for severe-core-damage frequency and large-release frequency at the Pickering B station. Those estimates, published in 2013, are provided in Table 5.3-8. One sees that, summed across all categories of initiating event, estimated severe-core-damage frequency at Pickering B exceeds the OPG safety-goal target, while large-release frequency exceeds the OPG safety-goal limit. These frequencies might be mean values. The overall conditional probability of large release, given severe core damage at Pickering B, is 94%.

OPG's estimate of large-release frequency at the Pickering B station has risen dramatically over a period of several years. This change is evident from Table 5.3-9, which shows licensee estimates of the frequencies of various release categories – EPRCs – at the Bruce A, Bruce B, and Pickering B stations. For Pickering B, the estimates were made by OPG and published in 2008. One sees that the combined frequencies of EPRC1 through EPRC4 at Pickering B, as estimated by OPG in 2008, total $3.7\text{x}10^{-10}$ per RY. It is reasonable to assume that categories EPRC1 through EPRC4 bound all releases that would be "large" by CNSC's definition.

CHANGES IN PRA FINDINGS OVER TIME

Comparisons across Tables 5.3-2 through 5.3-9 show some interesting changes in PRA findings over time. For Darlington, the relevant time points are 1987, when the DPSE summary was published, and 2012, when the DARA summary was published. For Pickering B, the relevant time points are 2008 and 2013, when the previous and most recent versions of the Pickering B PRA findings were published.

Changes in estimated large-release frequency are of particular interest from the perspective of radiological risk. Those changes have occurred in two respects. First, the large-release frequency attributable solely to internal initiating events has changed. Second, the earlier studies for Darlington and Pickering B did not consider external initiating events, while the later studies did, resulting in a further change in estimated large-release frequency.

Notable changes in **estimated large-release frequency** over time were as follows:

- For Darlington, considering internal initiating events only, the 1987 DPSE estimate was $8.2\text{x}10^{-7}$ per RY whereas the 2012 DARA estimate was $5.2\text{x}10^{-6}$ per RY, representing an increase by a factor of 6.3.
- For Darlington, across all initiating events considered, the 1987 DPSE estimate was $8.2\text{x}10^{-7}$ per RY whereas the 2012 DARA estimate was $9.5\text{x}10^{-6}$ per RY, representing an increase by a factor of 12.
- For Pickering B, considering internal initiating events only, OPG's 2008 estimate was $3.7\text{x}10^{-10}$ per RY whereas OPG's 2013 estimate was $3.9\text{x}10^{-6}$ per RY, representing an increase by a factor of 10,500.
- For Pickering B, across all initiating events considered, OPG's 2008 estimate was $3.7\text{x}10^{-10}$ per RY whereas OPG's 2013 estimate was $1.7\text{x}10^{-5}$ per RY, representing an increase by a factor of 46,000.

To summarize, industry estimates of large-release frequency rose by a factor of 12 for the Darlington station over the period 1987-2012, and rose by a factor of 46,000 for the Pickering B station over the period 2008-2013. Both increases are significant, in the Pickering B case dramatically so.

To this author's knowledge, OPG has not explained these large differences in the findings of previous and current studies. Yet, the previous findings were issued with pretensions of high confidence and scientific objectivity. A citizen could reasonably suspect that the current findings are similarly pretentious.

CREDIBILITY OF DPSE AND DARA

Experience with reactor accidents shows that PRAs have typically under-estimated both the frequency and impacts of such accidents. That finding is clearly applicable to DPSE and DARA. For example, DARA estimated the frequency of severe core damage at DNGS to be 8.2×10^{-6} per RY, using an "enhanced" model and accounting for SIOs. (See Table 5.3-6.) Yet, Gallucci's "simple" estimate from experience suggests a frequency of 6.0×10^{-4} per RY. (See Section 5.2.) As another example, the largest collective dose estimated by DARA is 5.5×10^{4} person-Sv, for release category RC1. (See Table 5.3-5.) Yet, the Chernobyl accident caused a collective dose of 1.2×10^{6} person-Sv. (See Table 5.2-3.)

The focused review of DPSE that was conducted by this author and his colleagues identified major deficiencies in DPSE. These deficiencies resulted in DPSE's substantial under-estimation of the frequency of core damage, and the frequency and magnitude of atmospheric releases. For example, our review identified an accident sequence – involving failure of service water supply – that was completely missed by DPSE. Inclusion of just that one sequence would increase the frequency of a severe core damage accident at DNGS, initiated by internal events, by a factor of 4.[99] As another example, our review showed that DPSE had not properly accounted for a set of phenomena that could increase the frequency and magnitude of an atmospheric release. These interrelated phenomena are: (i) rapid, but incomplete, expulsion of heavy water moderator from the calandria following loss of core cooling; (ii) the functioning of the calandria vessel as a crucible to hold molten core material; and (iii) breach of containment by a hydrogen deflagration or detonation.[100]

DPSE did make an effort to address uncertainty, although its approach was crude. It seems that DARA made no effort to systematically address uncertainty. Neither DPSE nor DARA systematically addressed variability, despite the potential for this phenomenon to yield a broad spread of findings from a PRA.

DARA has not been published in full. Nor has it been subjected to independent peer review. Thus, it scores poorly in terms of its openness and transparency, and in terms of peer review. A citizen could reasonably suspect that DARA has major deficiencies that are similar to the deficiencies in DPSE that were revealed by our group's focused review.

5.4 Malevolent Acts

DNGS was not designed to resist attack, either by insiders or by outsiders. However, it has some capacity to resist attack as a result of design for other objectives. Notably, its structures are massive, to provide radiation shielding and to accommodate the loads from routine operation and design-basis accidents. Also, it has a variety of safety systems. Moreover, as a response to the Fukushima accident, OPG is implementing a variety of new safety measures, including the acquisition of emergency mitigating equipment – such as portable generators and pumps – that could be deployed during an incident. In addition, the Darlington site has a security perimeter and a guard force.

Regrettably, the capacity of DNGS to resist attack is not commensurate with the threat. A successful attack on DNGS or another nuclear station in Ontario could result in severe impacts to Canada and the USA. Due to the nature and magnitude of those impacts, nuclear stations are uniquely attractive to hostile entities as targets. From the perspective of national security, nuclear stations can be regarded as massive, pre-emplaced radiological weapons awaiting activation by an enemy.

The primary threat is that a well-resourced, knowledgeable group of hostile persons will attack DNGS or another nuclear station as a strategic move. The mounting of a successful attack would require careful preparation, and the attackers would face high personal risk. However, the perceived reward from an attack, in terms of social, economic, and political impacts in the afflicted countries, could be very high.

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[99] IRSS, 1992, Volume 2, pp 13-14.

[100] IRSS, 1992, Volume 2, Annex II.

The Canadian government, like the US government and the governments of other countries that use nuclear power, seems unaware of the full dimensions of this threat. That governmental viewpoint is evident from the fact that DNGS is provided with only a "light" defense against attack. For example, there is no evidence of an air defense at the Darlington site, either active or passive.

This report is intended for general distribution. It is not appropriate to discuss in such a report the specific vulnerabilities of DNGS, or the specific tactics that attackers might employ. Instead, this report presents some general information to illustrate the reality of the threat. That information is widely available around the world, and would already be known to the type of group that could pose a significant threat. Tables 5.4-1 through 5.4-3, and Figures 5.4-1 through 5.4-4, provide the information.

5.5 Multi-Unit Incidents

In 1987, this author wrote a report for the Ontario Nuclear Safety Review.[101] That report identified six salient areas of concern about the accident potential of CANDU reactors, with particular attention to the unusual Ontario practice of building CANDU reactors in clusters of four or eight units that share a single safety system. The six areas of concern were:

- Containment bypass or isolation failure
- High pressure sequences
- Pressure tube failure
- Hydrogen burns
- Earthquake effects
- Multiple reactor accidents

In the context of multiple reactor accidents, this author said:[102]

> "Given Ontario Hydro's practice of co-locating up to eight reactors employing a common containment system, it is very important to understand the potential for multiple reactor accidents. It was not possible within the scope of this effort to examine the extent, if any, to which common dependencies or interactions between reactor support and safety systems could initiate multiple accidents. That should clearly be an important task in any PRA effort. Of perhaps greater importance is the possibility of a severe earthquake which disables support or safety systems at more than one reactor, and which might also disable the common containment system. Finally, one should consider the effect of an accident at one reactor on the ability to control other reactors at the site."

That warning was ignored. Neither DPSE nor DARA considered multi-unit incidents. To the author's knowledge, there has been no systematic study of multi-unit incidents at any CANDU station.

The author subsequently expanded his warning to encompass not only multi-reactor incidents but also multi-facility incidents. Here, the term "facility" includes both reactors and onsite facilities for storage of spent fuel. As discussed in Section 5.3, above, neither OPG nor CNSC properly understands the radiological risk associated with storage of spent fuel at DNGS. In November 2008, the author completed a report on the scope of an EIS for new reactors at the Darlington site. One of the report's recommendations was:[103]

> "R11. Section 13 of the Draft Guidelines, titled "Cumulative Effects", should be modified by addition of a new paragraph. The new paragraph would explicitly require OPG to assess the cumulative impacts of accidents and malfunctions affecting each nuclear power plant and spent-fuel-storage facility on the Darlington site. That assessment would consider the potential for an initiating event – such as an earthquake, or a malevolent act affecting site services – to affect more than one facility."

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[101] Thompson, 1987.

[102] Thompson, 1987, pp 31-32.

[103] Thompson, 2008a, Section 9.

In March 2011, three concurrent reactor accidents occurred at the Fukushima #1 site in Japan. A fourth reactor had been temporarily defueled, but there was great concern at the time that the adjacent spent-fuel pool would experience a fire that released a large amount of radioactive material to the atmosphere. That experience suggests that the author's recommendations in 1987 and 2008 had merit. Nevertheless, neither OPG nor CNSC has acted on those recommendations.

The concurrent accidents at Fukushima drew attention to the fact that PRA practice has almost entirely neglected linkage of risk among multiple reactors at a site. That neglect was summarized in a July 2011 paper by a USA-based nuclear industry consultant, Karl Fleming. The paper said:[104]

> "Our current state of knowledge about the risks from accidents is derived from PRAs. For the most part PRAs on multi-unit sites have been performed on individual reactors separately. In fact, some multi-unit sites have performed a PRA only for one of the sited reactors, arguing that symmetry considerations justify a single reactor PRA. In order to meet expectations for PRA quality, as defined in the various PRA standards, such PRAs must address certain multi-unit dependencies in the modeling of risks that involve damage to a single reactor. The capability to use equipment from one reactor to back up failures on another is typically considered, however the probability that resources are consumed by concurrent reactor accidents is almost always ignored."

In a 2013 journal article, the analysts Schroer and Modarres proffered an event classification schema for applying PRA to multiple reactors at a site.[105] At the time of publication, co-author Suzanne Schroer was a member of the NRC staff. The article said:[106]

> "Currently, multi-unit nuclear power plant PRAs consider the risk from each unit separately and do not consider combination events between the units. To gain an accurate view of the site's risk profile, the CDF for the site rather than the unit must be considered. This paper has presented a classification system that utilizes existing single-unit PRAs and combines them into a multi- unit PRA. Six main commonality classes that can cause multiple units to be dependent have been presented: initiating events, shared connections, identical components, proximity dependencies, human dependencies, and organizational dependencies. A seventh class, independent events, was only marginally discussed because it does not address dependencies between the units."

From the two preceding paragraphs and the documents cited therein, one sees that linkage of radiological risk among multiple reactors at a site has been long neglected, but is beginning to receive some attention from NRC and its licensees. Linkage of spent-fuel-storage risk and reactor risk at a site has been similarly neglected. NRC has promised to address that linkage, but the credibility of that promise is questionable.[107]

Ontario's unusual practice of sharing a single safety system among four or eight reactors means that the potential for multi-unit incidents is especially high in Ontario. Thus, a citizen could have reasonably expected that Canada's nuclear industry and its regulators would have properly addressed this potential many years ago. After the Fukushima accident, a citizen could have reasonably expected that this potential would be addressed with urgency and high purpose.

CNSC has, in its Licence Conditions Handbook for the Pickering station, described its plan to address the potential for multi-unit incidents. CNSC said:[108]

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[104] Fleming, 2011.
[105] Schroer and Modarres, 2013.
[106] Schroer and Modarres, 2013, page 49.
[107] Thompson, 2013.
[108] CNSC, 2013a, page 124.

> "CNSC staff will work jointly with the industry in consultation with the international community on the concept-level metrics and/or re-define safety goals, for a multi-unit PSA [PRA]. OPG will develop the PSA methodologies. This may take account of work required to perform research and benchmarking against industry and international best practices for a consensus approach. It is recognized that PSA for multi-units is cutting edge work in progress for the PSA international community, and it will require a phased approach. With the goal of meeting the Commission directions the first stage should point to concept-level metrics and methodologies for multi-unit. It is expected that more work will be carried out after the hold point to develop more detailed metrics and methodologies for multi-unit sites."

That plan does not exhibit urgency, leadership, or technical sophistication. It is unlikely to develop a good understanding of multi-unit incidents, and will certainly not do so with the rapidity that is needed.

5.6 IRSN Analysis of Impacts

Section 3 of this report describes work done by IRSN analysts to estimate the costs (i.e., economic damage) that would arise from an accidental, atmospheric release of radioactive material from the Dampierre nuclear generating station in France. The analysts presented a summary of their findings at the 2012 Eurosafe conference.[109] No detail was provided.

Early in 2013, the findings of a previous IRSN report were leaked to the French media. Subsequently, IRSN released that report, which was completed in 2007.[110] That report addressed the same subject that the IRSN analysts discussed in their presentation at the 2012 Eurosafe conference, but provided more detail and contained somewhat different findings.

IRSN's 2007 report provides the most comprehensive analysis that is currently available regarding the costs of a large, atmospheric release from a nuclear station. Its findings are summarized in Table 5.6-1. One sees that the estimated costs range from 290 billion Euro to 5,760 Euro. These costs would arise from a release, at the Dampierre station, that would contain 97 PBq of Cs-137.

Table 5.6-2 translates the findings in Table 5.6-1 into a risk cost expressed in Euro per kWh of electricity. On sees that the risk cost appears large or small, depending upon the frequency of the hypothesized release. Table 5.6-3 translates the findings in Table 5.6-1 into an annualized, Europe-wide cost. Again, that cost appears large or small, depending upon the frequency of the hypothesized release. In both instances, the apparent smallness of cost of a less-frequent event is deceptive. Recall the statement of the IRSN analysts that the hypothesized release would be "an unmanageable European catastrophe".[111] That statement reminds us that the "arithmetic" definition of risk cannot capture the full dimensions of risk associated with nuclear power.

5.7 The Insurers' Perspective

This report has, up to this point, discussed two approaches to assessing the radiological risk posed by a nuclear station. One approach is PRA, and the other is examination of experience. A third approach is now discussed here. That approach is to examine the premiums that insurance companies charge for coverage of liability for damage from nuclear incidents.

In Canada and elsewhere, legislation shields the owners and operators of commercial reactors from full liability. Nevertheless, OPG is obliged to buy some liability coverage in the commercial insurance market. Presumably, the premium charged for this coverage reflects some type of analysis by insurance companies. Those companies do not disclose their analysis, but it seems reasonable to assume that experience – such as the Fukushima accident – is one of the factors they consider.

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[109] Pascucci-Cahen and Patrick, 2012.

[110] IRSN, 2007.

[111] Pascucci-Cahen and Patrick, 2012.

Table 5.7-1 shows the annual premiums paid by OPG for insurance coverage of DNGS over the period 2005-2012. Then, Table 5.7-2 uses those data and other information to calculate the implied frequency of a nuclear incident at DNGS. The implied frequency represents the insurers' assessment of the likelihood of a claim up to the liability limit.[112] For the class of incidents not caused by a malevolent act, the implied frequency of an incident at DNGS causing offsite bodily injury or property damage exceeding a specified monetary-equivalent level is as follows:

Monetary-Equivalent Injury or Damage Exceeds	Implied Frequency of Incident
$75 million	$1.7\text{x}10^{-3}$ per RY
$650 million	$7.8\text{x}10^{-4}$ to $1.2\text{x}10^{-3}$ per RY
$1,000 million	$6.4\text{x}10^{-4}$ to $1.0\text{x}10^{-3}$ per RY

That range of implied frequency is a fairly close match to the range of estimated severe-accident frequency that is shown in Table 5.2-1, based on experience. As discussed earlier in this report, Table 5.2-1 shows frequency estimates developed within a JAEC subcommittee. The only frequency estimate in Table 5.2-1 that is substantially lower than the incident frequency implied by Darlington's insurance premium is an estimate of 1.0×10^{-5} per RY that was based upon aspiration, not experience.

The range of implied frequency shown above is also a fairly close match to the "Empirical Records" curve shown in Figure 5.2-3. The match suggests that the Canadian nuclear insurers, whether by judgment or analysis, have reached conclusions similar to those of Sornette et al, the authors of Figure 5.2-3.

If offsite damage exceeds $1 billion, the implied frequency of the incident, based on insurance premiums, is $6.4\text{x}10^{-4}$ to $1.0\text{x}10^{-3}$ per RY. That range can be compared with the DARA estimates shown in Table 5.3-5. If collective dose is valued at $1 million per person-Sv, one sees from Table 5.3-5 that release category RC1 has an estimated frequency of $4.9\text{x}10^{-6}$ per RY and would yield offsite damage of $55 billion. Release categories RC2 through RC7 have lower estimated frequencies and damages. Clearly, Canada's nuclear insurers are not persuaded by the low estimates of incident frequency that are presented in DARA. The insurers assume an incident frequency more than two orders of magnitude greater than the estimates presented in DARA.

5.8 A Prudent Assessment for DNGS

This report shows that DARA substantially under-estimated the frequency of core damage at DNGS, and the frequency and magnitude of atmospheric releases that would arise from core damage. To show the potential magnitude of these under-estimates, this report provides some illustrative analysis. This analysis and its assumptions are configured to provide a "prudent" assessment of the radiological risk of operating DNGS.

FREQUENCY OF A SUBSTANTIAL RELEASE

This illustrative, prudent assessment begins by assuming a frequency of substantial atmospheric release from DNGS. The assumed frequency is intended to account for both accidents and attacks. Two cases are used. The Low Case assumes a release frequency of $1\text{x}10^{-4}$ per station-year, and the High Case assumes a release frequency of $1\text{x}10^{-3}$ per station-year. These frequencies would be smaller by a factor of 4 if expressed on a per-reactor-year basis. Given worldwide experience and the judgment of Canada's nuclear insurers, the assumed frequencies are reasonable, and not necessarily conservative.

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[112] A claim up to the liability limit implies that damage exceeded the liability limit.

MAGNITUDE OF A SUBSTANTIAL RELEASE

The next step in this assessment is to assume a magnitude of substantial atmospheric release from DNGS. In this context, one faces the problem that Canada's nuclear industry and its regulators have not published, and may not have properly conducted, a credible study on the potential for a large, atmospheric release from a CANDU station.

A Canadian engineer with long experience in the AECB, John W. Beare, has commented on the Canadian practice of not examining the nature and impacts of the largest potential releases from a nuclear station, stating:[113]

> "If the Commission [CNSC] is concerned about the cost-benefit aspects of its safety requirements it could start by completing the Severe Accident Study research project started about 1988 but never completed. The conclusion of the preliminary study is that, in the event of a catastrophic accident, a release of radioactive material proportionately as large as that from Chornobyl could not be ruled out. In the case of a water-cooled reactor like CANDU such a release could be in the form of a relatively cool aerosol and not be dispersed as much as at Chornobyl. The radiation doses close to the reactor could be higher than at Chornobyl."

Neither DPSE nor DARA took account of a potential atmospheric release of the magnitude described by Beare. Table 5.3-4 shows the small release fractions of I-131 and Cs-137 that were considered in DPSE. Comparison of the collective-dose estimates in Tables 5.3-3 and 5.3-5 shows that the release fractions considered in DARA were similarly low.

Given the longstanding failure of OPG, CNSC, and their predecessors to examine the nature and impacts of a large atmospheric release, it remains appropriate to employ the same assumption as was used by the author and his colleagues in their 1992 study.[114] That assumption is that DNGS experiences a 2 x "PWR2" release, in which 2 reactors each experience release fractions equal to the PWR2 case in NRC's Reactor Safety Study. The same overall release could occur if 3 or 4 reactors were involved, with smaller release fractions.

During a PWR2 release, the release fractions of Iodine and Cesium isotopes would be 70% and 50%, respectively. A scenario at DNGS that could yield such release fractions could involve interrelated phenomena that are discussed in Section 5.3, above. These phenomena are: (i) rapid, but incomplete, expulsion of heavy water moderator from the calandria following loss of core cooling; (ii) the functioning of the calandria vessel as a crucible to hold molten core material; and (iii) breach of containment by a hydrogen deflagration or detonation. [115]

OFFSITE IMPACTS OF THE ASSUMED RELEASE

Table 5.8-1 describes an estimation of collective dose from a 2 x "PWR2" atmospheric release at DNGS, for selected weather conditions. The release would include 4,100 PBq of I-131 and 67 PBq of Cs-137. From Table 5.2-2 one sees that a release of 67 PBq of Cs-137 would be smaller than the Chernobyl release (85 PBq) and larger than the Fukushima release (37 PBq). From Table 5.8-1 one sees that the weighted average of collective dose across the selected weather conditions, for a distance range of 0-1,000 km, is 2.7 million person-Sv.

As discussed in Section 5.6, above, IRSN estimated the costs arising from an atmospheric release at the Dampierre station that would include 97 PBq of Cs-137. The estimated costs range from 290 billion Euro to 5,760 billion Euro. The average across that range is 3,025 billion Euro. No one has done an estimate of this kind for a release in North America. In the absence of such an estimate, the IRSN findings are adjusted here so that they can be applied to a release from DNGS. One adjustment is to scale estimated costs in proportion to the Cs-137 content of the assumed release, which is 97 PBq in the Dampierre case and 67 PBq in the DNGS case. The other adjustment is currency conversion at the rate of Can$1.5 per Euro. These adjustments yield an average estimate of costs in the DNGS case of: (3,025 billion)x(67/97)x(1.5) = Can$3,130 billion.

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[113] Beare, 2005, paragraph 192.

[114] IRSS, 1992.

[115] IRSS, 1992, Volume 2, Annex II.

To some analysts, a cost estimate of $3 trillion might seem implausibly high. However, as discussed in Section 5.2, above, data compiled by an ASME task force show that the cost of the Fukushima accident now exceeds US$0.5 trillion and is continuing to grow. The task force expressed a concern that additional, "staggering" economic impacts would arise if Japan phases out nuclear power.

In the Fukushima case the majority of the radioactive fallout was over the Pacific Ocean. Only about 6 PBq of Cs-137 was deposited on Japan. By contrast, DNGS is at an inland site. If 67 PBq of Cs-137 were released at DNGS, much of that material would be deposited on Canada and the USA. As a result, the overall cost could be greater in the DNGS case than in the Fukushima case.

Another comparison is to consider the cost of the collective dose that would be caused by an atmospheric release. As discussed above and presented in Table 5.8-1, our group estimated the collective dose from a release at DNGS that would include 67 PBq of Cs-137. The weighted average of collective dose across selected weather conditions, for a distance range of 0-1,000 km, was estimated at 2.7 million person-Sv. If collective dose were valued at $1 million per person-Sv, the total cost would be $2.7 trillion. In the Chernobyl case, as shown in Table 5.2-3, the collective dose is 1.2 million person-Sv. The total cost in that case, assuming a value of $1 million per person-Sv, would be $1.2 trillion.

As shown in Table 5.2-4, each person-Sv of collective dose corresponds to 0.051 premature, solid-cancer deaths. Thus, adopting a value of $1 million per person-Sv is equivalent to valuing a premature, solid-cancer death at: ($1 million)/(0.051) = $19.6 million. In this context, it is interesting to note that, in the early 1990s, the owners of nuclear stations in the USA were spending an average amount of US$1,170,000 per person-Sv (in 2013$) to reduce occupational exposure of their workers.[116]

A study sponsored by Defence Research and Development Canada sheds light on the plausibility of a $3 trillion cost estimate. That study estimated the economic impact of an open-air explosion of a radiological dispersal device (i.e., dirty bomb) at the CN Tower in Toronto.[117] The assumed release consisted of 0.037 PBq of Cs-137. The estimated economic impact varied considerably, according to the cleanup standard that was assumed in the analysis. That standard was expressed in terms of the radiation dose rate that would remain after completion of the cleanup. For a cleanup standard of 5 mSv per year, the estimated economic impact would be $28 billion, whereas for a cleanup standard of 0.15 mSv per year the impact would be $250 billion. The magnitudes of those costs are enlightening when one considers that the assumed release (i.e., 0.037 PBq of Cs-137) is very small in comparison to the DNGS release assumed here, which includes 67 PBq of Cs-137.

OFFSITE RISK COSTS OF THE ASSUMED RELEASE

Using the assumptions set forth above, Table 5.8-2 sets forth a calculation of the offsite risk costs of the assumed atmospheric release. In the Low Case, these risk costs sum to 1.2 cents per kWh, and in the High Case they sum to 11.5 cents per kWh.

OTHER IMPACTS OF THE ASSUMED RELEASE

The concept of a monetized risk cost reflects an "arithmetic" definition of risk. As discussed in Section 3, above, that definition cannot capture the full dimensions of risk associated with nuclear power. Thus, consideration of the risk costs set forth in Table 5.8-2 should be supplemented by considering aspects of risk that are not readily quantifiable. That matter is discussed further in Section 7, below.

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[116] The average expenditure was $734,000 per person-Sv in 1990$. (See: Baum et al, 1994, Figure 4 and Table 15.) That amount is adjusted here to 2013$ using a relative GDP deflator of 1.59.

[117] Cousins and Reichmuth, 2007.

6. Assessing Program Risk at DNGS

In the context of refurbishment and continued operation of DNGS, categories of program risk include the potential for:

1. Budget or timeline overruns during refurbishment;
2. Failure of refurbished units to perform as predicted;
3. Regulatory change that constrains reactor operation or requires expensive plant modifications, perhaps as a result of an incident at another nuclear station; and
4. A radiological incident at DNGS that disables the station and requires expensive cleanup.

OPG's business case for refurbishment of DNGS proffers assertions about program risk in categories #1 and #2.[118] However, OPG has not published the data, assumptions, and analytic methods underlying those assertions. If refurbishment proceeds, the accuracy of OPG's assertions will become evident over time.

The IRSN analysis that is described in Section 5.6, above, encompasses aspects of program risk in category #3. By extension, that part of the IRSN analysis is reflected in the prudent assessment of DNGS radiological risk that is set forth in Section 5.8, above.

Here, the focus is on program risk in category #4. Ontario Hydro addressed that type of risk in DPSE. To the author's knowledge, OPG has not performed any comparable analysis in the current period.

Table 6-1 summarizes DPSE's treatment of program risk in category #4. That table presents DPSE's findings without alteration except that costs in Canadian dollars are adjusted from 1985 values to 2013 values, using a GDP deflator. An interesting feature of the estimates in Table 6-1 is that incidents with a comparatively high frequency could cause large onsite economic impacts. For example, an FDC6 incident is said to have a mean frequency of 2.0×10^{-3} per RY (i.e., 8% per station-decade), and would cause onsite economic impacts of $2.2 billion to $4.2 billion.

Table 6-2 translates the DPSE estimates shown in Table 6-1 into risk costs expressed as cents per kWh of electricity generated by DNGS. There is one adjustment during that translation. The incident frequencies shown in Table 6-1, which account only for internal initiating events, are multiplied by a factor of 2, to account for external initiating events and malevolent acts.

The "bottom line" finding in Table 6-2 is that the program risk costs of a radiological incident that disables DNGS are estimated to total 0.9 cents per kWh as a mean estimate, and 4.8 cents per kWh as a 95th-percentile estimate. These estimates are by Ontario Hydro, with a modest adjustment to account for external initiating events and malevolent acts.

A thorough, independent assessment of program risk associated with DNGS refurbishment would update the DPSE analysis summarized in Table 6-1. That new work might lead to an upward or downward revision of the program risk costs presented here. In addition, a thorough assessment would investigate various other aspects of program risk, and those investigations would yield additional program risk costs. Thus, the program risk costs presented here are reasonable for illustrative purposes, and are not necessarily conservative.

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[118] Robinson et al, 2014.

7. An Overview of Risk at DNGS, and its Implications

Section 5.8 of this report sets forth a "prudent" estimate of the radiological risk of operating DNGS. Section 6 sets forth an estimate, based on analysis by Ontario Hydro, of the program risk of operating DNGS. In both instances, the "bottom line" indicator is an amalgam of risk costs, expressed in cents per kWh of electricity. These two estimates can be combined to provide an illustrative estimate of the overall risk – radiological risk plus program risk – associated with refurbishment and continued operation of DNGS.

Table 7-1 shows the estimated overall risk costs. They sum to 2.1 cents per kWh in the Low Case, and 16.3 cents per kWh in the High Case. Neither case is necessarily conservative.

These risk costs are at a level where they are significant for decision making about the refurbishment of DNGS. For example, one sees from Figure 2-1, which was authored by OPG, that an increase of 4 cents per kWh in the cost of electricity from a refurbished DNGS could tip the balance of choice in favor of a new, gas-fired station that does not emit CO_2.

The concept of a monetized risk cost reflects an "arithmetic" definition of risk. As discussed at length in Section 3, above, that definition cannot capture the full dimensions of risk associated with nuclear power. Canadian experts have recognized this inadequacy. Thus, consideration of the risk costs set forth in Table 7-1 should be supplemented by considering aspects of risk that are not readily quantifiable. Those aspects include the potential for an accident or attack at DNGS to severely disrupt Canada's society, economy, politics, international relations, and trade.

The magnitude of the potential disruption is illustrated by the possibility that an atmospheric release from DNGS could impose costs in the vicinity of $3 trillion. Those costs would be distributed across Canada and the USA. In most instances, those costs would never be compensated. Thus, numerous parties would be aggrieved, and their grievances could poison Canada-US relations and Canadian politics for many decades.

The level of risk that has been identified here has substantial implications. In Ontario, it has implications for decision making about the refurbishment and continued operation of the Darlington and Bruce reactors, and about the remaining years of operation of the Pickering reactors. It also has implications for Ontario's emergency-response planning. Across Canada, it has implications for:

- The adequacy of emergency-response planning;
- The need for upgrading of Canada's *Nuclear Liability Act*;
- The need to enhance the safety and security of nuclear reactors; and
- Canada's national security.

8. Conclusions and Recommendations

CONCLUSIONS

C1. Canada's *Nuclear Safety and Control Act* obliges CNSC to obtain, prior to authorizing the refurbishment and continued operation of DNGS, a rigorous assessment of "the risks to national security, the health and safety of persons and the environment" that would arise from that action. At this time, the only document OPG has proffered to CNSC that might support such an assessment is a PRA known as DARA.

C2. A well-conducted PRA can provide useful information about the radiological risk posed by a nuclear generating station, if the limitations of PRA are kept firmly in mind. However, a PRA cannot provide a comprehensive, objective assessment of that risk. This conclusion reflects intrinsic properties of radiological risk, and is amply supported by worldwide experience in the use of nuclear power.

C3. DARA does not rank high as a PRA. It does not address the most severe potential releases and their impacts. It does not consider uncertainty and variability, scores low on openness and transparency, and has not been subjected to independent peer review. It does not address multi-unit incidents. Consistent with those deficiencies and the general limitations of PRA, experience indicates that DARA substantially under-estimates the frequency and impacts of severe accidents at DNGS. The premiums charged by Canadian nuclear insurers confirm that conclusion.

C4. Neither OPG nor CNSC has publicly addressed, in DARA or elsewhere, the vulnerability of DNGS to malevolent acts and the potential consequences of such acts. Yet, DNGS and other nuclear stations in Canada and the USA are uniquely attractive to hostile entities as strategic targets. From the perspective of national security, nuclear stations can be regarded as massive, pre-emplaced radiological weapons awaiting activation by an enemy.

C5. OPG has not provided a systematic assessment of program risk associated with refurbishment and continued operation of DNGS. Yet, Ontario Hydro considered aspects of that risk in its 1987 DPSE study, showing that the risk could be substantial.

C6. In light of the preceding conclusions, it is clear that decision making about refurbishment and continued operation of DNGS has been conducted without full information about the associated radiological risk and program risk.

C7. Illustrative analysis in this report shows that monetized risk costs, not yet considered by OPG or CNSC, could be substantial. For radiological risk, those costs could be 1.2-11.5 cents per kWh of electricity. For program risk, those costs could be 0.9-4.8 cents per kWh. Taken together, these risk costs sum to 2.1-16.3 cents per kWh. An indication of the significance of such costs is OPG's determination that an increase of 4 cents per kWh in the cost of electricity from a refurbished DNGS could tip the balance of choice in favor of a new, gas-fired station that does not emit CO_2.

C8. The concept of a monetized risk cost reflects an approach to risk assessment in which risk is the numerical product of indicators of frequency and impact. Experience shows that this approach cannot capture the full dimensions of risk associated with nuclear power. Canadian experts have recognized this inadequacy. Thus, consideration of the risk costs set forth in Conclusion C7 should be supplemented by considering aspects of risk that are not readily quantifiable. Those aspects include the potential for an accident or attack at DNGS to severely disrupt Canada's society, economy, politics, international relations, and trade.

C9. In light of the preceding conclusions, it is almost certain that a thorough, independent assessment of the radiological risk and program risk associated with refurbishment and continued operation of DNGS would identify large costs and impacts that have not yet been recognized by decision makers.

C10. Conclusions C1 through C9 focus on the Darlington reactors, but apply equally to the Bruce reactors, including the two previously-refurbished Bruce reactors. Also, they are relevant to the remaining years of operation of the Pickering reactors. Moreover, these conclusions have important Canada-wide implications regarding the adequacy of emergency response planning for nuclear incidents, the need for upgrading of Canada's *Nuclear Liability Act*, the need to enhance the safety and security of reactors, and Canada's national security.

RECOMMENDATIONS

R1. The governments of Ontario and Canada should promptly arrange a thorough, independent assessment of the radiological risk and program risk associated with refurbishment and continued operation of DNGS. That assessment should be designed so that its findings are transferable to the Bruce and Pickering stations and other CANDU stations.

R2. The government of Ontario should ensure that the findings of the independent assessment are properly reflected in decisions about the refurbishment and continued operation of Ontario's nuclear reactors, and in Ontario's planning for emergency response in the event of a nuclear incident.

R3. The government of Canada should ensure that the findings of the independent assessment are properly reflected in decisions regarding the adequacy of emergency response planning for nuclear incidents, the need for upgrading of Canada's *Nuclear Liability Act*, the need to enhance the safety and security of reactors, and Canada's national security.

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Table 3-1

Framework of Principles for Design and Appraisal of an Infrastructure Investment so as to Achieve Sustainable Outcomes

OBJECTIVE	DESIGN APPROACH DICTATED BY OBJECTIVE
#1. Serve a societal purpose	Design to meet societal needs with optimal efficiency, consistent with objectives #2, #3, and #4
#2. Build and preserve assets	Design for preservation and enhancement of: ▪ Human capital ▪ Natural capital ▪ Engineered capital
#3. Create options for the future	Design for: ▪ Reversibility ▪ Resilience ▪ Adaptability ▪ Flexibility
#4. Manage risk	Prepare for unusual events by: ▪ Identifying and characterizing potential events ▪ Designing infrastructure to ride out events or to fail in a manner consistent with objectives #1, #2, and #3 ▪ Planning for emergency response

NOTES:

(a) This framework of principles is attributable solely to the author. However, each principle in the framework has been widely discussed and has, to some extent, been applied to the design and appraisal of infrastructure. At present, there is no generally accepted framework that integrates these principles.

(b) This framework reflects the definition of sustainable development that was set forth by the World Commission on Environment and Development in 1987, as follows (WCED, 1987, beginning of Chapter 2):

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs."

(c) In most instances, a societal purpose could be served by a range of infrastructure options, each reflecting a different design approach. This framework of principles could be used to identify infrastructure options, assess their comparative sustainability, and develop design specifications for the chosen option.

Table 3-2

Some Categories of Risk Posed by a Commercial Nuclear Facility (e.g., DNGS)

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

NOTES:

(a) In this report, the general term “risk” is defined as the potential for an unplanned, undesired outcome. There are various categories of risk, including the three categories in this table.

(b) In the case of radiological risk, the events leading to unplanned exposure to radiation could be accidents or attacks.

(c) The term “proliferation risk” is often used to refer to the potential for diversion of fissile material, for use in nuclear weapons. Here, the term also covers the potential for diversion of radioactive material, for use in radiological weapons.

Table 4-1

Future World Scenarios Identified by the Stockholm Environment Institute

SCENARIO	CHARACTERISTICS
Conventional Worlds	
Market Forces	Competitive, open, and integrated global markets drive world development. Social and environmental concerns are secondary.
Policy Reform	Comprehensive and coordinated government action is initiated for poverty reduction and environmental sustainability.
Barbarization	
Breakdown	Conflict and crises spiral out of control and institutions collapse.
Fortress World	This scenario features an authoritarian response to the threat of breakdown, as the world divides into a kind of global apartheid with the elite in interconnected, protected enclaves and an impoverished majority outside.
Great Transitions	
Eco-Communalism	This is a vision of bio-regionalism, localism, face-to-face democracy and economic autarky. While this scenario is popular among some environmental and anarchistic subcultures, it is difficult to visualize a plausible path, from the globalizing trends of today to eco-communalism, that does not pass through some form of barbarization.
New Sustainability Paradigm	This scenario changes the character of global civilization rather than retreating into localism. It validates global solidarity, cultural cross-fertilization and economic connectedness while seeking a liberatory, humanistic, and ecological transition.

SOURCE: Raskin et al, 2002

Table 5.2-1

Commercial Reactor Severe-Accident Frequency: Range of Views Within a JAEC Subcommittee

FREQUENCY	BASIS FOR FREQUENCY
1.0×10^{-5} per RY	Frequency is based on the IAEA safety standard for early large release frequency of existing reactors.
2.1×10^{-4} per RY	Frequency is calculated based on the operation years of commercial reactors in the world and three accidents at TMI-2, Chernobyl-4, and Fukushima Dai-ichi station by regarding the incidents in units 1 to 3 as a single event.
3.5×10^{-4} per RY	Frequency is calculated based on the operation years of commercial reactors in the world and five accidents at TMI-2, Chernobyl-4, and Fukushima Dai-ichi station by regarding the incidents in units 1 to 3 as three separate events.
6.7×10^{-4} per RY	Frequency is calculated based on the operation years of commercial reactors in Japan and by regarding the incidents in units 1 to 3 at the Fukushima Dai-ichi station as a single event.
2.0×10^{-3} per RY	Frequency is calculated based on the operation years of commercial reactors in Japan and by regarding the incidents in units 1 to 3 at the Fukushima Dai-ichi station as three separate events.

NOTES:

(a) This table is adapted from: JAEC Subcommittee, 2011, page 14.

(b) Here, the term "frequency" applies to a severe reactor accident involving substantial core damage and an atmospheric release.

(c) This table shows a range of potential assumptions about severe-accident frequency, and the basis for each assumption, that were articulated within the subcommittee. The subcommittee could not reach consensus on a single appropriate assumption. An assumption was needed for the subcommittee's analysis of future "risk cost".

(d) The context for the subcommittee's work was a JAEC study on nuclear-power economics, considering a "model" power plant – a 1,200 MWe capacity LWR similar to those constructed in the seven years up to 2011.

Table 5.2-2

Amounts of Cesium-137 Related to the Chernobyl and Fukushima #1 Accidents

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

NOTES:

(a) This table shows estimated amounts of Cesium-137 from: Stohl et al, 2012. The estimates for release from Fukushima #1 and deposition on Japan may change as new information becomes available. The cited authors subsequently stated that the Fukushima release might have been somewhat less than 37 PBq. (See: Seibert et al, 2013.)

(b) Stohl et al, 2012, provide the following data and estimates for Fukushima #1, Units 1-4, just prior to the March 2011 accident:

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

(The core capacity of Unit 4 was 548 assemblies. The core of Unit 3 contained some MOX fuel assemblies at the time of the accident.)

(c) For the Fukushima case, assuming a total Cesium-137 release to atmosphere of 37 PBq, originating entirely from the reactor cores of Units 1, 2, and 3, which contained 760 PBq, the overall release fraction to atmosphere for Cesium-137 was 37/760 = 0.049 = 4.9 percent.

(d) The atmospheric release of Cesium-137 at Chernobyl represented about 40 percent of the inventory of that isotope in the core of the affected reactor. (See: Krass, 1991, Table 2.)

Table 5.2-3

Estimated Human Dose Commitment from the 1986 Chernobyl Release of Radioactive Material to the Atmosphere

REGION	50-Year Collective Dose Commitment (person-Gy)	50-Year Average Individual Dose Commitment (mGy)
USSR (European)	4.7E+05	6.1E+00
USSR (Asian)	1.1E+05	Not available
Europe (non-USSR)	5.8E+05	1.2E+00
Asia (non-USSR)	2.7E+04	1.4E-02
USA	1.1E+03	4.6E-03
Northern Hemisphere Total	1.2E+06	Not available

NOTES:

(a) These estimated doses are whole-body doses, from: DOE, 1987, Table 5.16, “preferred estimate”.

(b) Most of the dose is attributable to Cesium-137 (see: DOE, 1987, page x).

(c) Estimates for non-USSR countries show that, on average, about 50% of the collective dose is attributable to external exposure, and about 50% is attributable to ingestion (see: DOE, 1987, Table 5.14). Uncertainty in these estimates is greater for ingestion than for external exposure.

(d) In this instance, 1 Gy is equivalent to 1 Sv.

Table 5.2-4

Estimated Lifetime Incidence and Mortality of Solid Cancer and Leukemia per 100,000 People, With or Without Exposure to 0.1 Gy of Radiation

CATEGORY OF HEALTH EFFECT	ALL SOLID CANCER		LEUKEMIA	
	Males	Females	Males	Females
Number of cases in the absence of radiation exposure (i.e., Incidence)	45,500	36,900	830	590
Number of deaths in the absence of radiation exposure (i.e., Mortality)	22,100	17,500	710	530
Number of excess cases from exposure to 0.1 Gy	800	1,300	100	70
Number of excess deaths from exposure to 0.1 Gy	410	610	70	50

NOTES:

(a) Estimates are from: BEIR VII, 2006, Table 12-13. That table shows confidence intervals for the numbers of radiation-induced health effects.

(b) These health effects arise in a population of 100,000 with an age distribution typical of the USA.

(c) These BEIR VII estimates of radiation-induced health effects rely upon a “linear no-threshold” (LNT) model of dose response for solid cancer, and a “linear-quadratic” model for leukemia.

(d) The radiation exposure considered here is a one-time dose of 0.1 Gy. Where exposure is attributable to Cesium-137, 1 Gy is equivalent to 1 Sv.

(e) Individual risk of a radiation-induced health effect varies with age at exposure. From Table 12D-2 of BEIR VII, 2006, one sees that the lifetime, radiation-induced, solid-cancer mortality risk for males (females) is 1,028 (1,717) per 100,000 people if radiation exposure occurs at birth, declining to 102 (152) per 100,000 people if the exposure occurs at age 80 years.

(f) The LNT model allows individual risk of exposure to be estimated as follows:

- For a typical (average) person, the lifetime, radiation-induced, solid-cancer mortality risk is: (((410+610)/2)/100,000)/(0.1) = 0.051 per Gy (or Sv) of exposure.
- For a newborn, the lifetime, radiation-induced, solid-cancer mortality risk is: (((1,028+1,717)/2)/100,000)/(0.1) = 0.14 per Gy (or Sv) of exposure.

(g) The first-listed finding in note (f) can be re-stated as follows:

- Across a steady-state population with an age distribution similar to that of the USA, there will be 0.051 excess, solid-cancer deaths per person-Sv of cumulative, collective radiation exposure, where the exposure can occur at any point(s) in time, or across any time period(s).

Table 5.3-1

Estimated Inventory of Selected Radioactive Isotopes in the Core of a Darlington Reactor or the Indian Point 2 Reactor, in Full-Power, Steady-State Operation

RADIOACTIVE ISOTOPE	CORE INVENTORY (PBq)		NORMALIZED CORE INVENTORY (PBq per GWt)	
	Darlington	Indian Point 2	Darlington	Indian Point 2
Iodine-131 (Half-life = 8 days)	2,920	3,200	1,100	995
Cesium-137 (Half-life = 30 years)	65	420	24.5	129
Plutonium-239 (Half-life = 24,000 years)	?	1.2	?	0.38

NOTES:

(a) Darlington data are from: ISR, 2003, Annex B, Table 35. That source does not provide a core inventory of Plutonium-239.

(b) Indian Point data are from: Entergy, 2007, Appendix E, Table E.1-13.

(c) Here, it is assumed that each Darlington reactor has a power capacity of 2,651 MWt, and the Indian Point 2 reactor has a capacity of 3,216 MWt.

(d) The higher normalized inventory of Iodine-131 for the Darlington reactor, compared with Indian Point 2, presumably reflects a combination of differences in the neutron spectrum, the fissile composition of the core, and the estimation model.

(e) Data provided by Entergy suggest that Indian Point 2 fuel is typically driven to a burnup of about 60 GWt-day per MgU.

(f) There is a spent-fuel pool adjacent to the Indian Point 2 reactor. The US Nuclear Regulatory Commission estimates that the current inventory of Cesium-137 in that pool is 2,300 PBq. (See: Satorius, 2013, Enclosure 1, Table 72, at page 132.)

Table 5.3-2

Estimated Frequencies of Occurrence of Categories of Fuel Damage at the Darlington Station: DPSE Study of 1987, and DARA Study of 2012

DPSE STUDY OF 1987		DARA STUDY OF 2012	
Fuel Damage Category (FDC)	**Estimated Mean Frequency (per RY)**	**Fuel Damage Category (FDC)**	**Estimated Frequency (per RY)**
FDC0	3.8E-06	FDC1	1.4E-11
FDC1	2.0E-06	FDC2	7.9E-06
FDC2	8.0E-05	FDC3	1.8E-05
FDC3	4.7E-04	FDC4	1.7E-04
FDC4	3.0E-05	FDC5	1.3E-05
FDC5	1.0E-04	FDC6	2.0E-06
FDC6	2.0E-03	FDC7	2.8E-03
FDC7	3.0E-03	FDC8	4.6E-03
FDC8	2.0E-03	FDC9	2.6E-02
FDC9	2.3E-02		
Severe Core Damage (FDC0)	3.8E-06	Severe Core Damage (FDC1 + FDC2)	7.9E-06

NOTES:

(a) Data for the Darlington Probabilistic Safety Evaluation (DPSE) are from: Ontario Hydro, 1987, Table 5-2. Data for the Darlington Risk Assessment (DARA) are from: OPG, 2012, Table 13. DARA data are from the “baseline” study.

(b) Estimated frequencies are for accidents initiated by internal events.

(c) Definitions of Fuel Damage Categories are different in DPSE and DARA.

(d) In DPSE, category FDC0 covered all event sequences leading to severe core damage (i.e., “loss of core structural integrity”). Category FDC0 included three sub-categories, with a combined mean frequency of 5.0E-07 per RY, covering event sequences involving failure to shut down the fission reaction. (See: Ontario Hydro, 1987, Table 5-3 and Section 5.3.1.2.)

(e) Categories FDC1 and FDC2 in DARA cover all event sequences leading to severe core damage. Sequences covered by category FDC1 would involve “rapid accident progression resulting from failures to shut down the reactor when required” (i.e., failures to shut down the fission reaction). Category FDC2 covers all other event sequences leading to severe core damage. DARA assumes that all event sequences covered by category FDC1 would lead to “early consequential containment failure”. (See: OPG, 2012, Section 5.1.)

Table 5.3-3

Ontario Hydro Estimate (in DPSE Study of 1987) of Frequency and Radiological Impact of Potential Atmospheric Releases from the Darlington Station

RELEASE CATEGORY (EPRC = Ex-Plant Release Category)	Mean Frequency		Mean Collective Dose (person-Sv)	$ Equivalent of Mean Collective Dose @ $1M per person-Sv
	(per reactor-year)	(per station-year)* *(* If reactor release potentials are independent)*		
EPRC0	4.4E-06	1.8E-05	?	?
EPRC1	9.2E-06	3.7E-05	1.3E+03	1.3E+09
EPRC2	5.7E-06	2.3E-05	3.2E+02	3.2E+08
EPRC3	1.7E-05	6.8E-05	2.9E+01	2.9E+07
EPRC4	1.5E-04	6.0E-04	1.9E+00	1.9E+06
EPRC5	3.1E-02	1.2E-01	?	?

NOTES:

(a) Data in columns 1, 2, and 4 are from the Darlington Probabilistic Safety Evaluation. (See: Ontario Hydro, 1987, Table 5-6.)

(b) Data in column 3 are calculated by multiplying the column 2 data by a factor of 4, which assumes that 4 reactors are operational at Darlington. Data in column 5 are calculated from column 4, as described in the column 5 heading.

(c) Estimated frequencies are for accidents initiated by internal events.

(d) Collective dose was estimated for the population within 100 km of the Darlington station, assuming no application of offsite countermeasures. Dose calculations included external exposure and inhalation, but excluded ingestion.

(e) DPSE found that event sequences contributing to EPRC0 that would yield a "large" atmospheric release would have a combined mean frequency of 8.2E-07 per RY. The subset of those sequences that involved failure to shut down the fission reaction would have a combined mean frequency of 2.8E-07 per RY. (See; Ontario Hydro, 1987, Table 5-7 and Section 5.3.2.4.)

(f) DPSE found that Fuel Damage Category FDC0 had a mean frequency of 3.8E-06 per RY, and that event sequences involving failure to shut down the fission reaction contributed a combined mean frequency of 5.0E-07 per RY to that total. (See: Ontario Hydro, 1987, Table 5-3 and Section 5.3.1.2.)

(g) From Notes (e) and (f) one sees that DPSE found that the conditional probability of a large, atmospheric release, given severe core damage, would be (8.2E-07)/(3.8E-06) = 0.22. For the subset of event sequences involving failure to shut down the fission reaction, this conditional probability would be (2.8E-07)/(5.0E-07) = 0.56.

(h) DPSE did not explain why the estimated mean frequency of EPRC0 (4.4E-06 per RY) exceeds the mean frequency of FDC0 (3.8E-06 per RY).

Table 5.3-4

Ontario Hydro Estimate (in DPSE Study of 1987) of Magnitudes of Potential Atmospheric Releases of Iodine-131 and Cesium-137 from the Darlington Station

RELEASE CATEGORY (EPRC = Ex-Plant Release Category)	RELEASE OF IODINE-131		RELEASE OF CESIUM-137	
	Amount (Bq)	Fraction of Inventory in one Reactor Core	Amount (Bq)	Fraction of Inventory in one Reactor Core
EPRC0	?	?	?	?
EPRC1	2.9E+15	1.0E-03	2.0E+14	3.0E-03
EPRC2	4.1E+14	1.4E-04	1.3E+13	1.9E-04
EPRC3	2.0E+14	6.9E-05	3.3E+10	4.9E-07
EPRC4	9.4E+12	3.2E-06	0	0
EPRC5	?	?	?	?

NOTES:

(a) Underlying data are from: Ontario Hydro, *Darlington NGS Probabilistic Safety Evaluation* (Toronto: Ontario Hydro, December 1987), Chapters 10 and 12.

(b) DPSE stated that the radioactive inventory of the reactor core of each Darlington unit at full-power, steady-state operation would include 2.9E+18 Bq of Iodine-131 and 6.7E+16 Bq of Cesium-137. Those values are used to calculate the data shown in columns 3 and 5 of the table.

Table 5.3-5

OPG Estimate (in DARA Study of 2012) of Frequency and Radiological Impact of Potential Atmospheric Releases from the Darlington Station

RELEASE CATEGORY	MEAN FREQUENCY		COLLECTIVE DOSE (person-Sv)	$ EQUIVALENT OF COLLECTIVE DOSE @ $1M PER PERSON-SV
	(per reactor-year)	(per station-year)* (* If reactor release potentials are independent)		
D-RC1	4.9E-06	2.0E-05	5.5E+04	5.5E+10
D-RC2	3.7E-07	1.5E-06	1.1E+03	1.1E+09
D-RC4	2.0E-09	8.0E-09	9.6E+02	9.6E+08
D-RC7	1.5E-06	6.0E-06	4.9E+01	4.9E+07
PDS5	2.9E-03	1.2E-02	7.1E+00	7.1E+06
PDS6	4.2E-05	1.7E-04	1.2E+01	1.2E+07

NOTES:

(a) Data in columns 1, 2, and 4 are from: OPG, 2012, Table 17. Data in column 3 are calculated by multiplying the column 2 data by a factor of 4, which assumes that 4 reactors are operational at Darlington. Data in column 5 are calculated from column 4, as described in the column 5 heading.

(b) OPG estimates in this table are from the "baseline" PRA for Darlington.

(c) Estimated frequencies are for accidents initiated by internal events.

(d) Collective dose is estimated for the population within 100 km of the Darlington station, assuming application of "late" offsite countermeasures implemented according to the Ontario Provincial Nuclear Emergency Plan. The estimates shown for collective dose may be mean values, but DARA is silent on that matter.

(e) OPG states that "large" atmospheric releases would be those in release categories RC1 through RC3. (See: OPG, 2012, Section 5.4.) Also, OPG finds that the frequency of release category RC3 is zero. (See: OPG, 2012, Table 16.)

Table 5.3-6

OPG Estimate (in DARA Study of 2012) of Frequencies of Severe Core Damage and Large, Atmospheric Release at the Darlington Station, During Reactor Operation

EVENT CATEGORY	Severe Core Damage Frequency (per RY)	Large Release Frequency (per RY)
Internal events ("baseline" study)	7.9E-06	5.2E-06
Fire	1.9E-06	9.7E-08
Seismic	3.7E-06	3.7E-06
Flooding	4.8E-07	<4.8E-07
TOTAL	1.4E-05	9.5E-06
OPG Safety Goal Target	1.0E-05	1.0E-06
OPG Safety Goal Limit	1.0E-04	1.0E-05

NOTES:

(a) Data are from: OPG, 2012, Tables 11 and 12.

(b) Data shown in the internal-events category are for OPG's "baseline" study. OPG also made frequency estimates using an "enhanced" analytic model, and estimates using that model plus the assumed implementation of four Safety Improvement Opportunities (SIOs). The four SIOs are described in: OPG, 2012, Sections 7.1 and 7.2.

(c) For internal events, at power, the enhanced model estimated a severe core damage frequency of 3.3E-06 per RY, and a large release frequency of 1.3E-06 per RY; the enhanced model with assumed implementation of SIOs estimated a severe core damage frequency of 2.1E-06 per RY, and a large release frequency of 4.1E-07 per RY. (See; OPG, 2012, Table 11.) Assuming no change in core-damage or large-release frequency in the fire, seismic, and flooding event categories, **total** estimated frequencies would be:

VERSION OF DARA STUDY	Severe Core Damage Frequency (per RY)	Large Release Frequency (per RY)
Baseline study	1.4E-05	9.5E-06
Enhanced model	9.4E-06	5.6E-06
Enhanced model + SIOs	8.2E-06	4.7E-06

(d) In each event category, the affected reactors are assumed here to be at power. OPG also made frequency estimates for the event category, "internal events, outage".

(e) OPG states that "large" atmospheric releases would be those in release categories RC1 through RC3. (See: OPG, 2012, Section 5.4.) Also, OPG finds that the frequency of release category RC3 is zero. (See: OPG, 2012, Table 16.)

(f) CNSC has stated that a "large" atmospheric release would be one involving a release of more than 1.0E+14 Bq of Cesium-137. (See: CNSC, 2009, Table B.1.)

Table 5.3-7

Ontario Hydro (DPSE Study) and OPG (DARA Study) Estimates of Frequencies of Severe Core Damage and Large, Atmospheric Release at the Darlington Station, During Reactor Operation

Event Category	Severe Core Damage Frequency (per RY)	Large Release Frequency (per RY)	Conditional Probability of Large Release, given Severe Core Damage
Internal events, DPSE study	3.8E-06	8.2E-07	0.22
Internal events, DPSE study, failure to shut down	5.0E-07	2.8E-07	0.56
Internal events, DARA "baseline" study	7.9E-06	5.2E-06	0.66
Internal events, DARA "baseline" study, failure to shut down	1.4E-11	1.4E-11	1.00
Fire, DARA study	1.9E-06	9.7E-08	0.05
Seismic, DARA study	3.7E-06	3.7E-06	1.00
Flooding, DARA study	4.8E-07	<4.8E-07	<1.00
TOTAL, DARA study	1.4E-05	9.5E-06	0.68
OPG Safety Goal Target	1.0E-05	1.0E-06	0.10
OPG Safety Goal Limit	1.0E-04	1.0E-05	0.10

NOTES:

(a) Data are from Tables 5.3-3 through 5.3-6.

(b) DPSE identified several types of internal-events sequence that involve failure to shut down the fission reaction. (See: Ontario Hydro, 1987, Tables 5-3 and 5-7.) DARA did not provide an equivalent level of detail in the available DARA document. (See: OPG, 2012). Nevertheless, the data shown in this table provide a reasonable basis for comparing the respective treatments of this type of event sequence in DPSE and DARA.

Table 5.3-8

OPG Estimates of Frequencies of Severe Core Damage and Large, Atmospheric Release at the Pickering B Station, During Reactor Operation

EVENT CATEGORY	Severe Core Damage Frequency (per RY)	Large Release Frequency (per RY)	Conditional Probability of Large Release, given Severe Core Damage
Internal events	4.2E-06	3.9E-06	0.93
Fire	3.8E-06	3.4E-06	0.89
Seismic	9.7E-07	9.7E-07	1.00
Flooding	7.0E-07	<7.0E-07	<1.00
High wind	8.0E-06	<8.0E-06	<1.00
Total	1.8E-05	<1.7E-05	<0.94
OPG Safety Goal Target	1.0E-05	1.0E-06	0.10
OPG Safety Goal Limit	1.0E-04	1.0E-05	0.10

NOTES:

(a) Data, except as indicated in note (d), are from Tables 10 and 11 of: OPG, 2013b.

(b) The “fire” and “flooding” event categories in this table are limited to internal fires and floods.

(c) Event categories that are not considered by OPG include: external fire or explosion; external flooding; turbine missile; aircraft crash; and malevolent action.

(d) OPG says that, for high-wind event sequences, Large Release Frequency is bounded by, and can be considered equal to, Severe Core Damage Frequency. At the same time, OPG says that values of Large Release Frequency for different categories of event should not be added. (See: Jager, 2013.) In this table, OPG’s latter position is rejected, and the values of Large Release Frequency are added.

(e) In this table, a “Large Release” would be an atmospheric release with a Cesium-137 component exceeding 1.0E+14 Bq.

Table 5.3-9

Licensee Estimates of Frequency and Collective Dose for Potential Atmospheric Releases of Radioactive Material from the Bruce and Pickering Stations

EX-PLANT RELEASE CATEGORY	Bruce A		Bruce B		Pickering B	
	Frequency (per RY)	Collective Dose (person-Sv)	Frequency (per RY)	Collective Dose (person-Sv)	Frequency (per RY)	Collective Dose (person-Sv)
EPRC1	1.5E-07	32,700	2.8E-09	32,900	1.1E-10	38,200
EPRC2	3.6E-07	36,100	9.1E-08	35,400	1.0E-11	16,000
EPRC3	6.4E-08	10,500	2.7E-08	10,400	1.0E-11	19,800
EPRC4	8.6E-08	8,700	6.9E-08	8,730	2.4E-10	7,920
EPRC5A	2.2E-09 (EPRC5)	22,700 (EPRC5)	2.0E-10 (EPRC5)	22,700 (EPRC5)	7.1E-07	900
EPRC5B					2.1E-08	230
EPRC6	9.1E-07	2,750	1.8E-07	2,800	1.0E-11	3,600
EPRC7	2.6E-05	770	3.5E-06	760	1.0E-11	22,000
EPRC8	7.0E-10	40	4.7E-10	40	1.3E-06	11
EPRC9	2.8E-05	240	5.9E-06	240	1.0E-06	40
EPRC10	3.0E-05	7	5.8E-05	7	?	?

NOTES:

(a) Bruce A estimates are from: Bruce Power, 2005, Table 3.5.11-5. Quantities shown are mean estimates. Population dose is to 200 km radius. It appears that frequency estimates cover internal initiating events.

(b) Bruce B estimates are from: OPG, 1999, Tables 2-11 and 2-12. Quantities shown are mean estimates. Population dose is to 200 km radius. Frequency estimates cover internal initiating events and loss of offsite power.

(c) Pickering B estimates are from: OPG, 2008, Table 5; and SENES, 2007, Table 5.3-3. Quantities shown are mean estimates. Population dose is to 100 km radius. Frequency estimates cover internal initiating events, loss of offsite power, and some screen-house failures.

(d) EPRC definitions differ across the studies cited.

Table 5.4-1

Some Potential Modes and Instruments of Attack on a Nuclear Power Plant

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

NOTES:

(a) This table is adapted from: Thompson, 2007, Table 7-4. Further citations are provided in that table and its supporting narrative. For additional, supporting information of more recent vintage, see: Ahearne et al, 2012, Chapter 5.

(b) Defenses at Canadian plants are no more robust than at US plants. See: Frappier, 2007.

Table 5.4-2

The Shaped Charge as a Potential Instrument of Attack

CATEGORY OF INFORMATION	Selected Information in Category
General information	▪ Shaped charges have many civilian and military applications, and have been used for decades ▪ Applications include human-carried demolition charges or warheads for anti-tank missiles ▪ Construction and use does not require assistance from a government or access to classified information
Use in World War II	▪ The German MISTEL, designed to be carried in the nose of an un-manned bomber aircraft, is the largest known shaped charge ▪ Japan used a smaller version of this device, the SAKURA bomb, for kamikaze attacks against US warships
A large, contemporary device	▪ Developed by a US government laboratory for mounting in the nose of a cruise missile ▪ Described in detail in an unclassified, published report (citation is voluntarily withheld here) ▪ Purpose is to penetrate large thicknesses of rock or concrete as the first stage of a "tandem" warhead ▪ Configuration is a cylinder with a diameter of 71 cm and a length of 72 cm ▪ When tested in November 2002, created a hole of 25 cm diameter in tuff rock to a depth of 5.9 m ▪ Device has a mass of 410 kg; would be within the payload capacity of many general-aviation aircraft
A potential delivery vehicle	▪ A Beechcraft King Air 90 general-aviation aircraft will carry a payload of up to 990 kg at a speed of up to 460 km/hr ▪ A used King Air 90 can be purchased in the US for $0.4-1.0 million

SOURCE: Thompson, 2007, Table 7-6. Further citations are provided in that table and its supporting narrative.

Table 5.4-3

Performance of US Army Shaped Charges, M3 and M2A3

TARGET MATERIAL	INDICATOR	VALUE FOR STATED TYPE OF SHAPED CHARGE	
		Type: M3	Type: M2A3
Reinforced concrete	Maximum wall thickness that can be perforated	150 cm	90 cm
	Depth of penetration in thick walls	150 cm	75 cm
	Diameter of hole	▪ 13 cm at entrance ▪ 5 cm minimum	▪ 9 cm at entrance ▪ 5 cm minimum
	Depth of hole with second charge placed over first hole	210 cm	110 cm
Armor plate	Perforation	At least 50 cm	30 cm
	Average diameter of hole	6 cm	4 cm

NOTES:

(a) Data are from US Army Field Manual FM 5-25: Army, 1967, pp 13-15 and page 100.

(b) The M2A3 charge has a mass of 5 kg, a maximum diameter of 18 cm, and a total length of 38 cm including the standoff ring.

(c) The M3 charge has a mass of 14 kg, a maximum diameter of 23 cm, a charge length of 39 cm, and a standoff pedestal 38 cm long.

Table 5.6-1

IRSN Estimates of Costs Arising from a “Massive” Atmospheric Release of Radioactive Material from a French 900 MWe PWR

Cost Category	Estimated Cost (billion Euro)		
	Base Case	Low Case	High Case
On-site costs	10	5	15
Off-site radiological costs	106	38	281
Contaminated territories	393	130	4,875
Image costs	130	75	176
Costs related to power production	90	30	360
Indirect effects	31	9	50
Total (rounded)	760	290	5,760

NOTES:

(a) Data are from: IRSN, 2007, Tables A4.4.4 and A4.4.5. Additional, background information is available from: Pascucci-Cahen and Patrick, 2012; IRSN, 2013a; IRSN, 2013b; JDD, 2013; MacLachlan, 2013.

(b) The assumed release would be from the Dampierre nuclear generating station, which has four 900 MWe PWR units and is located on the Loire River south of Paris. The release is described (IRSN, 2007, page 37) as follows: “Par simplification, le scenario considere la dispersion en deux heures d’un tiers de l’inventaire du coeur, ce qui est le bon ordre de grandeur pour le cesium, contributeur preponderant des couts.” Thus, the release apparently includes one-third of the core inventory of Cesium isotopes, which are said to be the major contributors to the estimated costs. The many radio-isotopes in a reactor core have widely varying volatilities and chemical properties. Thus, their release fractions will vary. The IRSN text, quoted above, does not address this matter.

(c) An approximate estimate of the core inventory of Cesium-137 in a 900 MWe PWR can be made by assuming: (i) total fuel mass = 75 Mg HM; (ii) average fuel burnup at discharge = 50 GWt-days per Mg HM; (iii) Cesium-137 yield = 1.17E+14 Bq per GWt-day of fission; and (iv) one-third of the core is discharged at each refueling, and a refueling outage is imminent, so that average fuel burnup in the core = (2/3) x discharge burnup. With those assumptions, the core inventory of Cesium-137 = 1.17E+14 x 75 x (2/3) x 50 = 2.9E+17 Bq. One-third of that inventory = 9.7E+16 Bq = 97 PBq.

(d) IRSN used the COSYMA code to estimate plume behavior and radiological impacts for 144 weather conditions. The “base case” estimates shown in the table are said to reflect median results. The “low case” (scenario favorable) and “high case” (scenario defavorable) estimates reflect non-median results, together with changes in analytic assumptions.

Table 5.6-2

Risk Cost (Euro per kWh), Calculated from IRSN-Estimated Costs Arising from a “Massive” Atmospheric Release of Radioactive Material from a French 900 MWe PWR

EVENT FREQUENCY (HYPOTHESIZED)	Risk Cost (Euro per kWh generated)		
	Low-Case Event Cost (290 billion Euro)	Base-Case Event Cost (760 billion Euro)	High-Case Event Cost (5,760 billion Euro)
1.0E-03 per RY	0.041	0.11	0.81
1.0E-04 per RY	0.0041	0.011	0.081
1.0E-05 per RY	0.00041	0.0011	0.0081

NOTES:

(a) The potential event and its costs, as estimated by IRSN, are discussed in Table 5.6-1.

(b) The assumed release would be from the Dampierre nuclear generating station, which has four 900 MWe PWR units and is located on the Loire River south of Paris. The release would include about 100 PBq of Cesium-137.

(c) The affected PWR unit is assumed to have a net capacity of 900 MWe and to achieve an average capacity factor (for electricity output) of 90 percent.

(d) Here, “risk cost” = (event cost)x(event frequency per reactor-yr)/(kWh generated per reactor-yr)

(e) The calculated risk cost would apply across a fleet of reactors in France and neighboring countries, if “event frequency” were constant across the fleet, and “event cost” and “kWh generated” scaled linearly with reactor capacity.

Table 5.6-3

Annualized, Europe-Wide Cost (billion Euro per yr), Calculated from IRSN-Estimated Costs Arising from a “Massive” Atmospheric Release of Radioactive Material from a French Commercial Reactor

EVENT FREQUENCY (HYPOTHESIZED)	Annualized, Europe-Wide Cost (179 Reactors) (billion Euro per yr)		
	Low-Case Event Cost (290 billion Euro)	Base-Case Event Cost (760 billion Euro)	High-Case Event Cost (5,760 billion Euro)
1.0E-03 per RY	52	140	1,030
1.0E-04 per RY	5.2	14	103
1.0E-05 per RY	0.52	1.4	10.3

NOTES:

(a) This table is based upon the IRSN cost estimates set forth in Table 5.6-1. Here, the IRSN estimates are expressed as annualized cost across the European fleet of 179 operational commercial reactors. Underlying this concept of annualized cost are assumptions that: (i) the frequency of the hypothesized atmospheric release, and the resulting costs, would be the same for all reactors in the fleet; and (ii) a massive release of the type studied by IRSN would have adverse impacts across all of Europe.

(b) As of January 2013, 184 nuclear power plants were operational in Europe, with an average net capacity of 880 MWe. Of these plants, 5 were in the Asian part of the Russian Federation, and are neglected here. (See: European Nuclear Society, “Nuclear power plants in Europe”, accessed on 24 August 2013 from: http://www.euronuclear.org/info/encyclopedia/n/nuclear-power-plant-europe.htm)

(c) Here, “annualized, Europe-wide cost” = (event cost)x(event frequency per RY)x(179)

Table 5.7-1

Insurance Premiums Paid by OPG for Nuclear Liability and Terrorism Coverage of the Darlington Station, 2005-2012

PERIOD	PREMIUM FOR PERIOD ($)
2012	753,680
2011	749,654
2010	734,585
2009	728,262
2008	715,920
2007	708,934
2006	717,413
2005	714,373
Total, 2005-2012	5,822,821
Average Year, 2005-2012	727,853

NOTES:

(a) Premium data were obtained from copies of annual invoices from Marsh Canada Limited to OPG. These copies were provided by OPG to Shawn-Patrick Stensil of Greenpeace Canada in February 2013, pursuant to a request by Stensil under the Freedom of Information and Protection of Privacy Act.

(b) Marsh Canada received the premium payments on behalf of the Nuclear Insurance Association of Canada and other insurance pools, which may have included British Nuclear Insurers and American Nuclear Insurers.

(c) In addition to paying the amounts shown to Marsh Canada, OPG also paid an 8% sales tax on each amount to the province of Ontario.

(d) The components of the total premium (i.e., nuclear liability, and terrorism) are available, for the years shown, only for 2005. In that year, the terrorism premium was $88,086 (12.3% of the total premium) and the nuclear liability premium was $626,287 (87.7% of the total premium).

(e) Prior to 2005, a combined premium payment was made for the Darlington and Pickering stations and, in earlier years, for the Bruce station as well.

Table 5.7-2

Accident-Frequency Implications of Insurance Premiums Paid by OPG for Coverage Associated with Operation of the Darlington Station

LIABILITY LIMIT: COVERAGE A, ACCIDENTS	Net Premium to Cover Stated Liability (per RY)	Implied Frequency of Event (per RY)
$75 million	$127,000	1.69E-03
$650 million	$508,000 to $762,000	7.82E-04 to 1.17E-03
$1,000 million	$635,000 to $1,016,000	6.35E-04 to 1.02E-03

NOTES:

(a) Table 5.7-1 shows gross, pre-tax insurance premiums paid by OPG for nuclear liability and terrorism coverage of the 4-unit Darlington station, over the period 2005-2012. The annual average gross premium for the station during that period was $727,853. In 2005, the terrorism premium accounted for 12.3% of the gross premium. Here, it is assumed that 30% of the gross premium is allocated to: (i) terrorism premium; (ii) administration; (iii) contingency; (iv) reinsurance premium paid to the Canadian government; and (v) profit. Thus, 70% of the gross premium is assumed here to be the net premium that supports offsite Coverage A (i.e., legal liability for bodily injury or property damage) through the private insurers in the NIAC pool, for an accident not involving a malevolent act. Throughout the period 2005-2012 and currently, the limit on that liability is $75 million. Thus, the net premium per RY for a $75 million maximum liability = $727,853 x 0.7 x 0.25 = $127,000 per RY.

(b) Dermot Murphy of NIAC has said that increasing the liability limit from $75 million to $650 million would require a premium increase by a factor of approximately 4 to 6, while a limit of $1,000 million would require a premium increase by a factor of approximately 5 to 8. (See: Murphy, 2009.) These factors are applied in the second column of the table.

(c) The implied frequency of event, in the third column, is calculated by dividing the amount in the second column by the amount in the first column, for each row. This implied frequency represents NIAC's assessment of the frequency of a claim up to the liability limit.

Table 5.8-1

Estimated Collective Dose from a Large (2 x "PWR2") Atmospheric Release of Radioactive Material from DNGS

SECTOR (WIND INTO)	COLLECTIVE DOSE (PERSON-SV)	
	Distance: 0-100 km	**Distance: 100-1,000 km**
NE	2.2E+05 to 1.4E+06	1.3E+05 to 2.7E+05
ENE	5.8E+05 to 8.8E+05	5.3E+05 to 9.2E+05
E	1.2E+04 to 2.1E+04	1.1E+05 to 1.4E+06
W	2.6E+06 to 1.4E+07	4.2E+04 to 6.9E+05

NOTES:

(a) Data are from: IRSS, 1992, Annex III.

(b) The assumed atmospheric release is from two Darlington reactors. The release from each reactor (i.e., the "source term" for that reactor) has isotopic release fractions, timing, and other characteristics as for the "PWR2" release in the NRC's Reactor Safety Study. (See: NRC, 1975, Appendix VI, Table VI 2-1.) Although the Darlington reactors are not PWRs, use of the PWR2 source-term parameters is reasonable, given that neither Ontario Hydro nor OPG has provided such parameters for a severe accident at Darlington.

(c) The radioactive inventory of the reactor core of each Darlington unit at full-power, steady-state operation would include 2.9E+18 Bq of Iodine-131 and 6.7E+16 Bq of Cesium-137. PWR2 release fractions are 70% for the Iodine group and 50% for the Cesium group. Thus, the assumed release includes the following contributions:

- Iodine-131 release = (2.9E+18) x 0.7 x 2 = 4.1E+18 Bq
- Cesium-137 release = (6.7E+16) x 0.5 x 2 = 6.7E+16 Bq

(d) Collective dose was calculated by the MACCS code, assuming no implementation of countermeasures. Exposure by ingestion was considered. The calculation was performed for a subset of weather conditions at Darlington, as discussed below. Funding limitations precluded analysis of all weather conditions.

(e) Collective dose was calculated, and is presented here, for the four wind directions whose annual frequency at Darlington is 9 percent or more. The range of collective dose shown for each wind direction reflects the most frequent categories of atmospheric stability and wind speed associated with that direction. Overall, the weather conditions represented by these estimates account for 19 percent of the frequency of all weather conditions at Darlington. The weighted average collective dose across this subset of weather conditions, for a distance range of 0-1,000 km, is 2.7E+06 person-Sv.

(f) The "worst case" weather condition, in terms of human health effects, would involve a narrow, low-level plume traveling WSW from the Darlington site and encountering rain over metropolitan Toronto. That weather condition is possible but comparatively unlikely. The cited study (IRSS, 1992) did not perform calculations for that condition.

Table 5.8-2

Illustrative Calculation of Offsite Risk Costs of a Large (2 x "PWR2") Atmospheric Release from DNGS

INDICATOR	VALUE OF INDICATOR	
	Low Case: Release Frequency = $1x10^{-4}$ per yr	**High Case: Release Frequency = $1x10^{-3}$ per yr**
Electricity produced by DNGS (4 reactors)	$2.72x10^{10}$ kWh per yr	$2.72x10^{10}$ kWh per yr
Offsite economic costs (i.e., monetized impacts) arising from the radioactive release	Can$3,130 billion (average value)	Can$3,130 billion (average value)
Risk costs of monetized impacts of the radioactive release	1.15 Can cent per kWh	11.51 Can cent per kWh

NOTES:

(a) The release would involve core damage at two or more of the four reactors at DNGS. Radioactive material would be released to atmosphere at one or more locations. The released material would include 67 PBq of Cs-137.

(b) Electricity production is calculated by assuming that four reactors are operational at DNGS, each reactor has a capacity of 881 MWe, and the average capacity factor is 88%.

(c) Table 5.6-1 shows IRSN estimates of offsite costs arising from a release containing 97 PBq of Cs-137. The IRSN estimates range from a low case of 290 billion Euro to a high case of 5,760 billion Euro. The average of those numbers is 3,025 billion Euro. Here, that average is scaled linearly according to the Cs-137 content of the release, and converted to Can$ at the rate: Can$1.5 per Euro. Thus, the average value of offsite costs = (3,025 billion)x(67/97)x(1.5) = Can$3,130 billion

(d) Risk costs are calculated as: (offsite costs)x(frequency of release)/(annual electricity production)

(e) A release frequency of $1x10^{-4}$ per year is equivalent to a release frequency of $2.5x10^{-5}$ per RY.

Table 6-1

Ontario Hydro Estimate (in the DPSE Study) of Onsite Economic Impacts from Fuel-Damage Events at DNGS

FUEL DAMAGE CATEGORY	EST. MEAN FREQUENCY AND (UNCERTAINTY FACTOR, UF)	EST. ONSITE ECONOMIC IMPACTS (MILLION 2013 CAN$)	Frequency x Magnitude of Onsite Economic Impacts (million 2013 Can$ per RY)	
			Using Mean Estimate of FDC Frequency	Using 95th Percentile Estimate of FDC Frequency
FDC0	3.8E-06 per RY (UF = 6)	?	?	?
FDC1	2.0E-06 per RY (UF = 6)	7,180 to 13,040	0.014 to 0.026	0.086 to 0.16
FDC2	8.0E-05 per RY (UF = 6)	6,590 to 11,520	0.53 to 0.92	3.16 to 5.53
FDC3	4.7E-04 per RY (UF = 4)	3,840 to 6,640	1.80 to 3.12	7.22 to 12.5
FDC4	3.0E-05 per RY (UF = 10)	3,840 to 7,030	0.12 to 0.21	1.15 to 2.11
FDC5	1.0E-04 per RY (UF = 10)	3,050 to 5,820	0.31 to 0.58	3.05 to 5.82
FDC6	2.0E-03 per RY (UF = 10)	2,160 to 4,170	4.32 to 8.34	43.2 to 83.4
FDC7	3.0E-03 per RY (UF = 5)	890 to 2,780	2.67 to 8.34	13.4 to 41.7
FDC8	2.0E-03 per RY (UF = 10)	140 to 680	0.28 to 1.36	2.80 to 13.6
FDC9	2.3E-02 per RY (UF = 3)	440 to 790	10.1 to 18.2	30.4 to 54.5
Total			**20.2 to 41.1**	**104.4 to 219.3**

NOTES:

(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$. These estimates are adjusted here to 2013 Can$ by a multiplier of 1.92, based on Canadian GDP deflators provided by the International Monetary Fund for the years 1985 and 2013. (See: IMF World Economic Outlook Database, April 2008.)

(c) DPSE did not estimate 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 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 at one unit, 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 6-2

Risk Costs of Onsite Impacts from Fuel-Damage Events at DNGS, Based on an Ontario Hydro Estimate in the DPSE Study

INDICATOR	VALUE OF INDICATOR	
	Using Mean Estimate of Frequency of a Fuel Damage Category	Using 95th Percentile Estimate of Frequency of a Fuel Damage Category
Risk of onsite economic impacts (OH estimate for internal initiating events only)	20.2 to 41.1 (million 2013 Can$ per RY)	104.4 to 219.3 (million 2013 Can$ per RY)
Risk costs of onsite economic impacts (OH estimate for internal initiating events only)	0.30 to 0.61 (2013 Can cent per kWh)	1.54 to 3.23 (2013 Can cent per kWh)
Risk costs of onsite economic impacts (internal initiating events + external events + malevolent acts)	0.60 to 1.21 (average: 0.91) (2013 Can cent per kWh)	3.08 to 6.46 (average: 4.77) (2013 Can cent per kWh)

NOTES:

(a) This table is developed from data shown in Table 6-1.

(b) Ontario Hydro (OH) considered the occurrence of accidents involving Fuel Damage Categories FDC1 through FDC9, but not the most severe Category (FDC0).

(c) Ontario Hydro considered fuel damage in a reactor core or a fueling machine, caused by accidents initiated by internal events.

(d) Values in the first row are from Table 6-1. Values in the second row are calculated from the first row, assuming a reactor capacity of 881 MWe and an average capacity factor of 88%.

(e) Values in the third row are adjusted upward from values in the second row by a multiplier of 2, to account for: (i) accidents initiated by external events; and (ii) malevolent acts.

Table 7-1

Estimated Values of Selected Indicators of Radiological Risk and Program Risk at DNGS

INDICATOR	RISK COSTS (2013 CAN CENT PER KWH)	
	Low Case	High Case
Radiological Risk		
Risk costs of monetized offsite impacts of a 2 x “PWR2” release	1.2	11.5
Program Risk		
Risk costs of onsite impacts from fuel-damage events	0.9	4.8
Sum of Radiological Risk and Program Risk		
Sum of above-stated indicators	2.1	16.3

NOTES:

(a) Values for radiological risk are from Table 5.8-2. The Low Case assumes a release frequency of $1x10^{-4}$ per year, and the High Case assumes a release frequency of $1x10^{-3}$ per year.

(b) Values for program risk are from Table 6-2. The Low Case uses a mean estimate of the frequency of a Fuel Damage Category (FDC), and the High Case uses a 95th percentile estimate of the frequency of a FDC.

Figure 1-1

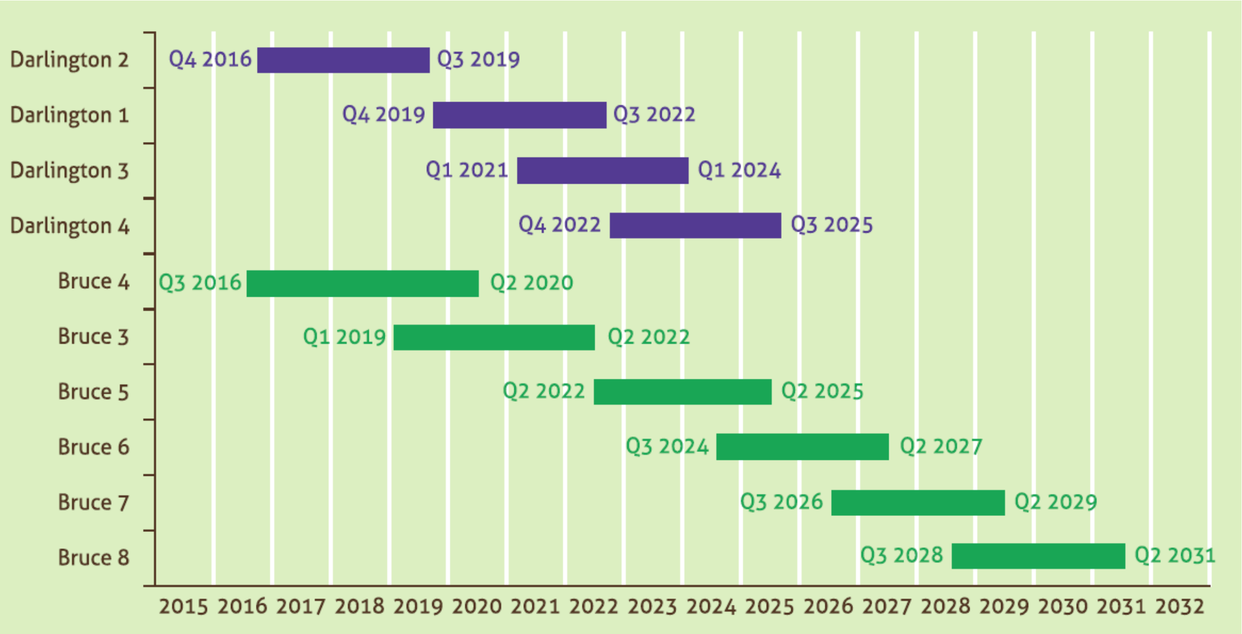
Aerial View of DNGS

SOURCE:

OPG, 2013a, cover page.

Figure 1-2

Schedule of Refurbishment of Darlington and Bruce Reactors, as Envisioned in Ontario's Long-Term Energy Plan of 2013 (LTEP-2013)



NOTES:

(a) This figure reproduces Figure 14 (at page 30) of the LTEP-2013 document, cited here as: Ontario Ministry of Energy, 2013.

(b) The LTEP-2013 document says (at page 29):

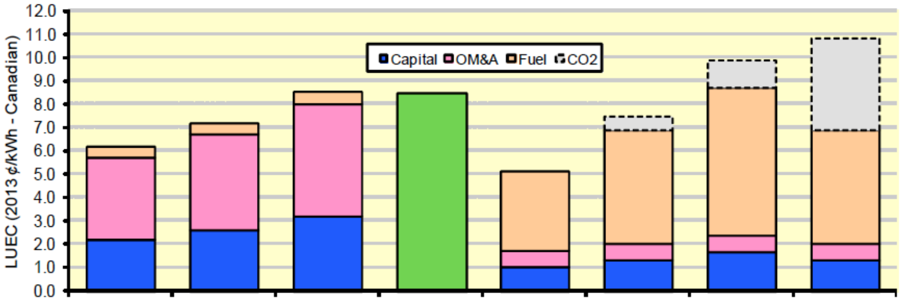
> "Darlington and Bruce plan to begin refurbishing one unit each in 2016. Final commitments on subsequent refurbishments will take into account the performance of the initial refurbishments with respect to budget and schedule by establishing appropriate off-ramps."

(c) The LTEP-2013 document further says (at page 29) that the nuclear refurbishment process will adhere to the following principles:

1. "Minimize commercial risk on the part of ratepayers and government;
2. Mitigate reliability risks by developing contingency plans that include alternative supply options if contract and other objectives are at risk of non-fulfillment;
3. Entrench appropriate and realistic off-ramps and scoping;
4. Hold private sector operator accountable to the nuclear refurbishment schedule and price;
5. Require OPG to hold its contractors accountable to the nuclear refurbishment schedule and price;
6. Make site, project management, regulatory requirements and supply chain considerations, and cost and risk containment, the primary factors in developing the implementation plan; and
7. Take smaller initial steps to ensure there is opportunity to incorporate lessons learned from refurbishment including collaboration by operators."

Figure 2-1

OPG Estimates of Levelized Unit Energy Cost (LUEC) of Electricity from Darlington Refurbishment, Bruce A Units 1 and 2 Refurbishment, or a New Combined-Cycle Gas Turbine (CCGT) Unit



Assumptions:	**Darlington Refurb**			**Bruce 1/2**	**New CCGT**			
Scenarios	Low	Median	High	-	Low	Median	High	Carbon-free based on Median
Overnight capital (C$B)	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Overnight capital (C$/kW)	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
Annual Fixed Operating Cost (C$M)	885	965	1,075	N/A	15	15	15	15
Annual Capacity Factor (%)	93%	88%	83%	85% (est.)	93%	88%	83%	88%
Gas Price (C$/mmBtu @ Henry Hub)					4	6	8	6
CO2 Offset Cost (C$/tonne)					0	15	30	100

NOTES:

(a) This figure is reproduced from Figure C6 (at page 45) of: Robinson et al, 2014. These authors are OPG officials.

(b) Data redactions are in the original figure.

(c) OM&A refers to operation, maintenance, and administration.

(d) The "Bruce 1/2" case refers to previously completed refurbishments of Units 1 and 2 at the Bruce A station.

(e) The new CCGT unit would be fueled by natural gas. The "New CCGT, Carbon-free" case refers to a median-cost new CCGT unit with 100% sequestration of carbon dioxide effluent. The incremental cost of this sequestration is assumed to be $100 per Mg (of carbon?), which would add 4 cents/kWh to the LUEC of a CCGT.

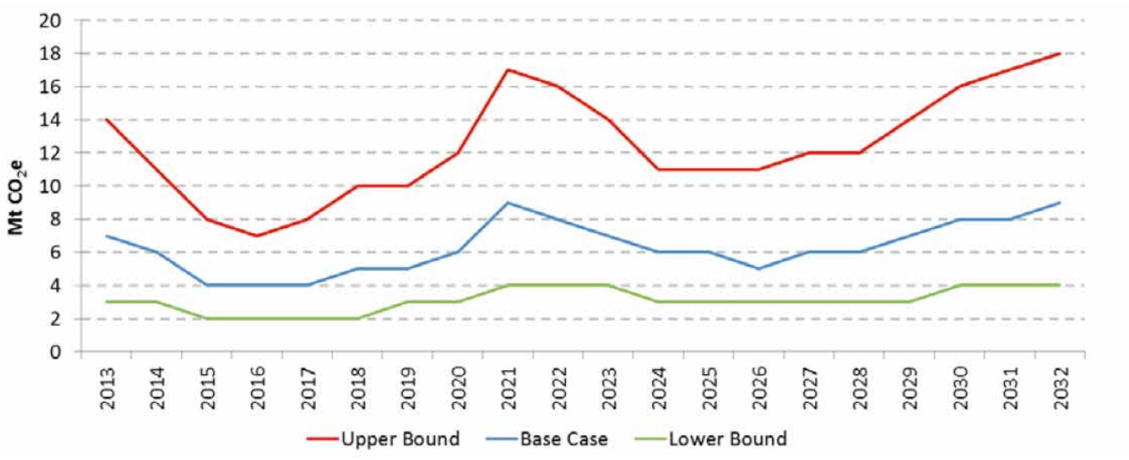
(f) Apparently, the LUEC estimates shown here for Darlington refurbishment, and for a new CCGT unit, exclude interest and escalation.

(g) The source document (Robinson et al, 2014) expresses "high confidence" that the cost of Darlington refurbishment will be less than $10 billion in 2013$, excluding interest and escalation. The document says that inclusion of those cost components would add an additional $2.9 billion. Thus, the predicted maximum cost would be $12.9 billion in 2013$.

(h) In November 2012, OPG officials stated that the cost of Darlington refurbishment would be less than $10.8 billion in 2012$, excluding interest and escalation. (See: Sweetnam and Mitchell, 2012, page 1.)

Figure 2-2

Projections of GHG Emissions from Electricity Generation in Ontario, 2013-2032



NOTES:

(a) This figure is reproduced from Figure 3 (at page 9) of: Miller, 2013.

(b) The projections originated in a February 2013 report by the Ontario Power Authority.

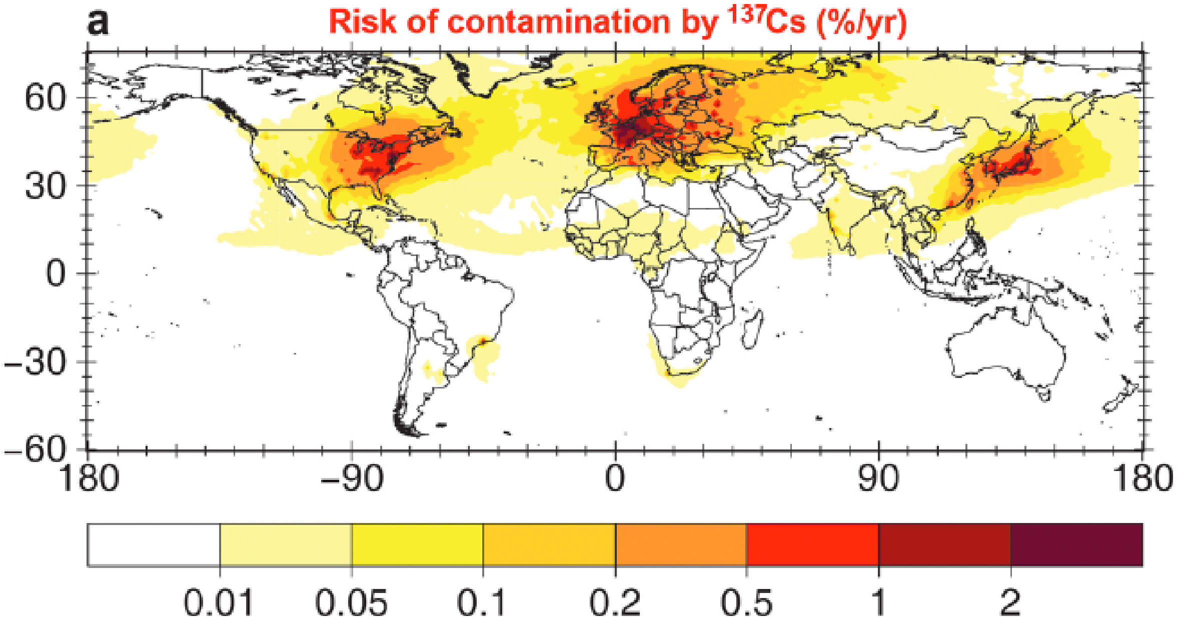
(c) GHG = greenhouse gases, whose emissions are measured in Mt CO2e per year.

(d) The source document (Miller, 2013) notes that: (i) these projections do not include GHG emissions in Ontario from non-utility electricity generation (which primarily uses natural gas); and (ii) those neglected emissions could now exceed 0.7 Mt CO2e per year.

(e) The source document (Miller, 2013) says: (i) the range of projected GHG emissions (lower bound to upper bound) in this figure is primarily attributable to uncertainty about the use of natural gas for electricity generation; and (ii) the spike in expected emissions around 2021 is attributable to the unavailability of Ontario's nuclear reactors during their refurbishment.

Figure 3-1

Estimate, by Lelieveld et al, of Worldwide Risk of Land Contamination by Cs-137 Attributable to Large, Unplanned, Atmospheric Releases from Commercial Reactors



NOTES:

(a) This figure is reproduced from Figure 2(a) of: Lelieveld et al, 2012.

(b) The assumed atmospheric release of Cs-137 from each reactor is (85 PBq)x(the ratio of the rated power of this reactor to the rated power of the Chernobyl Unit 4 reactor). This assumption is based on an estimated release of 85 PBq of Cs-137 during the Chernobyl accident in 1986. This assumption over-estimates the potential releases of Cs-137 from CANDU reactors because it does not account for the comparatively low burnup of CANDU fuel.

(c) The frequency of release is assumed to be 1 per 5,000 reactor-years.

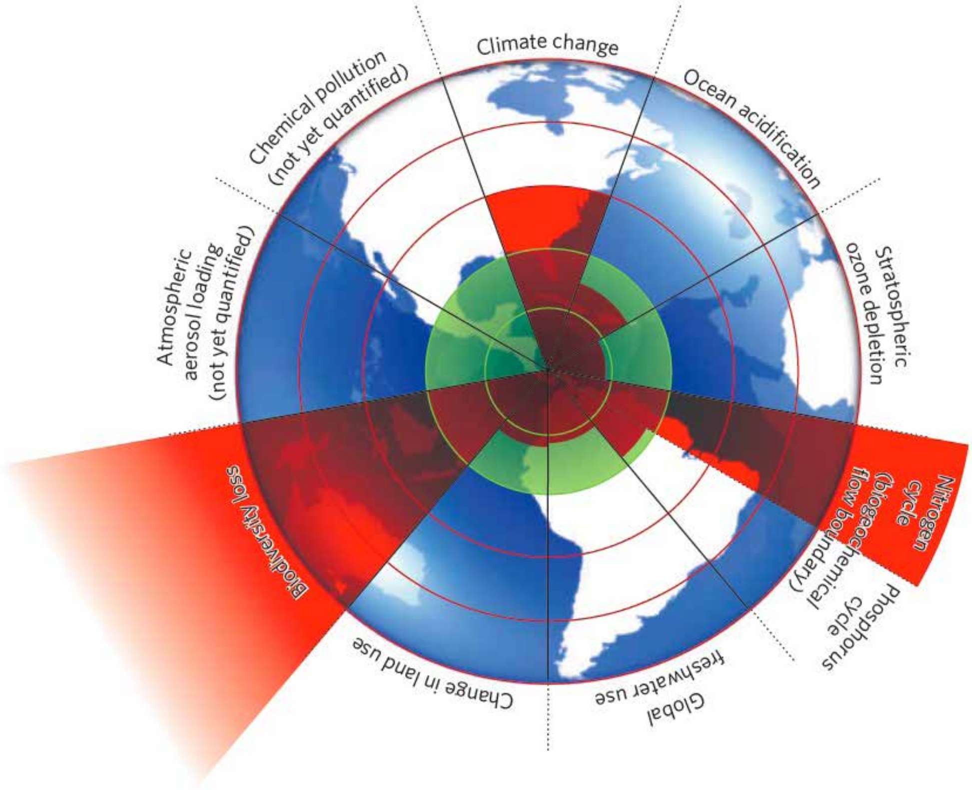
(d) Land is assumed to be contaminated when the deposition of Cs-137 exceeds 40 kBq per m2, following an IAEA definition.

(e) Atmospheric dispersion and deposition of Cs-137 are modeled by assuming the occurrence, with a frequency of 1 per 5,000 reactor-years, of a continuous release of Cs-137 from each of 440 reactors worldwide throughout a 1-year period. The total release from each reactor over that period is as stated in note (b). The modeling is done with the EMAC general circulation model, using atmospheric conditions across the year 2005.

(f) The figure shows the modeled frequency (% per year) of occurrence of Cs-137 land contamination exceeding 40 kBq per m2, at locations worldwide. This frequency is described as the “risk of contamination” by Cs-137. One sees that this risk exceeds 2% per year at some locations.

Figure 4-1

Earth's "Safe Operating Space" and the Present Impact of Human Activity, According to Rockstrom et al



NOTES:

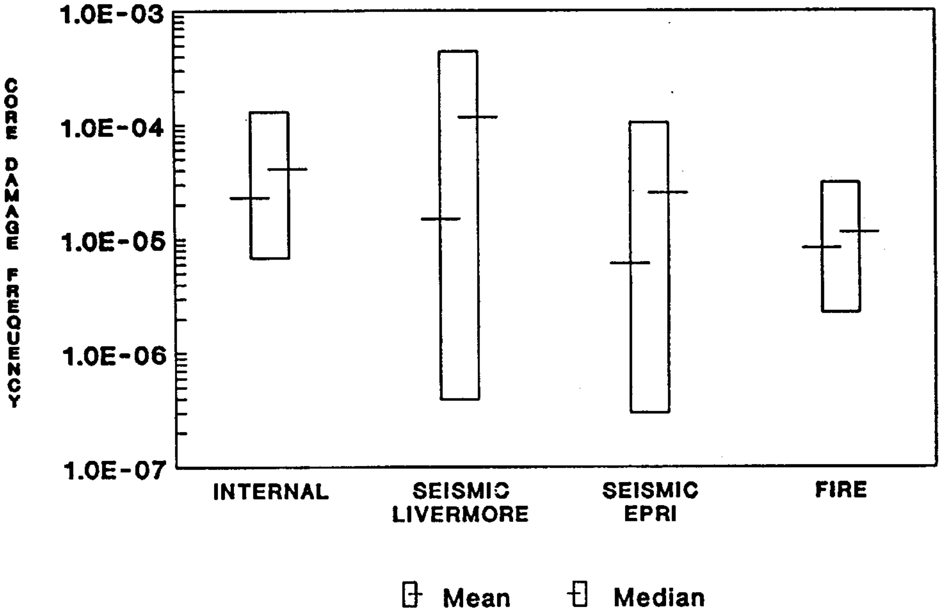
(a) This figure is reproduced from Figure 1 of: Rockstrom et al, 2009b.

(b) The inner green shading represents Rockstrom et al's proposed safe operating space for nine planetary systems. The nitrogen and phosphorus cycles are treated as parts of a single planetary system. The red wedges represent Rockstrom et al's estimate of the current position for each variable. The safe boundaries of three systems (rate of biodiversity loss, climate change, and human interference with the nitrogen cycle) have already been exceeded.

(c) Rockstrom et al present numerical indicators for the green- and red-shaded areas, for seven of the nine planetary systems.

Figure 5.1-1

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 core damage frequency (CDF). CDF values shown are per reactor-year (RY).

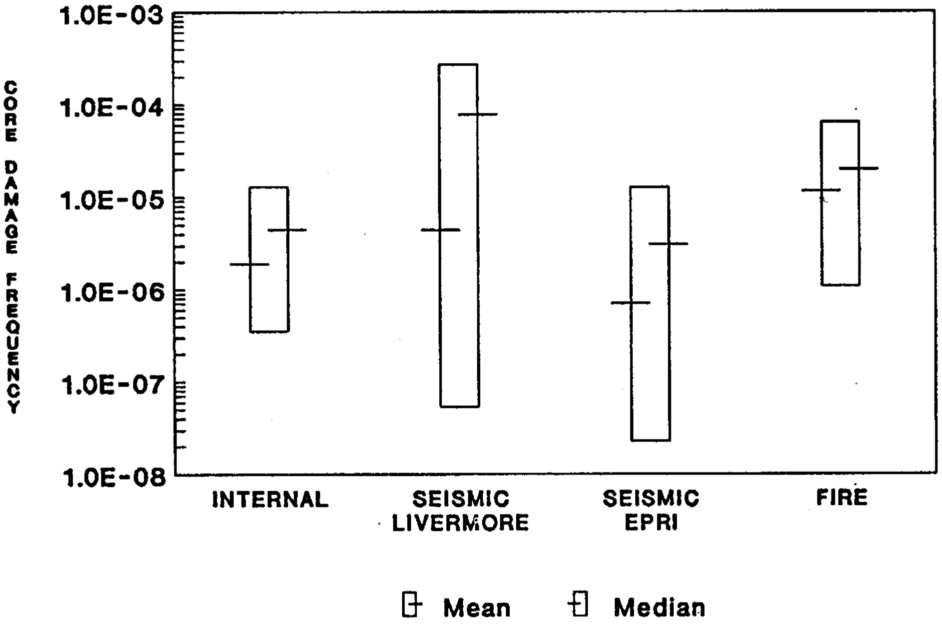
(c) Two estimates are shown for the CDF from earthquakes (seismic effects). One estimate derives from seismic predictions done at Lawrence Livermore National Laboratory (Livermore), the other from predictions done at the Electric Power Research Institute (EPRI).

(d) CDFs are not shown here for external initiating events other than earthquakes and fires.

(e) Malevolent acts were not considered.

Figure 5.1-2

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 core damage frequency (CDF). CDF values shown are per reactor-year (RY).

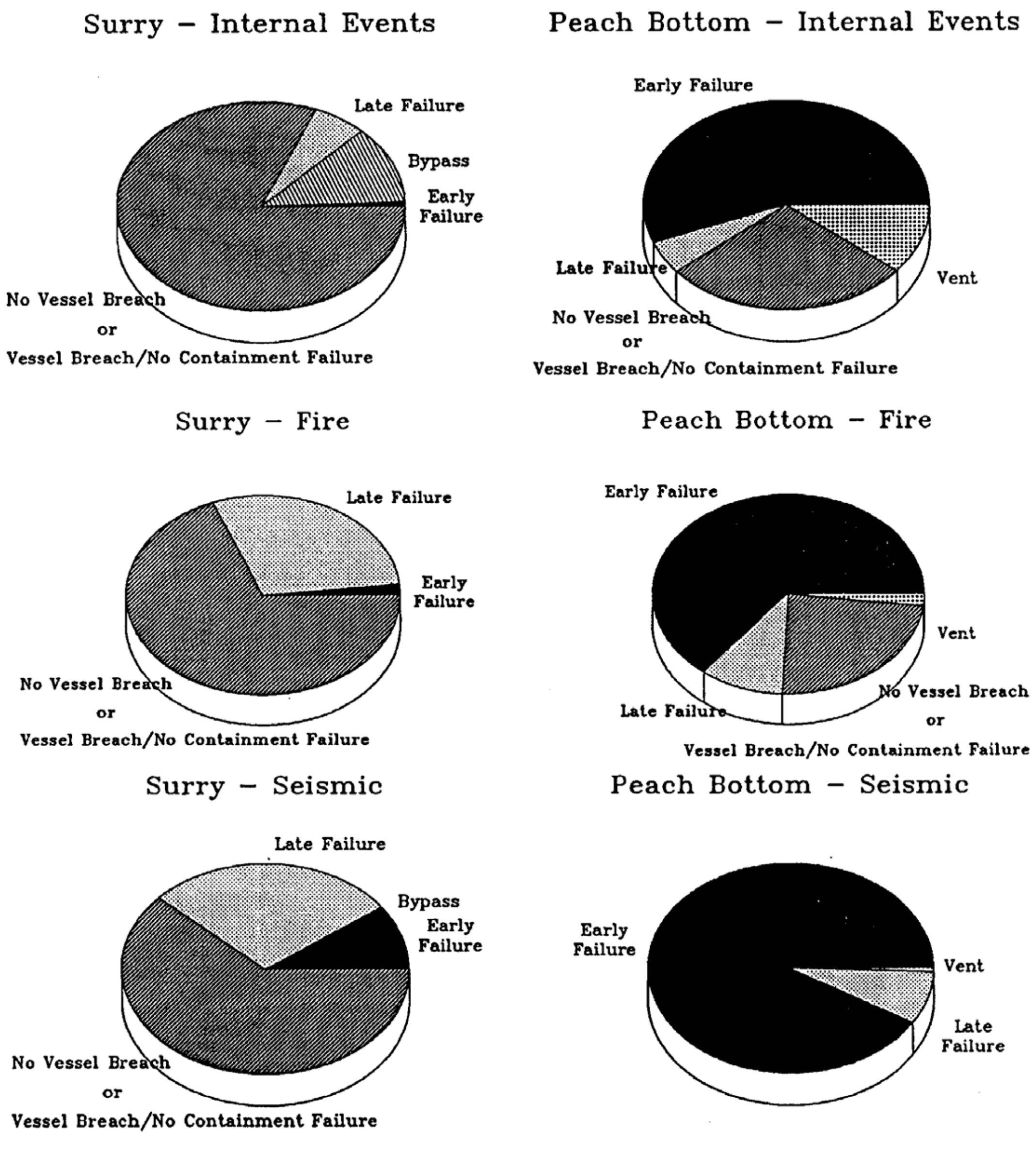
(c) Two estimates are shown for the CDF from earthquakes (seismic effects). One estimate derives from seismic predictions done at Lawrence Livermore National Laboratory (Livermore), the other from predictions done at the Electric Power Research Institute (EPRI).

(d) CDFs are not shown here for external initiating events other than earthquakes and fires.

(e) Malevolent acts were not considered.

Figure 5.1-3

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


Surry – Internal Events

Peach Bottom – Internal Events

Surry – Fire

Peach Bottom – Fire

Surry – Seismic

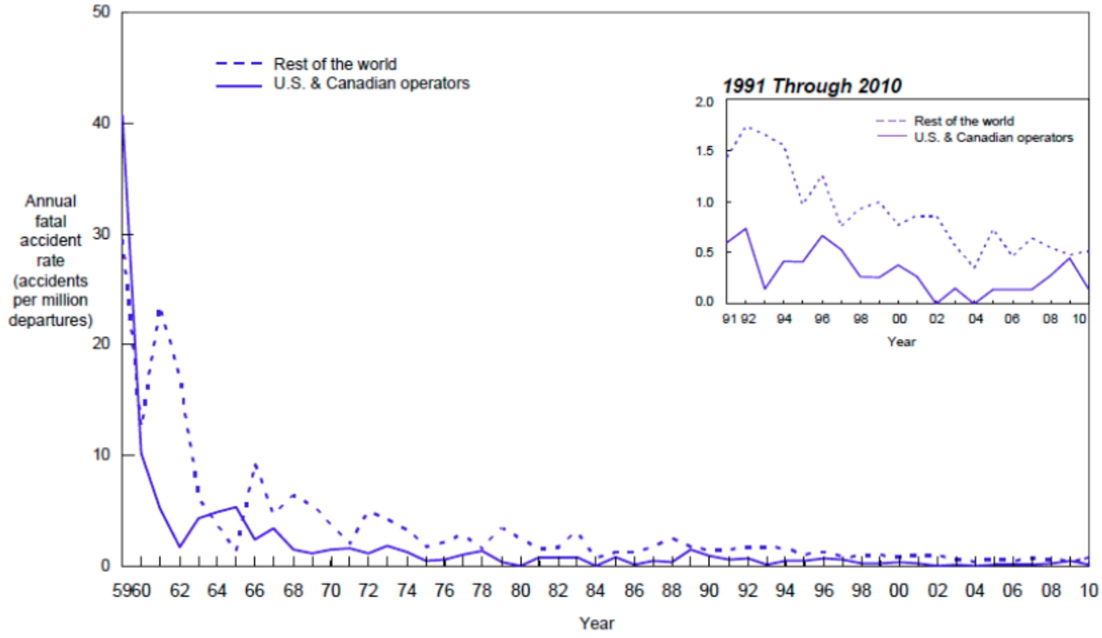
Peach Bottom – Seismic

NOTE:

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

Figure 5.2-1

Incidence of Commercial Aircraft Accidents Involving Fatality, 1959 through 2010



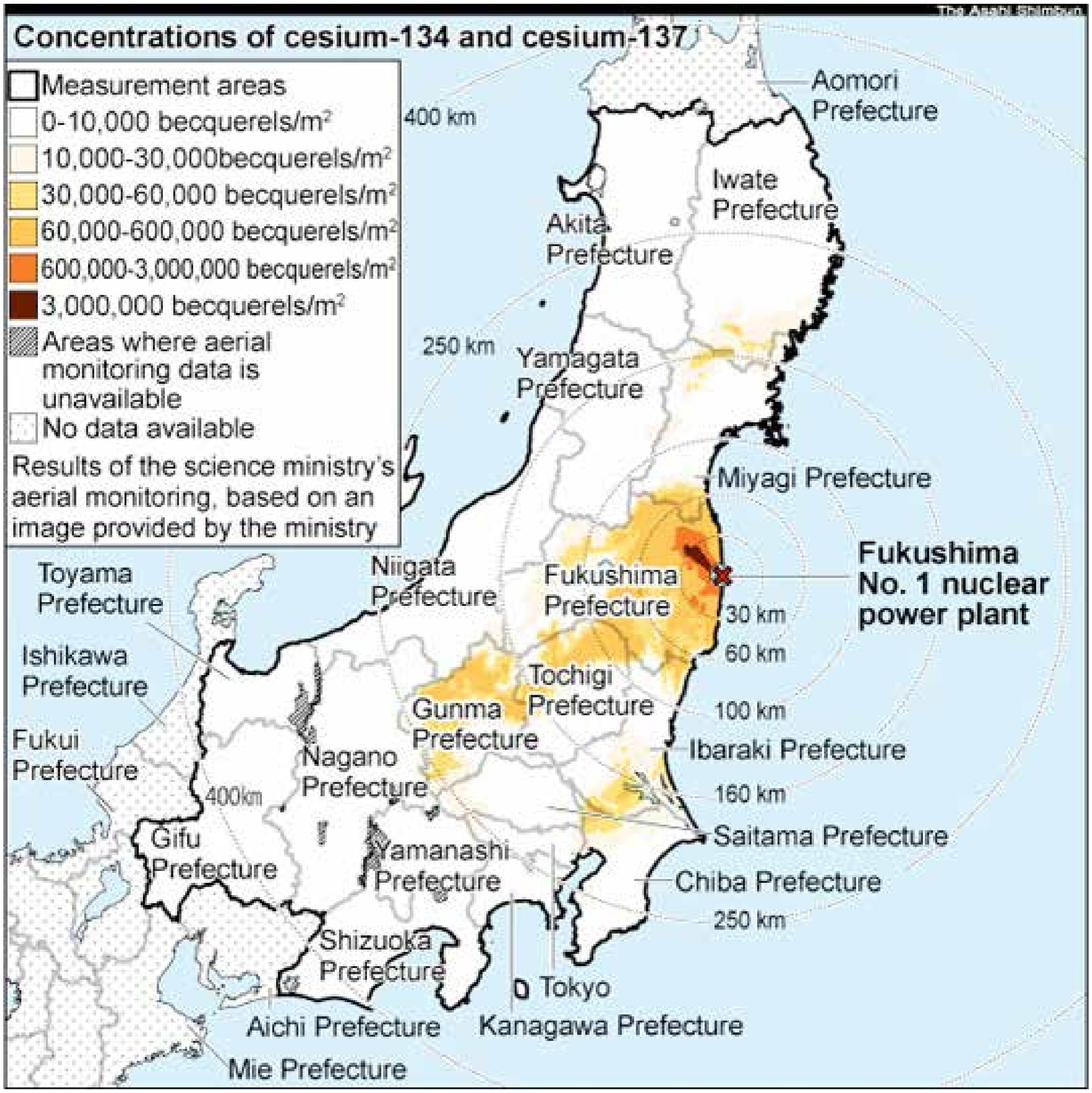
NOTES:

(a) This figure is reproduced from Figure 3 (at page 10) of: ASME, 2012.

(b) Apparently, this figure includes the four crashes of hijacked aircraft that occurred in the USA on 11 September 2001.

Figure 5.2-2

Contamination of Land in Japan by Radioactive Cesium Released to the Atmosphere During the Fukushima #1 Accident of 2011

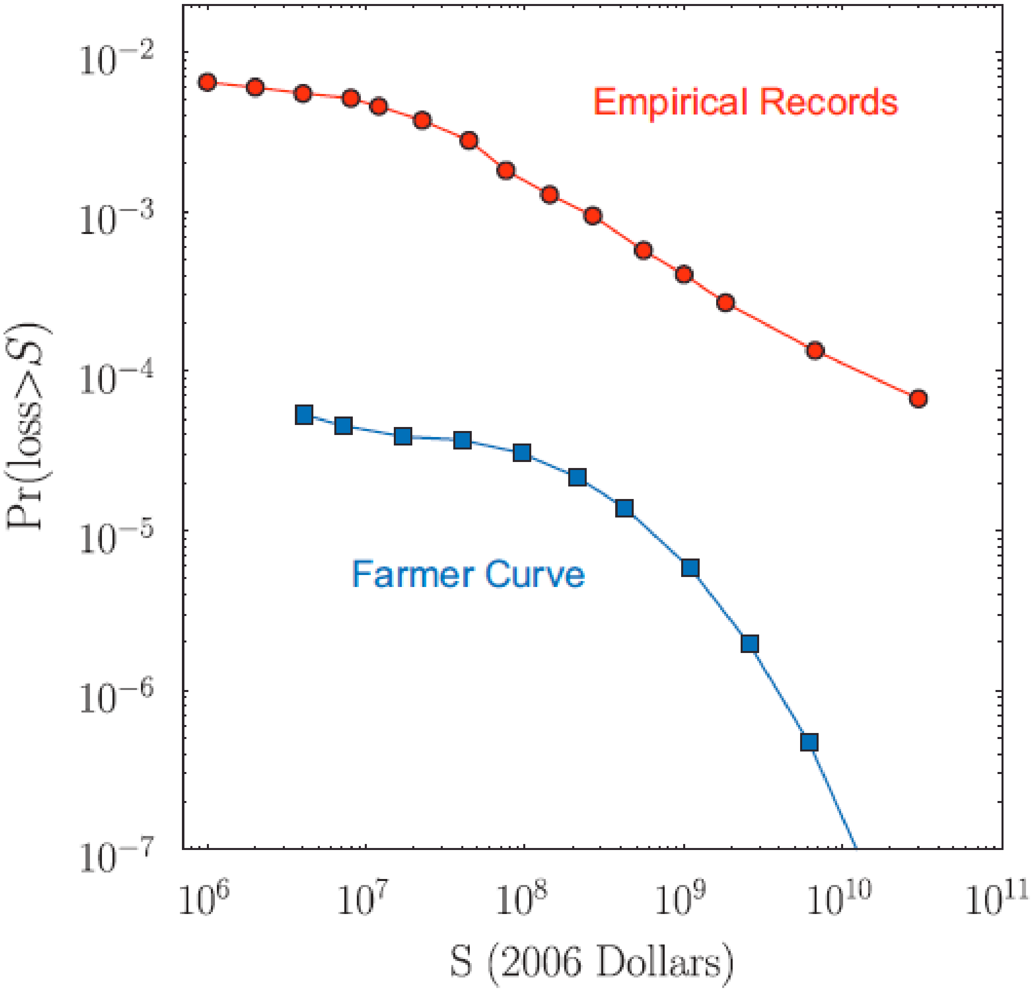


SOURCE:

Asahi Shimbun, 2011.

Figure 5.2-3

Probability Distribution of Monetized Losses from Nuclear-Facility Incidents: Sornette et al's Comparison of Empirical Data with PRA Estimates



NOTES:

(a) This figure is a reproduction of Figure 1 from: Sornette et al, 2013.

(b) The curves shown are complementary cumulative distribution functions.

(c) The vertical axis is probability per reactor-year (or facility-year).

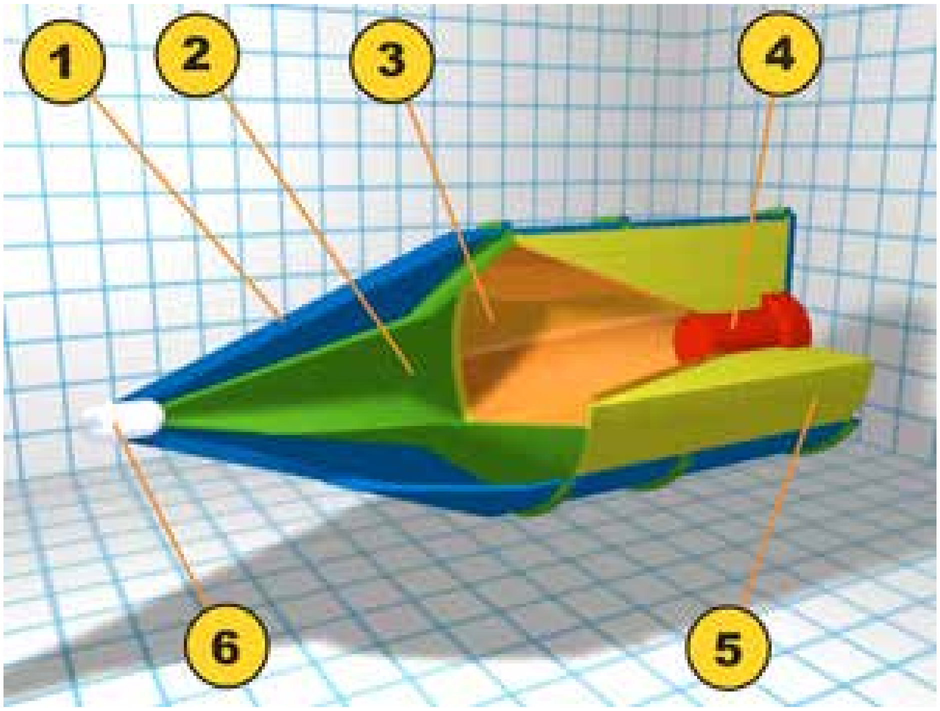
(d) S = monetized loss.

(e) The "Farmer Curve" is based on findings from NRC's Reactor Safety Study, which was the first reactor PRA. In this curve, monetized losses are associated with radiological impacts.

(f) The "Empirical Records" curve is based on Sovacool's compilation of data on 99 incidents at nuclear facilities. In this curve, monetized losses may, or may not, be associated with radiological impacts.

Figure 5.4-1

Schematic View of a Generic Shaped-Charge Warhead



NOTES:

(a) Figure accessed on 4 March 2012 from: http://en.wikipedia.org/wiki/Shaped_charge

(b) Key:

Item 1: Aerodynamic cover

Item 2: Empty cavity

Item 3: Conical liner (typically made of ductile metal)

Item 4: Detonator

Item 5: Explosive

Item 6: Piezo-electric trigger

(c) Upon detonation, a portion of the conical liner would be formed into a high-velocity jet directed toward the target. The remainder of the liner would form a slower-moving slug of material.

Figure 5.4-2

MISTEL System for Aircraft Delivery of a Shaped Charge, World War II

NOTES:

(a) Photograph accessed on 5 March 2012 from: http://www.historyofwar.org/Pictures/pictures_Ju_88_mistel.html

(b) A shaped-charge warhead can be seen at the nose of the lower (converted bomber) aircraft, replacing the cockpit. The aerodynamic cover in front of the warhead would have a contact fuse at its tip, to detonate the shaped charge at the appropriate standoff distance.

(c) A human pilot in the upper (fighter) aircraft would control the entire rig, and would point it toward the target. Then, the upper aircraft would separate and move away, and the lower aircraft would be guided to the target by an autopilot.

Figure 5.4-3

January 2008 Test of a Raytheon Shaped Charge, Intended as the Penetration (Precursor) Stage of a Tandem Warhead System

BEFORE TEST

AFTER TEST (VIEWED FROM THE ATTACKED FACE)

NOTES:

(a) These photographs are from: Raytheon, 2008. For additional, supporting information, see: Warwick, 2008.

(b) The shaped-charge jet penetrated about 5.9 m into a steel-reinforced concrete block with a thickness of 6.1 m. Although penetration was incomplete, the block was largely destroyed, as shown. Compressive strength of the concrete was 870 bar.

(c) The shaped charge had a diameter of 61 cm and contained 230 kg of high explosive. It was sized to fit inside the US Air Force's AGM-129 Advanced Cruise Missile.

Figure 5.4-4

Aftermath of a Small-Aircraft Suicide Attack on an Office Building in Austin, Texas, February 2010

NOTES:

(a) Photograph and information in these notes are from: Brick, 2010.

(b) A major tenant of the building was the Internal Revenue Service (IRS).

(c) The aircraft was a single-engine, fixed-wing Piper flown by its owner, Andrew Joseph Stack III, an Austin resident who worked as a computer engineer.

(d) A statement left by Mr Stack indicated that a dispute with IRS had brought him to a point of suicidal rage.

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33, Cecil Street, **Toronto** (Ontario) M5T 1N1
1726, Commercial Drive, **Vancouver** (Colombie-Britannique) V5N 4A3
6238 - 104 Street NW, **Edmonton** (Alberta) T6H 2K9
454, avenue Laurier Est, 3e étage, **Montréal** (Québec) H2J 1E7

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