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COMMENTS ON PROPOSED SCREENING REPORT ON ENVIRONMENTAL ASSESSMENT OF REFURBISHMENT & CONTINUED OPERATION OF DARLINGTON NUCLEAR GENERATING STATION

by
Gordon R. Thompson

12 October 2012

Prepared under the sponsorship of
Northwatch (Northeastern Ontario)

Abstract

The Canadian Nuclear Safety Commission (CNSC), and Fisheries and Oceans Canada (DFO), are conducting an environmental assessment (EA) process to consider a proposal by Ontario Power Generation (OPG). The proposal is to refurbish the Darlington Nuclear Generating Station (DNGS) and continue its operation thereafter. As part of the EA process, CNSC staff and DFO published in September 2012 a Proposed EA Screening Report, referred to here as the "Proposed Screening Report". A draft version of that document – referred to here as the "Draft Screening Report" – was published by CNSC and DFO in June 2012. This report provides comments on the Proposed Screening Report, focusing on a selected set of issues. Those issues pertain to the radiological risk arising from onsite management and storage of spent nuclear fuel (SNF) discharged from the nuclear reactors at DNGS. In addressing those issues, this report incorporates by reference, and attaches herewith, a report dated 16 July 2012 by the same author, which commented on the Draft Screening Report. From the perspective of this report, the Proposed Screening Report is identical to the Draft Screening Report.

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 Thompson is the executive director of IRSS and a senior research scientist at the George Perkins Marsh Institute, Clark University, Worcester, Massachusetts. He studied engineering at the University of New South Wales, practiced engineering in the electricity industry in Australia, and then 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 environmental, security, and economic issues related to commercial and military nuclear facilities.

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Contents

Attachment

The following report is attached herewith:

Gordon R. Thompson, *Comments on Draft Screening Report on Environmental Assessment of Refurbishment and Continued Operation of Darlington Nuclear Generating Station* (Cambridge, Massachusetts: Institute for Resource and Security Studies, 16 July 2012).

1. Introduction

The Canadian Nuclear Safety Commission (CNSC), and Fisheries and Oceans Canada (DFO), are conducting an environmental assessment (EA) process to consider a proposal by Ontario Power Generation (OPG). The proposal is to refurbish the Darlington Nuclear Generating Station (DNGS) and continue its operation thereafter.

As part of the EA process, CNSC staff and DFO published in September 2012 a Proposed EA Screening Report.[1] That document is referred to here as the "Proposed Screening Report". A draft version of that document – referred to here as the "Draft Screening Report" – was published by CNSC and DFO in June 2012.[2]

This report provides comments on the Proposed Screening Report, focusing on a selected set of issues. Those issues pertain to the radiological risk arising from onsite management and storage of spent nuclear fuel (SNF) discharged from the nuclear reactors at DNGS. The term "radiological risk", as used here, refers to the potential for harm to humans as a result of their exposure to ionizing radiation due to an unplanned release of radioactive material.

This report incorporates by reference, and attaches herewith, a report dated 16 July 2012 by the same author, which commented on the Draft Screening Report.[3] That document is referred to here as the "Thompson Comments on the Draft Screening Report".

From the perspective of this report, as explained in Section 3, below, the Proposed Screening Report is identical to the Draft Screening Report. Thus, the Thompson Comments on the Draft Screening Report apply without alteration to the Proposed Screening Report.

2. Overview of Thompson Comments on the Draft Screening Report

The Thompson Comments on the Draft Screening Report contain nine conclusions and one recommendation, restated here with slight editing. The conclusions are:

C1. A number of credible studies show that management and storage of SNF discharged from commercial light-water reactors (LWRs) can create substantial radiological risk, and that options for reducing the risk are available. Experience with the Fukushima accident has highlighted the relevance of these studies to the regulation of nuclear generating stations.

C2. The major contributor to SNF radiological risk at LWR stations is the potential for SNF to be uncovered (exposed to air) due to loss of water from a spent-fuel pool. In that event, the zircaloy cladding of the SNF could undergo an exothermic reaction with steam

[1] CNSC and DFO, 2012a.
[2] CNSC and DFO, 2012b.
[3] Thompson, 2012.

and/or air, leading to a substantial release of radioactive material to the atmosphere. Also, a zircaloy-steam reaction would generate hydrogen gas, which could explode violently when mixed with air.

C3. While SNF radiological risk has been extensively studied in an LWR context, comparable studies have not been done for SNF discharged from CANDU reactors such as those used at DNGS. Nevertheless, the CNSC's Fukushima Task Force has acknowledged that a substantial radiological risk arises from storage of SNF under water in IFBs at stations such as DNGS.[4] The Task Force has acknowledged that uncovering of the SNF could cause the fuel to overheat, leading to a release of radioactive material and hydrogen gas.

C4. The Fukushima Task Force has implicitly recognized the lack of studies of SNF radiological risk at CANDU stations. The Task Force has called upon Canadian licensees to enhance their modeling capabilities in this area, and to conduct systematic analyses of beyond-design-basis accidents at irradiated fuel bays (IFBs). The Task Force has said that these analyses should include the estimation of releases, into the atmosphere and water, of radioactive material and hydrogen gas.

C5. A report prepared by SENES Consultants for OPG shows that OPG is aware that uncovering of SNF is an event to be feared.[5] Also, one could reasonably expect that OPG would be fully cognizant of the findings of the Fukushima Task Force.

C6. The Draft Screening Report cites the SENES report and the Fukushima Task Force report. Yet, the Draft Screening Report fails to acknowledge the risk associated with uncovering of SNF in an IFB. Instead, the Draft Screening Report focuses its discussion of SNF radiological risk on two comparatively minor events – drop of a dry storage container (DSC), and drop of an SNF storage module. In those cases, it seems that the Draft Screening Report has simply adopted the position of OPG.

C7. The Draft Screening Report explicitly excludes consideration of malevolent acts as contributors to radiological risk. That exclusion may lead to substantial under-estimation of risk.

C8. Technical understanding of SNF radiological risk and risk-reduction options in a CANDU context could be brought up to or beyond the present level of understanding of SNF radiological risk and risk-reduction options in an LWR context. Achieving that outcome would require the conduct of a number of independent, CANDU-focused studies that are openly published and subjected to peer review and public review.

[4] CNSC-FTF, 2011.
[5] SENES, 2011.

C9. Completion of a credible EA process for refurbishment and continued operation of DNGS would require, among other ingredients, that OPG and CNSC demonstrate a thorough technical understanding of SNF radiological risk and risk-reduction options associated with DNGS. The studies outlined in Conclusion C8 could provide that understanding, if conducted appropriately.

Based on these conclusions, the recommendation is:

R1. Completion of the EA process for refurbishment and continued operation of DNGS should be deferred until OPG and CNSC demonstrate a thorough technical understanding of SNF radiological risk and risk-reduction options associated with DNGS, and this understanding is clearly communicated to the public in relevant EA documents. (See Conclusions C8 and C9.)

3. The Proposed Screening Report's Response to Thompson Comments

The Proposed Screening Report responds to the Thompson Comments on the Draft Screening Report, doing so in its Appendix B, at pages B146 to B148. The nature of the response is evident from its first line: "No change to the EA Screening Report".

That statement has two implications. First, the Proposed Screening Report rejects the conclusions and recommendation set forth here in Section 2, above. Second, from the perspective of this report, the Proposed Screening Report is identical to the Draft Screening Report. Thus, the Thompson Comments on the Draft Screening Report apply without alteration to the Proposed Screening Report.

The Proposed Screening Report does offer some arguments, attributed to CNSC staff, for rejecting the conclusions and recommendation set forth in the Thompson Comments. The significant arguments are:

i. Loss of IFB cooling would be a slow-progressing event that could be mitigated by operator actions;
ii. There is no requirement under the Canadian Environmental Assessment (CEA) Act to consider malevolent actions;
iii. Licensee measures effectively counter the Design Basis Threat and mitigate the Beyond Design Basis Threat; and
iv. CANDU plant layout differs from LWR plant layout.

None of these arguments is compelling. They are addressed briefly in the following paragraphs.

Would loss of IFB cooling be a slow-progressing event that could be mitigated by operator actions?

This question misses the point. What matters most from the perspective of SNF radiological risk is the potential for fuel to be uncovered (exposed to air), and the outcome of that event.

Fuel could be uncovered at DNGS if water is lost from an IFB. Mechanisms for water loss include leakage, boiling away, siphoning, pumping, displacement by falling objects, or sloshing during an earthquake. These mechanisms could operate in various ways during an accident or an attack. Loss of water and loss of cooling are inter-related. It is likely that the cooling system for each IFB at DNGS extracts water from the top layer of the pool, and would therefore cease functioning after loss of a comparatively small amount of water. If water is extracted at a lower level, then a potential pathway exists for loss of water by siphoning.

CNSC, OPG, and other arms of the Canadian nuclear industry should systematically assess all potential scenarios whereby fuel could be uncovered in an IFB, whether at DNGS or another CANDU station. This author sees no evidence that such a systematic assessment has been performed or contemplated.

When the potential for spent fuel to be uncovered is understood, the next step would be to assess the outcome of this event. Most importantly, could the uncovered fuel self-ignite and burn? There is general agreement that this outcome could occur at a contemporary LWR station. CNSC and the Canadian nuclear industry should conduct thorough studies to determine if uncovered fuel could self-ignite and burn at a CANDU station.

Is there a requirement under the CEA Act to consider malevolent actions?

This question raises legal issues that are not addressed here. From the perspective of risk assessment, however, it is clear that malevolent actions could be major contributors to radiological risk at CANDU stations. Thus, when the Proposed Screening Report excludes consideration of malevolent actions, it denies the public a credible assessment of the radiological risk posed by DNGS. Moreover, that denial undermines the credibility of any statement by CNSC or the Canadian nuclear industry regarding the vulnerability of CANDU stations to attack. Experience shows that organizations which deny reality in a public context are prone to denying reality in their secret deliberations.

Can licensee measures effectively counter the
Design Basis Threat and mitigate the Beyond Design Basis Threat?

CNSC and the Canadian nuclear industry cannot provide a credible answer to this question. They have undermined their credibility by refusing to acknowledge publicly that CANDU stations were not designed to resist attack, and are therefore vulnerable in various respects. It would not be appropriate for these organizations, or any responsible party, to publicly discuss details about the vulnerability. What is appropriate is to provide the public with a realistic assessment of risk, and to support that assessment with secret analyses that are rigorous and consistent with public statements.

Does CANDU plant layout differ from LWR plant layout?

Clearly, the design of a CANDU station differs in many ways from that of an LWR station. For example, the fuel bundles are significantly different. CANDU fuel is driven to a comparatively low burnup, and can be stored under (light) water in a compact configuration without the presence of neutron-absorbing plates. However, CANDU fuel and LWR fuel both employ zircaloy cladding. Thus, they share the potential for exothermic reaction of zircaloy with steam or air.

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

4. Conclusions and Recommendations

Conclusions

C1. The Thompson Comments on the Draft Screening Report apply without alteration to the Proposed Screening Report. (The Thompson Comments are attached herewith, and are incorporated by reference.)

C2. The Proposed Screening Report does not provide a credible assessment of SNF radiological risk at DNGS.

Recommendations

R1. CNSC, OPG, and other arms of the Canadian nuclear industry should thoroughly assess SNF radiological risk and risk-reduction options at DNGS and other CANDU stations.

R2. Completion of the EA process for Darlington refurbishment should be deferred until EA documents provide the public with a credible account of SNF radiological risk and risk-reduction options.

5. Bibliography

(CNSC and DFO, 2012a)
Canadian Nuclear Safety Commission, and Fisheries and Oceans Canada, *Proposed Environmental Assessment Screening Report: The Refurbishment and Continued Operation of the Darlington Nuclear Generating Station, Municipality of Clarington, Ontario* (Ottawa: Canadian Nuclear Safety Commission, September 2012).

(CNSC and DFO, 2012b)
Canadian Nuclear Safety Commission, and Fisheries and Oceans Canada, *Draft Screening Report on: Environmental Assessment of the Refurbishment and Continued Operation of the Darlington Nuclear Generating Station, Municipality of Clarington, Ontario* (Ottawa: Canadian Nuclear Safety Commission, June 2012).

(CNSC-FTF, 2011)
The Canadian Nuclear Safety Commission's Fukushima Task Force, *CNSC Fukushima Task Force Report, INFO-0824* (Ottawa: Canadian Nuclear Safety Commission, October 2011).

(SENES, 2011)
SENES Consultants Limited, *Malfunctions and Accidents Technical Support Document, Darlington Nuclear Generating Station Refurbishment and Continued Operation Environmental Assessment* (Richmond Hill, Ontario: SENES Consultants, December 2011).

(Thompson, 2012)
Gordon R. Thompson, *Comments on Draft Screening Report on Environmental Assessment of Refurbishment and Continued Operation of Darlington Nuclear Generating Station* (Cambridge, Massachusetts: Institute for Resource and Security Studies, 16 July 2012).

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COMMENTS ON DRAFT SCREENING REPORT ON ENVIRONMENTAL ASSESSMENT OF REFURBISHMENT & CONTINUED OPERATION OF DARLINGTON NUCLEAR GENERATING STATION

by
Gordon R. Thompson

16 July 2012

Prepared under the sponsorship of
Northwatch (Northeastern Ontario)

Abstract

The Canadian Nuclear Safety Commission (CNSC), and Fisheries and Oceans Canada (DFO), are conducting an environmental assessment (EA) process to consider a proposal by Ontario Power Generation (OPG). The proposal is to refurbish the Darlington Nuclear Generating Station (DNGS) and continue its operation thereafter. As part of the EA process, CNSC staff and DFO have prepared an EA Screening Report. A draft version of that document – referred to here as the "Draft Screening Report" – was published in June 2012. This report provides comments on the Draft Screening Report, focusing on a selected set of issues. Those issues pertain to the radiological risk arising from onsite management and storage of spent nuclear fuel (SNF) discharged from the nuclear reactors at DNGS. That risk has been extensively studied in the context of SNF discharged from light-water reactors (LWRs). Similar studies have not been done for SNF discharged from CANDU reactors, as are used at DNGS. Nevertheless, the CNSC's Fukushima Task Force has acknowledged that the uncovering of SNF stored under water, at stations such as DNGS, could lead to a substantial release of radioactive material. The Draft Screening Report does not discuss that threat, and focuses its discussion of SNF radiological risk on comparatively minor events.

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Gordon Thompson is the executive director of IRSS and a senior research scientist at the George Perkins Marsh Institute, Clark University, Worcester, Massachusetts. He studied engineering at the University of New South Wales, practiced engineering in the electricity industry in Australia, and then 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 environmental, security, and economic issues related to commercial and military nuclear facilities.

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Contents

(Tables and Figures are listed on the following pages.)

List of Tables and Figures
(These Tables and Figures appear after Section 10 of the report.)

Tables

Figures

1. Introduction

Ontario Power Generation (OPG) proposes to refurbish the Darlington Nuclear Generating Station (DNGS), and continue its operation thereafter. That proposal requires decisions under the Canadian Environmental Assessment Act (CEA) by the "Responsible Authorities" – the Canadian Nuclear Safety Commission (CNSC), and Fisheries and Oceans Canada (DFO). To guide those decisions, CNSC staff and DFO have prepared an Environmental Assessment (EA) Screening Report. A draft version of that document – referred to here as the "Draft Screening Report" – was published in June 2012.[6]

This report provides comments on the Draft Screening Report, focusing on a selected set of issues. Those issues pertain to the radiological risk arising from onsite management and storage of spent nuclear fuel (SNF) discharged from the nuclear reactors at the DNGS. The term "radiological risk" is discussed below.

The Institute for Resource and Security Studies (IRSS), an independent body based in Cambridge, Massachusetts, prepared this report under the sponsorship of Northwatch, a public-interest organization based in Northeastern Ontario.

Radiological risk associated with SNF

The term "radiological risk", as used in this report, refers to the potential for harm to humans as a result of their exposure to ionizing radiation due to an unplanned release of radioactive material. A more detailed discussion of radiological risk is provided in Section 4, below.

Credible studies, beginning in the late 1970s, as discussed in this report, show that management and storage of SNF discharged from commercial light-water reactors (LWRs) can create substantial radiological risk.[7] Experience with the 2011 accident at the Fukushima #1 site in Japan has highlighted the relevance of these studies to the regulation of nuclear generating stations.

Comparable studies have not been done for SNF discharged from CANDU reactors such as those used at DNGS.[8] Nevertheless, as discussed in this report, a Task Force established by the CNSC to investigate lessons learned from the Fukushima accident has acknowledged that substantial SNF radiological risk may exist at CANDU stations.[9]

Members of the public could reasonably expect that the Draft Screening Report would provide a thorough assessment of SNF radiological risk at DNGS, and a description of

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[6] CNSC and DFO, 2012.
[7] LWRs are cooled and moderated by ordinary (light) water. These reactors are either pressurized-water reactors (PWRs) or boiling-water reactors (BWRs).
[8] The term "CANDU" refers to a Canadian-designed pressurized-heavy-water reactor (PHWR) that is cooled and moderated by heavy water.
[9] CNSC-FTF, 2011.

options for reducing that risk. This report examines the extent to which the Draft Screening Report meets that expectation.

Structure of this report

The remainder of this report has nine sections. Section 2 summarizes the management and storage of SNF at DNGS. Section 3 reviews the discussion of SNF radiological risk in the Draft Screening Report, and in related documents prepared by OPG and CNSC. Then, Section 4 provides a general discussion of the definition and estimation of radiological risk. Section 5 describes the enhancement of public attention to SNF radiological risk that was stimulated by the Fukushima accident.

Section 6 reviews the state of technical understanding of SNF radiological risk in the LWR context, and Section 7 outlines options for risk reduction in that context. Section 8 outlines the steps needed to develop a technical understanding of SNF radiological risk and risk-reduction options in the CANDU context. Conclusions and recommendations are set forth in Section 9, and a bibliography is provided in Section 10. Citations throughout this report, if not provided directly, refer to entries in the bibliography.

2. Management and Storage of SNF at DNGS

Figure 2-1 shows a fuel bundle as used in the four DNGS reactors. The bundle contains 37 zirconium alloy (zircaloy) tubes containing uranium dioxide pellets made from natural uranium.[10] After a period of exposure in a reactor, the bundle becomes “spent” in the sense that it is no longer suitable for power production. The bundle is then discharged from the reactor, and is thereafter designated as SNF. Each SNF bundle contains a large inventory of radioactive isotopes that decay over time, and the decay generates a substantial amount of heat.

After being discharged from a DNGS reactor, an SNF bundle is transferred to one of two irradiated fuel bays (IFBs). One of these IFBs is located at each end of the long axis of the main DNGS building. At an IFB, an SNF bundle is placed in a storage module, which has a capacity of 96 bundles, and is then stored under water for a period of at least 10 years. The two IFBs have a combined total storage capacity of over 400,000 SNF bundles – enough for up to 20 station-years of operation.[11] These IFBs operate in the same general manner as spent-fuel pools at LWR stations. In both cases, water absorbs decay heat from the SNF and shields workers from the ionizing radiation emitted by the SNF. Figure 2-2 shows an IFB of the type used at DNGS.

After storage for at least 10 years in an IFB, an SNF bundle may be placed with other bundles into a dry storage container (DSC) and transferred to the Darlington Waste Management Facility (DWMF), which is located on the DNGS site. Figure 2-3 shows a

[10] OPG, 2011, Section 2.5.4.
[11] OPG, 2011, Section 2.5.4; OPG, 2010.

DSC, which has a capacity of 384 SNF bundles. At the DWMF, a DSC is stored inside a single-storey, concrete building, which has a capacity of 500 DSCs. One such building is now in use at the site, and OPG expects to construct second and third buildings in about 2013 and 2022, respectively. Refurbishment and continued operation of DNGS would require the construction of a fourth building in about 2031.[12]

3. Discussion of SNF Radiological Risk in the Draft Screening Report and Related Documents

The Draft Screening Report addresses radiological risk in its Section 7, titled "Malfunctions and Accidents". Section 7 opens with the statement:

> "The CEA Act requires that every EA of a project include consideration of the environmental effects of malfunctions or accidents that may occur in connection with the project. Malevolent events have not been considered in this environmental assessment, as CNSC staff are of the view that security issues are being appropriately managed by the ongoing regulatory process and that they do not warrant special consideration in this EA."

The categories of event considered in Section 7 of the Draft Screening Report are:

- Conventional malfunctions and accidents (Section 7.1)
- Radiological malfunctions and accidents (Section 7.2)
- Transportation accident (Section 7.3)
- Out-of-core criticality (Section 7.4)
- Nuclear accidents (Section 7.5)

According to the Draft Screening Report and OPG, out-of-core criticality is not a concern for SNF from DNGS, because this fuel will not become critical in either air or light water.[13] Also, "conventional" malfunctions and accidents are not relevant to radiological risk. Thus, radiological risk (as defined in this report) may pertain to the following three categories of event identified in the Draft Screening Report: (i) "radiological malfunctions and accidents"; (ii) "transportation accidents"; and (iii) "nuclear accidents". The first of those three categories features an inappropriate use of the word "radiological", because the category does not encompass all potential events that contribute to the radiological risk associated with continued operation of DNGS.

[12] OPG, 2011, Section 2.5.10; OPG, 2010.
[13] CNSC and DFO, 2012, Section 7.4; SENES, 2011, Section 7.0.

The Draft Screening Report identifies two events that contribute to SNF radiological risk. The events, described as "bounding scenarios", are:

- Drop of a DSC during on-site transport (Section 7.2.2)
- Drop of an SNF storage module onto the floor of an IFB (Section 7.2.4)

According to the Draft Screening Report (Section 7.2.2), the drop of a DSC during on-site transport could release to the atmosphere 1.02E+12 Bq of Hydrogen-3 (tritium) and 5.68E+12 Bq of Krypton-85. No other radioactive isotope would be released. The maximum dose to a worker would be 4.5 mSv, and the maximum dose to a member of the public would be 0.0015 mSv.

Also, according to the Draft Screening Report (Section 7.2.4), the drop of an SNF storage module (containing 96 fuel bundles) onto the floor of an IFB could lead to a release as follows: "The free inventory of noble gases is assumed to be instantly released followed by leaching from the fuel pellets." The isotopic composition, magnitude, release pathway, and timeframe of this release are not stated. The maximum dose to a member of the public would be 0.07 mSv, and the maximum dose to a worker is not estimated.

The SENES Report

The same two SNF-related events were discussed in a December 2011 report prepared by SENES Consultants for OPG, to provide technical support to this EA process.[14] Hereafter, that report is referred to as the "SENES Report". The SENES Report examined malfunctions and accidents relevant to the refurbishment and continued operation of DNGS. It employed the same five event categories as are used in Section 7 of the Draft Screening Report.

Section 4.4.2 of the SENES Report discussed the drop of a DSC during on-site transport. That discussion provided only slightly more detail than is provided in Section 7.2.2 of the Draft Screening Report. Also, Section 4.4.4 of the SENES Report discussed the drop of an SNF storage module onto the floor of an IFB. That discussion provided only slightly more detail than is provided in Section 7.2.4 of the Draft Screening Report. No other SNF event causing a radioactive release was considered in the SENES Report.

Thus, the Draft Screening Report and the SENES Report are in close alignment regarding "bounding scenarios" for events that contribute to SNF radiological risk. In this respect, it seems that the Draft Screening Report has simply adopted the position of OPG, as set forth in the SENES Report and related OPG documents.

A difference emerges in the way those two Reports address the implications of the 2011 Fukushima accident. The Draft Screening Report, in its Section 7.5.2, outlines safety improvements that OPG has implemented, or intends to implement, at DNGS. Some of

[14] SENES, 2011.

these improvements are said to respond to lessons learned from the Fukushima accident. None of the listed improvements is linked specifically to SNF radiological risk.[15]

By contrast, when the SENES Report discussed safety improvements at DNGS, including improvements that respond to lessons learned from the Fukushima accident, that Report opened up an issue that relates directly to SNF radiological risk.

In its Section 6.3.3.1, the SENES Report said, in the context of the DNGS design philosophy: "It is also a requirement that systems, other than the reactor proper, containing substantial amounts of radionuclides, (e.g., the irradiated fuel bays) not be unacceptably damaged." The issue of IFB-related damage was taken up again in Section 6.3.3.4 of the SENES Report (titled, "Safety Improvements to Respond to Fukushima"), where the following statement was made:

> "Preliminary analyses indicate that with current operational heat loads, at least 72 hours are available before any structural integrity issues arise for the DNGS IFBs (and it would take at least 13 days before fuel becomes uncovered due to boil-off of IFB water following a complete loss of IFB cooling and no operator action). Nonetheless, current operator response capabilities will be augmented by pre-staging provisions to allow for remote water addition to the IFBs using portable pumps. OPG has committed to complete confirmatory studies of these preliminary conclusions, and the studies are currently underway."

Thus, the SENES Report revealed that loss of water from an IFB, leading to uncovering of SNF, is an event to be feared. That information is not provided in the Draft Screening Report. Unfortunately, however, the SENES Report did not explain why the uncovering of SNF is an event to be feared, or what the outcome of that event might be. Moreover, the SENES Report showed that OPG had, as of December 2011, conducted only "preliminary analyses" of this issue.

The Fukushima Task Force Report

The issue of loss of water from an IFB was addressed in somewhat greater detail in the October 2011 report of a Task Force established by the CNSC to evaluate the implications of the Fukushima accident for Canadian nuclear power plants (NPPs).[16] That report is referred to here as the "Fukushima Task Force Report".

Section 4.2.3 of the Fukushima Task Force Report identified loss of cooling of an IFB as a safety concern, stating:

> "Existing Canadian NPPs and most of the proposed designs for new NPPs rely on active cooling for reactors, containment and irradiated fuel bays (spent fuel

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[15] In its Section 7.5.2, the Draft Screening Report mentions OPG studies on the provision of portable pumps to allow for remote water addition to IFBs. The Report does not explain why that provision is significant.
[16] CNSC-FTF, 2011.

> pools). All designs have some degree of passive cooling capability. The effective duration for the various passive heat sinks varies with the design.
>
> Loss of cooling of the irradiated fuel bays is generally a lesser concern than loss of core cooling as much more time is available before fuel overheats. However, irradiated fuel bays generally have fewer alternative cooling options than the core; therefore the issue is still important."

In its Section 6.3.6, the Fukushima Task Force Report identified the uncovering of SNF, as a result of boiling and/or leakage of the water in an IFB, as an event to be feared. The Report then revealed that this event could generate hydrogen gas, which could form an explosive mixture in air. The Report said:

> "The licensees' submissions do not generally discuss the need for hydrogen mitigation in the IFB area. In their July 28, 2011, submission, licensees conclude that, as long as water inventory is maintained and the fuel remains submerged, hydrogen generation is not an issue. Nonetheless, the CNSC Task Force finds that the need for hydrogen mitigation in the IFB area should be evaluated."

In its Section 6.4.5, the Fukushima Task Force Report provided a partial explanation of why the uncovering of SNF is an event to be feared. The Report said:

> "Fuel bays contain significant quantities of irradiated fuel. Because of decay, fission product inventories in the spent fuel decrease over time. Nevertheless, the long-lived radioactive materials could pose a significant threat if the spent fuel is uncovered and subsequently overheats. To mitigate this threat, provisions are taken to ensure reliable cooling of the spent fuel bays and to maintain their structural integrity in credible external events, such as earthquakes. The CNSC Task Force expects all Canadian NPP licensees to perform comprehensive deterministic and probabilistic analyses of events affecting irradiated fuel bays, in order to demonstrate that the mitigation is sufficient for events as discussed in section 6.3.6."

In that statement, the Task Force called for "deterministic and probabilistic analyses" by licensees. Yet, elsewhere, the Task Force said that the methodology to properly perform those analyses may not exist. In its Section 6.4.3 (titled, "Assessments of severe accidents"), The Fukushima Task Force Report stated:

> "However, the existing modelling capabilities may not be adequate to consider events affecting multiple reactors on the same site (multi-unit events), **accidents with spent fuel** [emphasis added], or releases of radioactive products from a degraded reactor core into water."

The Task Force set forth specific recommendations for analyses pertaining to SNF radiological risk. In Clause 3 of its Section 10.1, the Fukushima Task Force Report said:

> "Licensees should enhance their modelling capabilities and conduct systematic analyses of beyond-design-basis accidents to include analyses of:
> a) multi-unit events
> b) accidents triggered by extreme external events
> c) **spent fuel bay accidents** [emphasis added]
>
> The analyses should include estimation of releases, into the atmosphere and water, of fission products, aerosols and combustible gases."

Summary

From the discussion above, it is clear that the CNSC's Fukushima Task Force was aware of a substantial radiological risk arising from storage of SNF under water in IFBs at stations such as DNGS. The Task Force did not fully explain the risk, but acknowledged at least three points. First, water could be lost from an IFB by boiling and/or leakage, causing SNF to be uncovered. Second, SNF that is uncovered could overheat, whereupon it could release radioactive material and hydrogen gas. Third, the capabilities of Canadian licensees to model these phenomena require substantial improvement.

The SENES Report implied that OPG was aware of this risk. At the very least, OPG was aware that uncovering of SNF is an event to be feared. Also, a person could reasonably expect that OPG would be fully cognizant of the findings of the Fukushima Task Force.

The Draft Screening Report cites the SENES Report and the Fukushima Task Force Report.[17] Yet, the Draft Screening Report fails to acknowledge the risk associated with uncovering of SNF in an IFB. Instead, the Draft Screening Report focuses its discussion of SNF radiological risk on two comparatively minor events – drop of a DSC, and drop of an SNF storage module. In those cases, it seems that the Draft Screening Report has simply adopted the position of OPG.

4. Defining and Estimating Radiological Risk

As stated in Section 1, above, in this report the term "radiological risk" refers to the potential for harm to humans as a result of their exposure to ionizing radiation due to an unplanned release of radioactive material. There is no single indicator of this risk. Instead, the potential for harm can be assessed by compiling a set of qualitative and quantitative information about the likelihood and characteristics of the harm. Our terminology is consistent with a generic definition of "risk" as the potential for harm due to an unplanned event. The US Nuclear Regulatory Commission (NRC) has articulated a similar definition.[18]

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[17] CNSC and DFO, 2012, Section 13.

[18] The NRC Glossary defines risk as: "The combined answer to three questions that consider (1) what can go wrong, (2) how likely it is, and (3) what its consequences might be. These three questions allow the NRC to understand likely outcomes, sensitivities, areas of importance, system interactions, and areas of

Other perspectives on risk

In the nuclear industry and elsewhere, one often encounters a more limited definition, in which risk is the arithmetic product of a numerical indicator of harmful impact and a numerical indicator of the impact's probability.[19] That definition is hereafter designated as the "arithmetic" definition of risk. The arithmetic definition can be seriously misleading in two respects. First, the full spectrum of impact and/or probability may not be susceptible to numerical estimation, or numerical estimates may be highly uncertain. Second, many subscribers to the arithmetic definition argue that equal levels of the numerically-estimated risk should be equally acceptable to citizens. Their argument may be given a scientific gloss, but is actually a statement laden with subjective values and interests.

Quantitative analysis is essential to science, engineering, and other fields. Yet, the limitations of quantitative analysis should be recognized. Analysts should be especially careful to avoid the intellectual trap of ignoring issues that are difficult to quantify. Many practitioners of radiological risk assessment fall into that trap. Thus, important risk factors are ignored. Prominent examples include: (i) acts of malevolence or insanity; and (ii) gross errors in design, construction, and operation of facilities. Risk assessments for nuclear facilities routinely ignore these and other factors that may be major determinants of risk.[20]

A nuclear facility – such as a reactor, or a spent-fuel storage installation – typically has the potential to experience unplanned releases of radioactive material across a spectrum ranging from small releases to large releases. Risk analysts who subscribe to the arithmetic definition often conclude that small releases are more probable. With their arithmetic approach, it then appears that large releases with low probability are equivalent to small releases with high probability. Often, these analysts leap to the assumption that the apparent equivalence is "scientific". Thus, they argue, equal levels of the numerically-estimated risk should be equally acceptable to citizens.

In fact, the assumption of equivalence lacks a scientific basis. It is a subjective statement that reflects the values and interests of this group of analysts. 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 probability. That perspective could have a solid, rational basis, because a large release could have effects that are qualitatively different from the

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uncertainty, which can be used to identify risk-significant scenarios." (See: http://www.nrc.gov/reading-rm/basic-ref/glossary/risk.html, accessed on 16 February 2012.)

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

[20] For example, there is evidence that a major risk factor underlying the 1986 Chernobyl reactor accident was endemic secrecy in the USSR. (See: Shlyakhter and Wilson, 1992.) Also, there is evidence that a major risk factor underlying the 2011 Fukushima accident was collusion among government, the regulators, and the licensee (TEPCO). (See: Diet, 2012, page 16.) Radiological-risk studies performed by the nuclear industry and its regulators do not consider secrecy or collusion as risk factors.

effects of a small release. Moreover, a prudent citizen will be skeptical of the probability findings generated by arithmetic risk analysts, given the propensity of these analysts to ignore important risk factors.

Probabilistic risk assessment

The preceding paragraphs provide a basis for critical examination of an analytic art known as probabilistic risk assessment (PRA). This art can be useful in radiological risk assessment, provided that its limitations are kept firmly in mind.

PRA techniques have been developed to estimate the probabilities and impacts of potential unplanned releases of radioactive material from nuclear facilities. Similar techniques can be used to examine other types of risk, such as the potential for harm due to unplanned releases from chemical plants.

In the nuclear-facility context, most PRAs have been done for nuclear power plants. The first PRA for an NPP was known as the Reactor Safety Study, and was published by NRC in 1975.[21] A PRA for a nuclear power plant 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.[22]

PRAs for NPPs are conducted at Levels 1, 2 and 3, in increasing order of completeness, as discussed below. A thorough, full-scope PRA would be conducted at Level 3, and would consider internal and external initiating events. The findings of such a PRA would be expressed in terms of the magnitudes and probabilities of a set of adverse impacts, and the uncertainty and variability of those indicators. Typically, PRAs focus on atmospheric releases originating in the reactor core.[23] The adverse impacts of such releases at downwind locations would include:

> (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;

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[21] NRC, 1975.
[22] NRC, 1994.
[23] 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.

(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 (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 often known as core-damage frequency (CDF), 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, probability, 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 probability, not as single numbers. Even after such a thorough effort, there are substantial, irreducible uncertainties in the findings.[24] PRA findings rely on numerous assumptions and judgments. There is no certainty that all of the relevant factors are captured. Findings of very low probability cannot be validated by direct experience. Moreover, a PRA cannot estimate the probabilities of 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.

[24] Hirsch et al, 1989.

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.[25] 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.

Figures 4-1 through 4-3 show some findings from the NUREG-1150 study. The findings are for a pressurized-water reactor (PWR) plant at the Surry site, and a boiling-water reactor (BWR) plant at the Peach Bottom site. Those plants typify many of the Generation II plants in the present worldwide fleet of NPPs. In viewing the CDF findings in Figures 4-1 and 4-2, it should be noted that NUREG-1150 itself warns that estimated core-damage probabilities lower than 1 per 100,000 RY should be viewed with caution because of limitations in PRA. NRC has published for comment a draft report from its SOARCA program, describing new analysis of some core-damage sequences at the Surry and Peach Bottom plants.[26] The merit of that analysis, and its implications regarding the NUREG-1150 findings, are unclear at present.

Estimating core-damage probability from direct experience

Severe fuel damage at an NPP is often thought of as a rare event. Yet, a 2011 inventory lists twelve events involving severe damage to fuel in the reactor core of an NPP.[27] That 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 NPPs, five have both: (i) occurred at a Generation II plant; and (ii) involved substantial fuel melting. These five events were at Three Mile Island (TMI) Unit 2 (a PWR plant in the USA) in 1979, Chernobyl Unit 4 (an RBMK

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[25] NRC, 1990.
[26] NRC, 2012.
[27] Cochran, 2011.

plant in the USSR) in 1986, and Fukushima #1 Units 1 through 3 (BWR plants in Japan) in 2011.

These five events occurred in a worldwide fleet of commercial NPPs, of which about 440 plants are currently operable. These plants and previous plants in the fleet had accrued 14,760 RY of operating experience as of 17 February 2012.[28] The five 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 15,000 RY – one observes a CDF of 3.3E-04 per RY (1 event per 3,000 RY).[29]

Confidence in this reality check is enhanced by noting that the five events occurred in three different countries at three different types of NPP, 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.

Application of PRA techniques to SNF

This author is unaware of any study, in any country, that has systematically applied PRA techniques to examine the radiological risk posed by SNF. Credible studies related to that risk have been performed, but none has the systematic scope of a thorough PRA. The comparative lack of attention to SNF risk is notable because a spent-fuel pool containing SNF is located near every commercial reactor. That proximity, and current practice for storing SNF in pools, creates a linkage between SNF risk and reactor risk. (See Section 6, below.)

5. Public Attention to SNF Radiological Risk

The radiological risk posed by SNF has continued growing over the past several decades, due to the factors discussed in Section 6, below. During most of that period, public awareness of the risk was low. This situation was altered by the 2011 accident at the Fukushima #1 nuclear site. From the publicity accompanying the accident, citizens learned that SNF was stored in pools adjacent to the affected reactors, and that a large amount of radioactive material could have been released to atmosphere if a pool lost water and SNF became exposed to air. Table 5-1 shows the inventory of SNF at the site, as of March 2010.

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[28] World Nuclear Association website, http://www.world-nuclear.org/, accessed on 17 February 2012.

[29] 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 NPPs at Fukushima #1, and it appears that there were differences in the accident sequences at these plants. Also, multiple core-damage events with a common cause could occur in the future, potentially involving plants at single-unit sites.

Figure 5-1, which shows Unit 4 at the Fukushima #1 site during the 2011 accident, exemplifies the information that has become available to citizens. The Unit 4 reactor building exhibits severe damage from a hydrogen explosion. A concrete-pumping truck next to the building is spraying water, through the damaged roof of the building, into the Unit 4 spent-fuel pool. Before concrete-pumping trucks arrived at the site, unsuccessful attempts to add water to the spent-fuel pools at Units 1-4 involved the use of fire trucks and riot control vehicles to spray water, and the dropping of seawater from bags carried by helicopters. Television and press coverage of these activities gave citizens around the world an introduction to the risk posed by SNF.

The explosion in the Unit 4 reactor building involved the combustion of hydrogen in air. The only plausible source of this hydrogen was a reaction between steam and the zirconium alloy (zircaloy) cladding of overheated nuclear fuel.[30] This reaction could not have occurred in the Unit 4 reactor core, because the reactor had been defueled prior to the accident. Thus, when the explosion occurred, many analysts theorized that water had been lost from the Unit 4 spent-fuel pool, leading to overheating of SNF in the pool, culminating in steam-zircaloy reaction. A more recent, alternative theory is that the hydrogen traveled from Unit 3 to Unit 4 through a ventilation system.[31] This alternative theory seems to be a better fit with the facts known to date.[32] From the perspective of public awareness of SNF risk, what may be most significant about this experience is the visual demonstration – through violent hydrogen explosions – of the latent chemical energy in the zircaloy cladding of nuclear fuel.

Figure 5-2 represents another demonstration of SNF risk. This figure shows the contamination of land in Japan by radioactive Cesium released to atmosphere during the Fukushima accident. Various effects of the contamination – such as 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 Cesium would have been substantially greater if water had been lost from spent-fuel pools, causing SNF 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 SNF that would be "the radiation equivalent of two reactor cores".[33]

In this report, the isotope Cesium-137 is used to represent a radioactive release from SNF. The rationale for that representation is presented at the close of Section 6, below.

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[30] The steam-zirconium reaction is exothermic and proceeds as follows: Zr + 2H20 -> ZrO2 + 2H2
[31] Unit 3 also experienced a hydrogen explosion, the hydrogen in that case being created by steam-zircaloy reaction in overheated fuel in the Unit 3 reactor core.
[32] INPO, 2011.
[33] Associated Press, 2012.

6. Technical Understanding of SNF Radiological Risk in the LWR Context

Human-constructed fission reactors first began operating in the 1940s. The radiological risk posed by SNF has existed since that time. Over the intervening decades, the risk has increased due to: (i) growth in SNF inventories; (ii) changed properties of nuclear fuel; and (iii) design choices regarding modes of SNF storage. These factors are discussed here, with a focus on SNF from LWRs (which are either PWRs or BWRs). As shown in Table 6-1, LWRs dominate the world's inventory of NPPs.

Growth in SNF inventories

Table 6-2 shows the inventory and broad characteristics of SNF discharged from commercial reactors in the USA through 2010.[34] About three-quarters of that inventory is stored in spent-fuel pools adjacent to operating reactors, the remainder being stored in dry casks.[35] Other countries have accumulated smaller inventories of SNF, determined in each instance by the size, type, and history of operation of the country's fleet of NPPs.[36] The International Panel on Fissile Materials has published a useful review of worldwide experience in managing SNF.[37]

The units shown in Table 6-2 deserve an explanation. The mass of fuel is expressed in Mg (metric tons) of total initial uranium (Mg U), where "initial" refers to uranium in the fresh fuel inserted into a reactor. For uranium fuel, this mass is identical to the indicator "metric tons of heavy metal" (MTHM). However, MTHM is a more general indicator, because it encompasses situations in which uranium, plutonium, and other heavy metals are present in fresh fuel. The indicator Mg HM, which is equivalent to MTHM, is used at points in this report. Note that the indicators Mg U, Mg HM, and MTHM all refer to elemental mass in fresh fuel.

Table 6-2 shows the "burnup" of a spent-fuel assembly. This indicator is the cumulative thermal energy – in GWt-days per Mg U – released by fissions while the assembly is present in a reactor. The power unit GWt contrasts with GWe, which refers to electricity output from the NPP.

The growth in SNF inventories around the world reflects a long-term trend away from the reprocessing of spent fuel. When the nuclear fission industry was launched in the 1950s and 1960s, the industry's managers typically assumed that SNF would be reprocessed. One outcome of that assumption is that the spent-fuel pools at NPPs were originally designed to hold only a few years' discharge of spent fuel from the reactors. Over time,

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[34] For an overview of practices and regulations regarding SNF storage in the USA, see: EPRI, 2010.
[35] The NRC states that, as of the end of 2009, pools in the USA contained 48,818 Mg of commercial SNF while dry casks contained 13,856 Mg. See: http://www.nrc.gov/waste/spent-fuel-storage/faqs.html, accessed on 22 February 2012. Almost all of the SNF in pools is in pools adjacent to operating reactors.
[36] Choi, 2010.
[37] IPFM, 2011.

however, countries have turned away from reprocessing. For example, commercial SNF in the USA has not been reprocessed since 1972.

Growth in SNF inventories would, other factors remaining equal, have yielded a proportional increase in SNF radiological risk. The risk has actually grown at a faster, disproportionate rate, as a result of design decisions by the nuclear industry. One set of these decisions relates to the properties of nuclear fuel, and the other to choices regarding modes of SNF storage.

Properties of nuclear fuel

Figures 6-1 and 6-2 show schematic views of PWR and BWR fuel assemblies. Supporting data are shown in Table 6-3. The active portion of the assemblies consists of uranium oxide pellets – or, in some instances, mixed plutonium and uranium oxide (MOX) pellets – inside thin-walled metal tubes. When the fuel is fresh, the uranium is low-enriched (up to 5% U-235).[38] The tubes are typically known as “cladding”. In contemporary NPPs the cladding is made of zircaloy, whose primary ingredient is zirconium.

Zircaloy is not the only material that can be used for fuel cladding. Stainless steel is an alternative cladding material, and was used in a number of water-cooled reactors during the early years of development of LWR technology. As of mid-1979, about 7% (about 1,500 fuel assemblies) of the commercial SNF inventory in the USA was fuel with stainless steel cladding.[39] Generally, this fuel performed well. In illustration, a thorough examination was made of a stainless-steel-clad PWR fuel assembly that was driven to a burnup of 32 GWt-days per Mg U in the Connecticut Yankee reactor and then stored for 5 years in a spent-fuel pool.[40] No degradation was observed.

Zircaloy and stainless steel performed about equally well as a cladding material, in terms of durability under the conditions experienced in a water-cooled reactor.[41] However, zircaloy was superior in terms of its lower absorption of neutrons, which improved the economics of NPP operation. Thus:[42] “By 1966 economic considerations had led to the selection of zirconium alloy fuel cladding for all water-cooled reactors.” This outcome had been anticipated in a 1958 study that stated:[43]

> “In most of the nuclear reactors being designed today for commercial power production, it is technically feasible to use either stainless steel or zirconium or one of its alloys as structural material, fuel cladding or fuel diluent. When used within the neutron flux of the reactor the low neutron-absorption cross section of

[38] In a CANDU reactor, the fresh fuel contains natural uranium (0.7% U-235).
[39] Langstaff et al, 1982, page v.
[40] Langstaff et al, 1982.
[41] Gurinsky and Isserow, 1973.
[42] Gurinsky and Isserow, 1973, page 63.
[43] Benedict, 1958, page 1.

> zirconium gives that material an important economic advantage over stainless steel. Use of zirconium instead of stainless steel makes possible savings through the use of uranium of lower enrichment, through reduction in the critical mass of uranium, or through some combination of these cost-saving features."

Exothermic reaction of zircaloy cladding

Although the economic advantage of zircaloy cladding during routine operation of an NPP is clear, there is a price to be paid in terms of radiological risk. Zircaloy, like zirconium, is a chemically reactive material that will react vigorously and exothermically with either air or steam if its temperature reaches the ignition point – about 1,000 deg. C. This temperature is well above the operating temperature of a water-cooled reactor, where zircaloy exhibits good corrosion resistance.[44]

The potential for ignition of zircaloy is well known in the field of reactor risk, and has been observed in practice on a number of occasions. For example, during the TMI reactor accident of 1979, steam-zirconium reaction occurred in the reactor vessel, generating a substantial amount of hydrogen. Some of that hydrogen escaped into the reactor containment, mixed with air, and exploded. Fortunately, the resulting pressure pulse did not rupture the containment. Similar explosions during the Fukushima #1 accident of 2011 caused severe damage to the reactor buildings of Units 1, 3, and 4.

Table 6-4 illustrates the significance of zircaloy's chemical reactivity in the context of SNF radiological risk. The calculation presented in this table assumes that a PWR fuel assembly surrounded by air experiences a rise in temperature to the point where the zircaloy cladding ignites and burns. Then, it is assumed, 50% of the heat from complete combustion of the cladding enters the adjacent fuel pellets. This amount of heat would raise the pellet temperature to well above the boiling point of Cesium. Thus, a substantial fraction of the pellet's inventory of Cesium would be released. A similar result is obtained if the fuel assembly is surrounded by steam, even though the heat of reaction of zirconium with steam (6.53 MJ per kg Zr) is smaller than the heat of reaction with air (11.9 MJ per kg Zr). These findings provide useful insight into the behavior of SNF in risk-relevant circumstances, despite the simplicity of the calculation.

Replacing zircaloy with alternative cladding materials

As mentioned above, stainless steel could substitute for zircaloy as a cladding material. The nuclear industry would undoubtedly resist this substitution, which would adversely affect the economics of NPP operation and would disrupt long-established practices in

[44] Formation of a thin film of oxide on the water-facing surface of the zircaloy enhances corrosion resistance. This film becomes less effective in suppressing oxidation as the zircaloy temperature approaches the ignition point of about 1,000 deg. C. Moreover, as the temperature of zircaloy-clad fuel rises toward that point, the cladding will swell and burst from internal pressure, thus exposing un-oxidized surfaces to air or steam.

the industry. Also, stainless steel can react exothermically with air or steam, although with a lower heat of reaction than is exhibited by zircaloy.[45]

During the past two decades, there have been efforts to develop ceramic cladding as a replacement for zircaloy. Two major objectives drive these efforts. First, ceramic cladding may allow higher burnup of fuel, which would reduce NPP operating cost. Second, ceramic cladding may behave better in accident conditions, in part by avoiding the heat production and hydrogen generation that are unleashed in the steam-zircaloy reaction.

Currently, efforts to develop ceramic cladding appear to be focused on a "triplex" silicon carbide cladding. The developers hope to begin a prototype test program – in which complete fuel assemblies made with the triplex cladding are placed in commercial reactors – by about 2020.[46] If they keep to this schedule and the tests are successful, then reactors might be routinely fueled with ceramic-clad fuel by about 2030. In that event, ceramic-clad spent fuel would begin adding to SNF inventories in significant quantity by about 2040. Thus, for at least the next three decades, worldwide inventories of SNF will be dominated by fuel using zircaloy cladding.

Re-racking of spent-fuel pools, and its risk implications

At every LWR, a spent-fuel pool is located adjacent to the reactor. Fresh fuel enters the reactor via the pool, and spent fuel is discharged into the pool. As mentioned above, the pools were originally designed to hold only a few years' discharge of spent fuel from the reactors. As part of that design, the pools were equipped with low-density, open-frame racks into which fuel assemblies were placed. Figure 6-3 shows a PWR fuel rack of this type. Similar, open-frame racks were used for BWR fuel.

If water were lost from a pool equipped with low-density racks, there would be vigorous, natural convection of air and steam throughout the racks, providing cooling to the SNF.[47] Thus, in most situations, the temperature of the zircaloy cladding of SNF in the racks would not rise to the ignition point. Exceptional circumstances that could lead to ignition include the presence of SNF very recently discharged from a reactor, and deformation of the racks. Even then, propagation of combustion to other fuel assemblies would be comparatively ineffective, and the total release of radioactive material would be limited to the comparatively small inventory in the pool.

Faced with the problem of growing inventories of SNF, the nuclear industry could have continued using low-density racks in the pools while placing excess fuel in dry casks. That approach would have limited SNF radiological risk. Instead, the industry adopted a

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[45] The heat of reaction of stainless steel with air is 5.98 MJ per kg SS, and the heat of reaction with water is 1.06 MJ per kg SS. (See: Baker and Liimatainen, 1973, Table 3-1.)
[46] Yueh et al, 2010.
[47] Convective cooling of BWR fuel would be improved by separating the channel boxes from the fuel assemblies.

cheaper option. Beginning in the 1970s, the industry re-equipped its pools with higher-density racks. In the high-density racks that are now routinely used around the world, the center-center spacing of fuel assemblies approaches the spacing in a reactor. (See Table 6-3 for the reactor spacing.) To suppress criticality, the assemblies are separated by plates containing neutron-absorbing material such as boral (boron carbide particles in an aluminum matrix). Figure 6-4 illustrates the use of high-density racks, in this instance at Unit 4 at the Fukushima #1 site.

The neutron-absorbing plates divide the racks into long, narrow, vertical cells, open only at the top and bottom. If water were lost from a pool, this arrangement would suppress heat transfer by convection and radiation. The presence of residual water in the lower portion of the pool, which would occur in many water-loss situations, would limit heat transfer to only one effective mechanism – convective cooling by steam rising from the residual water. Over a range of water-loss scenarios, radioactive decay heating in the SNF would cause cladding temperature to rise toward the ignition point.[48]

Table 6-5 sets forth a simple calculation that illustrates the timeframe for cladding temperature to reach the ignition point (about 1,000 deg. C). The calculation assumes adiabatic conditions, which would be approached in the situation where a pool contains residual water. It will be seen that the fuel temperature rises at a rate of 9R deg. C per hour, where R is the fuel assembly's output of radioactive decay heat in kW per Mg HM. Various values of R are shown in Table 6-6. Consider, for example PWR-U fuel with a burnup of 50 GWt-days per Mg HM, aged 100 days after reactor shutdown. In that case, R = 28. Thus, under adiabatic conditions, fuel temperature would rise at a rate of 252 deg. C per hour.

The preceding discussion sets the scene for considering the attributes of a "pool fire". This incident would involve the following sequence of events:

> (i) loss of water from a spent-fuel pool due to leakage, boiling away, siphoning, or other mechanism;
> (ii) failure to provide water makeup or cooling;
> (iii) uncovering of SNF assemblies;
> (iv) heat-up of some SNF assemblies to the ignition point of zircaloy, followed by combustion of these assemblies in steam and/or air;
> (v) a hydrogen explosion (not inevitable, but likely) that damages the building surrounding the pool;
> (vi) release of radioactive material from affected SNF assemblies to the atmosphere; and
> (vii) propagation of combustion to other SNF assemblies.

A pool-fire event sequence would unfold over a timeframe ranging from a few hours to a number of days. During this timeframe, there would be opportunities for personnel to

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[48] For supporting information, see: Alvarez et al, 2003.

halt or mitigate the event sequence through actions such as plugging holes in a pool, or adding water. However, addition of water after zircaloy ignites could be counter-productive, because the water could feed combustion. Circumstances accompanying the pool-fire event sequence, such as a core-damage event sequence at an adjacent reactor, could preclude mitigating actions.

Recognition of the pool-fire risk

Two studies completed in March 1979 independently identified the potential for a pool fire. One study was by members of a scientific panel assembled by the state government of Lower Saxony, Germany, to review a proposal for a nuclear fuel cycle center at Gorleben.[49] After a public hearing where the study was presented, the Lower Saxony government ruled in May 1979, as part of a broader decision, that high-density pool storage of spent fuel would not be acceptable at Gorleben.[50] Subsequently, new facilities built in Germany to store SNF used dry casks exclusively.

The second study was done by Sandia Laboratories for NRC.[51] In light of knowledge that has accumulated since 1979, the Sandia report generally stands up well, provided that one reads the report in its entirety. However, the report's introduction contains an erroneous statement that complete drainage of the pool is the most severe situation. The body of the report clearly shows that partial drainage can be a more severe case, as was recognized in the Gorleben study.

After receiving the Sandia report, NRC conducted and sponsored a number of studies related to pool-fire risk, which were published over a period of two decades. Unfortunately, those studies employed the erroneous assumption that complete drainage is the most severe case, until NRC partially corrected this error in October 2000. After September 2001, NRC ceased publishing analysis on pool-fire risk, but claims to have done some classified (secret) studies. Overall, NRC’s work to assess pool-fire risk has useful elements but is deficient in several important respects.[52]

Nevertheless, NRC’s published findings support the analysis presented here. NRC concedes that a fire could spontaneously break out in a spent-fuel pool following a loss of water, and that radioactive material released to the atmosphere during the fire would have significant, adverse impacts on the environment. To offset those concessions, NRC argues that the probability of a pool fire is low. NRC has attributed the alleged low probability, in part, to secret security measures and damage-control preparations that were implemented at NPPs in the USA after September 2001.[53] After the Fukushima accident of 2011, NRC released some information about the secret damage-control

[49] Beyea et al, 1979.
[50] Albrecht, 1979.
[51] Benjamin et al, 1979.
[52] NRC studies on pool-fire risk have been identified, summarized, and critiqued in: Thompson, 2009.
[53] Thompson, 2009.

preparations. This author's review and NRC's own analysis revealed major deficiencies in those preparations.[54]

Independent studies on pool-fire risk have been performed. In 2003, eight authors published a paper on pool-fire risk and the options for reducing that risk.[55] That paper aroused vigorous comment, and its findings were disputed by NRC officials and others. In an effort to resolve this controversy, the US Congress requested the National Research Council (an affiliate of the National Academy of Sciences) to conduct a study on the safety and security of SNF storage. The Council submitted a classified (secret) report to Congress in 2004, and in 2005 released an unclassified version that was formally published in 2006.[56] Press reports described considerable tension between the Council and NRC regarding the inclusion of material in the unclassified report.[57] That report and the eight-author paper described above are mutually consistent, and both support the analysis in this report.

Linkage between pool-fire risk and reactor core-damage risk

At LWR stations, a spent-fuel pool is located adjacent to each reactor. Figure 6-5 shows the respective locations of the reactor and pool in the case of a BWR reactor with a Mark I containment. At PWR plants, the pool is typically located in a separate building that is outside the reactor containment but immediately adjacent to it. The pool shown in Figure 6-5 is elevated above ground level. At PWR plants, the floor of the pool is typically at ground level or a few meters below it. There may be open spaces (rooms, corridors) below the pool floor.

Systems to cool the water in the pool, and to provide makeup water, are integrated with similar systems that support reactor operation. Thus, cooling and water makeup to the pool would be interrupted during many of the potential event sequences that could lead to reactor core damage. This interruption could initiate – or contribute to – a sequence of events that lead to a pool fire. As mentioned above, that sequence would unfold over a timeframe ranging from a few hours to a number of days.

There would be opportunities during this period for personnel to halt or mitigate the event sequence. In some cases, simply adding water to the pool would be sufficient to prevent a pool fire. However, accompanying circumstances could prevent personnel from taking the necessary actions. For example, the site could be contaminated by radioactive material released from one or more reactors, and structures and equipment could be damaged by hydrogen explosion and/or the influence (e.g., an earthquake) that initiated the event sequence. Indeed, these circumstances arose during the Fukushima #1 accident, and substantially impeded mitigating actions by onsite personnel.[58]

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[54] NRC, 2011; Thompson, 2011.
[55] Alvarez et al, 2003.
[56] National Research Council, 2006.
[57] Wald, 2005.
[58] INPO, 2011.

A reactor and its adjacent pool (if filled with SNF at high density) can be thought of as a coupled risk system. The reactor and the pool can affect each other in ways that increase the total risk posed by the system. To illustrate, consider the following hypothetical sequence of events. First, a reactor experiences core damage and a breach of containment. These events lead to severe contamination of the site by short-lived radio-isotopes that are released from the reactor. Intense radiation fields from this contamination, together with damage from a hydrogen explosion, preclude onsite mitigating actions by personnel. The pool then boils dry, or drains due to a related influence. That outcome initiates a pool fire that leads to another hydrogen explosion and a large release of longer-lived radio-isotopes (especially Cesium-137) from the pool. Those phenomena further preclude onsite mitigating actions by personnel, thus prolonging the reactor release and, potentially, initiating releases from other reactors and pools on the site.

This hypothetical sequence of events is not far-fetched. The Fukushima accident could have followed a similar course, given a few changes in site preconditions, in the initiating earthquake/tsunami, and/or in site management during the accident.[59] In that case, the accident would have involved a much larger release of radioactive material than was actually experienced.

The potential for malevolent action

The prospect of a linked sequence of reactor and pool events is especially ominous when one considers the possibility that a malevolent group of people would deliberately trigger the sequence. A technically knowledgeable and operationally capable group could focus and time an attack in such a manner that both a reactor release and a pool fire would be likely outcomes.[60] The group's investment of resources would be small by comparison with the damage inflicted on the attacked country. Thus, from a military-strategic perspective, a reactor and an adjacent pool filled with SNF at high density are, taken together, a large, pre-emplaced radiological weapon awaiting activation by an enemy.

Detailed discussion of attack scenarios is not appropriate in a document intended for general publication, as is this report. Instead, some general observations are provided here. Relevant literature is publicly available.[61]

[59] Funabashi and Kitazawa, 2012.
[60] This report is intended for general publication. Thus, the optimal foci and timing of an attack are not discussed here. However, technically knowledgeable attackers could readily determine these factors without external advice.
[61] There is a body of publicly-available technical literature about attacks on commercial nuclear facilities. See, for example: Ramberg, 1984; Ramberg, 1980; Rotblat, 1981; Fetter, 1982; Fetter and Tsipis, 1980; Knox, 1983; Thompson, 2005; Thompson, 1996; Sdouz, 2007; Morris et al, 2006; Honnellio and Rydell, 2007; POST, 2004.

Table 6-7 shows some potential modes and instruments of attack on an NPP, and the present defenses at US plants. One sees that the defenses are limited in scope. In other countries, NPP defenses are typically no more robust than in the USA. Also, SNF systems that are not co-located with NPPs typically have less robust defenses than do NPPs.

One of the instruments of attack that could be used against a nuclear facility is a shaped charge. Table 6-8 summarizes the properties of this instrument. Table 6-9, Figure 6-6, and Figure 6-7 provide supporting information. Expertise in the design and use of shaped charges is widely available around the world. Arms manufacturers are actively developing tandem warheads that employ shaped charges. For example, in January 2008 Raytheon successfully tested the shaped-charge penetrating stage for its Tandem Warhead System.[62] The shaped charge penetrated 5.9 m into steel-reinforced concrete with a compressive strength of 870 bar.

Table 6-10 shows some characteristics of the containments of selected NPPs. That table gives particular attention to the materials, configurations, and thicknesses of the containment walls, which are indicators of a containment's ability to resist external attack. Clearly, these containments vary in their ability to resist attack, but each of them could be penetrated by instruments that are available to well-resourced attackers. Most spent-fuel pools are similarly vulnerable. For example, at the Pilgrim NPP in the USA, the outward-facing (reinforced concrete) walls of the spent-fuel pool have thicknesses ranging from 1.2 m to 1.9 m, and the pool floor (also reinforced concrete) has a thickness of 1.7 m.[63]

A successful attack on a spent-fuel pool would not necessarily involve physical damage to structures by the attackers. For example, attackers might be able to take control of a nuclear site, or a portion of the site where a pool is located. Then, they could siphon or pump water from the pool. Uncovering of the SNF would lead to production of hydrogen, which would explode in the upper part of the pool building, and to release of Cesium from fuel pellets. The hydrogen explosion would create a pathway for Cesium to travel directly from damaged fuel pellets to the atmosphere. Also, the explosion would hinder efforts by site personnel to regain control of the pool from the attackers.

Indirect effects of violence and disorder

The preceding discussion assumes a deliberate attack on a nuclear facility.[64] There may also be situations in which a nuclear facility could be indirectly threatened by war or other forms of political violence, and/or by societal disorder. Events of this type could,

[62] Warwick, 2008; Raytheon, 2008.
[63] Thompson, 2006, Table 3-2. The inward-facing wall of the pool is integrated with the reactor shield wall.
[64] A facility might be attacked inadvertently or contrary to the wishes of high commanders, as a result of a communication failure or other factor. For the purposes of this report, such an attack can be regarded as deliberate.

for example: (i) interrupt the provision of electricity, water, and other services to a facility; and/or (ii) prevent personnel from performing their duties at the facility. Those influences could, in turn, initiate an event sequence that leads to an outcome such as a pool fire. The potential for such event sequences could be examined using the same analytic approach as would be used to examine accident-initiated event sequences.

Release of radioactive material from a dry cask

Dry casks are widely used for storing and transporting SNF discharged from LWRs. Figure 6-8 shows a type of cask (the Holtec HI-STORM 100 cask system) that is popular in the USA. The SNF is housed in a sealed, multi-purpose canister (MPC) made of stainless steel and filled with helium. During storage, the MPC is located inside a concrete-and-steel storage overpack as shown in Figure 6-8. During transportation, the MPC is located inside a transportation overpack.

The MPC-plus-overpack concept is one approach to the design of a dry cask. Another approach is the "monolithic" cask that consists of a single structure. Some monolithic casks are designed solely for storage use, some are designed solely for transportation use, and some are dual-purpose.

The nuclear industry and regulators around the world have given some attention to the radiological risk posed by a dry cask. With a few exceptions, the attention has focused on the potential for humans to be exposed by inhalation of radioactive gases and small particles.

Calculations summarized in Table 6-11 illustrate the potential for inhalation exposure. These calculations postulate an event that creates a small hole (equivalent diameter of 2.3 to 36 mm) in a multi-purpose canister, and also involves severe shaking of the canister. The canister would experience "blowdown" through the hole, driven by the pressure of helium in the canister plus gases released from SNF rods as a result of damage to their cladding. This event would be slightly more severe than a "design basis" accident. It could, for example, represent the accidental crash of a fighter aircraft on a HI-STORM 100 cask system.

One sees from Table 6-11 that the fractional release of Cesium-137 would be small. The Cesium-137 release would be somewhat greater if the cask were engulfed by a fire, during and/or after blowdown. If the event were an aircraft crash, a fire could arise from combustion of jet fuel.

There has been some regulatory consideration of scenarios involving an attack on a dry cask. Various analyses and experiments have been done to estimate the characteristics and radiological consequences of a radioactive release from a dry cask if a shaped-charge warhead were to penetrate the cask.[65] In a typical attack scenario considered in these

[65] Luna et al, 2001.

studies, some SNF rods would experience cladding rupture, and some fuel pellets would be pulverized, creating a radioactive "dust". The warhead would create a pressure pulse inside the cask, helping to drive the radioactive dust into the external atmosphere. The resulting inhalation dose to a nearby, downwind person could exceed the levels shown in Table 6-11.

These industry and regulatory studies have typically not considered the initiation of a zirconium-air reaction inside the cask. Thus, they do not predict a significant fractional release of Cesium-137. Clearly, these studies have not addressed a full spectrum of potential attacks. The rationale for this incomplete investigation is unclear. A few studies have gone against the general trend and considered the potential for cladding ignition during an attack. Unsurprisingly, they have identified a potential for a substantial fractional release of Cesium-137.[66]

Table 6-4 shows that a zircaloy-air reaction, once initiated, could generate a substantial release of Cesium-137 from SNF rods. Thus, the basic mechanisms of a "cask fire" – analogous to a pool fire – are in place. In order for a cask fire to occur in an actual situation, three conditions must be satisfied. First, a circulating pathway between SNF and the atmosphere must exist, so that air can reach the SNF, and combustion products and Cesium-137 can reach the atmosphere. Second, circulation of fluid through this pathway must be driven by natural convection. Third, the temperature of the cladding of a portion of the SNF in the cask must be raised to the ignition point, so that a self-sustaining reaction can begin.

These conditions are unlikely to be satisfied in an accident situation. They could be satisfied, however, during an attack by a knowledgeable, well-resourced group. A successful attack would probably involve the use of incendiary instruments, together with breaching of the cask in a manner that encourages a "chimney" effect, whereby air flows through the cask interior and feeds a zircaloy-air reaction.

Use of Cesium-137 to represent a radioactive release

SNF contains a variety of radioactive isotopes. In this report, attention is focused on a single isotope – the fission product Cesium-137. Other studies of SNF radiological risk have also focused on Cesium-137, for five reasons.[67] First, Cesium is a comparatively volatile material that is readily released from overheated nuclear fuel, as is evident from its release to atmosphere during the Fukushima accident. Second, when released to atmosphere, Cesium forms small particles that travel downwind and are deposited on the ground and other surfaces, from which they can be difficult to remove.[68] Third, the radioactive decay of Cesium-137 creates penetrating gamma radiation.[69] Fourth, Cesium-

[66] See, for example: Mannan, 2007.
[67] See, for example: Alvarez et al, 2003.
[68] Radioactive Cesium can also contaminate food and water supplies.
[69] Most (95%) of Cesium-137 decays are to an excited state of Barium-137 that decays with a half-life of about 150 seconds, yielding a gamma ray with an energy of 0.66 MeV.

137 has a 30-year half-life, so its radiological impact is of concern over a typical human lifetime and beyond. Fifth, because of the four preceding reasons, Cesium-137 accounts for most of the offsite radiation exposure that is attributable to the 1986 Chernobyl accident.[70]

Table 6-12 shows the inventories of Cesium-137 in the reactor cores of three types of NPP. Also shown are the core inventories of Iodine-131, which can represent the shorter-lived isotopes in an operating reactor. Table 6-13 shows amounts of Cesium-137 that are related to the Chernobyl and Fukushima accidents.

7. Options for Risk Reduction in the LWR Context

The present level of radiological risk posed by commercial nuclear facilities is not inevitable. Instead, this level of risk reflects choices made by the nuclear industry and accepted by regulatory organizations. The most significant choices relate to facility design, and the designs are strongly influenced by two factors. First, cost minimization is a major driver of the initial design decisions. Second, the nuclear industry is reluctant to revisit those decisions at a later time, even if evidence accumulates that the initial designs were deficient.

Table 7-1 describes some options to reduce the risk of a fire in a spent-fuel pool at a PWR or BWR plant. One can see that the option of re-equipping the pool with low-density, open-frame racks would be the most effective and reliable method of reducing risk. This would be a design option that requires no alteration in reactor operation. Excess spent fuel would be transferred to dry casks located at the plant site or elsewhere.

The cost of introducing this option would be comparatively modest.[71] The dominant component of the cost would be the expense of deploying additional dry casks. Moreover, the same expense could be incurred some years later even if risk reduction were not a concern. That would be the case if SNF remained at the site of an NPP after the plant is shut down, which is an increasingly likely outcome at many plants. Given that outcome, the SNF in the plant's pool would typically be transferred to dry storage soon after plant shut-down. Thus, the true incremental cost of transferring SNF to dry storage now, rather than after plant shut-down, would be the time value of the transfer expense.

NRC established a task force of staff members to study the Fukushima accident and make recommendations about incorporating lessons from the accident into NRC regulation. The task force reported in July 2011. Some of its recommendations were intended to reduce the risk of a pool fire. For example, the task force recommended that each NPP owner be required to install fixed pipes that could spray water into each reactor-adjacent

[70] DOE, 1987, page x.
[71] Alvarez et al, 2003.

pool, with a ground-level connection so that a portable pump could feed water to the pipes.[72] Table 7-1 mentions this option.

Dry casks pose a much lower radiological risk than do spent-fuel pools, especially if the pools are equipped with high-density racks. Nevertheless, dry casks could be attacked, and attackers could initiate a cask fire as discussed in Section 6, above. In recognition of the potential for attack, analysts have proposed that dry casks be given additional protection. For example, a researcher at Tokyo University has discussed options for underground placement of dry casks.[73]

Holtec has developed a design for a vertical-axis, dry-cask system in which, for most of its height, the cask would be below ground. The system is known as the HI-STORM 100U, and is a variant of the system shown in Figure 6-8. Holtec has described the robustness of the 100U system as follows:[74]

> "Release of radioactivity from the HI-STORM 100U by any mechanical means (crashing aircraft, missile, etc.) is virtually impossible. The only access path into the cavity for a missile is vertically downward, which is guarded by an arched, concrete-fortified steel lid weighing in excess of 10 tons. The lid design, at present configured to easily thwart a crashing aircraft, can be further buttressed to withstand more severe battlefield weapons, if required in the future for homeland security considerations. The lid is engineered to be conveniently replaceable by a later model, if the potency of threat is deemed to escalate to levels that are considered non-credible today."

Options for reducing the risk posed by nuclear facilities may be significant in terms of national strategy. That issue is addressed in summary form in Table 7-2.

8. Developing a Technical Understanding of SNF Radiological Risk and Risk-Reduction Options in the CANDU Context

Section 6 examines the present technical understanding of SNF radiological risk in the LWR context, and Section 7 discusses the present understanding of risk-reduction options in the LWR context. The same level of understanding on these matters, or a higher level, could be achieved in the CANDU context if CNSC and the Canadian nuclear industry sponsored an appropriate set of studies.

The Draft Screening Report has already identified the locations of potential events that could be major contributors to SNF radiological risk at a station such as DNGS. Those locations are the IFBs and the DSCs, where the SNF is stored. For each of these locations, studies should be conducted to identify and characterize a range of scenarios

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[72] NRC, 2011, Appendix A.
[73] Choi, 2010.
[74] Holtec, 2007. Also, see: Holtec, 2012.

that could involve a release of radioactive material.[75] Then, additional studies should be conducted to identify and characterize a set of risk-reduction options that respond to the release scenarios.

The studies should be conducted by independent institutions and investigators, should be openly published, and should be subjected to peer review and public review. (Caveats apply in regard to consideration of malevolent acts, as discussed below.) Investigators could draw upon related analyses in the LWR context (see Sections 6 and 7, above), and upon Canadian expertise in PRA and associated disciplines.[76]

The Draft Screening Report does not consider malevolent acts, and seeks to justify that omission with the argument that "security issues are being appropriately managed". (See the quote at the beginning of Section 3, above.) Thus, the Draft Screening Report assumes a probability of zero for an entire class of events that are technically feasible, and that could generate outcomes that serve the interests of potential attackers. That assumption is imprudent, and may lead to substantial under-estimation of SNF radiological risk.

Studies about radiological risk and risk reduction should generally be open and transparent. Clearly, however, these studies should not disclose detailed information that would assist potential attackers. Fortunately, experience shows that these interests can be balanced, so that general openness is maintained but certain details are withheld from publication. Many investigators of radiological risk are familiar with striking such a balance.

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[75] Relevant characteristics of a release scenario would include the magnitude, composition, timing, and pathway of the release.
[76] For a recent example of Canadian work in the PRA field, see: OPG, 2012.

9. Conclusions and Recommendations

Conclusions

C1. A number of credible studies show that management and storage of SNF discharged from commercial LWRs can create substantial radiological risk, and that options for reducing the risk are available. Experience with the Fukushima accident has highlighted the relevance of these studies to the regulation of nuclear generating stations.

C2. The major contributor to SNF radiological risk at LWR stations is the potential for SNF to be uncovered (exposed to air) due to loss of water from a spent-fuel pool. In that event, the zircaloy cladding of the SNF could undergo an exothermic reaction with steam and/or air, leading to a substantial release of radioactive material to the atmosphere. Also, a zircaloy-steam reaction would generate hydrogen gas, which could explode violently when mixed with air.

C3. While SNF radiological risk has been extensively studied in an LWR context, comparable studies have not been done for SNF discharged from CANDU reactors such as those used at DNGS. Nevertheless, the CNSC's Fukushima Task Force has acknowledged that a substantial radiological risk arises from storage of SNF under water in IFBs at stations such as DNGS. The Task Force has acknowledged that uncovering of the SNF could cause the fuel to overheat, leading to a release of radioactive material and hydrogen gas.

C4. The Fukushima Task Force has implicitly recognized the lack of studies of SNF radiological risk at CANDU stations. The Task Force has called upon Canadian licensees to enhance their modeling capabilities in this area, and to conduct systematic analyses of beyond-design-basis accidents at IFBs. The Task Force has said that these analyses should include the estimation of releases, into the atmosphere and water, of radioactive material and hydrogen gas.

C5. The SENES Report shows that OPG is aware that uncovering of SNF is an event to be feared. Also, one could reasonably expect that OPG would be fully cognizant of the findings of the Fukushima Task Force.

C6. The Draft Screening Report cites the SENES Report and the Fukushima Task Force Report. Yet, the Draft Screening Report fails to acknowledge the risk associated with uncovering of SNF in an IFB. Instead, the Draft Screening Report focuses its discussion of SNF radiological risk on two comparatively minor events – drop of a DSC, and drop of an SNF storage module. In those cases, it seems that the Draft Screening Report has simply adopted the position of OPG.

C7. The Draft Screening Report explicitly excludes consideration of malevolent acts as contributors to radiological risk. That exclusion may lead to substantial under-estimation of risk.

C8. Technical understanding of SNF radiological risk and risk-reduction options in a CANDU context could be brought up to or beyond the present level of understanding of SNF radiological risk and risk-reduction options in an LWR context. Achieving that outcome would require the conduct of a number of independent, CANDU-focused studies that are openly published and subjected to peer review and public review.

C9. Completion of a credible EA process for refurbishment and continued operation of DNGS would require, among other ingredients, that OPG and CNSC demonstrate a thorough technical understanding of SNF radiological risk and risk-reduction options associated with DNGS. The studies outlined in Conclusion C8 could provide that understanding, if conducted appropriately.

Recommendations

R1. Completion of the EA process for refurbishment and continued operation of DNGS should be deferred until OPG and CNSC demonstrate a thorough technical understanding of SNF radiological risk and risk-reduction options associated with DNGS, and this understanding is clearly communicated to the public in relevant EA documents. (See Conclusions C8 and C9.)

10. Bibliography

(Ade and Gauld, 2011)
Brian J. Ade and Ian C. Gauld, *Decay Heat Calculations for PWR and BWR Assemblies Fueled with Uranium and Plutonium Mixed Oxide Fuel Using Scale, Report ORNL/TM-2011/290* (Oak Ridge, Tennessee: Oak Ridge National Laboratory, September 2011).

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

(Albrecht, 1979)
Ernst Albrecht, Minister-President of Lower Saxony, "Declaration of the state government of Lower Saxony concerning the proposed nuclear fuel center at Gorleben" (English translation), May 1979.

(Alvarez et al, 2003)
Robert Alvarez, Jan Beyea, Klaus Janberg, Jungmin Kang, Ed Lyman, Allison Macfarlane, Gordon Thompson, and Frank von Hippel, "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States", *Science and Global Security,* Volume 11, 2003, pp 1-51.

(Asahi Shimbun, 2012)
Asahi Shimbun, "Video shows debris inside Fukushima reactor storage pool", 11 February 2012. Accessed on 15 February 2012 from:
http://ajw.asahi.com/article/0311disaster/fukushima/AJ201202110016

(Asahi Shimbun, 2011)
Asahi Shimbun, "Radioactive cesium spread as far as Gunma-Nagano border", 12 November 2011. Accessed on 28 November 2011 from:
http://ajw.asahi.com/article/0311disaster/fukushima/AJ2011111217258

(Associated Press, 2012)
Associated Press, "AP Interview: Japanese official who outlined worst nuclear scenario blames plant's design", accessed on 21 February 2012 from:
http://www.washingtonpost.com/world/asia-pacific/japanese-official-who-described-worst-nuclear-scenario-blames-plant-design-defends-secrecy/2012/02/14/gIQAJfPtCR_story.html

(Baker and Liimatainen, 1973)
Louis Baker and Robert C. Liimatainen, "Chemical Reactions", Chapter 17 in T. J. Thompson and J. G. Beckerly (editors), *The Technology of Nuclear Reactor Safety, Volume 2* (Cambridge, Massachusetts: MIT Press, 1973).

(Benedict, 1958)
Manson Benedict, *Summary Report: Economic Comparison of Zircaloy and Stainless Steel in Nuclear Power Reactors* (Cambridge, Massachusetts: Columbia-National Corporation, 6 February 1958).

(Benjamin et al, 1979)
Allan S. Benjamin and three other authors, *Spent Fuel Heatup Following Loss of Water During Storage, NUREG/CR-0649* (Washington, DC: US Nuclear Regulatory Commission, March 1979).

(Beyea et al, 1979)
Jan Beyea, Yves Lenoir, Gene Rochlin, and Gordon Thompson, "Potential Accidents and Their Effects," Chapter 3 in *Report of the Gorleben International Review*, March 1979.

(Carter et al, 2011)
Joe T. Carter, Robert H. Jones, and Alan J. Luptak, *US Radioactive Waste Inventory and Characteristics Related to Potential Future Nuclear Energy Systems, Report FCRD-USED-2011-000068, Rev 2* (Washington, DC: US Department of Energy, May 2011).

(Choi, 2010)
Jor-Shan Choi, "Managing spent nuclear fuel from non-proliferation, security and environmental perspectives", *Nuclear Engineering and Technology*, Volume 42, Number 3, June 2010, pp 231-236.

(CNSC and DFO, 2012)
Canadian Nuclear Safety Commission, and Fisheries and Oceans Canada, *Draft Screening Report on: Environmental Assessment of the Refurbishment and Continued Operation of the Darlington Nuclear Generating Station, Municipality of Clarington, Ontario* (Ottawa: Canadian Nuclear Safety Commission, June 2012).

(CNSC-FTF, 2011)
The Canadian Nuclear Safety Commission's Fukushima Task Force, *CNSC Fukushima Task Force Report, INFO-0824* (Ottawa: Canadian Nuclear Safety Commission, October 2011).

(Cochran, 2011)
Thomas Cochran (Natural Resources Defense Council), prepared statement for an appearance at joint hearings of the Subcommittee on Clean Air and Nuclear Safety, and the Committee on Environment and Public Works, US Senate, 12 April 2011.

(CRC, 1986)
CRC Press, *CRC Handbook of Chemistry and Physics, 67th Edition* (Boca Raton, Florida: CRC Press, 1986).

(Diet, 2012)
National Diet of Japan, *The official report of The Fukushima Nuclear Accident Independent Investigation Commission, Executive summary* (Tokyo: National Diet of Japan, 2012).

(DOE, 1987)
US Department of Energy, *Health and Environmental Consequences of the Chernobyl Nuclear Power Plant Accident, DOE/ER-0332* (Washington, DC: DOE, June 1987).

(EPRI, 2010)
Electric Power Research Institute, *Industry Spent Fuel Storage Handbook* (Palo Alto, California: EPRI, July 2010).

(Fetter, 1982)
Steve Fetter, *The Vulnerability of Nuclear Reactors to Attack by Nuclear Weapons* (Cambridge, Massachusetts: Program in Science and Technology for International Security, Massachusetts Institute of Technology, August 1982).

(Fetter and Tsipis, 1980)
Steve Fetter and Kosta Tsipis, *Catastrophic Nuclear Radiation Releases* (Cambridge, Massachusetts: Program in Science and Technology for International Security, Massachusetts Institute of Technology, September 1980).

(Funabashi and Kitazawa, 2012)
Yoichi Funabashi and Kay Kitazawa, “Fukushima in review: A complex disaster, a disastrous response”, *Bulletin of the Atomic Scientists*, Volume 68, Number 2, March/April 2012, pp 9-21.

(Gurinsky and Isserow, 1973)
D. H. Gurinsky and S. Isserow, “Nuclear Fuels”, Chapter 13 in T. J. Thompson and J. G. Beckerly (editors), *The Technology of Nuclear Reactor Safety, Volume 2* (Cambridge, Massachusetts: MIT Press, 1973).

(Hirsch et al, 1989)
H. Hirsch and three other authors, *IAEA Safety Targets and Probabilistic Risk Assessment* (Hannover, Germany: Gesellschaft fur Okologische Forschung und Beratung, August 1989).

(Holtec, 2012)
Holtec International, "HI-STORM 100U Under-ground Storage System", accessed at http://www.holtecinternational.com/divisions/products/hi-storm-100u-under-ground-storage-system on 10 March 2012.

(Holtec, 2007)
Holtec International, "The HI-STORM 100 Storage System", accessed at http://www.holtecinternational.com/hstorm100.html on 17 June 2007.

(Honnellio and Rydell, 2007)
Anthony L. Honnellio and Stan Rydell, "Sabotage vulnerability of nuclear power plants", *International Journal of Nuclear Governance, Economy and Ecology*, Volume 1, Number 3, 2007, pp 312-321.

(IAEA, 2011)
International Atomic Energy Agency, *Nuclear Power Reactors in the World, Reference Data Series No. 2* (Vienna: IAEA, June 2011).

(INPO, 2011)
Institute of Nuclear Power Operations, *Special Report on the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station, INPO 11-005*, Revision 0 (Atlanta, Georgia: INPO, November 2011).

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

(Knox, 1983)
Joseph B. Knox (Lawrence Livermore National Laboratory), "Global Scale Deposition of Radioactivity from a Large Scale Exchange", paper presented at the Third International Conference on Nuclear War, Erice, Italy, 16-24 August 1983.

(Kumano, 2010)
Yumiko Kumano (Tokyo Electric Power Company), "Integrity Inspection of Dry Storage Casks and Spent Fuels at Fukushima Daiichi Nuclear Power Station", 16 November 2010, viewgraphs for display at ISSF 2010: Session 6.

(Langstaff et al, 1982)
D. C. Langstaff and five other authors, *Examination of Stainless Steel-Clad Connecticut Yankee Fuel Assembly S004 After Storage in Borated Water, PNL-3828* (Richland, Washington: Pacific Northwest Laboratory, September 1982).

(Luna et al, 2001)
R.E. Luna and seven other authors, "Perspectives on Spent Fuel Cask Sabotage", paper presented at WM'01 Conference, Tucson, Arizona, 25 February to 1 March, 2001.

(Mannan, 2007)
Abdul Mannan, *Preventing Nuclear Terrorism in Pakistan: Sabotage of a Spent Fuel Cask or a Commercial Irradiation Source in Transport* (Washington, DC: Henry L. Stimson Center, April 2007).

(Morris et al, 2006)
Robert H. Morris et al, "Using the VISAC program to calculate the vulnerability of nuclear power plants to terrorism", *International Journal of Nuclear Governance, Economy and Ecology*, Volume 1, Number 2, 2006, pp 193-211.

(National Research Council, 2006)
National Research Council Committee on the Safety and Security of Commercial Spent Nuclear Fuel Storage (a committee of the Council's Board on Radioactive Waste Management), *Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report* (Washington, DC: National Academies Press, 2006).

(Nero, 1979)
Anthony Nero, *A Guidebook to Nuclear Reactors* (Berkeley, California: University of California Press, 1979).

(NRC, 2012)
US Nuclear Regulatory Commission, *State-of-the-Art Reactor Consequence Analyses (SOARCA) Report, Draft Report for Comment, NUREG-1935* (Washington, DC: Nuclear Regulatory Commission, January 2012).

(NRC, 2011)
US Nuclear Regulatory Commission, *Recommendations for Enhancing Reactor Safety in the 21st Century: The Near-Term Task Force Review of Insights from the Fukushima Dai-Ichi Accident* (Washington, DC: Nuclear Regulatory Commission, 12 July 2011).

(NRC, 1994)
US Nuclear Regulatory Commission, "10 CFR Part 73, RIN 3150-AE81, Protection Against Malevolent Use of Vehicles at Nuclear Power Plants", *Federal Register*, Volume 59, Number 146, 1 August 1994, pp 38889-38900.

(NRC, 1990)
US Nuclear Regulatory Commission, *Severe Accident Risks: An Assessment for Five US Nuclear Power Plants, NUREG-1150* (Washington, DC: Nuclear Regulatory Commission, December 1990).

(NRC, 1979)
US Nuclear Regulatory Commission, *Generic Environmental Impact Statement on Handling and Storage of Spent Light Water Power Reactor Fuel, NUREG-0575* (Washington, DC: Nuclear Regulatory Commission, August 1979).

(NRC, 1975)
US Nuclear Regulatory Commission, *Reactor Safety Study, WASH-1400 (NUREG-75/014)* (Washington, DC: Nuclear Regulatory Commission, October 1975).

(OPG, 2012)
Ontario Power Generation, *Darlington NGS Risk Assessment Summary Report* (Toronto, Ontario: Ontario Power Generation, 2012).

(OPG, 2011)
Ontario Power Generation, *DNGS Refurbishment Project*, *Environmental Impact Statement* (Toronto, Ontario: Ontario Power Generation, December 2011).

(OPG, 2010)
Ontario Power Generation, *Darlington Waste Management Facility* (Toronto, Ontario: Ontario Power Generation, 2010).

(Popov et al, 2000)
S. G. Popov and three other authors, *Thermophysical Properties of MOX and UO_2 Fuels Including the Effects of Irradiation, Report ORNL/TM-2000/351* (Oak Ridge, Tennessee: Oak Ridge National Laboratory, November 2000).

(POST, 2004)
UK Parliamentary Office of Science and Technology (POST), *Assessing the risk of terrorist attacks on nuclear facilities* (London: POST, 2004).

(Ramberg, 1984)
Bennett Ramberg, *Nuclear Power Plants as Weapons for the Enemy: An Unrecognized Military Peril* (Berkeley, California: University of California Press, 1984).

(Ramberg, 1980)
Bennett Ramberg, *Destruction of Nuclear Energy Facilities in War: The Problem and the Implications* (Lexington, Massachusetts: Lexington Books, 1980).

(Raytheon, 2008)
Raytheon Company, "Raytheon Unveils New Record-Breaking Bunker Busting Technology", 12 March 2008, accessed on 7 March 2012 at: http://www.raytheon.com/newsroom/feature/bb_03-10/

(Rotblat, 1981)
Joseph Rotblat, *Nuclear Radiation in Warfare* (London: Taylor and Francis, 1981).

(Sdouz, 2007)
Gert Sdouz, "Radioactive release from VVER-1000 reactors after a terror attack", *International Journal of Nuclear Governance, Economy and Ecology*, Volume 1, Number 3, 2007, pp 305-311.

(SENES, 2011)
SENES Consultants Limited, *Malfunctions and Accidents Technical Support Document, Darlington Nuclear Generating Station Refurbishment and Continued Operation Environmental Assessment* (Richmond Hill, Ontario: SENES Consultants, December 2011).

(Shlyakhter and Wilson, 1992)
Alexander Shlyakhter and Richard Wilson, "Chernobyl: the inevitable results of secrecy", *Public Understanding of Science*, Volume 1, July 1992, pp 251-259.

(Silberberg et al, 1986)
M. Silberberg and three other authors, *Reassessment of the Technical Bases for Estimating Source Terms, NUREG-0956* (Washington, DC: US Nuclear Regulatory Commission, July 1986).

(Stohl et al, 2011)
A. Stohl, P. Seibert, G. Wotawa, D. Arnold, J.F. Burkhart, S. Eckhardt, C. Tapia, A. Vargas, and T.J. Yasunari, "Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: determination of the source term, atmospheric dispersion, and deposition," *Atmospheric Chemistry and Physics Discuss*ions, Volume 11, 2011, pp 28319-28394.

(Thompson, 2011)
Gordon R. Thompson, *New and Significant Information From the Fukushima Daiichi Accident in the Context of Future Operation of the Pilgrim Nuclear Power Plant* (Cambridge, Massachusetts: Institute for Resource and Security Studies, 1 June 2011).

(Thompson, 2009)
Gordon R. Thompson, *Environmental Impacts of Storing Spent Nuclear Fuel and High-Level Waste from Commercial Nuclear Reactors: A Critique of NRC's Waste Confidence Decision and Environmental Impact Determination* (Cambridge, Massachusetts: Institute for Resource and Security Studies, 6 February 2009).

(Thompson, 2008)
Gordon R. Thompson, *Scope of the EIS for New Nuclear Power Plants at the Darlington Site in Ontario: Accidents, Malfunctions and the Precautionary Approach* (Cambridge, Massachusetts: Institute for Resource and Security Studies, November 2008).

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

(Thompson, 2006)
Gordon R. Thompson, *Risks and Risk-Reducing Options Associated with Pool Storage of Spent Nuclear Fuel at the Pilgrim and Vermont Yankee Nuclear Power Plants* (Cambridge, Massachusetts: Institute for Resource and Security Studies, 25 May 2006).

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

(Thompson, 1996)
Gordon Thompson, *War, Terrorism and Nuclear Power Plants* (Canberra: Peace Research Centre, Australian National University, October 1996).

(Wald, 2005)
Matthew L. Wald, "Agencies Fight Over Report on Sensitive Atomic Wastes", *The New York Times*, 30 March 2005.

(Warwick, 2008)
Graham Warwick, "VIDEO: Raytheon tests bunker-busting tandem warhead", *Flightglobal*, 26 February 2008, accessed on 7 March 2012 from: http://www.flightglobal.com/news/articles/video-raytheon-tests-bunker-busting-tandem-warhead-221842/

(Yueh et al, 2010)
Ken Yueh, David Carpenter, and Herbert Feinroth, "Clad in clay", *Nuclear Engineering International*, 8 March 2010.

Table 5-1
SNF Inventory at Fukushima #1 Nuclear Site in Japan, as of March 2010

Storage Method	Storage Capacity (number of fuel assemblies)	Inventory (number of fuel assemblies)
Spent-fuel pools at six reactors	8,310	3,450
Common spent-fuel pool	6,840	6,291
Dry casks	408	408
Total	15,558	10,149

Notes:
(a) These data are from: Kumano, 2010.
(b) Six reactors were operational at the Fukushima #1 site prior to the accident of March 2011. These reactors discharged about 700 spent fuel assemblies each year. The site's total spent-fuel storage capacity of 15,558 assemblies was approximately 450% of the total core capacity of the six reactors.
(c) The six reactors entered commercial service between March 1971 (Unit 1) and October 1979 (Unit 6).

Table 6-1
Number of Commercial Nuclear Reactors Worldwide, by Type

Type Code	Description	Number of Reactors as of 31 December 2010	
		Operational	In Construction
PWR	Pressurized Light-Water-Moderated and Cooled Reactor	269	56
BWR	Boiling Light-Water-Moderated and Cooled Reactor	92	4
PHWR	Pressurized Heavy-Water-Moderated and Cooled Reactor	46	4
GCR	Gas-Cooled, Graphite-Moderated Reactor	18	
LWGR	Light-Water-Cooled, Graphite-Moderated Reactor	15	1
FBR	Fast Breeder Reactor	1	2
TOTAL		441	67

Notes:
(a) This table is adapted from: IAEA, 2011, Table 23.
(b) PHWR reactors are in Argentina, Canada, China, India, South Korea, Pakistan, and Romania. The PHWR reactors built by the Canadian nuclear industry are known as CANDU reactors.
(c) All GCR reactors are in the UK.
(d) LWGR reactors were constructed only in the former USSR, where they were known as RBMK reactors.
(e) The fast breeder reactors listed in this table are cooled by sodium.

Table 6-2
Inventory and Characteristics of Spent Fuel Discharged from US Commercial Reactors through 2010

Reactor Type	Total Number of Spent Fuel Assemblies	Total Initial Uranium (Mg U)	Average Enrichment when Fresh (% U-235)	Average Burnup (GWt-days per Mg U)	Average Age After Discharge (yr)
PWR	97,400	42,300	3.74	39.6	14.9
BWR	128,600	23,000	3.12	33.3	15.4
Total	226,000	65,200	N/A	N/A	N/A

Notes:
(a) Data are from: Carter et al, 2011, Sections 2.1 and 2.2.
(b) Almost all fuel currently being discharged from US reactors has a burnup exceeding 45 GWt-days per Mg U, and some fuel approaches 60 GWt-days per Mg U. Burnup is currently limited in the USA by the reactor licensing basis of 62.5 GWt-days per Mg U, and by the 5% U-235 licensing basis for enrichment and fuel fabrication plants.

Table 6-3
Selected Characteristics of Representative PWR and BWR Reactors

Characteristic	Value	
	PWR	**BWR**
Rated thermal power	3,411 MWt	3,579 MWt
Rated electrical output	1,100 MWe	1,220 MWe
Core (or fuel rod) active length	3.7 m	3.8 m
Number of fuel assemblies	193 (15x15 assembly array)	748 (8x8 assembly array)
Av. thermal power per assembly	17.7 MWt	4.78 MWt
Total number of fuel rods	39,372	46,376
Fuel cladding material	Zircaloy-4	Zircaloy-2
Cladding diameter (OD)	1.07 cm	1.23 cm
Cladding thickness	0.06 cm	0.08 cm
Fuel material	UO_2	UO_2
Pellet diameter	0.9 cm	1.04 cm
Pellet height	1.5 cm	1.04 cm
Total mass of fuel (UO_2)	98.4 Mg	155 Mg
Total mass of fuel (U)	86.7 Mg	137 Mg
Av. mass of fuel (U) per assembly	449 kg	183 kg
Core diameter	3.4 m	4.9 m
Av. area density of fuel mass (U) over core footprint	9.55 Mg per m^2	7.27 Mg per m^2
Av. center-center spacing of fuel assemblies	21.7 cm	15.9 cm
Design fuel burnup	32 GWt-days per Mg U	28.4 GWt-days per Mg U
Fresh fuel assay	3.2% U-235	2.8% U-235
Spent fuel assay (design)	0.9% U-235, 0.6% Pu-239 & 241	0.8% U-235, 0.6% Pu-239 & 241

Notes:
(a) Data are from: Nero, 1979, Tables 5-1 and 6-1.
(b) The PWR is a Westinghouse plant, and the BWR is a General Electric plant.
(c) The values shown are correct only for the specific, representative reactors. Other reactors have somewhat different values.
(d) Typical fuel burnup has increased substantially since these data were compiled. Almost all fuel currently being discharged from US reactors has a burnup exceeding 45 GWt-days per Mg U, and some fuel approaches 60 GWt-days per Mg U. (See: Carter et al, 2011, Section 2.2.)

Table 6-4
Illustrative Calculation of Heat-Up of a Fuel Rod in a PWR Fuel Assembly Due to Combustion in Air

Calculation Step	**Properties and Behavior of Rod Components**	
	Zircaloy Cladding	**UO_2 Pellets**
Solid volume, per m length	1.90E-05 m^3 (OD = 1.07 cm; thickness = 0.06 cm)	6.36E-05 m^3 (OD = 0.9 cm)
Mass, per m length	0.124 kg (@ 6.55 Mg per m^3)	0.700 kg (@ 11.0 Mg per m^3)
Heat output from complete combustion of material in air, per m length	1.48 MJ (@ 2,850 cal per g Zr, where 1 cal = 4.184 J)	Neglected (Pellet combustion would be incomplete, and a minor contributor to heat output)
Heat input if material receives 50% of heat output from adjacent combustion, and if heat loss from material is neglected	Neglected (Cladding and its combustion products have comparatively low thermal mass)	1.48x0.5 = 0.74 MJ (i.e., 1.06 MJ per kg UO_2)
Equilibrium temperature rise due to heat input	Neglected (Cladding and its combustion products have comparatively low thermal mass)	approx. 2,700 deg. C (The enthalpy rise if UO_2 temp. rises from 300 K to 3,000 K = 1.05 MJ per kg UO_2)

Notes:
(a) This table is adapted from Table 6-2 of: Thompson, 2009.
(b) Melting point of UO_2 is 2,850 deg. C (3,123 K), and boiling point of elemental Cesium is 685 deg. C.
(c) Boiling point of CsI is 1,280 deg. C, and boiling point of CsOH is 990 deg. C. (See: Silberberg et al, 1986, Table 3.2.)
(d) Average enthalpy rise per deg. C as UO_2 temperature rises from 300 K to 3,000 K: $(1.05x10^3)/2,700$ = 0.39 kJ per kg UO_2 per deg. C. (See also: Popov et al, 2000.)
(e) An analogous table could be prepared for combustion of the zircaloy cladding in steam. In that case the heat of reaction would be 1,560 cal per g Zr = 6.53 MJ per kg Zr. (See: Baker and Liimatainen, 1973, Table 3-1.) As shown above, the heat of reaction in air would be 2,850 cal per g Zr = 11.9 MJ per kg Zr. Both values are approximate.
(f) Oxidized Zr will form a liquefied two-phase mixture with UO_2 at about 1,900 deg. C. (See: Silberberg et al, 1986, Table 3.2.)

Table 6-5
Illustrative Calculation of Adiabatic Heat-Up of a Fuel Rod in a PWR Spent Fuel Assembly

Calculation Step	**Properties and Behavior of Rod Components**	
	Zircaloy Cladding	**UO_2 Pellets**
Solid volume, per m length	1.90E-05 m^3 (OD = 1.07 cm; thickness = 0.06 cm)	6.36E-05 m^3 (OD = 0.9 cm)
Mass, per m length	0.124 kg (@ 6.55 Mg per m^3)	0.700 kg (@ 11.0 Mg per m^3)
Specific heat (approx.)	300 J/kg/K	300 J/kg/K
Heat output from radioactive decay (assembly)	R = decay heat in kW per Mg U	
Heat output from radioactive decay (rod)	0 (W per kg Zr)	(238/270)R = (0.88)R (W per kg UO_2)
Rate of temperature rise from decay heat, if pellets and cladding are a tightly coupled adiabatic system	(0.88)R(0.7/(0.7 + 0.124))/300 = (2.5E-03)R (K per second) or (9.0)R (K per hr)	

Notes:
(a) Data are from: Thompson, 2009, Table 6-2; Popov et al, 2000; CRC, 1986.
(b) As an example, consider PWR fuel with a burnup of 50 GWt-days per Mg U, aged 100 days after reactor shutdown. In this case, R = 28 kW per Mg U. Thus, the adiabatic rate of temperature rise would be 9x28 = 252 K per hr (deg. C per hr).

Table 6-6
Radioactive Decay Heat in Spent Fuel at Selected Times After Reactor Shutdown, with a Fuel Burnup of 50 GWt-days per Mg HM

Type of Fuel	Decay Heat (kW per Mg HM) at Selected Times After Reactor Shutdown				
	1 day	**10 days**	**100 days**	**1,000 days**	**10,000 days**
PWR-U	182	78	28	5.1	1.3
PWR-MOX	187	93	41	7.7	2.9
BWR-U	180	77	27	4.9	1.2
BWR-MOX	180	91	40	7.3	2.7

Notes:
(a) Data are from: Ade and Gauld, 2011. These data were estimated using the SCALE code system. Decay heat was estimated for burnups of 35, 40, 45 and 50 GWt-days per Mg HM, and for times from 0.01 to 19,300 days after reactor shutdown.
(b) PWR-U and BWR-U fuel pellets contain only uranium oxide when fresh. PWR-MOX and BWR-MOX fuel pellets contain a mixture of uranium oxide and plutonium oxide when fresh. ("MOX" refers to mixed-oxide fuel.) The decay heats shown for MOX fuel are for fuel made from reactor-grade plutonium.
(c) "HM" refers to heavy metal (uranium and plutonium) in fresh fuel.

Table 6-7
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 nuclear power plants around the world are typically no more robust than at US plants.

Table 6-8
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 can carry a payload of up to 990 kg at a speed of up to 460 km/hr • The price of a used King Air 90 in the USA can be as low as $0.4 million

Source:
This table is adapted from Table 7-6 of: Thompson, 2009.

Table 6-9
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) This table is adapted from Table 7-7 of: Thompson, 2009. The data are from US Army Field Manual FM 5-25, published May 1967.
(b) The M2A3 charge has a mass of 5 kg, a maximum diameter of 18 cm, and a total length of 38 cm including the standoff ring.
(c) The M3 charge has a mass of 14 kg, a maximum diameter of 23 cm, a charge length of 39 cm, and a standoff pedestal 38 cm long.

Table 6-10
Some Characteristics of Containments of Selected NPPs in the Generation II and Generation III Categories

Plant Name or Type	Containment Characteristics
Indian Point Units 2 and 3	• The containment is a reinforced concrete vertical cylinder topped by a hemispherical dome made of the same material. The cylinder walls are 1.4 m thick with a 1.0 cm thick steel liner, and the dome is 1.1 m thick with a 1.3 cm thick steel liner. • There is no shield building.
ACR-1000	• The containment is a vertical cylinder with a domed top, made of pre-stressed (cable-tensioned) concrete and equipped with a steel liner. The wall thickness of the cylinder is 1.8 m. According to Bruce Power: "The containment structure is designed for tornado conditions, including tornado missiles, and aircraft crashes." • There is no shield building.
US-EPR	• The containment is a vertical cylinder with a domed top, made of pre-stressed (cable-tensioned) concrete and equipped with a steel liner. The wall of the cylinder is 1.3 m thick, and the dome is 1.0 m thick. • Surrounding the containment is a shield building (with a configuration similar to that of the containment) made of reinforced concrete. This building's wall and dome are each 1.8 m thick.
AP1000	• The containment is a vertical, steel cylinder with a wall thickness of 4.4 cm. • Surrounding the containment is a cylindrical shield building made of reinforced concrete, with a wall thickness of 0.9 m.

Notes:
(a) Data are from: Thompson, 2007, Section 7.5; Thompson, 2008, Section 5.
(b) Indian Point Units 2 and 3 are Generation II PWR plants operating in New York State, USA, and are located on the Hudson River upstream of New York City.
(c) The other three plants are generic, proposed, Generation III plants. The ACR-1000 is an “advanced CANDU” plant. The US-EPR and AP1000 are PWR plants. Data for specific plants that are built may differ from the values shown here.
(d) These characteristics provide an indication of each containment’s ability to resist external attack. Other characteristics would also be relevant to a full-scope assessment of the radiological risk posed by each plant.

Table 6-11
Estimated Atmospheric Release of Radioactive Material and Downwind Inhalation Dose for Blowdown of the Multi-Purpose Canister in a Spent-Fuel-Storage Module

Indicator		**Release Characteristics for Selected Values of MPC Leakage Area**		
		4 sq. mm (equiv. dia. = 2.3 mm)	**100 sq. mm (equiv. dia. = 11 mm)**	**1,000 sq. mm (equiv. dia. = 36 mm)**
Fuel Release Fraction	Gases	3.0E-01	3.0E-01	3.0E-01
	Crud	1.0E+00	1.0E+00	1.0E+00
	Volatiles	2.0E-04	2.0E-04	2.0E-04
	Fines	3.0E-05	3.0E-05	3.0E-05
MPC Blowdown Fraction		9.0E-01	9.0E-01	9.0E-01
MPC Escape Fraction	Gases	1.0E+00	1.0E+00	1.0E+00
	Crud	7.0E-02	5.0E-01	8.0E-01
	Volatiles	4.0E-03	3.0E-01	6.0E-01
	Fines	7.0E-02	5.0E-01	8.0E-01
Inhalation Dose (CEDE) to a Person at a Distance of 900 m		0.063 Sv	0.48 Sv	0.79 Sv

Notes:
(a) This table is adapted from Table 6-1 of: Thompson, 2009.
(b) The assumed multi-purpose canister (MPC) contains 24 PWR spent fuel assemblies with a burnup of 40 MWt-days per kgU, aged 10 years after discharge.
(c) The following radioisotopes were considered: Gases (H-3, I-129, Kr-85); Crud (Co-60); Volatiles (Sr-90, Ru-106, Cs-134, Cs-137); Fines (Y-90 and 22 other isotopes).
(d) The calculation followed NRC guidance for calculating radiation dose from a design-basis accident, except that the MPC Escape Fraction was drawn from a study by Sandia National Laboratories that used the MELCOR code package.
(e) CEDE = committed effective dose equivalent. In this scenario, CEDE makes up most of the total dose (TEDE) and is a sufficient approximation to it.
(f) The overall fractional release of a radioisotope from fuel to atmosphere is the product of Fuel Release Fraction, MPC Blowdown Fraction, and MPC Escape Fraction.
(g) For a leakage area of 4 square mm, the overall fractional release is: Gases (0.27); Crud (0.063); Volatiles (7.2E-07); Fines (1.9E-06). Fines account for 95 percent of CEDE, and Crud accounts for 4 percent.

Table 6-12
Estimated Core Inventories of Iodine-131 and Cesium-137 at Three Types of NPP in the Generation III Category

Plant Type	Core Inventory (PBq)		Normalized Core Inventory (PBq per GWe)	
	Iodine-131	Cesium-137	Iodine-131	Cesium-137
ACR-1000	3,640	172	3,640	172
US-EPR	5,140	914	3,210	571
AP1000	3,560	418	3,560	418

Notes:
(a) This table is adapted from Table 3-2 of: Thompson, 2008. Core inventories are estimates by Bruce Power, which operates NPPs in Ontario, Canada. It can be presumed that the core inventories were estimated for full-power, steady-state operation.
(b) According to Bruce Power, the nominal electricity-generating capacities of the three plant types are:

- ACR-1000: 1,000 MWe
- US-EPR: 1,600 MWe
- AP1000: 1,000 MWe

(c) These plants are generic, proposed, Generation III plants. The ACR-1000 is an "advanced CANDU" plant. The US-EPR and AP1000 are PWR plants. Data for specific plants that are built may differ from the values shown here.
(d) The half-lives of Iodine-131 and Cesium-137 are 8 days and 30 years, respectively.

Table 6-13
Amounts of Cesium-137 Related to the Chernobyl and Fukushima Accidents

Category	**Amount of Cesium-137 (PBq)**
Chernobyl release to atmosphere (1986)	85
Fukushima release to atmosphere (2011)	36
Deposition on Japan due to the Fukushima atmospheric release	6.4
Pre-release inventory in reactor cores of Fukushima #1, Units 1-3 (total for 3 cores)	940
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, 2011. The estimates for release from Fukushima #1 and deposition on Japan may change as new information becomes available.
(b) Stohl et al, 2011, 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	3.49E+17	3.49E+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.)

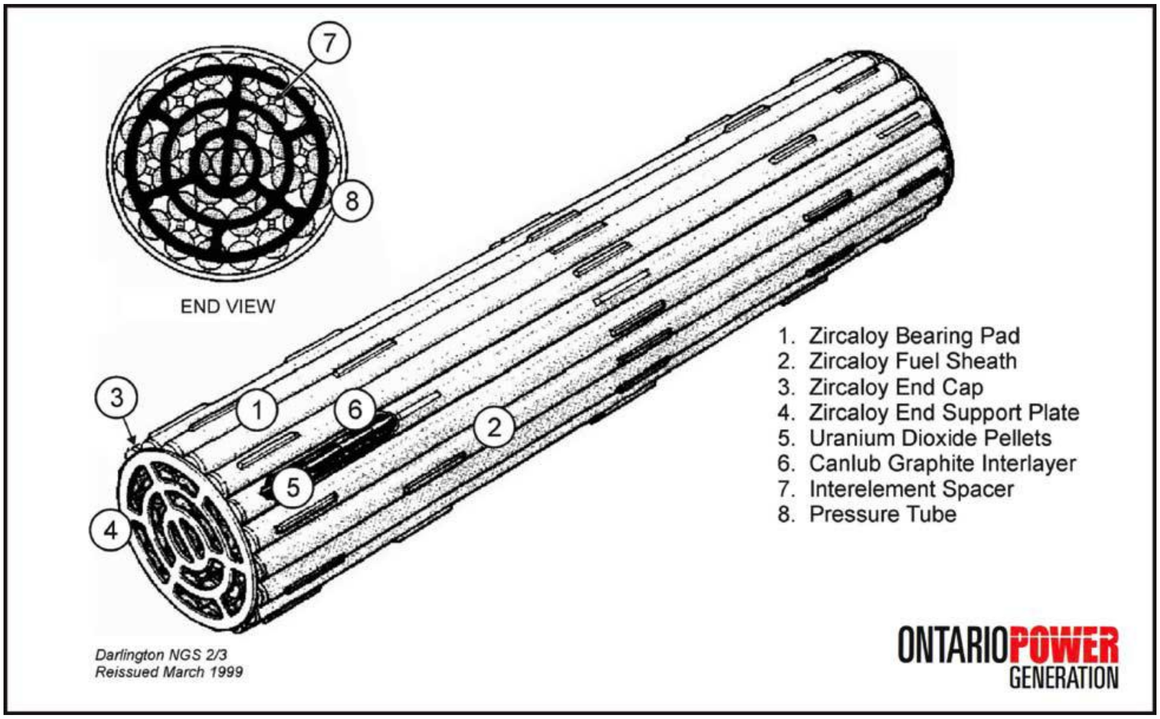
Table 7-1
Selected Options to Reduce the Risk of a Pool Fire at a PWR or BWR Plant

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

Table 7-2
Selected Approaches to Protecting a Country's Critical Infrastructure From Attack by Sub-National Groups, and Some Strengths and Weaknesses of these Approaches

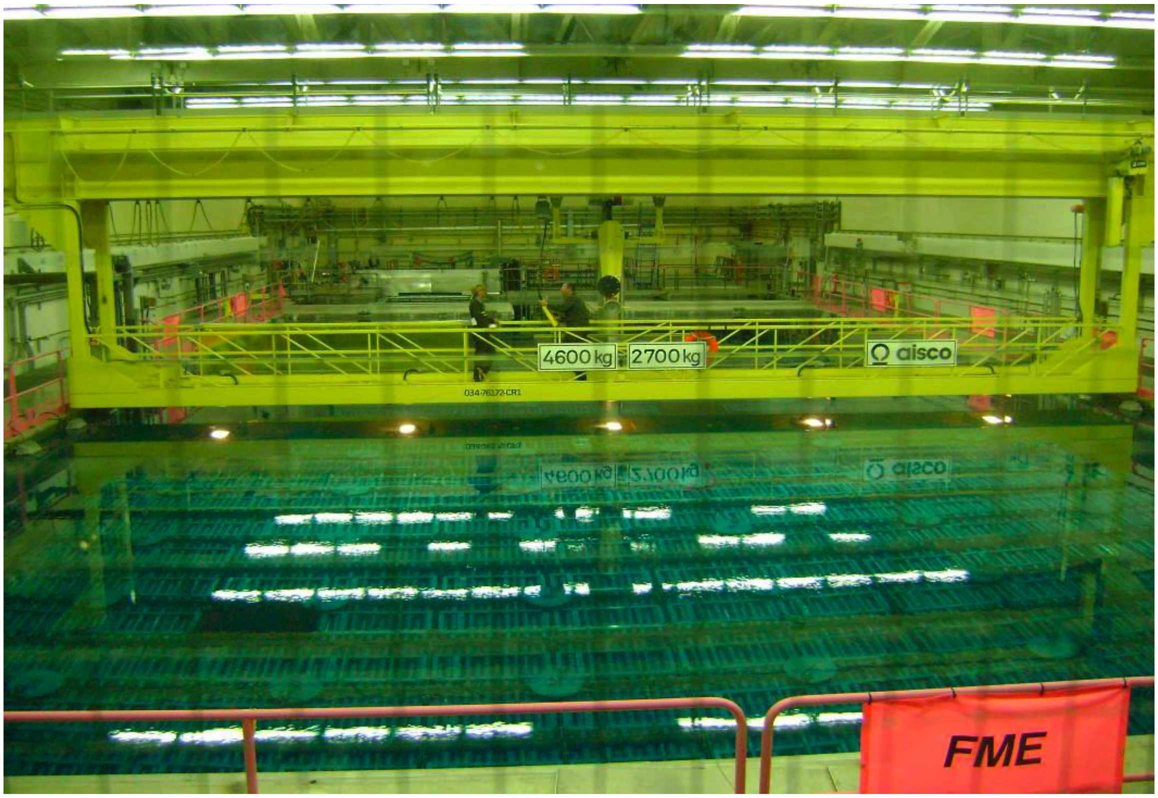
Approach	Strengths	Weaknesses
Offensive military operations internationally	• Could deter or prevent governments from supporting sub-national groups hostile to the Country	• Could promote growth of sub-national groups hostile to the Country, and build sympathy for these groups in foreign populations • Could be costly in terms of lives, money, etc.
International police cooperation within a legal framework	• Could identify and intercept potential attackers	• Implementation could be slow and/or incomplete • Requires ongoing international cooperation
Surveillance and control of the domestic population	• Could identify and intercept potential attackers	• Could destroy civil liberties, leading to political, social and economic decline
Secrecy about design and operation of infrastructure facilities	• Could prevent attackers from identifying points of vulnerability	• Could suppress a true understanding of risk • Could contribute to political, social and economic decline
Active defense of infrastructure facilities (by use of guards, guns, gates, etc.)	• Could stop attackers before they reach the target	• Requires ongoing expenditure & vigilance • May require military involvement
Robust and inherently-safe design of infrastructure facilities	• Could allow target to survive attack without damage, thereby enhancing protective deterrence • Could substitute for other protective approaches, avoiding their costs and adverse impacts • Could reduce risks from accidents & natural hazards	• Could involve higher capital costs

Figure 2-1
DNGS Fuel Bundle



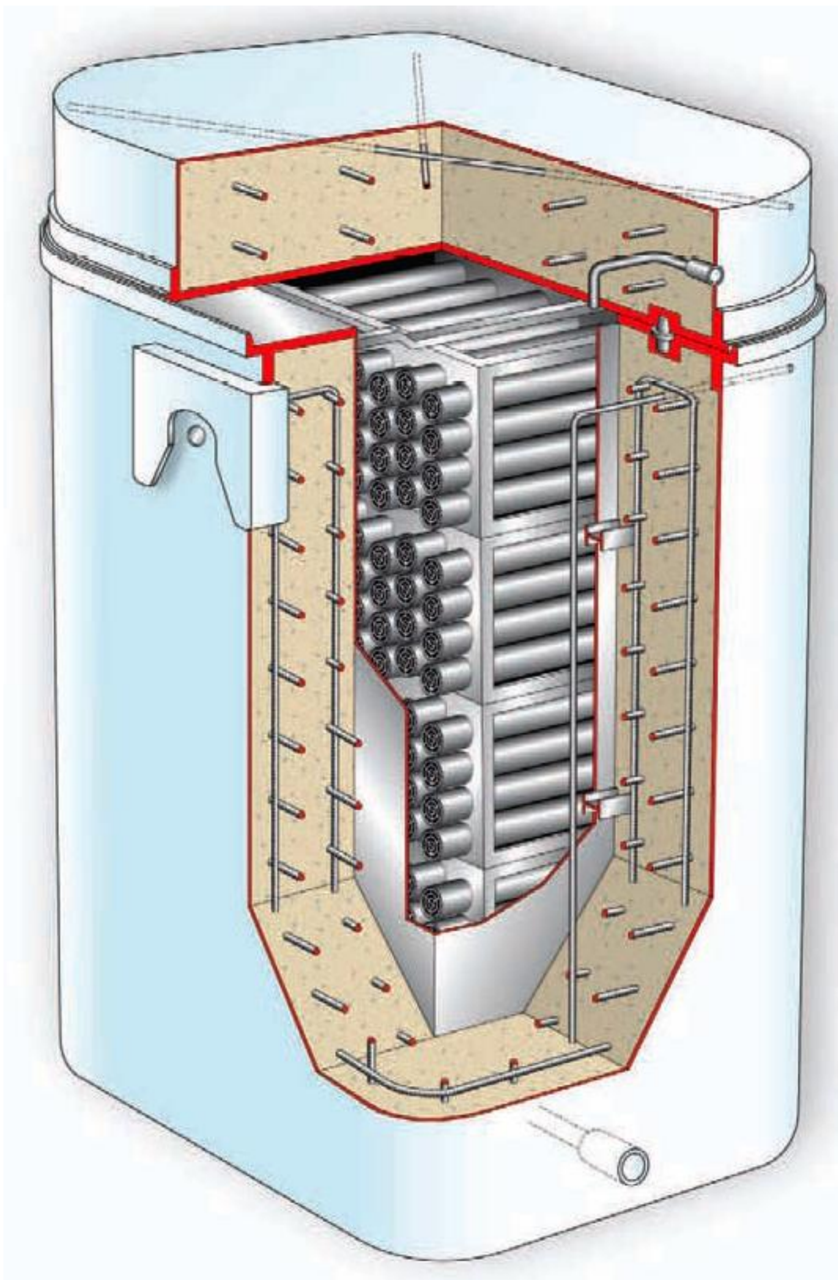
Source:
Adapted from Figure 2.5-3 of: OPG, 2011.

Figure 2-2
Typical Irradiated Fuel Bay at a CANDU Station



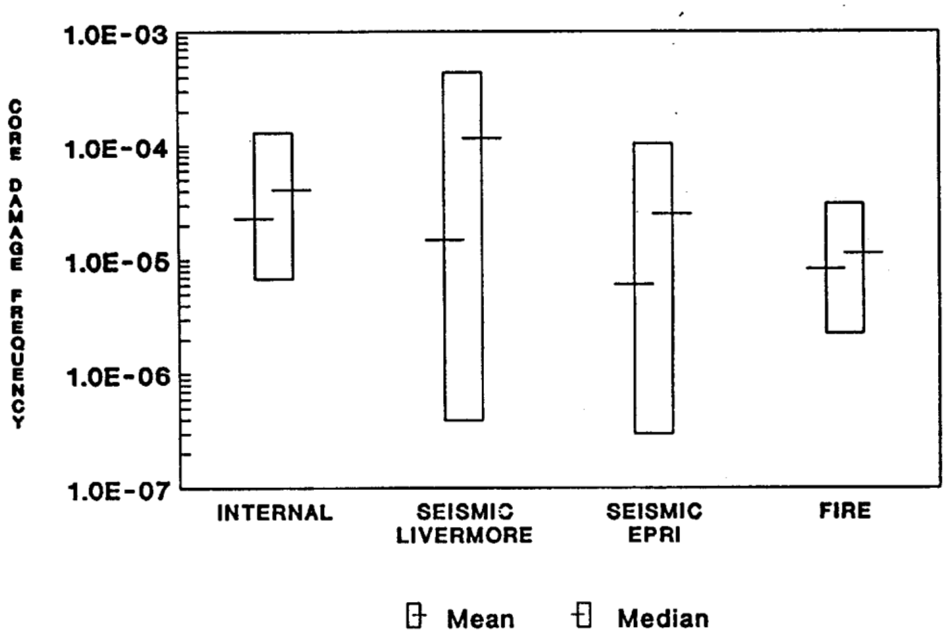
Source:
Adapted from Figure A.9 of: CNSC-FTF, 2011.

Figure 2-3
Dry Storage Container for DNGS Spent Fuel



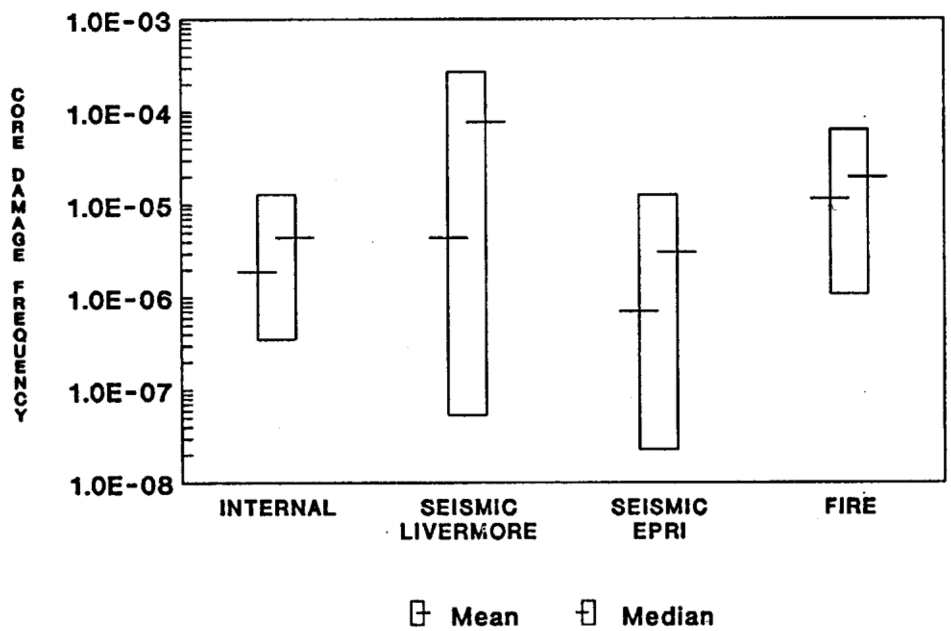
Source:
Adapted from: OPG, 2010.

Figure 4-1
Core Damage Frequency for Accidents at a Surry PWR Nuclear Power Plant, as Estimated in the NRC Study NUREG-1150



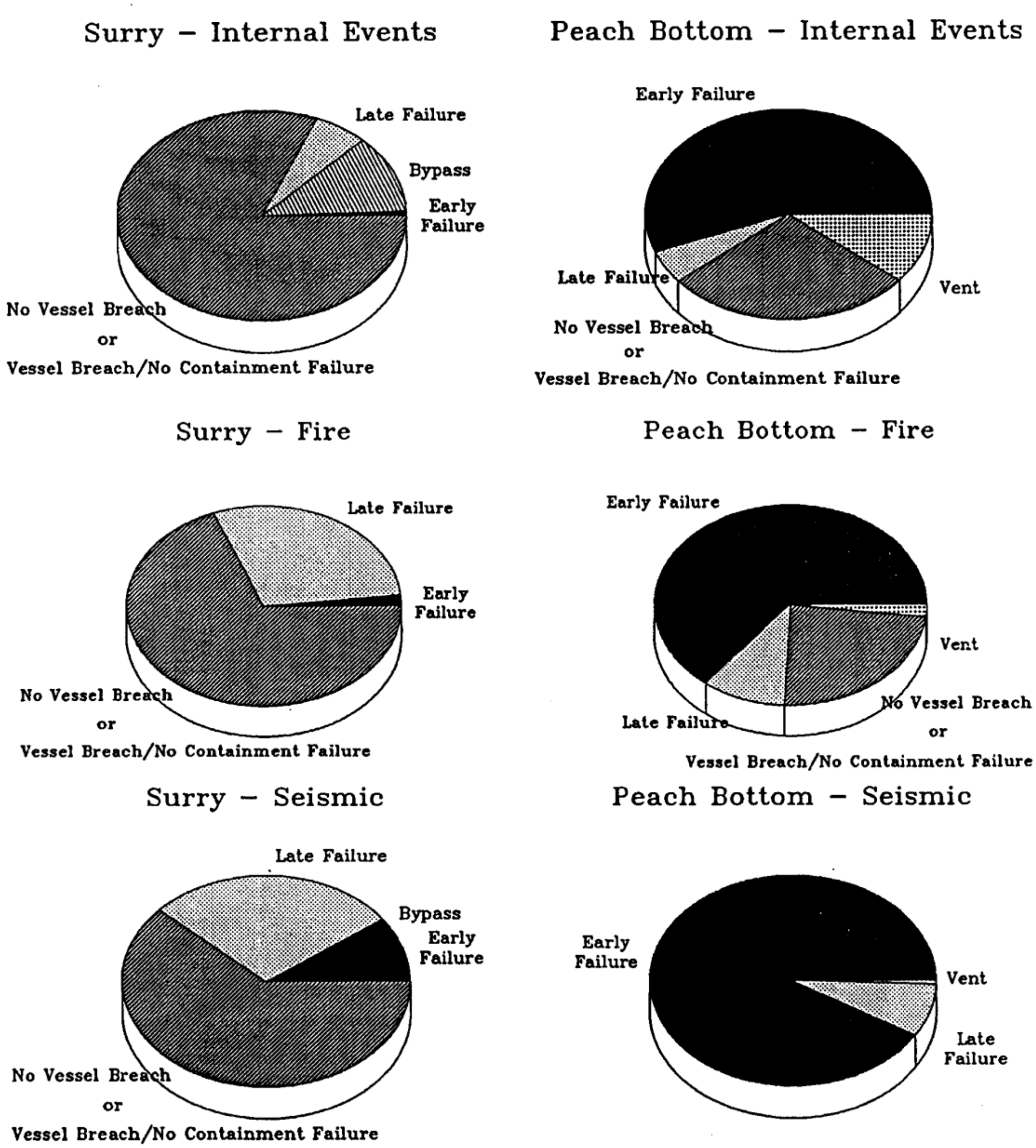
Notes:
(a) This figure is adapted from Figure 8.7 of: NRC, 1990.
(b) The bars range from the 5th percentile (lower bound) to the 95th percentile (upper bound) of the estimated core-damage frequency (CDF). CDF values shown are per reactor-year (RY).
(c) Two estimates are shown for the CDF from earthquakes (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 estimated for external initiating events other than earthquakes and fires.
(e) Malevolent acts and gross errors in design, construction, or operation are not considered.

Figure 4-2
Core Damage Frequency for Accidents at a Peach Bottom BWR Nuclear Power Plant, as Estimated in the NRC Study NUREG-1150



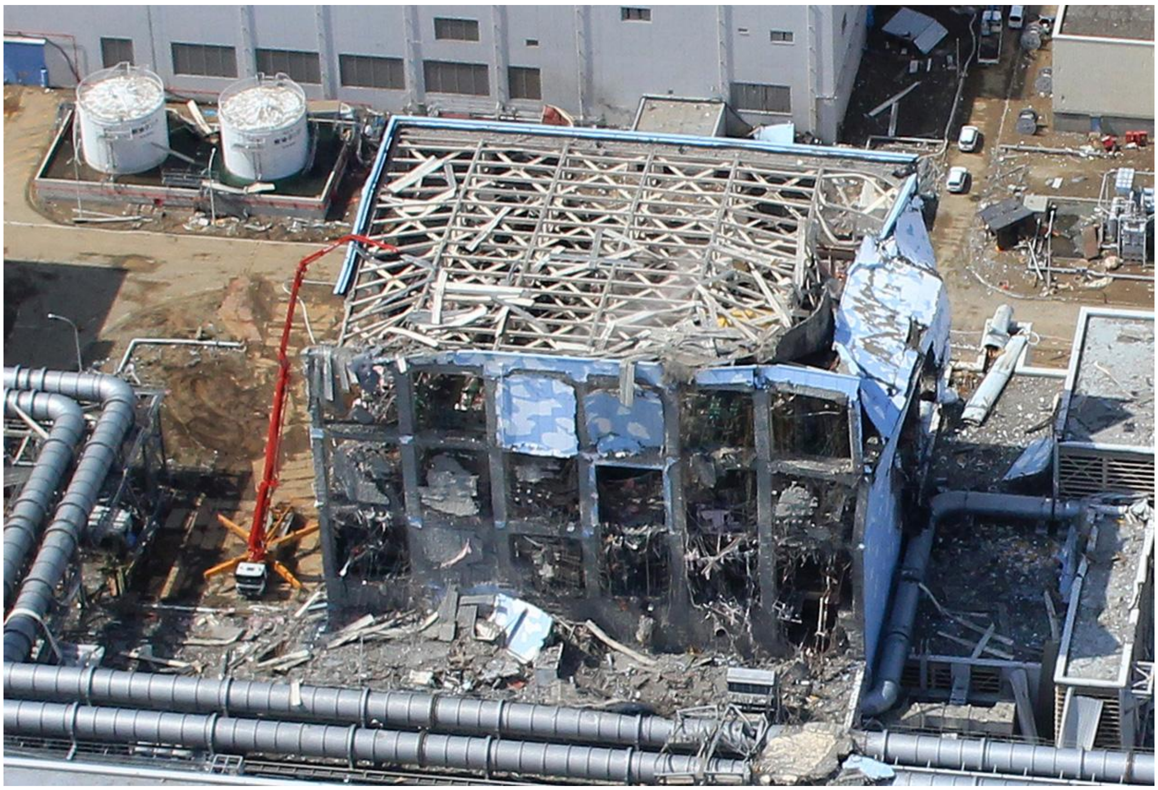
Notes:
(a) This figure is adapted from Figure 8.8 of: NRC, 1990.
(b) The bars range from the 5th percentile (lower bound) to the 95th percentile (upper bound) of the estimated core-damage frequency (CDF). CDF values shown are per reactor-year (RY).
(c) Two estimates are shown for the CDF from earthquakes (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 estimated for external initiating events other than earthquakes and fires.
(e) Malevolent acts and gross errors in design, construction, or operation are not considered.

Figure 4-3
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



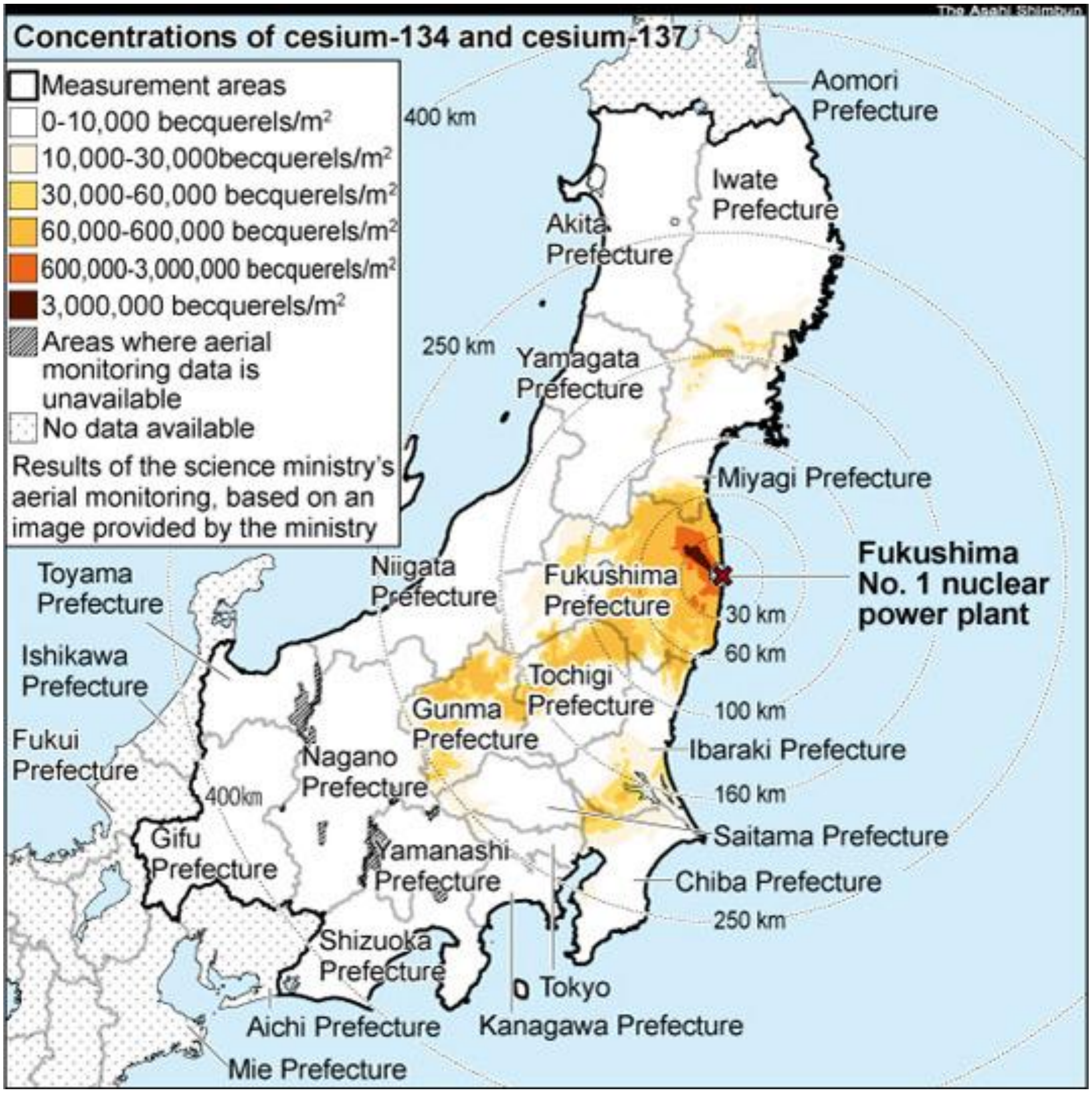
Source:
Adapted from Figure 9.5 of: NRC, 1990.

Figure 5-1
Unit 4 at the Fukushima #1 Site During the 2011 Accident



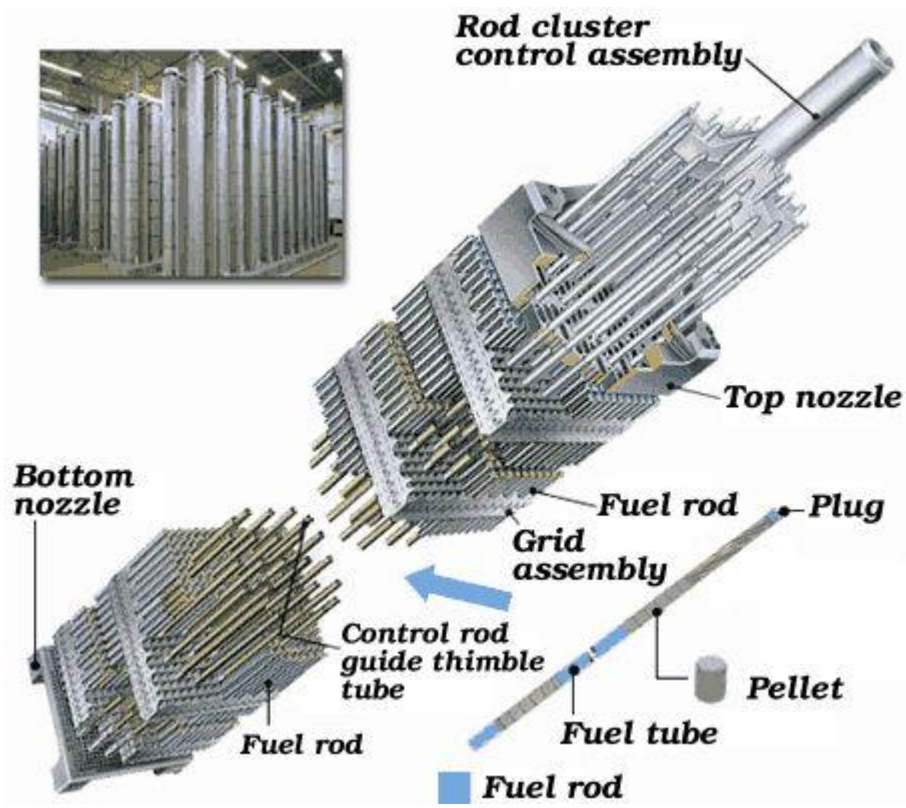
Source:
Accessed on 20 February 2012 from Ria Novosti at:
http://en.rian.ru/analysis/20110426/163701909.html; image by Reuters Air Photo Service.

Figure 5-2
Contamination of Land in Japan by Radioactive Cesium Released to Atmosphere During the Fukushima Accident of 2011



Source:
Asahi Shimbun, 2011.

Figure 6-1
Schematic View of a PWR Fuel Assembly (Mitsubishi Nuclear Fuel)

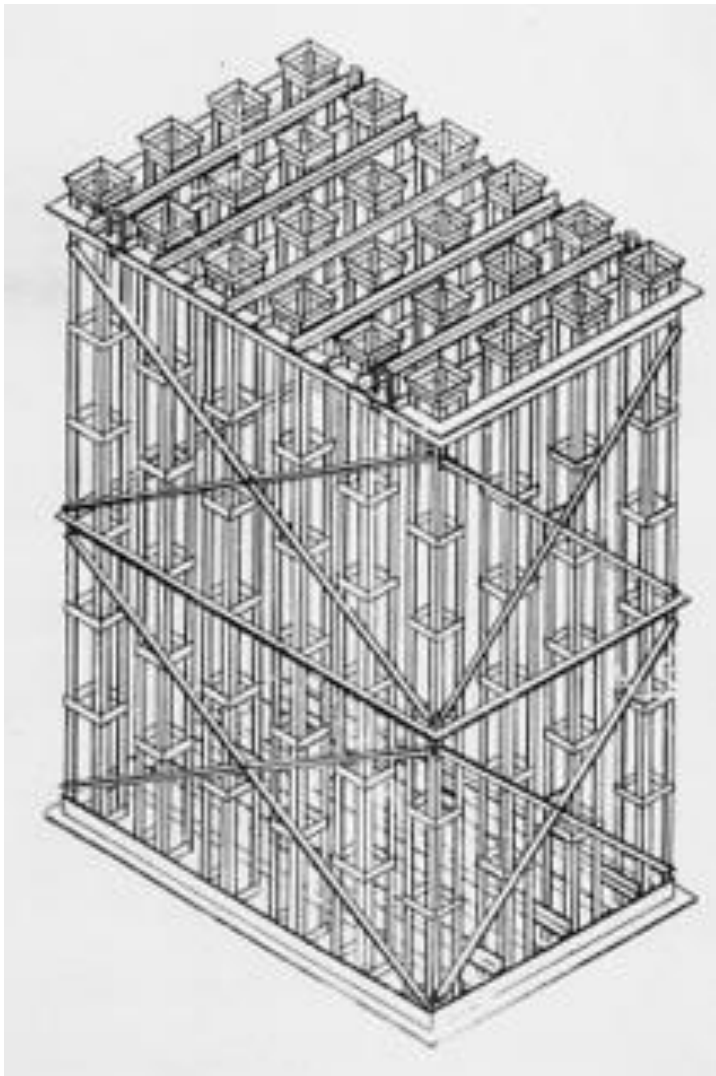


Source:
Accessed on 22 February 2012 from: http://www.world-nuclear.org/info/nuclear_fuel_fabrication-inf127.html

Figure 6-2
Schematic View of BWR Fuel Assemblies (General Electric)

Source:
Accessed on 22 February 2012 from: http://www.world-nuclear.org/info/nuclear_fuel_fabrication-inf127.html

Figure 6-3
Typical Low-Density, Open-Frame Rack for Pool Storage of PWR Spent Fuel

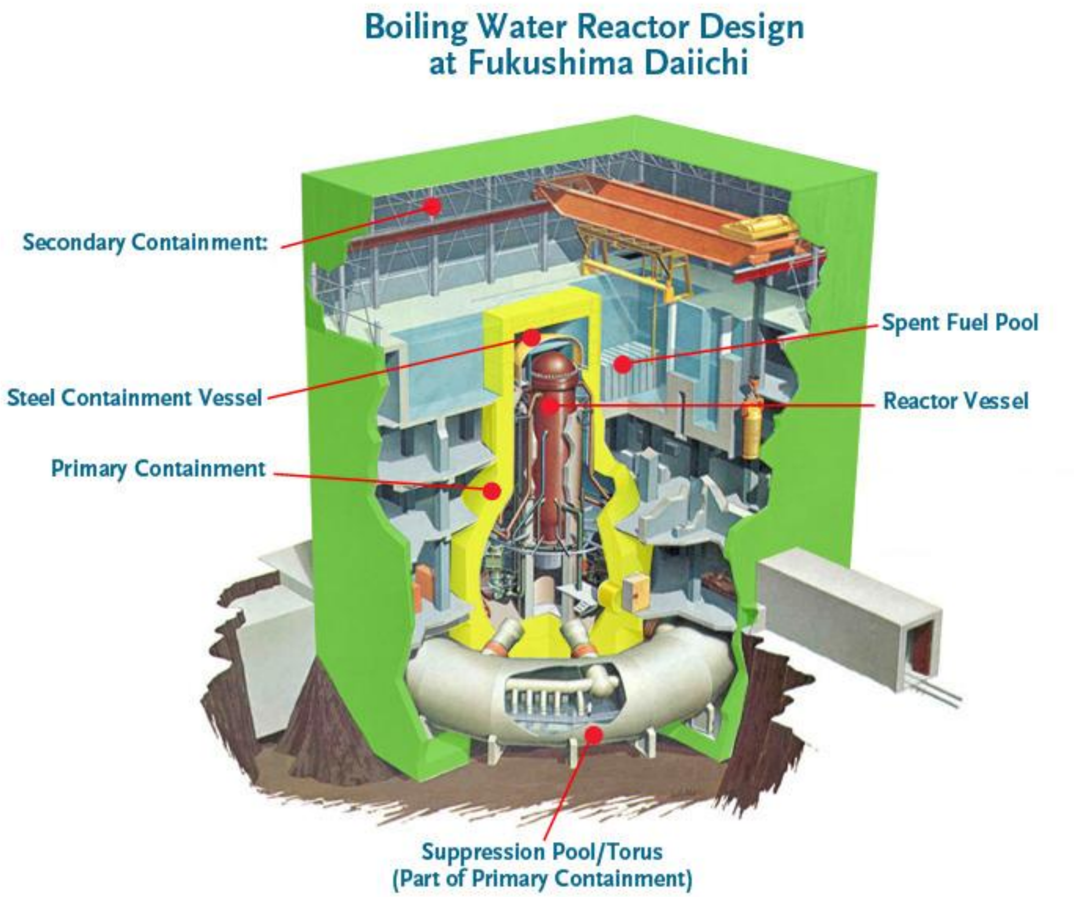


Source:
Adapted from Figure B.2 of: NRC, 1979.

Figure 6-4
February 2012 View of Spent Fuel in the Unit 4 Pool at Fukushima #1

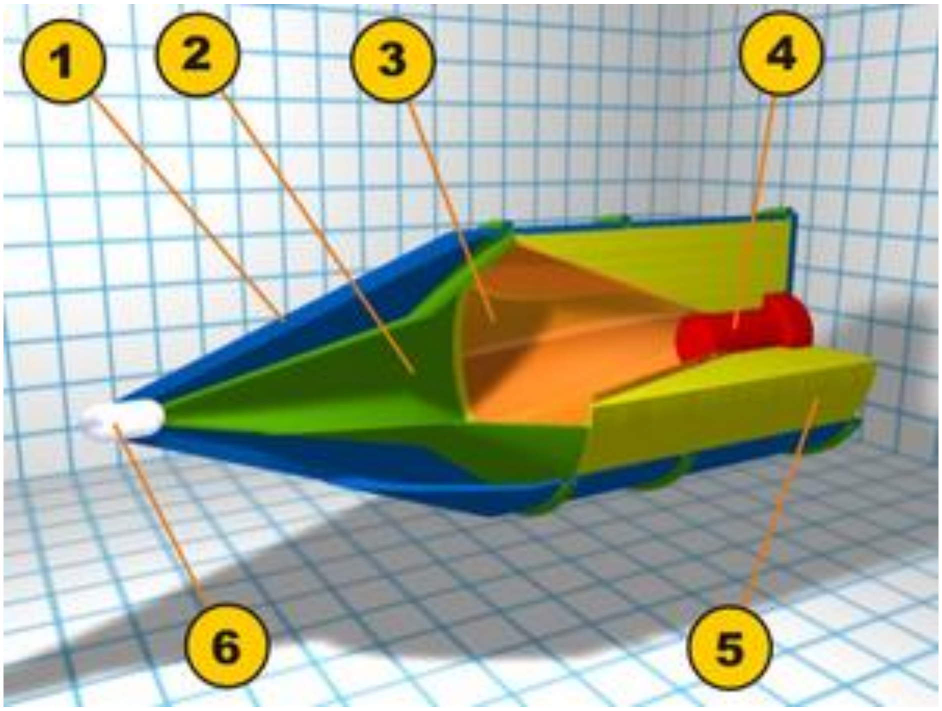
Notes:
(a) This figure is from: Asahi Shimbun, 2012.
(b) The figure is from video footage taken by TEPCO on 9 February 2012
(c) The storage configuration shown here is a high-density, closed-frame rack.
(d) A variety of debris, such as that shown in the figure, is distributed across the pool.

Figure 6-5
Schematic View of a BWR Reactor with a Mark I Containment, as Used at the Fukushima #1 Site and Elsewhere



Notes:
(a) This figure accessed on 24 February 2012 from:
http://safetyfirst.nei.org/japan/background-on-fukushima-situation/
(b) All BWR reactors with Mark I containments have the same basic configuration. Details vary for specific reactors.

Figure 6-6
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:

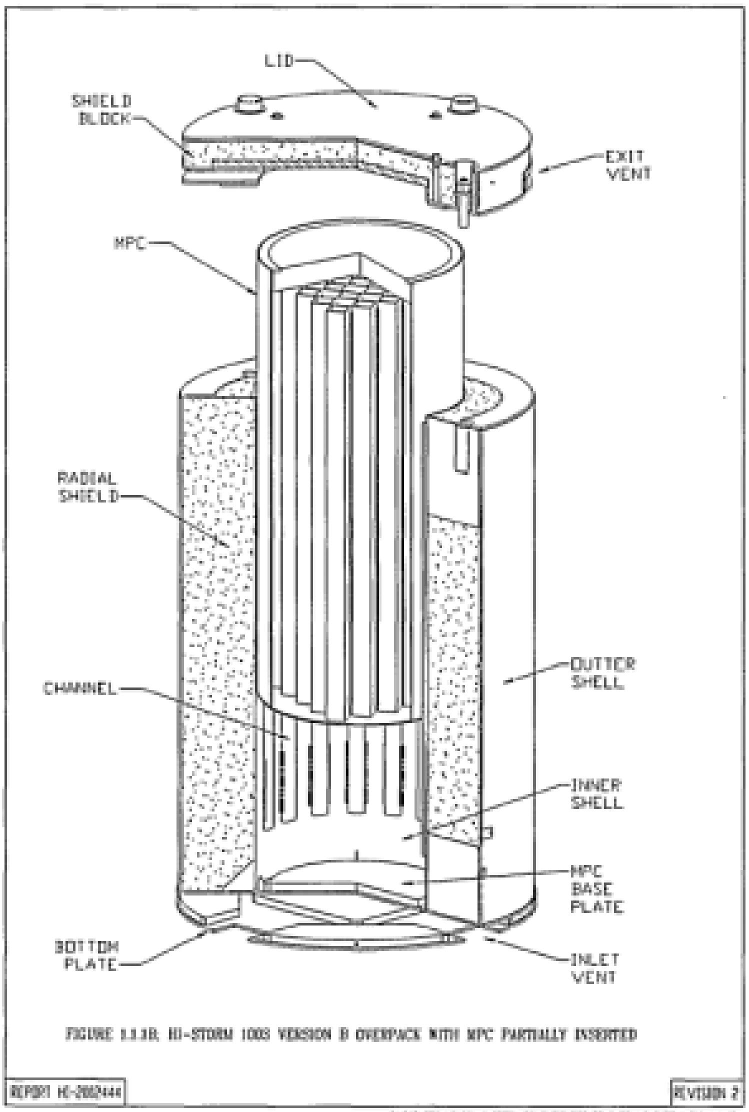
Item 1: Aerodynamic cover
Item 2: Empty cavity
Item 3: Conical liner (typically made of ductile metal)
Item 4: Detonator
Item 5: Explosive
Item 6: Piezo-electric trigger

(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 6-7
MISTEL System for Aircraft Delivery of a Shaped Charge, World War II

Notes:
(a) Photo 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 6-8
Schematic View of Dry Cask for Storing PWR or BWR Spent Fuel (Holtec HI-STORM 100 Cask System)



Source:
Accessed on 28 February 2012 from: http://www.nrc.gov/reading-rm/sensitive-info/faq.html