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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

by
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6 February 2009

Prepared under the sponsorship of
Texans for a Sound Energy Policy

Abstract

The US Nuclear Regulatory Commission (NRC) issued its Waste Confidence Decision in 1984, expressing NRC's confidence that radioactive waste from commercial nuclear reactors would be safely stored and ultimately disposed of in a safe manner. The 1984 Decision was reaffirmed and revised in 1990. In October 2008, NRC issued a Draft Update to its Waste Confidence Decision. At the same time, NRC issued a Proposed Rule, confirming a previous, generic determination by NRC that interim storage of spent nuclear fuel (SNF) has no significant environmental impact, and relaxing the time limit for application of that determination.

This report provides a critical review of the findings in the Waste Confidence Decision, as modified by the Draft Update, insofar as those findings relate to the environmental impacts of interim storage of SNF or high-level radioactive waste (HLW) originating in commercial reactors. Also, this report provides a critical review of the Proposed Rule. To support its critical review of the Waste Confidence Decision and the Proposed Rule, this report provides a general summary of selected, adverse impacts on the environment that can arise from interim storage of SNF and HLW.

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Acknowledgements

This report was prepared by IRSS under the sponsorship of Texans for a Sound Energy Policy, an organization based in Victoria, Texas. Diane Curran assisted the author by obtaining information that was used during preparation of the report. The author, Gordon R. Thompson, is solely responsible for the content of the report.

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1. Introduction

In October 2008, the US Nuclear Regulatory Commission (NRC) issued a set of proposed findings that address, among other matters, the interim storage of radioactive waste generated by commercial nuclear reactors. This report provides a critical review of the proposed findings, insofar as those findings relate to the environmental impacts of storing radioactive waste.

An overview of radioactive waste from commercial reactors

Commercial nuclear reactors periodically discharge nuclear fuel assemblies that are "spent", in the sense that they are no longer suitable for generating power from nuclear fission. Each spent nuclear fuel (SNF) assembly contains a large amount of radioactive material, and the decay of that material generates heat. Release of radioactive material from an assembly to the environment could cause significant adverse impacts on exposed persons.

With some minor exceptions, spent fuel discharged from US commercial reactors is now being stored at the reactor sites. Initially, a spent fuel assembly is stored under water in a pool adjacent to the reactor. After some years of storage in this pool, an assembly could be transferred to an on-site, dry-storage facility known as an independent spent fuel storage installation (ISFSI). In the future, assemblies might also be shipped to ISFSIs built at off-site locations.[1]

Current national policy for managing SNF is to store spent fuel assemblies for an interim period, followed by their disposal in a mined, underground repository. The US Department of Energy (DOE) has applied to NRC for a license to operate such a repository at Yucca Mountain, Nevada. Many observers doubt that this repository will open.

As a separate initiative, DOE has established the Global Nuclear Energy Partnership (GNEP) program. That program is pursuing the development of alternative nuclear fuel cycles that would involve the physical and chemical processing of SNF to separate its components (plutonium, uranium, fission products, etc.). The separation processes would generate radioactive waste streams including streams of high-level radioactive waste (HLW).

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[1] As an alternative, spent fuel assemblies generated at several reactor sites might be stored in an ISFSI located at one reactor site.

NRC findings regarding management of SNF and HLW

In 1984, NRC issued its Waste Confidence Decision, expressing NRC's confidence that radioactive waste from commercial nuclear reactors would be safely stored and ultimately disposed of in a safe manner. The 1984 Decision was reaffirmed and revised in 1990. In October 2008, NRC issued, for public comment, a draft Update to its Waste Confidence Decision.[2] Hereafter, that document is referred to as the "Draft Update". In parallel, NRC issued a proposed rule regarding consideration of the environmental impacts of temporary storage of spent fuel.[3] That document is referred to, hereafter, as the "Proposed Rule". The Proposed Rule provides a generic determination that interim storage of spent fuel has no significant environmental impact.

Table 1-1 shows the five findings set forth in the 1990 version of the Waste Confidence Decision, together with the modification of two of those findings that is proposed in the Draft Update. It is interesting to compare these two versions of the findings with each other and with the original findings, issued in 1984. Notably, Finding 2 stated in 1984 that a repository would – with "reasonable assurance" – be available by 2007-2009. In 1990, that date was extended to 2025 (within the first quarter of the 21st century), and NRC now proposes to further extend that date to 2049-2059 (50-60 years after expiration of the Dresden 1 operating license).[4] This progression invites skepticism about NRC's "reasonable assurance".[5]

The Proposed Rule proposes a revision of the NRC regulations set forth in 10 CFR Part 51. With the proposed revision, paragraph (a) of section 51.23 would read:[6]

> "**51.23 Temporary storage of spent fuel after cessation of reactor operation – generic determination of no significant environmental impact.**
>
> (a) The Commission has made a generic determination that, if necessary, spent fuel generated in any reactor can be stored safely and without significant environmental impacts beyond the licensed life for operation (which may include the term of a revised or renewed license) of that reactor at its spent fuel storage basin or at either onsite or offsite independent spent fuel storage installations until a disposal facility can reasonably be expected to be available."

The principal difference between this language and the previous language, established in 1990, is the relaxation of the time limit for application of paragraph 51.23 (a). In the

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[2] NRC, 2008a.

[3] NRC, 2008b.

[4] NRC, 2008a.

[5] NRC's estimated time horizon for repository availability has receded with each revision of its Waste Confidence Decision, beginning at 23-25 years in 1984, then receding to 35 years in 1990, and to 41-51 years in 2008.

[6] NRC, 2008b.

1990 version, there was a time limit – at least 30 years beyond a reactor's licensed life for operation.[7] The revised version contains no specific time limit for its application.

Purposes of this report

This report provides a critical review of the findings in the Waste Confidence Decision, as modified by the Draft Update, insofar as those findings relate to the environmental impacts of interim storage of SNF or HLW originating in commercial reactors. Thus, the focus here is on Findings 3, 4 and 5, as shown in Table 1-1.[8] Also, this report provides a critical review of the Proposed Rule.

To support its critical review of the Draft Update and the Proposed Rule, this report provides a general summary of selected, adverse impacts on the environment that can arise from interim storage of SNF and HLW. This summary could be useful outside the context of the Draft Update and the Proposed Rule.

Categories of environmental impacts

Two categories of adverse impacts on the environment are examined here. The first category consists of the risk of radiological harm arising from unplanned releases of radioactive material. The second category consists of adverse impacts, including social and economic impacts, that could arise from deficiencies in NRC's approach to regulating the storage of SNF and HLW.

In examining the risk of radiological harm, this report considers the potential for unplanned releases of radioactive material to the environment, especially to the atmosphere.[9] The primary focus here is on unplanned releases from spent fuel. The affected fuel could be stored in a pool adjacent to a commercial reactor, or in an ISFSI located at a reactor site or elsewhere. This report also provides a brief, limited discussion of unplanned releases from reactors. That discussion relates to potential associations and interactions between spent-fuel releases and reactor releases. Unplanned releases, as discussed in this report, are distinct from the comparatively small, planned releases that occur during operation of a nuclear power plant or a spent-fuel storage facility.

In this report, the term "risk" – used here in the context of radiological harm – encompasses the type and scale of potential adverse outcomes together with the probabilities of occurrence of those outcomes.[10] The radiological harm could be direct,

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[7] NRC, 2008b.

[8] This author has published, in other contexts, writings that relate to Findings 1 and 2. See, for example: Thompson, 2008a.

[9] Unplanned releases to ground or surface water could also yield significant adverse impacts. The spatial extent of significant impacts is likely to be greatest for atmospheric releases.

[10] Some analysts define "risk" as the arithmetic product of two quantitative indicators: a consequence indicator; and a probability indicator. That definition is simplistic and can be misleading, and is not used in

as measured by outcomes such as the number of radiation-induced human illnesses. Alternatively, the radiological harm could be indirect, in the form of social and economic impacts that arise from the direct harm.

Unplanned releases of radioactive material

Unplanned releases of radioactive material from a spent-fuel storage facility or a reactor could arise as a result of two types of accident. The term "conventional accidents" is used here to refer to incidents caused by human error, equipment failure or natural events.[11] By contrast, "malice-induced accidents" are incidents caused by deliberate, malicious actions. The parties taking those malicious actions could be national governments or sub-national groups.[12] In considering malicious actions, this report focuses on actions by sub-national groups.

Adverse impacts arising from regulatory deficiencies

As mentioned above, the second category of adverse, environmental impacts examined in this report consists of impacts, including social and economic impacts, that could arise from deficiencies in NRC's approach to regulating the storage of SNF and HLW. One factor to be examined in this context is NRC's refusal to perform any environmental impact statement (EIS) that addresses the risk of malice-induced accidents at a nuclear facility. A second factor is NRC's heavy reliance on secrecy as a protective measure, without acknowledgment that secrecy can be counterproductive, and can have adverse impacts on society and the economy. A third factor is the role of "protective deterrence" in the defense and security of the USA, and the potential to enhance protective deterrence by implementing protective measures of the type called for in the National Infrastructure Protection Plan (NIPP).

Protection of sensitive information

In examining the radiological risk associated with malice-induced accidents, this report necessarily discusses the potential for a deliberate attack on a nuclear power plant or an ISFSI. Any responsible analyst who discusses the potential for such an attack is careful about making statements in public settings. The author of this report exercises such care. The author has no access to classified information, and this report contains no such

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this report. That definition is especially inappropriate for risks associated with malicious actions, because there is usually no statistical basis to support quantitative estimates of the probabilities of such actions. In this report, the risk of an activity is defined as a set of quantitative and qualitative information that describes the potential adverse outcomes from the activity and the probabilities of occurrence of those outcomes.

[11] NRC's Glossary, accessed at the NRC web site (www.nrc.gov) on 23 January 2009, contains no definition of "accident". The terms "conventional accident" and "malice-induced accident" are used in this report. Both types of accident can be foreseen, and a licensee should be able to maintain control of a facility if either type of accident occurs.

[12] Relevant sub-national groups could be based in the USA or in other countries.

information. However, a higher standard of discretion is necessary. An analyst should not publish sensitive information, defined here as detailed information that could substantially assist an attacking group to attain its objectives, even if this information is publicly available from other sources. On the other hand, if a facility's design and operation leave the facility vulnerable to attack, and the vulnerability is not being addressed appropriately, then a responsible analyst is obliged to publicly describe the vulnerability in general terms.

This report exemplifies the balance of responsibility described in the preceding paragraph. Vulnerabilities of nuclear facilities are described here in general terms. Detailed information relating to those vulnerabilities is withheld here, although that information has been published elsewhere or could be re-created by many persons with technical education and/or military experience. For example, this report does not provide cross-section drawings of nuclear facilities, although such drawings have been published for many years and are archived around the world.

NRC license proceedings provide potential forums at which sensitive information could be discussed without concern about disclosure to potential attackers. Rules and practices are available so that the parties to a license proceeding could discuss sensitive information in a protected setting.

Structure of this report

The remainder of this report has eleven sections. Sections 2 through 10 are as listed in the table of contents. Conclusions are set forth in Section 11, and a bibliography is provided in Section 12. All documents cited in the text and tables of this report are listed in the bibliography, unless the full citation is provided directly in a footnote. Tables are provided at the end of the report.

2. Radioactive Waste from Commercial Reactors: History & Likely Future Trends

During normal operation of a commercial nuclear reactor, the reactor periodically discharges spent fuel assemblies. Also, the reactor releases a comparatively small amount of radioactive material to the environment, and generates a stream of packaged, low-level, radioactive waste. Decommissioning of the reactor generates an additional stream of radioactive waste, including wastes that are not suitable for disposal as low-level waste. Here, our focus is on spent fuel, and on HLW that may be generated by processing spent fuel.

The early assumption of reprocessing

When the commercial reactors now operating in the USA were designed, the designers assumed that spent fuel would be stored at each reactor for only a few years.[13] After that storage period, each spent fuel assembly would be transported to a "reprocessing" plant where it would be separated into its components (plutonium, uranium, fission products, etc.) through physical and chemical processes. Most of the radioactive material in the assemblies would emerge from the reprocessing plant as a stream of HLW, packaged in a solid form such as borosilicate glass in a stainless steel canister.

Reprocessing fell out of favor and was banned by President Carter in 1977.[14] Although the ban was subsequently lifted, reprocessing has not resumed. The current national policy for managing spent fuel is to store the fuel for an interim period (measured in decades), with eventual disposal of the fuel in a mined repository. The GNEP program envisions a change in that policy, as discussed below.

When a spent fuel assembly is discharged from a reactor, it is placed in a water-filled pool adjacent to the reactor. Given the expectation of reprocessing, the pools at the present generation of US reactors were originally designed so that each held only a small inventory of spent fuel. Low-density, open-frame storage racks were used.[15] Cooling fluid can circulate freely through such a rack.

Use of high-density racks in spent-fuel pools

After reprocessing was abandoned in the 1970s, spent fuel began to accumulate in the pools. Excess spent fuel could have been offloaded to other storage facilities, allowing continued use of low-density racks. Instead, as a cost-saving measure, high-density racks were introduced, allowing much larger amounts of spent fuel to be stored in the pools. The high-density racks have a closed-form configuration in which each fuel assembly is surrounded by neutron-absorbing plates, to suppress criticality.[16] That configuration creates the potential for auto-ignition and propagating combustion of the fuel's zirconium cladding if water were lost from the pool.[17] The resulting event can be termed a "pool fire". To date, no such event has occurred.

As shown later in this report, NRC has never properly assessed either the risk of a pool fire or the opportunities to reduce that risk. Instead, NRC has enabled and encouraged the use of high-density racks in spent-fuel pools. Such racks are now used at all

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[13] NRC, 1979.
[14] The ban reflected a widely shared view that reprocessing is uneconomic and promotes the proliferation of nuclear weapons.
[15] NRC, 1979.
[16] NRC, 1979.
[17] Alvarez et al, 2003.

commercial reactors in the USA. Licensees have naturally preferred to use high-density racks, because this is the cheapest option for storing spent fuel.

The national inventory of spent fuel, and its management

The quantity of spent fuel is often measured in terms of metric tons of heavy metal (MTHM), based on the fresh (pre-irradiation) form of the fuel. The same indicator can be used for HLW, by tracing the HLW back to the fresh fuel from which it originated.

As of early 2008, about 57,000 MTHM of commercial spent fuel was in storage across the USA, in 35 states. This stock of fuel is growing at the rate of about 2,000 MTHM annually.[18] The majority of this stock of fuel is stored in pools at operating reactors.[19] As mentioned above, those pools are equipped with high-density racks. The remainder of the fuel is stored in ISFSIs. There are 49 licensed ISFSIs across the USA, of which 45 are at reactor sites.[20] At some of those reactor sites, decommissioning activities have removed the reactor, leaving an ISFSI as the remaining major facility on the site.

ISFSIs were first established in the 1980s, and the number of ISFSIs began to grow rapidly in the mid-1990s.[21] This growth reflects the fact that spent-fuel pools are reaching their maximum capacity of spent fuel. When a pool approaches that point, and the licensee wishes to continue operating the reactor, older fuel in the pool is offloaded to an ISFSI to make room for fuel newly discharged from the reactor.[22] The offloading occurs on a batch basis, reflecting the use of modular storage at ISFSIs. Storage modules are filled one at a time, and then installed at the ISFSI.

According to NRC, all pools across the USA will be packed at full capacity by 2015.[23] From that point forward, growth in the national inventory of spent fuel from existing reactors will be accommodated entirely in ISFSIs, until a repository is opened.

When a reactor reaches the end of its operating life, storage of spent fuel in the associated pool will continue for some time thereafter. However, dry storage in an ISFSI will be a cheaper option for long-term storage. Thus, ongoing pool storage at permanently shut-down reactors will be comparatively rare.

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[18] NRC, 2008c.

[19] The NRC does not publish spent-fuel inventory data broken down by reactor, site or storage mode. Other sources show that the majority of the inventory is now in pools at operating reactors. See, for example: Alvarez et al, 2003.

[20] One ISFSI license is for an away-from-reactor site in Utah. Actual establishment of that ISFSI appears unlikely.

[21] NRC, 2008c.

[22] The older fuel is appropriate for transfer to an ISFSI because it produces less heat from radioactive decay than is produced by newly-discharged fuel.

[23] Figure, "Nuclear Fuel Pool Capacity", accessed at the NRC web site (www.nrc.gov) on 27 January 2009.

To summarize, NRC has enabled and encouraged the development of a de facto, national strategy for storing spent fuel from commercial reactors. Major elements of the strategy are: (i) storage of spent fuel, after discharge from a reactor, in a pool equipped with high-density racks; (ii) placement of the pool in close proximity to the reactor, with sharing of systems; (iii) accumulation of spent fuel in the pool until the pool is packed nearly to full capacity, followed by periodic offloading of older fuel from the pool to an on-site ISFSI in order to make room for newly-discharged fuel; and (iv) after permanent shut-down of the reactor, transfer of the remaining fuel from the pool to the ISFSI.

Future trends in reactor operation and spent-fuel storage

At present, 104 commercial reactors are licensed for operation in the US. Each of these reactors was licensed for an initial 40-year period, and many have received 20-year license extensions. A number of reactors with license extensions are now licensed for operation into the 2040s, one of them (Nine Mile Point 2) being licensed to operate until 2046. If reactors that were commissioned more recently receive 20-year license extensions, which seems likely, they will be licensed into the 2050s. Watts Bar 1 would be licensed until 2055.[24]

Thus, if the present practice of high-density pool storage continues, we can expect that existing reactors will operate in close proximity to pools, packed with spent fuel at high density to nearly their full capacity, for future periods as long as 46 years. That conclusion has significant implications for the environmental impacts of spent-fuel storage, as discussed later in this report.

NRC is considering applications for operating licenses for new commercial reactors. Some people see those applications as the beginning of a "renaissance" of nuclear power. The accuracy of that perception will become clear over time. For the purpose of examining potential impacts on the environment, one can assume that a number of new reactors will enter service. A member of the initial cohort of reactors might begin commercial operation in, for example, 2020. Assuming a 60-year operating life, that reactor would shut down in 2080.

NRC has taken no action to encourage or require a spent-fuel storage strategy for new reactors that differs from the strategy now being implemented for existing reactors. Thus, for the purpose of examining potential environmental impacts, one can assume a continuation of the present strategy. Indeed, it appears that reactor vendors, license applicants and the NRC have all assumed, without any evident analysis or debate, that the present spent-fuel storage strategy will continue.

If new reactors employed spent-fuel pools similar in size to the pools at existing reactors, then a typical new pool would become packed to near its capacity in the middle of a

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[24] NRC, 2008c.

reactor's 60-year operating life. Thus, if a reactor entered service in 2020, its pool would become packed to near its capacity around 2050, and would remain packed at that level until the reactor ceased operating in 2080. Given such an outcome, a cohort of new reactors would yield large, densely-packed inventories of spent fuel in their adjacent pools during the time period when existing reactors with similar spent-fuel inventories are shutting down. In that manner, new reactors would prolong the present strategy of spent fuel storage, and its environmental impacts, into the late 21st century and potentially beyond.

The Global Nuclear Energy Partnership

The US government is pursuing, through the GNEP program at DOE, the development of "alternative" nuclear fuel cycles.[25] Current national policy is to operate a "once-through" fuel cycle in which spent fuel is stored and eventually disposed of in a radioactive waste repository. One of the explicit purposes of the GNEP program is to develop fuel-cycle options that would require less repository capacity than would be required for a once-through fuel cycle producing the same amount of electrical energy. Thus, the GNEP program is relevant to NRC's Waste Confidence Decision.

Each of the GNEP fuel cycles would involve the processing of spent fuel in facilities that would produce streams of HLW. The HLW waste forms would require storage prior to their placement in a repository. The storage period could be long. For example, some fuel cycles would involve the separation of cesium and strontium isotopes from the other constituents of spent fuel. The cesium and strontium isotopes would be incorporated into some type of liquid or solid HLW waste form that would be stored for about 300 years.[26]

Separation of cesium and strontium isotopes for extended storage would be done to reduce the need for repository capacity. Over 300 years of storage, radioactive decay would substantially reduce the inventory of these isotopes, and their heat output would decline accordingly.[27] From a purely technical perspective, the construction and operation of a repository would become easier and cheaper if that approach were adopted. However, the approach raises important questions about the risk of prolonged storage and the inter-generational equity of deferred disposal.

According to DOE, the transition to an alternative fuel cycle could begin as soon as 10-15 years in the future.[28] Yet, NRC's Draft Update and Proposed Rule are silent regarding the implications of the GNEP program.

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[25] DOE, 2008.

[26] DOE, 2008.

[27] Cesium-137 has a half-life of 30 years. Over 300 years, the inventory of this isotope would decline by a factor of about 1,000.

[28] DOE, 2008.

3. Radioactive Inventories at Spent-Fuel Storage Facilities

The inventories of radioactive material at spent-fuel storage facilities are illustrated here by considering the Indian Point site as a representative site. At that site, the Indian Point 2 (IP2) and Indian Point 3 (IP3) commercial reactors remain operational, and the Indian Point 1 (IP1) reactor is permanently shut down. The IP2 and IP3 reactors are pressurized-water reactors (PWRs). An ISFSI has been established on the site.

All but a small fraction of the site's inventory of radioactive material is contained within fuel assemblies at six facilities: the IP2 and IP3 reactors; the IP1, IP2 and IP3 spent-fuel pools; and the ISFSI. The IP1 pool is not discussed here.

Active or spent fuel assemblies contain a variety of radioactive isotopes.[29] One isotope, namely cesium-137, is especially useful as an indicator of the potential for radiological harm. Cesium-137 is a radioactive isotope with a half-life of 30 years. This isotope accounts for most of the offsite radiation exposure that is attributable to the 1986 Chernobyl reactor accident, and for about half of the radiation exposure that is attributable to fallout from the testing of nuclear weapons in the atmosphere.[30] Cesium is a volatile element that would be liberally released during conventional accidents or attack scenarios that involve overheating of nuclear fuel.

Table 3-1 shows estimated amounts of cesium-137 in nuclear fuel in the IP2 and IP3 reactors and spent-fuel pools, and in one of the spent-fuel storage modules of the Indian Point ISFSI. Table 3-2 compares these amounts with atmospheric releases of cesium-137 from detonation of a 10-kilotonne fission weapon, the Chernobyl reactor accident of 1986, and atmospheric testing of nuclear weapons. These data show that release of a substantial fraction of the cesium-137 in an Indian Point nuclear facility would create comparatively large radiological consequences.

In the IP2 and IP3 spent-fuel pools, as at commercial reactors across the USA, spent fuel is stored in high-density racks. This configuration has significant implications for risk because loss of water from such a pool would, over a wide range of scenarios, lead to spontaneous ignition of the hottest spent fuel and a fire that would spread across the pool. That fire would release to the atmosphere a substantial fraction of the pool's inventory of cesium-137, together with other radioactive isotopes. The potential for this event is discussed further in Section 5, below.

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[29] In an operating reactor, an active fuel assembly contains radioactive isotopes with half-lives ranging from seconds to millennia. After the reactor is shut down or a fuel assembly becomes spent (i.e., it is discharged from the reactor), the assembly's inventory of each isotope declines at a rate determined by the isotope's half-life. Thus, an atmospheric release from an operating reactor would contain short- and longer-lived isotopes, while a release from a spent-fuel-storage facility would contain only longer-lived isotopes. That difference has implications for the emergency response that would be appropriate for each release.

[30] DOE, 1987.

4. An Overview of Radiological Risk

As explained in Section 1, above, two categories of adverse impacts on the environment are examined in this report. The first category consists of the risk of radiological harm arising from unplanned releases of radioactive material. The radiological harm could be direct, as measured by outcomes such as the number of radiation-induced human illnesses. Alternatively, the radiological harm could be indirect, in the form of social and economic impacts that arise from the direct harm.

In considering the potential for unplanned releases, this report focuses on atmospheric releases. Such a release could cause radiological consequences at the site where the release occurs and at downwind, offsite locations. The released material would travel in a plume of gases and small particles. The particles would settle on the ground and other surfaces at downwind locations, and would then be re-distributed by rain, wind, etc. Humans could be irradiated through various pathways including inhalation, external exposure, and ingestion of contaminated food and water. Types of radiological consequences could include:

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

An unplanned atmospheric release could arise as a result of a conventional accident or a malice-induced accident. The potential for a conventional accident can be examined using the techniques of probabilistic risk assessment (PRA). In the PRA field, accident-initiating events are typically categorized as "internal" events (human error, equipment failure, etc.) or "external" events (earthquakes, fires, strong winds, etc.). A malice-induced accident would involve a deliberate attack. Such an attack could be mounted by a variety of actors, in a variety of ways, for various motives. The potential for an attack is discussed further in Section 7, below. That discussion shows how PRA techniques can be adapted to examine the risks of malice-induced accidents.

Development of PRA capability

From the earliest years of the nuclear-technology era, analysis and experience have shown that a nuclear reactor can undergo an accident in which the reactor's fuel is damaged. This damage can lead to a release of radioactive material within the reactor and, potentially, from the reactor to the external environment. An early illustration of this accident potential occurred in the UK in 1957, when an air-cooled reactor at

Windscale caught fire and released radioactive material to the atmosphere. At that time, spent fuel was not perceived as a significant hazard.

When the basic designs of the existing fleet of commercial reactors were being established in the 1960s, there was limited technical understanding of the potential for severe accidents at reactors. In this context, "severe" means that the reactor core is severely damaged, which typically involves melting of some fraction of the core materials. Analysts in the PRA field typically refer to such an event as a "core-damage" accident. Knowledge about the potential for core-damage accidents was substantially improved by completion of the Reactor Safety Study (WASH-1400) in 1975.[31] That study, although deficient in various respects, established the basic principles for a reactor PRA. More knowledge has accumulated from analysis and experience since 1975.[32]

The "high point" of PRA practice was reached in 1990 with publication by NRC of its NUREG-1150 study, which examined five different US reactors using a common methodology.[33] The study was well funded, involved many experts, was conducted in an open and transparent manner, was done at Level 3 (i.e., radiological consequences were estimated), considered internal and external initiating events, explicitly propagated uncertainty through its chain of analysis, was subjected to peer review, and left behind a large body of published documentation. Each of those features is necessary if the findings of a PRA are to be credible. There are deficiencies in the NUREG-1150 findings, which can be corrected by fresh analysis and the use of new information. The process of correction is possible because the NUREG-1150 study was conducted openly and left a documentary record.

PRA practice in the USA has degenerated since the NUREG-1150 study. Now, PRAs are conducted by the nuclear industry, and the only published documentation is a summary statement of findings. NRC formerly sponsored independent reviews of industry PRAs, but no longer does so. Thus, PRA findings have lacked credibility for at least a decade. An illustration of the degeneration of PRA practice was the disclosure, during a July 2008 hearing before the NRC Commissioners, that the NRC Staff lacks an in-house capability to use the MACCS computer code.[34] That code is used to assess the radiological consequences of an atmospheric release of radioactive material.

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[31] NRC, 1975.

[32] Relevant experience includes the Three Mile Island reactor accident of 1979 and the Chernobyl reactor accident of 1986.

[33] NRC, 1990b.

[34] NRC, 2008e.

5. Potential for a Fire in a Spent-Fuel Pool

5.1 Recognition of the Spent-Fuel Hazard

Until 1979 it was widely assumed that stored spent fuel did not pose risks comparable to those associated with reactors. This assumption arose because a spent fuel assembly does not contain short-lived radioactivity, and therefore produces less radioactive decay heat than does a similar fuel assembly in an operating reactor. However, that factor was counteracted by the introduction of high-density, closed-form storage racks into spent-fuel pools, beginning in the 1970s.

The potential for a pool fire

Unfortunately, the closed-form configuration of the high-density racks would create a major problem if water were lost from a spent-fuel pool. The flow of air through the racks would be highly constrained, and would be almost completely cut off if residual water or debris were present in the base of the pool. As a result, removal of radioactive decay heat would be ineffective. Over a broad range of water-loss scenarios, the temperature of the zirconium fuel cladding would rise to the point (approximately 1,000 degrees C) where a self-sustaining, exothermic reaction of zirconium with air or steam would begin. Fuel discharged from the reactor for 1 month could ignite in less than 2 hours, and fuel discharged for 3 months could ignite in about 3 hours.[35] Once initiated, the fire would spread to adjacent fuel assemblies, and could ultimately involve all fuel in the pool. A large, atmospheric release of radioactive material would occur. For simplicity, this potential disaster can be described as a "pool fire".

Water could be lost from a spent-fuel pool through leakage, boiling, siphoning, pumping, displacement by objects falling into the pool, or overturning of the pool. These modes of water loss could arise from events, alone or in combination, that include: (i) acts of malice by persons within or outside the plant boundary; (ii) an aircraft impact; (iii) an earthquake; (iv) dropping of a fuel cask; (v) accidental fires or explosions; and (vi) a severe accident at an adjacent reactor that, through the spread of radioactive material and other influences, precludes the ongoing provision of cooling and/or water makeup to the pool.

These events have differing probabilities of occurrence. None of them is an everyday event. Nevertheless, they are similar to events that are now routinely considered in planning and policy decisions related to commercial nuclear reactors. To date, however, such events have not been given the same attention in the context of spent-fuel pools.

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[35] This sentence assumes adiabatic conditions.

Some people have found it counter-intuitive that spent fuel, given its comparatively low decay heat and its storage under water, could pose a fire hazard. This perception has slowed recognition of the hazard. In this context, a simple analogy may be helpful. We all understand that a wooden house can stand safely for many years but be turned into an inferno by a match applied in an appropriate location. A spent-fuel pool equipped with high-density racks is roughly analogous, but in this case ignition would be accomplished by draining water from the pool. In both cases, a triggering event would unleash a large amount of latent chemical energy.

The sequence of studies related to pool fires

Two studies completed in March 1979 independently identified the potential for a fire in a drained spent-fuel pool equipped with high-density racks. One study was by members of a scientific panel assembled by the German state government of Lower Saxony to review a proposal for a nuclear fuel cycle center at Gorleben.[36] After a public hearing, 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. The second study was done by Sandia Laboratories for NRC.[37] 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 context. Unfortunately, NRC continued, until October 2000, to employ the erroneous assumption that complete drainage is the most severe case.

NRC has published various documents that discuss aspects of the potential for a spent-fuel-pool fire. Several of these documents are discussed below. Only three of the various documents are products of processes that provided an opportunity for formally structured public comment and, potentially, for in-depth analysis of risks and alternatives. One such document is the August 1979 generic environmental impact statement (GEIS) on handling and storage of spent fuel (NUREG-0575).[38] The second document is the May 1996 GEIS on license renewal for nuclear power plants (NUREG-1437).[39] These two documents purported to provide systematic analysis of the risks and relative costs and benefits of alternative options. The third document is NRC's September 1990 review (55 FR 38474) of its Waste Confidence Decision.[40] That document did not purport to provide an analysis of risks and alternatives.

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[36] Thompson et al, 1979.
[37] Benjamin et al, 1979.
[38] NRC, 1979.
[39] NRC, 1996.
[40] NRC, 1990a.

NUREG-0575 addresses the potential for a spent-fuel-pool fire in a single sentence that cites the 1979 Sandia report. The sentence reads:[41]

> "Assuming that the spent fuel stored at an independent spent fuel storage installation is at least one year old, calculations have been performed to show that loss of water should not result in fuel failure due to high temperatures if proper rack design is employed."

Although this sentence refers to pool storage of spent fuel at an independent spent fuel storage installation, NUREG-0575 regards at-reactor pool storage as having the same properties. This sentence misrepresents the findings of the Sandia report. The sentence does not define "proper rack design". It does not disclose Sandia's findings that high-density racks promote overheating of exposed fuel, and that overheating can cause fuel to self-ignite and burn. NRC has never corrected this deficiency in NUREG-0575.

NUREG-1437 also addresses the potential for a spent-fuel-pool fire in a single sentence, which in this instance states:[42]

> "NRC has also found that, even, under the worst probable cause of a loss of spent-fuel pool coolant (a severe seismic-generated accident causing a catastrophic failure of the pool), the likelihood of a fuel-cladding fire is highly remote (55 FR 38474)."

The parenthetic citation is to NRC's September 1990 review of its Waste Confidence Decision. Thus, NUREG-1437's examination of pool fires is totally dependent on the September 1990 review. In turn, that review bases its opinion about pool fires on the following four NRC documents:[43] (i) NUREG/CR-4982;[44] (ii) NUREG/CR-5176;[45] (iii) NUREG-1353;[46] and (iv) NUREG/CR-5281.[47] These documents are discussed in Section 5.2, below. That discussion reveals substantial deficiencies in the documents' analysis of the potential for a pool fire.

Thus, neither of the two GEISs (NUREG-0575 and NUREG-1437), nor the September 1990 review of the Waste Confidence Decision, provides a technically defensible examination of spent-fuel-pool fires and the associated risks and alternatives. The statements in each document regarding pool fires are inconsistent with the findings of subsequent, more credible studies discussed below.

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[41] NRC, 1979, page 4-21.
[42] NRC, 1996, pp 6-72 to 6-75.
[43] NRC, 1990a, page 38481.
[44] Sailor et al, 1987.
[45] Prassinos et al, 1989.
[46] Throm, 1989.
[47] Jo et al, 1989.

The most recent published NRC technical study on the potential for a pool fire is an NRC Staff study, originally released in October 2000 but formally published in February 2001, that addresses the risk of a pool fire at a nuclear power plant undergoing decommissioning.[48] This author submitted comments on the study to the NRC Commissioners in February 2001.[49] The study was in several respects an improvement on previous NRC documents that addressed pool fires. It reversed NRC's longstanding, erroneous position that total, instantaneous drainage of a pool is the most severe case of drainage. However, it did not consider acts of malice. Nor did it add significantly to the weak base of technical knowledge regarding the propagation of a fire from one fuel assembly to another. Its focus was on a plant undergoing decommissioning. Therefore, it did not address potential interactions between pools and operating reactors, such as the interactions discussed in Section 5.3, below.

In 2003, eight authors, including the present author, published a paper on the risks of spent-fuel-pool fires and the options for reducing these risks.[50] That paper aroused vigorous comment, and its findings were disputed by NRC officials and others. Critical comment was also directed to a related report by this author.[51] In an effort to resolve this controversy, the US Congress requested the National Academy of Sciences (NAS) to conduct a study on the safety and security of spent-fuel storage. NAS submitted a classified report to Congress in July 2004, and released an unclassified version in April 2005.[52] Press reports described considerable tension between NAS and NRC regarding the inclusion of material in the unclassified NAS report.[53]

Since September 2001, NRC has not published any document that contains technical analysis related to the potential for a pool fire. Instead, NRC has issued statements claiming that the risk of a pool fire has been limited by secret studies and secret actions.

NRC concedes, in the Draft Update and elsewhere, that a fire could spontaneously break out in a spent-fuel pool following a loss of water. NRC also concedes that radioactive material released to the atmosphere during a pool fire would have significant, adverse impacts on the environment. To offset those concessions, NRC argues that the probability of a pool fire is very low. NRC attributes the alleged low probability, in part, to unspecified, secret security measures and damage-control preparations that have been implemented at commercial reactors since September 2001. NRC further attributes the alleged low probability, in part, to unspecified, secret studies that find that a fire would not break out in certain scenarios for loss of water from a pool.[54] This approach by NRC is discussed further in Section 9, below.

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[48] Collins and Hubbard, 2001
[49] Thompson, 2001a.
[50] Alvarez et al, 2003.
[51] Thompson, 2003.
[52] NAS, 2006.
[53] Wald, 2005.
[54] NRC, 2008a; NRC, 2008d.

5.2 Technical Understanding of Pool Fires

Section 5.1, above, introduces the concept of a pool fire and describes the history of analysis of pool-fire risk. There is a body of technical literature on this risk, containing documents of varying degrees of completeness and accuracy. Current opinions about the risk vary widely, but the differences of opinion are more about the probabilities of pool-fire scenarios than about the physical characteristics of these scenarios. In turn, differing opinions about probabilities lead to differing support for risk-reducing options. This situation is captured in a comment by Allan Benjamin on a paper (Alvarez et al, 2003) by this author and seven colleagues.[55] Benjamin's comment is quoted in the unclassified NAS report as follows:[56]

> "In a nutshell, [Alvarez et al] correctly identify a problem that needs to be addressed, but they do not adequately demonstrate that the proposed solution is cost-effective or that it is optimal."

The "proposed solution" to which Benjamin refers is the re-equipment of spent-fuel pools with low-density, open-frame racks, transferring excess spent fuel to onsite dry storage. In fact, however, the [Alvarez et al] authors had not claimed to complete the level of analysis, especially site-specific analysis, that risk-reducing options should receive in an Environmental Report or EIS. These authors stated:[57]

> "Finally, all of our proposals require further detailed analysis and some would involve risk tradeoffs that also would have to be further analyzed. Ideally, these analyses could be embedded in an open process in which both analysts and policy makers can be held accountable."

The paper by Alvarez et al is consistent with current knowledge of pool-fire phenomena, including the findings set forth in the unclassified NAS report. The same cannot be said for all of the NRC documents that were cited in NRC's September 1990 review of its Waste Confidence Decision. As discussed in Section 5.1, above, four NRC documents were cited to support that review's finding regarding the risks of pool fires.[58] In turn, the May 1996 GEIS on license renewal (NUREG-1437) relied on the September 1990 review for its position on the risks of pool fires. The four NRC documents are discussed in the following paragraphs.

NUREG/CR-4982 was prepared at Brookhaven National Laboratory to provide "an assessment of the likelihood and consequences of a severe accident in a spent fuel storage

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[55] Allan Benjamin was one of the authors of: Benjamin et al, 1979.
[56] NAS, 2006, page 45.
[57] Alvarez et al, 2003, page 35.
[58] NRC, 1990a, page 38481.

pool".[59] The postulated accident involved complete, instantaneous loss of water from the pool, thereby excluding important phenomena from consideration. The Brookhaven authors employed a simplistic model to examine propagation of a fire from one fuel assembly to another. That model neglected important phenomena including slumping and burn-through of racks, slumping of fuel assemblies, and the accumulation of a debris bed at the base of the pool. Each of these neglected phenomena would promote fire propagation. The study ignored the potential for interactions between a pool fire and a reactor accident. It did not consider acts of malice. Overall, this study did not approach the completeness and quality needed to support consideration of a pool fire in an EIS.

NUREG/CR-5176 was prepared at Lawrence Livermore National Laboratory.[60] It examined the potential for earthquake-induced failure of the spent-fuel pool and the pool's support systems at the Vermont Yankee and Robinson Unit 2 plants. It also considered the effect of dropping a spent-fuel shipping cask on a pool wall. Overall, this study appears to have been a competent exercise within its stated assumptions. With appropriate updating, NUREG/CR-5176 could contribute to the larger body of analysis that would be needed to support consideration of a pool fire in an EIS.

NUREG-1353 was prepared by a member of the NRC Staff to support resolution of NRC Generic Issue 82.[61] It postulated a pool accident involving complete, instantaneous loss of water from the pool, thereby excluding important phenomena from consideration. It relied on the fire-propagation analysis of NUREG/CR-4982. As discussed above, that analysis is inadequate. In considering heat transfer from boiling water reactor (BWR) fuel after water loss, NUREG-1353 assumed that a high-density rack configuration would involve a 5-inch open space between each row of fuel assemblies. That assumption is inappropriate and non-conservative. Modern, high-density BWR racks have a center-to-center distance of about 6 inches in both directions. Thus, NUREG-1353 underestimated the potential for ignition of BWR fuel. Overall, NUREG-1353 did not approach the completeness and quality needed to support consideration of a pool fire in an EIS.

NUREG/CR-5281 was prepared at Brookhaven National Laboratory to evaluate options for reducing the risk of pool fires.[62] It took NUREG/CR-4982 as its starting point, and therefore shared the deficiencies of that study.

Clearly, these four NRC documents do not provide an adequate technical basis for an EIS that addresses the risk of pool fires. The knowledge that they do provide could be supplemented from other documents, including the unclassified NAS report, the paper by Alvarez et al, and the NRC Staff study (NUREG-1738) on pool-fire risk at a plant

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[59] Sailor et al, 1987.
[60] Prassinos et al, 1989.
[61] Throm, 1989.
[62] Jo et al, 1989.

undergoing decommissioning.[63] However, this combined body of information would be inadequate to support the preparation of an EIS. For that purpose, a comprehensive, integrated study would be required, involving analysis and experiment. The depth of investigation would be similar to that involved in preparing the NRC's December 1990 study on the risks of reactor accidents (NUREG-1150).[64]

A pool-fire "source term"

The incompleteness of the present knowledge base is evident when one needs a "source term" to estimate the radiological consequences of a pool fire. The concept of a source term encompasses the magnitude, timing and other characteristics of an atmospheric release of radioactive material. Present knowledge does not allow an accurate theoretical or empirically-based prediction of the source term for a postulated pool-fire scenario. Available information indicates that, for a broad range of scenarios, the atmospheric release fraction of cesium-137 would be between 10 and 100 percent. This report assumes a cesium-137 release fraction of about 50 percent. Table 3-1 shows that the inventory of cesium-137 in a representative pool – the IP2 or IP3 pool during the period of license extension – would be about 70 MCi. Thus, a release of 35 MCi of cesium-137 is used here to examine the consequences of a pool fire.

Secret studies by NRC

The Draft Update mentions secret studies allegedly conducted or sponsored by NRC, after September 2001, to improve technical understanding of pool fires. Aspects of those studies include "detailed and realistic analytical modeling", "extensive testing of zirconium oxidation kinetics in an air environment", and "full scale coolability and "zirc fire" testing of spent fuel assemblies".[65] If those studies were indeed carried out, and done competently, they could have yielded an improved technical understanding of pool fires. However, the Draft Update provides no citation to any document, secret or otherwise, that describes the alleged studies.

Secret studies are also mentioned in an August 2008 decision by the NRC Commissioners to deny petitions for rulemaking, filed by the Attorneys General of Massachusetts and California, regarding the environmental impacts of storing spent fuel at high density in pools.[66] In that decision, the secret studies are referred to as the "Sandia studies", because they were done at Sandia National Laboratories. The decision cites two documents that were not previously cited by NRC. One of these documents is entirely secret and the other is available in a highly redacted version.[67] The redacted

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[63] Collins and Hubbard, 2001.
[64] NRC, 1990b.
[65] NRC, 2008a, page 59565.
[66] NRC, 2008d.
[67] The two citations are provided in Footnote 6 at page 46207 of the Rulemaking Petition Decision (NRC, 2008d). Both citations are to reports prepared at Sandia National Laboratories. One report, which is

document describes theoretical analyses using the MELCOR computer code, and the other document appears, from its title, to describe similar theoretical analyses. Thus, one can reasonably conclude that neither document describes empirical investigations (e.g., "full scale coolability and "zirc fire" testing of spent fuel assemblies") as mentioned in the Draft Update. (See previous paragraph.)

To summarize, the Draft Update, issued in October 2008, mentions one set of secret studies, while the rulemaking petition decision, issued in August 2008, mentions a different set of secret studies. This inconsistency represents, at a minimum, carelessness and a lack of respect for the public.

5.3 Initiation of a Pool Fire

The initiation of a pool fire would require the loss of water from a pool, and the absence of water makeup or spray cooling of the exposed fuel during the period while it heats up to the ignition temperature. As stated above, that period would be just a few hours if fuel has been recently discharged from the reactor. After ignition, water spray would be counterproductive, because it would feed a steam-zirconium reaction.

Water could be lost from a spent-fuel pool through leakage, boiling, siphoning, pumping, displacement by objects falling into the pool, or overturning of the pool. These modes of water loss could arise from events, alone or in combination, that include: (i) acts of malice by persons within or outside the plant boundary; (ii) an accidental aircraft impact; (iii) an earthquake; (iv) dropping of a fuel cask; (v) accidental fires or explosions; and (vi) a severe accident at an adjacent reactor that, through the spread of radioactive material and other influences, precludes the ongoing provision of cooling and/or water makeup to the pool.

Given the major consequences of a pool fire, analyses should have been performed to examine pool-fire scenarios across a full range of initiating events. NRC has devoted substantial attention and resources to the examination of reactor-core-damage scenarios, through studies such as NUREG-1150.[68] Neither NRC nor the nuclear industry has conducted a comparable, comprehensive study of pool fires. In the absence of such a study, this report provides illustrative analysis of selected issues.

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entirely secret, was prepared in November 2006 and titled *Mitigation of Spent Fuel Pool Loss-of-Coolant Inventory Accidents and Extension of Reference Plant Analyses to Other Spent Fuel Pools*. It is said to be a Letter Report, implying that it is comparatively short. The other report was available from NRC's ADAMS document archive in a severely redacted version; when obtained, it was revealed to be a June 2003 draft report titled *MELCOR 1.8.5 Separate Effect Analyses of Spent Fuel Pool Assembly Accident Response*. Footnote 6 describes the latter report, illogically, as “a version of the Sandia Studies”.

[68] NRC, 1990b.

The NUREG-1353 estimate of pool-fire probability

As discussed above, the NRC document NUREG-1353 was deficient in various respects. It did, however, provide an estimate for the probability of a pool fire at a PWR plant. That estimate is 2 per million reactor-years.[69] NRC has not issued a revised estimate for that probability. Thus, it is appropriate to examine the implications of the NUREG-1353 estimate for pool-fire risk. IRSS performs such an examination, as described below. It does not follow that IRSS accepts the NUREG-1353 probability estimate as definitive.

A pool fire accompanied by a reactor accident

At a typical US nuclear power plant, the spent-fuel pool is outside but immediately adjacent to the reactor containment, and shares some essential support systems with the reactor. Thus, it is important to consider potential interactions between the pool and the reactor in the context of accidents. There could be at least three types of interaction. First, a pool fire and a core-damage accident could occur together, with a common cause. For example, a severe earthquake could cause leakage of water from the pool, while also damaging the reactor and its supporting systems to such an extent that a core-damage accident occurs. Second, the high radiation field produced by a pool fire could initiate or exacerbate an accident at the reactor by precluding the presence and functioning of operating personnel. Third, the high radiation field produced by a core-damage accident could initiate or exacerbate a pool fire, again by precluding the presence and functioning of operating personnel. Many core-damage sequences would involve the interruption of cooling to the pool, which would call for the presence of personnel to provide makeup water or spray cooling of exposed fuel.

The third type of interaction was considered in a license-amendment proceeding in regard to expansion of spent-fuel-pool capacity at the Harris nuclear power plant. There were three parties to the proceeding – the NRC Staff, Carolina Power and Light (CP&L), and Orange County. The Harris plant has one reactor and four pools. The reactor – a PWR – is in a cylindrical, domed containment building. The four pools are in a separate, adjacent building that was originally intended to serve four reactors. Only one reactor was built. Two pools were in use at high density prior to the proceeding, and the proceeding addressed the activation of the two remaining pools, also at high density.

During the proceeding, the Atomic Safety and Licensing Board (ASLB) determined that the potential for a pool fire should be considered, and ordered the three parties to analyze a single scenario for such a fire.[70] In the ASLB's postulated scenario, a severe accident at the Harris reactor would contaminate the Harris site with radioactive material to an extent that would preclude actions needed to supply cooling and makeup to the Harris pools.

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[69] Throm, 1989, Table 4.7.1.

[70] ASLB, 2000.

Thereafter, the pools would boil and dry out, and fuel within the pools would burn. Following the ALSB's order, Orange County submitted a report by this author.[71] The NRC Staff submitted an affidavit by members of the Staff.[72] CP&L – the licensee – submitted a document prepared by ERIN Engineering.[73]

Orange County's analysis found that the minimum value for the best estimate of a pool fire, for the ASLB's postulated scenario, is 1.6 per 100 thousand reactor-years. That estimate did not account for acts of malice, degraded standards of plant operation, or gross errors in design, construction or operation. The NRC Staff estimated, for the same scenario, that the probability of a pool fire is on the order of 2 per 10 million reactor-years. The ASLB accepted the Staff's estimate, thereby concluding that, for the particular configuration of the Harris plant, the postulated scenario is "remote and speculative"; the ASLB then terminated the proceeding without conducting an evidentiary hearing.[74] Elsewhere, the author has described deficiencies in the ASLB's ruling.[75]

One reason for the difference in the probability estimates proffered by Orange County and the NRC Staff was their differing assessments of the spread of radioactive material from the reactor containment building to the separate, adjacent pool building. The Staff agreed with Orange County on some other matters. For example, the Staff reversed its previous, erroneous position that comparatively long-discharged fuel will not ignite in the event of water loss from a high-density pool. NRC Staff members stated that loss of water from pools containing fuel aged less than 5 years "would almost certainly result in an exothermic reaction", and also stated: "Precisely how old the fuel has to be to prevent a fire is still not resolved."[76] Moreover, the Staff assumed that a fire would be inevitable if the water level fell to the top of the racks.

Most importantly for present purposes, the technical submissions of all three parties agreed that the onset of a pool fire in two of the pools in the Harris pool building would preclude the provision of cooling and water makeup to the other two pools. This effect would arise from the spread of hot gases and radioactive material throughout the pool building, which would preclude access by operating personnel. Thus, the pools not involved in the initial fire would boil and dry out, and their fuel would burn. The parties' agreement on this point established that the radiation field created by an accident at one part of a nuclear power plant could, by precluding access by personnel, cause an accident at another part of the plant. Whether or not this effect would occur in a particular scenario would depend on the specific configuration of the plant and the characteristics of the scenario.

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[71] Thompson, 2000.
[72] Parry et al, 2000.
[73] ERIN, 2000.
[74] ASLB, 2001.
[75] Thompson, 2001b.
[76] Parry et al, 2000, paragraph 29.

Interactions between a core-damage accident and a pool fire could be especially important in the context of an attack from outside and/or inside the plant. Attackers could, either deliberately or inadvertently, release radioactive material from one facility (e.g., a reactor) that precludes personnel access to other facilities (e.g., a pool), thereby initiating accidents at those facilities. This matter is discussed in Section 7, below.

Sabotage analysis in NUREG-0575

IRSS is aware of one instance in which NRC published an analysis of the impacts of deliberate, malicious actions at a spent-fuel pool. Such an analysis was provided in NUREG-0575, the August 1979 GEIS on handling and storage of spent fuel. That analysis is discussed further in Section 7, below.

5.4 Pool Fires in a SAMA Context

When the licensee of a commercial reactor applies for a license extension, the licensee is required to examine a set of Severe Accident Mitigation Alternatives (SAMAs) that could reduce risk. For each SAMA, a "benefit" is determined by estimating the amount by which this SAMA would, if adopted, reduce the present value of cost risk of reactor operation. The cost of implementing the SAMA is also estimated. If the benefit exceeds the cost, the SAMA is determined to be "cost effective".

The "present value of cost risk" is estimated as follows. First, the annual risk of core-damage events at the reactor is assessed, considering only conventional accidents. That risk is framed in terms of the monetized offsite and onsite costs of a set of potential atmospheric releases of radioactive material, multiplied for each release by its estimated annual probability. Then, the annual risk is summed (with discounting) over the 20-year period of license extension. The resulting indicator is the present value of cost risk for the reactor. Various assumptions and approximations are used during the estimation of this indicator.[77]

NRC does not require that spent-fuel-pool fires be considered in SAMA analyses. There is, however, no logical basis for that position. To illustrate, Table 5-1 shows the estimated present value of cost risk for the reactors and spent-fuel pools at the Indian Point site. The table shows that the present value of cost risk is greatest for a pool fire, even without considering the onsite impacts of such a fire.

In Table 5-1, the present value of cost risk for each reactor is an estimate by the licensee. For each pool, the present value of cost risk derives from two sources. First, it derives from an estimate of pool-fire probability that NRC set forth in NUREG-1353 and has not repudiated. Second, it derives from an estimate by Beyea et al of the offsite costs arising

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[77] IRSS does not necessarily accept any of the assumptions and approximations used in SAMA analyses.

from an atmospheric release of 35 MCi of cesium-137. (See the source term discussion in Section 5.2, above.)

Beyea et al estimate the offsite costs of a 35 MCi release of cesium-137 from the Indian Point site to be $461 billion.[78] Their study identifies a number of factors that, if considered, could increase the estimated costs. A further increase would occur if indirect impacts of the release were considered. Indirect economic impacts would include: (i) loss of market share for products from the region and across the US, due to stigma effects; (ii) loss of tourist revenue in the region and across the US, due to stigma effects; (iii) prolonged, costly litigation that retards recovery from the event; and (iv) loss of confidence in regional and national stability and governance, causing outflow of capital and skilled labor.

Consideration of pool fires in a SAMA context is addressed further in Sections 7 and 8, below.

6. Potential for Radioactive Release from an ISFSI

At an ISFSI, spent fuel is stored in modules. The inner portion of each module is a sealed, cylindrical multi-purpose canister (MPC) made of stainless steel. Spent fuel assemblies are stored inside the MPC, in a helium atmosphere. The MPC is placed inside an overpack made of concrete and steel. The overpack is penetrated by vents that allow ambient air to circulate over the MPC by natural convection, thereby removing heat that is generated in the fuel assemblies by radioactive decay.

Holtec's HI-STORM 100SA module, scheduled for use at the Diablo canyon ISFSI, is a typical module. This module takes the form of a cylinder with a vertical axis, anchored to a concrete pad in the open air. The overpack has an outer diameter of 3.7 meters and a height of 5.9 meters. Its outer, carbon steel shell is about 3/4 inch (2 cm) thick, the inner shell is about 1 1/4 inch (3 cm) thick, and the space between these shells is filled by about 27 inches (69 cm) of concrete (details vary by module version).[79] That is a robust structure in terms of its resistance to natural forces (e.g., tornado-driven missiles), but not in terms of its ability to withstand penetration by weapons available to sub-national groups. The cylindrical wall of the MPC is about 1/2 inch (1.3 cm) thick, and could be readily penetrated by available weapons. The spent fuel assemblies inside the MPC are composed of long, narrow tubes made of zirconium alloy, inside which uranium oxide fuel pellets are stacked. The walls of the tubes (the fuel cladding) are about 0.023 inch (0.6 mm) thick. Zirconium is a flammable metal. In finely divided form, it is used in military incendiary devices.

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[78] Beyea et al, 2004.

[79] Holtec FSAR, Chapter 1.

One type of scenario for an atmospheric release from an ISFSI module would involve mechanical loading of the module in a manner that creates a comparatively small hole in the MPC. The loading could arise, for example, from the air blast produced by a nearby explosion, or from the impact of an aircraft or missile. If the loading were sufficient to puncture the MPC, it would also shake the spent fuel assemblies and damage their cladding.

Table 6-1 addresses the "blowdown" (escape of helium and gases) of an MPC that has been subjected to a loading pulse sufficient to cause a comparatively small hole. The table shows that, for a hole with an equivalent diameter of 2.3 mm, radioactive gases and particles released during the blowdown would yield an inhalation dose (CEDE) of 6.3 rem to a person 900 m downwind from the release. Most of that dose would be attributable to release of two-millionths (1.9E-06) of the MPC's inventory of radioisotopes in the "fines" category.

Another type of scenario for an atmospheric release would involve the creation of one or more holes in an MPC, with a size and position that allows ingress and egress of air. In addition, the scenario would involve the ignition of incendiary material inside the MPC, causing ignition and sustained burning of the zirconium alloy cladding of the spent fuel. Heat produced by burning of the cladding would release volatile radioactive material to the atmosphere. Illustrative calculations in Table 6-2 show that heat from combustion of cladding would be ample to raise the temperature of adjacent fuel pellets to well above the boiling point of cesium.

Note from Table 3-2 that a typical ISFSI module would contain 1.3 MCi of cesium-137, about half the amount of cesium-137 released during the Chernobyl reactor accident of 1986. Most of the offsite radiation exposure from the Chernobyl accident was due to cesium-137. Thus, a fire inside an ISFSI module, as described in the preceding paragraph, could cause significant radiological harm. The potential for deliberate creation of such a fire is discussed in Section 7, below.

7. Potential for Attack on a Commercial Nuclear Facility

7.1 The General Threat Environment

The potential for a deliberate attack on a commercial nuclear facility arises within a larger context, namely the general threat environment for the US homeland. That environment reflects, in turn, a complex set of factors operating internationally.

As discussed in Section 2, above, we can expect that existing commercial reactors will operate in close proximity to pools, packed with spent fuel at high density to nearly their full capacity, for future periods as long as 46 years. That situation could persist into the 22nd century if new reactors are commissioned and employ the present strategy for storing spent fuel. Thus, in assessing the risk of malice-induced accidents affecting spent fuel, one should consider the general threat environment over the next century.

The threat from sub-national groups

The US homeland has not been attacked by another nation since World War II. One factor behind this outcome has been the US deployment of military forces with a high capability for counter-attack. There have, however, been significant attacks on the US homeland and other US assets by sub-national groups since World War II. Such attacks are typically not deterred by US capability for counter-attack, because the attacking group has no identifiable territory. Indeed, sub-national groups may attack US assets with the specific purpose of prompting US counter-attacks that harm innocent persons, thereby undermining the global political position of the US.

Attacks on the homeland by sub-national groups in recent decades include vehicle bombings of the World Trade Center in New York in February 1993 and the Murrah Federal building in Oklahoma City in April 1995, and aircraft attacks on the World Trade Center and the Pentagon in September 2001. Outside the homeland, attacks on US assets by sub-national groups have included vehicle-bomb attacks on a Marine barracks in Beirut in October 1983 and embassies in Tanzania and Kenya in August 1998, and a boat-bomb attack on the USS Cole in October 2000. Sub-national groups have repeatedly attacked US and allied forces in Iraq and Afghanistan.

In many of these incidents, the attacking group has been based outside the US. An exception was the Oklahoma City bombing, where the attacking group was domestic in both its composition and its motives. There is concern that future attacks within the US may be made by groups that are domestically based but have linkages to, or sympathy with, interests outside the US. This phenomenon was exhibited in London in July 2005, when young men born in the UK conducted suicide bombings in underground trains and a bus.

Reducing the risk of attack by sub-national groups requires a sophisticated, multi-faceted and sustained policy. An unbalanced policy can be ineffective or counterproductive. After September 2001, the US government implemented a policy that was heavily weighted toward offensive military action. Evidence has accumulated that this policy has been significantly counterproductive. Table 7-1 provides a sample of the evidence. The table shows public-opinion data from four Muslim-majority countries (Morocco, Egypt, Pakistan, Indonesia). In each country, a majority (ranging from 53 percent of respondents in Indonesia to 86 percent in Egypt) believes that the primary goal of the US "war on terrorism" is to weaken Islam or control Middle East resources (oil and natural gas). One expression of this belief is that substantial numbers of people (ranging from 19 percent of respondents in Indonesia to 91 percent in Egypt) approve of attacks on US troops in Iraq. Smaller numbers of people (ranging from 4 to 7 percent of respondents) approve of attacks on civilians in the US.[80]

The great majority of people, in these four countries and elsewhere, will not participate in attacks on US assets. However, there are consequences when millions of people believe that the US seeks to undermine their religion and culture and control their resources. Among other consequences, this belief creates a social climate that can help sub-national groups to form and to acquire the skills, funds and equipment they need in order to mount attacks. From a US perspective, such groups are "terrorists". Within their own cultures, they may be seen as soldiers engaged in "asymmetric warfare" with a powerful enemy.

Many experts who study these issues see a substantial probability that the US homeland will, over the coming years, be subjected to an attack comparable in severity to the attack of September 2001. Table 7-2 summarizes the judgment of a selected group of experts on this matter.

The threat environment over the coming decades

As mentioned above, an assessment of the risk of malice-induced accidents affecting spent fuel should consider the general threat environment over the next century. Forecasting trends in the threat environment over such a period is a daunting exercise, with inevitably uncertain findings. Nevertheless, a decision about the design and mode of operation of a nuclear facility must reflect either an implicit or an explicit forecast of trends in the general threat environment. It is preferable that the forecast be explicit, and global in scope, because the US cannot be insulated from broad trends in violent conflict and social disorder.

Numerous analysts – in academia, government and business – are involved in efforts to forecast possible worldwide trends that pertain to violence. These efforts rarely attempt to look forward more than one or two decades. Two examples are illustrative. First, a group based at the University of Maryland tracks a variety of indicators for most of the countries in the world, in a data base that extends back to 1950 and earlier. Using these data, the group periodically provides country-level assessments of the potential for outbreaks of violent conflict.[81] Second, the RAND corporation has conducted a literature review and assessment of potential worldwide trends that would be adverse for US national security.[82]

Several decades ago, some analysts of potential futures began taking an integrated world view, in which social and economic trends are considered in the context of a finite planet. In this view, trends in population, resource consumption and environmental degradation can be significant, or even dominant, determinants of the options available to human

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[80] Kull et al, 2007.
[81] Marshall and Gurr, 2005.
[82] Kugler, 1995.

societies. A well-known, early example of this genre is the *Limits to Growth* study, sponsored by the Club of Rome, which modeled world trends by using systems dynamics.[83] A more recent example is the work of the Global Scenario group, convened by the Stockholm Environment Institute (SEI).[84] This work was informed by systems-dynamics thinking, but focused on identifying the qualitative characteristics of possible future worldwide scenarios for human civilization. SEI identified three types of scenario, with two variants of each type, as shown in Table 7-3. The Conventional Worlds scenario has Market Forces and Policy Reform variants, the Barbarization scenario has Breakdown and Fortress World variants, while the Great Transitions scenario has Eco-Communalism and New Sustainability Paradigm variants.

The SEI scenarios provide a useful framework for considering the paths that human civilization could follow during the next century and beyond. Not all paths are possible. Notably, continued trends of resource depletion and irreversible degradation of ecosystems would limit the range of options available to succeeding generations. Similarly, destruction of human and industrial capital through large-scale warfare could inhibit economic and social recovery for many generations.

At present, the dominant world paradigm corresponds to the Market Forces scenario. Policy Reform is pursued at the rhetorical level, but is weakly implemented in practice. In parts of the world, notably in Africa, the Breakdown scenario is already operative. Aspects of the Fortress World scenario are also evident, and are likely to become more prominent if trends of resource depletion and ecosystem degradation continue, especially if major powers reject the dictates of sustainability and use armed force to secure resources. One sign of resource depletion is a growing body of analysis that predicts a peak in world oil production within the next few decades.[85] This prediction is sobering in view of the prominent role played by oil in the origins and conduct of war in the 20th century.[86] A now-familiar sign of ecosystem degradation is anthropogenic, global climate change. Analysts are considering the potential for climate change to promote, through its adverse impacts, social disorder and violence.[87] Other manifestations of ecosystem degradation are also significant. The recent Millennium Ecosystem Assessment determined that 15 out of the 24 ecosystem services that it examined "are being degraded or used unsustainably, including fresh water, capture fisheries, air and water purification, and the regulation of regional and local climate, natural hazards, and pests".[88] According to analysts at the United Nations University in Bonn, continuation of such trends could create up to 50 million environmental refugees by the end of the decade.[89]

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[83] Meadows et al, 1972.
[84] Raskin et al, 2002.
[85] Hirsch et al, 2005; GAO, 2007.
[86] Yergin, 1991.
[87] Gilman et al, 2007; Campbell et al, 2007; Smith and Vivekananda, 2007.
[88] MEA, 2005, page 1.
[89] Adam, 2005.

At present, human population and material consumption per capita are growing to a degree that visibly stresses the biosphere. Moreover, ecosystem degradation and resource depletion coexist with economic inequality, increasing availability of sophisticated weapons technology, and an immature system of global governance. Major powers are doing little to address these problems. It seems unlikely that these imbalances and sources of instability will persist at such a scale during the remainder of the 21st century without major change occurring. That change could take various forms, but two broad-brush scenarios can illustrate the range of possible outcomes. In one scenario, there would be a transition to a civilization similar to the New Sustainability Paradigm articulated by SEI. That civilization would be comparatively peaceful and technologically sophisticated. Alternatively, the world could descend into a form of barbarism such as the Fortress World scenario articulated by SEI. That society might be locally prosperous, within enclaves, but would be violent and unstable.

In assessing the likelihood of malicious actions at a nuclear facility, it would be prudent to adopt a pessimistic assumption of the potential for violent conflict in the future. Using SEI terminology, one could assume a Fortress World scenario with a high incidence of violent conflict of a type that involves sophisticated weapons and tactics. Violence might be perpetrated by national governments or by sub-national groups. A RAND corporation analyst has contemplated such a future in the following terms:[90]

> "A dangerous world may offer an insidious combination of nineteenth-century politics, twentieth-century passions, and twenty-first century technology: an explosive mixture of multipolarity, nationalism, and advanced technology."

7.2 National Policy and Practice on Homeland Security

To mount an effective response to the general threat environment for the US homeland, the nation needs a coherent homeland-security strategy that links responses to an array of specific threats, such as the potential for a deliberate attack on a commercial nuclear facility. As discussed below, there are deficiencies in the strategy that has been implemented. The nominal strategy was articulated by the White House in the *National Strategy for Homeland Security*, first published in July 2002 and updated in October 2007. That document sets forth four major goals:[91]

> "• Prevent and disrupt terrorist attacks;
> • Protect the American people, our critical infrastructure, and key resources;
> • Respond to and recover from incidents that do occur; and
> • Continue to strengthen the foundation to ensure our long-term success."

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[90] Kugler, 1995, page 279.
[91] White House, 2007, page 1.

The document defines critical infrastructure as including "the assets, systems, and networks, whether physical or virtual, so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, public health or safety, or any combination thereof".[92] Commercial nuclear reactors and their spent fuel are identified in the document as elements of the nation's critical infrastructure and key resources.

Protecting critical infrastructure

The US Department of Homeland Security has issued the *National Infrastructure Protection Plan* (NIPP), whose purpose is to provide "the unifying structure for the integration of critical infrastructure and key resources (CI/KR) protection into a single national program".[93] Other Federal agencies, including NRC, have confirmed their acceptance of the NIPP.

The NIPP identifies three purposes of measures to protect critical infrastructure and key resources: (i) deter the threat; (ii) mitigate vulnerabilities; and (iii) minimize consequences associated with an attack or other incident. The NIPP identifies a range of protective measures as follows:[94]

> "Protection can include a wide range of activities such as improving business protocols, hardening facilities, building resiliency and redundancy, incorporating hazard resistance into initial facility design, initiating active or passive countermeasures, installing security systems, leveraging "self-healing" technologies, promoting workforce surety programs, or implementing cyber security measures, among various others".

Protective measures of these types could significantly reduce the probability that an attack would be successful. Such measures could, therefore, "deter" attacks by altering attackers' cost-benefit calculations. That form of deterrence is different from deterrence attributable to an attacked party's capability to counter-attack. For convenience, the two forms of deterrence are described hereafter as "protective deterrence" and "counter-attack deterrence". It should be noted that the effective functioning of both forms of deterrence requires that: (i) potential attackers are aware of the deterrence strategy; and (ii) the deterrence strategy is technically credible. That requirement means that the existence and capabilities of protective measures, such as those identified in the NIPP, should be widely advertised. The technical details of a protective measure should, however, remain confidential if disclosure of those details would allow the measure to be defeated.

From the statement quoted above, it is clear that the authors of the NIPP recognize the potential benefits of designing protective measures into a facility before it is constructed.

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[92] White House, 2007, page 25.
[93] DHS, 2006, page iii.
[94] DHS, 2006, page 7.

At the design stage, attributes such as resiliency, redundancy, hardening and passive operation can often be incorporated into a facility at a comparatively low incremental cost. Capturing opportunities for low-cost enhancement of protective measures would allow decision makers to design against a more pessimistic (i.e., more prudent) threat assumption, thereby strengthening protective deterrence, reducing the costs of other security functions (e.g., guard forces), and enhancing civil liberties (e.g., by reducing the perceived need for measures such as wiretapping). Moreover, incorporation of enhanced protective measures would often reduce risks associated with conventional accidents (e.g., fires), extreme natural events (e.g., earthquakes), or other challenges not directly attributable to human malice.

Protective deterrence as part of a balanced policy for homeland security

As mentioned above, reducing the risk of attack by sub-national groups requires a sophisticated, multi-faceted and sustained policy. The policy must balance multiple factors operating within and beyond the homeland. An unbalanced policy can be ineffective or counterproductive.

A high-level task force convened by the Council on Foreign Relations (CFR) in 2002 understood the need for a balanced policy for homeland security.[95] One of the task force's major conclusions recognized the value of protective deterrence, while also recognizing that offensive military operations by the US could increase the risk of attack on the US. The conclusion was as follows:[96]

> "*Homeland security measures have deterrence value*: US counterterrorism initiatives abroad can be reinforced by making the US homeland a less tempting target. We can transform the calculations of would-be terrorists by elevating the risk that (1) an attack on the United States will fail, and (2) the disruptive consequences of a successful attack will be minimal. It is especially critical that we bolster this deterrent now since an inevitable consequence of the US government's stepped-up military and diplomatic exertions will be to elevate the incentive to strike back before these efforts have their desired effect."

The NIPP could support a vigorous national program of protective deterrence, as recommended by the CFR task force in 2002. However, priorities of the US government have not been consistent with such a program. Resources and attention devoted to offensive military operations are much larger than those devoted to the protection of critical infrastructure.[97] The White House stated, in the *National Strategy for Combating*

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[95] Members of the task force included two former Secretaries of State, two former chairs of the Joint Chiefs of Staff, a former Director of the CIA and the FBI, two former US Senators, and other eminent persons.
[96] Hart et al, 2002, pp 14-15.
[97] Flynn, 2007.

Terrorism, issued in September 2006:[98] "We have broken old orthodoxies that once confined our counterterrorism efforts primarily to the criminal justice domain." In practice, that statement means that the US government has relied overwhelmingly on military means to reduce the risks of attacks on US assets by sub-national groups. That policy has continued despite mounting evidence, as illustrated by Tables 7-1 and 7-2, that it is unbalanced and counterproductive.

A well-informed analyst of homeland security has summarized national priorities in the following statement:[99]

> "Since the White House has chosen to combat terrorism as essentially a military and intelligence activity, it treats homeland security as a decidedly second-rate priority. The job of everyday citizens is to just go about their lives, shopping and traveling, while the Pentagon, Central Intelligence Agency, and National Security Agency wage the war."

Under the new Presidential administration, national priorities may shift, leading to greater emphasis on protective deterrence. Unfortunately, critical-infrastructure facilities approved or constructed prior to that policy shift may lack the protective design features that are envisioned in the NIPP. Persons responsible for the design or licensing of nuclear facilities could anticipate a national policy shift and take decisions accordingly.

Section 8, below, discusses options and issues that should be considered in developing a balanced policy for protecting US critical infrastructure from attack by sub-national groups. That discussion shows the potential benefits that could be gained by assigning a higher priority to protective deterrence.

7.3 Commercial Nuclear Facilities as Potential Targets of Attack

A sub-national group contemplating an attack within the US homeland would have a wide choice of targets. Also, groups in that category could vary widely in terms of their capabilities and motivations. In the context of potential attacks on nuclear facilities, the groups of concern are those that are comparatively sophisticated in their approach and comparatively well provided with funds and skills. The group that attacked New York and Washington in September 2001 met this description. A group of this type could choose to attack a US nuclear facility for one or both of two broad reasons. First, the attack could be highly symbolic. Second, the impacts of the attack could be severe.

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[98] White House, 2006, page 1.

[99] Flynn, 2007, page 11.

Nuclear facilities as symbolic targets

From the symbolic perspective, commercial nuclear facilities are inevitably associated with nuclear weapons. The association further extends to the United States' large and technically sophisticated capability for offensive military operations. Application of that capability has aroused resentment in many parts of the world. Although nuclear weapons have not been used by the United States since 1945, US political leaders have repeatedly threatened, implicitly or explicitly, to use nuclear weapons again. Those threats coexist with efforts to deny nuclear weapons to other countries. The US government justified its March 2003 invasion of Iraq in large part by the possibility that the Iraqi government might eventually deploy nuclear weapons. There is speculation that the United States will attack nominally commercial nuclear facilities in Iran to forestall Iran's deployment of nuclear weapons.[100] Yet, the US government rejects the constraint of its own nuclear weapons by international agreements such as the Non-Proliferation Treaty.[101] As an approach to international security, this policy has been criticized by the director general of the International Atomic Energy Agency as "unsustainable and counterproductive".[102] It would be prudent to assume that this policy will motivate sub-national groups to respond asymmetrically to US nuclear superiority, possibly through an attack on a US commercial nuclear facility.

Radiological impacts of an attack on a nuclear facility

The impacts of an attack on a commercial nuclear facility could be severe because these facilities typically contain large amounts of radioactive material. Release of this material to the environment could create a variety of severe impacts. Also, as explained in Section 7.4, below, US nuclear facilities are provided with a defense that is "light" in a military sense. Moreover, imprudent design choices have made a number of these facilities highly vulnerable to attack. That combination of factors means that many US nuclear facilities can be regarded as potent radiological weapons that await activation by an enemy.

As explained in Section 3, above, a facility's inventory of cesium-137 provides an indicator of the facility's potency as a radiological weapon. Table 3-1 shows estimated amounts of cesium-137 in nuclear fuel in the Indian Point reactors and spent-fuel pools, and in one of the spent-fuel storage modules of the Indian Point ISFSI. Table 3-2 compares these amounts with atmospheric releases of cesium-137 from detonation of a 10-kilotonne fission weapon, the Chernobyl reactor accident of 1986, and atmospheric testing of nuclear weapons. These data show that release of a substantial fraction of the cesium-137 in a nuclear facility, such as those at Indian Point, would create comparatively large radiological consequences.

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[100] Hersh, 2006; Brzezinski, 2007.
[101] Deller, 2002; Scarry, 2002; Franceschini and Schaper, 2006.
[102] ElBaradei, 2004, page 9.

7.4 NRC's Approach to Nuclear-Facility Security

A policy on protecting nuclear facilities from attack is laid down in NRC regulation 10 CFR 50.13. That regulation was promulgated in September 1967 by the US Atomic Energy Commission (AEC) – which preceded the NRC – and was upheld by the US Court of Appeals in August 1968. It states:[103]

> "An applicant for a license to construct and operate a production or utilization facility, or for an amendment to such license, is not required to provide for design features or other measures for the specific purpose of protection against the effects of (a) attacks and destructive acts, including sabotage, directed against the facility by an enemy of the United States, whether a foreign government or other person, or (b) use or deployment of weapons incident to US defense activities."

Some readers might interpret 10 CFR 50.13 to mean that licensees are not required to design or operate nuclear facilities to resist potential attacks by sub-national groups. The NRC has rejected that interpretation in the context of vehicle-bomb attacks, stating:[104]

> "It is simply not the case that a vehicle bomb attack on a nuclear power plant would almost certainly represent an attack by an enemy of the United States, within the meaning of that phrase in 10 CFR 50.13."

Events have obliged the NRC to progressively require greater protection against attacks by sub-national groups. A series of events, including the 1993 vehicle-bomb attack on the World Trade Center in New York, persuaded the NRC to introduce, in 1994, regulatory amendments requiring licensees to defend nuclear power plants against vehicle bombs.[105] The attacks on New York and Washington in September 2001 led the NRC to require additional protective measures.

With rare exceptions, the NRC has refused to consider potential malicious actions in the context of license proceedings or environmental impact statements. The NRC's policy on this matter is illustrated by a September 1982 ruling by the Atomic Safety and Licensing Board in the operating-license proceeding for the Harris nuclear power plant. An intervenor, Wells Eddleman, had proffered a contention alleging, in part, that the plant's safety analysis was deficient because it did not consider the "consequences of terrorists commandeering a very large airplane.....and diving it into the containment." In refusing to consider this contention, the ASLB stated:[106]

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[103] Federal Register, Vol. 32, 26 September 1967, page 13445.
[104] NRC, 1994, page 38893.
[105] NRC, 1994.
[106] ASLB, 1982.

> "This part of the contention is barred by 10 CFR 50.13. This rule must be read *in pari materia* with 10 CFR 73.1(a)(1), which describes the "design basis threat" against which commercial power reactors *are* required to be protected. Under that provision, a plant's security plan must be designed to cope with a violent external assault by "several persons," equipped with light, portable weapons, such as hand-held automatic weapons, explosives, incapacitating agents, and the like. Read in the light of section 73.1, the principal thrust of section 50.13 is that military style attacks with heavier weapons are not a part of the design basis threat for commercial reactors. Reactors could not be effectively protected against such attacks without turning them into virtually impregnable fortresses at much higher cost. Thus Applicants are not required to design against such things as artillery bombardments, missiles with nuclear warheads, or kamikaze dives by large airplanes, despite the fact that such attacks would damage and may well destroy a commercial reactor."

The design basis threat

The NRC requires its licensees to defend against a design basis threat (DBT), a postulated attack that has become more severe over time. The present DBT for nuclear power plants was promulgated in January 2007. Details are not publicly available. (The NRC publishes a summary description, which is provided below.) The present DBT is similar to one ordered by the NRC in April 2003.[107] At that time, the NRC described its order as follows:[108]

> "The Order that imposes revisions to the Design Basis Threat requires power plants to implement additional protective actions to protect against sabotage by terrorists and other adversaries. The details of the design basis threat are safeguards information pursuant to Section 147 of the Atomic Energy Act and will not be released to the public. This Order builds on the changes made by the Commission's February 25, 2002 Order. The Commission believes that this DBT represents the largest reasonable threat against which a regulated private security force should be expected to defend under existing law."

From that statement, and from other published information, it is evident that the NRC requires a comparatively "light" defense for nuclear power plants and their spent fuel. The scope of the defense does not reflect a full spectrum of threats. Instead, it reflects a consensus about the level of threat that licensees can "reasonably" be expected to resist.[109] In illustration of this approach, when the NRC adopted the currently-applicable DBT rule in January 2007, it stated that the rule "does not require protection against a deliberate hit by a large aircraft", and that "active protection [of nuclear power plants]

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[107] NRC Press Release No. 07-012, 29 January 2007.
[108] NRC Press Release No. 03-053, 29 April 2003.
[109] Fertel, 2006; Wells, 2006; Brian, 2006.

against airborne threats is addressed by other federal organizations, including the military".[110]

The present DBT for "radiological sabotage" at a nuclear power plant has the following published attributes:[111]

> "(i) A determined violent external assault, attack by stealth, or deceptive actions, including diversionary actions, by an adversary force capable of operating in each of the following modes: A single group attacking through one entry point, multiple groups attacking through multiple entry points, a combination of one or more groups and one or more individuals attacking through multiple entry points, or individuals attacking through separate entry points, with the following attributes, assistance and equipment:
>
> > (A) Well-trained (including military training and skills) and dedicated individuals, willing to kill or be killed, with sufficient knowledge to identify specific equipment or locations necessary for a successful attack;
> > (B) Active (e.g., facilitate entrance and exit, disable alarms and communications, participate in violent attack) or passive (e.g., provide information), or both, knowledgeable inside assistance;
> > (C) Suitable weapons, including handheld automatic weapons, equipped with silencers and having effective long range accuracy;
> > (D) Hand-carried equipment, including incapacitating agents and explosives for use as tools of entry or for otherwise destroying reactor, facility, transporter, or container integrity or features of the safeguards system; and
> > (E) Land and water vehicles, which could be used for transporting personnel and their hand-carried equipment to the proximity of vital areas; and
>
> (ii) An internal threat; and
> (iii) A land vehicle bomb assault, which may be coordinated with an external assault; and
> (iv) A waterborne vehicle bomb assault, which may be coordinated with an external assault; and
> (v) A cyber attack."

That DBT seems impressive, and is more demanding than previously-published DBTs. However, the DBT cannot be highly demanding in practice, given the equipment that the NRC requires for a security force. Major items of required equipment are semiautomatic rifles, shotguns, semiautomatic pistols, bullet-resistant vests, gas masks, and flares for

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[110] NRC Press Release No. 07-012, 29 January 2007.
[111] 10 CFR 73.1 Purpose and scope, accessed from the NRC web site (www.nrc.gov) on 14 June 2007.

night vision.[112] Plausible attacks could overwhelm a security force equipped in this manner. Also, press reports state that the assumed attacking force contains no more than six persons.[113] The average US nuclear-plant site employs about 77 security personnel, covering multiple shifts.[114] Thus, comparatively few guards are on duty at any given time.[115]

Table 7-4 sets forth some potential modes and instruments of attack on a nuclear power plant, and summarizes the present defenses against these modes and instruments. That table shows that a variety of potential attack scenarios could not be effectively resisted by present defenses. Illustrative scenarios are discussed, in a general sense, in Section 7.5, below.

Protective deterrence and the NRC

A rationale for the present level of protection of nuclear facilities was articulated by the NRC chair, Richard Meserve, in 2002:[116]

> "If we allow terrorist threats to determine what we build and what we operate, we will retreat into the past – back to an era without suspension bridges, harbor tunnels, stadiums, or hydroelectric dams, let alone skyscrapers, liquid-natural-gas terminals, chemical factories, or nuclear power plants. We cannot eliminate the terrorists' targets, but instead we must eliminate the terrorists themselves. A strategy of risk avoidance – the elimination of the threat by the elimination of potential targets – does not reflect a sound response."

That statement shows no understanding of the need for a balanced policy to protect critical infrastructure, employing the principles of protective deterrence. There is considerable potential to embody those principles in the design of nuclear facilities, especially new facilities. It has been known for decades that nuclear power plants could be designed to be more robust against attack. For example, in the early 1980s the reactor vendor ASEA-Atom developed a preliminary design for an "intrinsically safe" commercial reactor known as the PIUS reactor. Passive-safety design principles were used. The design basis for the PIUS reactor included events such as equipment failures, operator errors and earthquakes, but also included: (i) takeover of the plant for one operating shift by knowledgeable saboteurs equipped with large amounts of explosives;

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[112] 10 CFR 73 Appendix B – General Criteria for Security Personnel, Section V, accessed from the NRC web site (www.nrc.gov) on 14 June 2007.

[113] Hebert, 2007.

[114] Holt and Andrews, 2006.

[115] If each member of a 77-person security force were on duty 40 hours/week for 42 weeks/year (allowing 10 weeks/year for vacation, illness, training, etc.), the average number of persons on duty at any time would be 15.

[116] Meserve, 2002, page 22.

(ii) aerial bombardment with 1,000-pound bombs; and (iii) abandonment of the plant by the operators for one week.[117]

Consideration of malicious actions in environmental impact statements

NRC has generally refused to consider potential malicious actions in environmental impact statements. An exception is NRC's August 1979 GEIS on handling and storage of spent fuel (NUREG-0575), which considered potential sabotage events at a spent-fuel pool.[118] Table 7-5 describes the postulated events, which encompass the detonation of explosive charges in the pool, breaching of the walls of the pool building and the pool floor by explosive charges or other means, and takeover of the central control room for one half-hour. Involvement of up to about 80 adversaries is implied.

NUREG-0575 did not recognize the potential for an attack with these attributes to cause a fire in the pool.[119] Technically-informed attackers operating within this envelope of attributes could cause a fire in a spent-fuel pool at any operating nuclear power plant in the USA.[120] Informed attackers could use explosives, and their command of the control room for one half-hour, to drain water from the pool and release radioactive material from the adjacent reactor. The radiation field from the reactor release and the drained pool could preclude personnel access, thus precluding recovery actions if command of the plant were returned to the operators after one half-hour. Exposure of spent fuel to air could initiate a fire that would release to the atmosphere a large fraction of the pool's inventory of cesium-137.[121]

Pursuant to a ruling obtained from the 9th Circuit of the US Court of Appeals by San Luis Obispo Mothers for Peace (SLOMFP), in 2007 the NRC Staff issued a Supplement to its October 2003 Environmental Assessment (EA) for a proposed ISFSI at the Diablo Canyon site. The Supplement purported to address the risk of potential malicious actions at the ISFSI. A draft version of the Supplement was issued in May 2007 and a final version was issued in August 2007.[122] IRSS prepared a detailed review of the draft version and a short review of the final version.[123] There was little change from the draft to the final version. Both versions exhibited grave deficiencies. Neither version provided a credible assessment of the risks of potential malicious actions. In October 2008 the NRC Commissioners rejected arguments submitted by SLMOFP regarding

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[117] Hannerz, 1983.

[118] NRC, 1979, Section 5 and Appendix J.

[119] The sabotage events postulated in NUREG-0575 yielded comparatively small estimated radioactive releases.

[120] Spent-fuel pools at all US nuclear power plants are currently equipped with high-density racks. Loss of water from such a pool would, over a wide range of water-loss scenarios, lead to ignition and burning of spent fuel assemblies.

[121] Alvarez et al, 2003; Thompson, 2006; NAS, 2006.

[122] NRC, 2007a; NRC, 2007b.

[123] Thompson, 2007a; Thompson, 2007b.

deficiencies in the EA, and ruled that an EIS is not required in this instance.[124] Commissioner Jaczko dissented strongly from the majority decision.[125] The decision may be appealed.

The NRC Staff has refused to implement the 9th Circuit ruling in regions of the USA, such as New York State, that do not fall under the jurisdiction of the 9th Circuit. Nevertheless, the US Environmental Protection Agency (EPA) has requested the NRC Staff to provide, in the EIS for license extension of the IP2 and IP3 plants, "an analysis of the impacts of intentional destructive acts (e.g., terrorism)".[126] The EPA cites the 9th Circuit ruling as requiring such an analysis.

7.5 Vulnerability of Typical Reactors, Pools and ISFSIs to Attack

Here, the vulnerability of reactors, pools and ISFSIs to attack is discussed in two parts. First, the vulnerability of reactors and pools is addressed by examining the vulnerability of nuclear power plants. Reactors and pools are, of course, components of those plants. Second, the vulnerability of ISFSIs is addressed, noting that most ISFSIs are at plant sites.

Vulnerability of nuclear power plants

Nuclear power plants in the USA were not designed to withstand an attack. Nor were they designed to withstand a conventional accident involving damage to the reactor core. However, they employ comparatively massive structures. Thus, they have some ability to survive an attack or a conventional core-damage accident without necessarily suffering a large release of radioactive material. To assess the potential for release, a range of attack scenarios and conventional core-damage scenarios could be articulated, and an atmospheric source term could be estimated for each scenario.

PRA techniques have been developed to examine conventional accident scenarios. Those techniques could be adapted to examine attack scenarios, by postulating for each scenario an initiating event (the attack) and assessing the conditional probabilities and other characteristics of the various possible outcomes of that event. The NRC employed that approach in developing its vehicle-bomb rule.[127]

PRAs and related studies have been done for all US commercial reactors. That work could be built upon to assess the vulnerability of these reactors to attack. The analysis could be further extended to assess the risk of a pool fire arising from a conventional accident or attack, with consideration of pool-reactor interactions. If done properly, the overall analysis could provide a comprehensive assessment of the risk posed by operation

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[124] This author prepared a declaration supporting SLOMFP's arguments. See: Thompson, 2008b.
[125] NRC, 2008e.
[126] EPA, 2007.
[127] NRC, 1994.

of each US nuclear power plant. Such an assessment could be performed without access to classified information, by using existing engineering knowledge and models, and by developing new models. Published professional literature provides illustrations of analytic techniques that could be used.[128]

Such a comprehensive assessment of risk does not exist. If that assessment did exist, parts of it would not be appropriate for publication. In the absence of such an assessment, IRSS provides here some illustrative analysis of the vulnerability of reactors and pools to attack. The analysis is general and brief, to avoid disclosing sensitive information. IRSS could expand upon this analysis if given the opportunity to do so in a protected setting. It should be noted that skilled attackers could readily obtain or infer a much greater depth of knowledge about a plant's vulnerability than is provided here.

Table 7-4 and the discussion in Section 7.4, above, show that a US nuclear power plant is provided with a comparatively light defense. Thus, a sub-national group with personnel, resources and preparation time comparable to those involved in the September 2001 attacks on New York and Washington could mount an attack with a substantial probability of success.

Modes of attack on a nuclear power plant

Consider the Indian Point site as an example. An attack at that site might begin with actions that put the IP2 and/or IP3 plant in a compromised state and create stress for plant personnel. For example, attackers could sever the site's electricity grid connection and disable the service water system without needing to penetrate the site boundary. Due to a design deficiency at this site, lack of service water would disable the emergency diesel generators. Thus, the site would lose its primary supplies of electricity and cooling water. Additional actions, which could be accomplished by an insider, could then initiate a core-damage sequence.[129] The attackers might be satisfied to achieve core damage, recognizing that core damage would not necessarily lead to a large release of radioactive material. Alternatively, the attack plan might include actions that compromise the integrity of the reactor containment, in order to ensure a large atmospheric release.

The IP2 (and IP3) containment structure is a reinforced concrete vertical cylinder topped by a hemispherical dome made of the same material. The side walls are 4.5 feet thick with a 0.4 inch thick steel liner, and the dome is 3.5 feet thick with a 0.5 inch thick steel liner.[130] By some standards, this is a robust structure. It could, however, be readily breached using instruments of attack that are available to sub-national groups. For example, Tables 7-6 and 7-7 show the capability of shaped charges.[131]

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[128] See, for example: Morris et al, 2006; Honnellio and Rydell, 2007; Sdouz, 2007.

[129] The additional actions, which could be taken in advance of the attack, would disable equipment that is needed to maintain core cooling if the primary supplies of electricity and cooling water are unavailable.

[130] Entergy, 2007, Section 5.1.2. This source describes the IP2 plant; the IP3 plant has a similar design.

[131] Also see: Walters, 2003.

A shaped charge could be delivered by a general-aviation aircraft used as a cruise missile in remote-control or kamikaze mode. Alternatively, shaped charges could be placed by attackers who reach the target locations by parachute, ultralight aircraft, helicopter, or site penetration from land or the Hudson River. The attack might involve a standoff component in which shaped-charge warheads are delivered from an offsite location by an instrument such as the TOW (tube-launched, optically-tracked, wire-guided) missile. A shaped charge could be the first stage of a tandem device. In that configuration, the first stage penetrates a structure and is followed by a second stage that damages equipment inside the penetrated structure via fragmentation, blast, incendiary or "thermobaric" effects.

Arms manufacturers are actively developing tandem-warhead systems. For example, in January 2008 Raytheon tested the shaped-charge penetrating stage for its Tandem Warhead System.[132] The shaped charge penetrated 19 feet into steel-reinforced concrete with a compressive strength of 12,600 psi. The purpose of this new system is to penetrate a target protected by concrete, steel and rock barriers, and to cause damage inside the target. Development of the system was self-funded by Raytheon. The current version would have a mass of about 1,000 pounds in its tandem configuration. Raytheon states that it could scale the technology, which implies both larger and smaller versions.

The spent-fuel pools at the IP2 and IP3 plants are immediately outside the respective reactor containments. The floor of each pool is below the local grade level. However, the site slopes downward toward the Hudson River, so the pool floor is above river level. The pool walls are made of concrete, 3 to 6 feet thick.[133] As discussed above, a sub-national group could obtain the instruments needed to breach such a wall. Attackers might choose to breach the wall at the local grade level. That action would cause the water level in the pool to fall to near the top of the spent-fuel storage racks. Thereafter, the remaining water would boil and, if makeup water were not supplied, the pool could boil dry in about a day. As fuel assemblies became exposed, their temperature would rise. An assembly exposed for the majority of its length could heat up to ignition temperature in a few hours.[134]

In favorable circumstances, plant operators and other personnel could potentially prevent the initiation of a pool fire by the attack postulated above. To prevent a fire, the operators would have to improvise a water makeup system, or a system to spray water on exposed fuel assemblies. The operators' tasks would be greatly complicated by the radiation field from exposed fuel.[135] To prevent operators from providing makeup or spray water, the attackers could combine an attack on the pool with an attack on the adjacent reactor. The release of radioactive material from the reactor would generate a

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[132] Raytheon, 2008.
[133] Entergy, 2007, Table 9.5-1. This source describes the IP2 plant; the IP3 plant has a similar design.
[134] Thompson, 2000.
[135] Alvarez et al, 2003.

local radiation field that would, over a wide range of attack scenarios, preclude operator access for a period of days.

Aircraft as instruments of attack

Many people have suggested that an aircraft could be used as an instrument of attack on a nuclear facility. The NRC Staff considered this possibility in its Supplement to the EA for the proposed Diablo Canyon ISFSI, as discussed above.[136] The Staff made the mistaken assumption that a large, fuel-laden commercial aircraft would pose the greatest threat using this attack mode. Large, commercial aircraft caused major damage to the World Trade Center and the Pentagon in September 2001, but they would not be optimal as instruments of attack on a nuclear facility. They are comparatively soft objects containing a few hard structures such as turbine shafts. They can be difficult to guide precisely at low speed and altitude. A well-informed group of attackers would probably prefer to use a smaller, general-aviation aircraft laden with explosive material, perhaps in a tandem configuration in which the first stage is a shaped charge. Note that the US General Accounting Office (GAO) expressed concern, in September 2003 testimony to Congress, about the potential for malicious use of general-aviation aircraft. The testimony stated:[137]

> "Since September 2001, TSA [the Transportation Security Administration] has taken limited action to improve general aviation security, leaving it far more open and potentially vulnerable than commercial aviation. General aviation is vulnerable because general aviation pilots are not screened before takeoff and the contents of general aviation planes are not screened at any point. General aviation includes more than 200,000 privately owned airplanes, which are located in every state at more than 19,000 airports. Over 550 of these airports also provide commercial service. In the last 5 years, about 70 aircraft have been stolen from general aviation airports, indicating a potential weakness that could be exploited by terrorists."

Modes of attack on an ISFSI

Section 6, above, describes two types of potential release of radioactive material from an ISFSI module. In one type, gases and small particles are swept out of the MPC during a blowdown of gases in the MPC through a comparatively small hole. That release would expose a person downwind to a comparatively small inhalation dose. In the second type of release, air would enter and leave the MPC through one or more holes, and the zirconium alloy cladding of the spent fuel would be ignited by use of incendiary material. That release could include a large amount of cesium-137 that would cause significant

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[136] NRC, 2007a; NRC, 2007b.
[137] Dillingham, 2003, page 14.

radiological harm at distances of tens of km downwind. An attacking group seeking to maximize the impact of its attack would clearly prefer the second type of release.

Table 7-8 broadens the discussion in the preceding paragraph by considering four types of potential, attack-induced release, designated as Types I through IV. If a Type I release is set aside as a special case, examination of Types II through IV reveals two interesting trends. First, as one moves from a Type II or Type III release to a Type IV release, the release event would become less dramatic in terms of indicators such as noise, flame and smoke. Second, the environmental impact would decrease as one moves from a Type II to a Type III release, but would then increase sharply for a Type IV release.

A well-informed sub-national group planning to attack an ISFSI would be likely to aim at creating a Type IV release. That release would require a comparatively small investment of resources and could produce a comparatively large environmental impact.

The NRC Staff reluctantly prepared an EA that examines the potential for an attack on the Diablo Canyon ISFSI.[138] Most of the analyses and assumptions underlying the EA are secret. However, it is clear that the Staff limited its examination to Type III releases. The Staff may have been misled by the comparatively dramatic appearance of the attack scenarios associated with Type III releases, leading to the false conclusion that Type IV releases would yield comparatively small environmental impacts.

Further discussion of potential attacks on ISFSIs, and their treatment by NRC, is provided in other documents prepared by this author.[139] Also relevant to this issue is a dissent by Commissioner Jaczko to an October 2008 decision by the NRC Commissioners.[140] Jaczko noted, for example, that the NRC Staff lacks an in-house capability to analyze the potential for a zirconium fire.

7.6 Potential Attacks in a SAMA Context

Section 5.4, above, discusses the potential for a pool fire in the context of SAMA analyses. To illustrate that discussion, Table 5-1 shows the estimated present value of cost risk for the reactors and spent-fuel pools at the Indian Point site, for conventional accidents. The table shows that the present value of cost risk is greatest for a pool fire, even without considering the onsite impacts of such a fire.

In order to consider potential attacks in SAMA analyses, it is necessary to assign a probability to each potential attack scenario. At present, there is no statistical basis to support quantitative estimates of these probabilities. However, reasonable assumptions of probability can be postulated and used in SAMA analyses to: (i) compare the risk of

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[138] NRC, 2007a; NRC, 2007b.
[139] Thompson, 2007b; Thompson, 2008b.
[140] NRC, 2008e.

conventional accidents with the risk of postulated attacks; and (ii) identify and examine SAMAs that reduce both categories of risk.

Here, IRSS provides some illustrative analysis of potential attacks that yield a large atmospheric release from a reactor and/or a pool fire. The probability of such an attack is postulated here to be 1 per 10,000 reactor-years. That number corresponds to a probability of about 1 per century across the US fleet of 104 commercial reactors, assuming that all the reactors are equally attractive as targets. In the SAMA analysis described here, the probability of 1 per 10,000 reactor-years includes a factor of uncertainty. Given the anticipated threat environment over the coming decades, and the vulnerability of the existing nuclear power plants, a postulated probability of 1 per 10,000 reactor-years is at the lower end of the range of assumptions that would be prudent in the context of homeland-security planning.

Table 7-9 shows the estimated present value of cost risk of an atmospheric release from the IP2 and IP3 plants. Attack-induced releases are considered, with a postulated probability of 1 per 10,000 reactor-years. Releases caused by conventional accidents are also considered, carrying forward the analyses summarized in Table 5-1 to include internal and external initiating events and uncertainty. Thus, Table 7-9 provides an overall summary of the present value of cost risks as estimated by the Indian Point licensee and IRSS.

8. Options for Reducing Radiological Risk

Options are available for reducing the risk of conventional accidents and malice-induced accidents during storage of spent fuel. These options would involve changes in the design and/or mode of operation of SNF storage facilities. Such risk-reducing options can be thought of as SAMAs, although in NRC licensing practice that term is currently used only in connection with conventional accidents at reactors.

Commercial nuclear facilities, such as reactors, pools and ISFSIs, are elements of the nation's critical infrastructure. Thus, options to reduce the risk of malice-induced accidents at nuclear facilities should be examined in the larger setting of national security, values and interests. Table 8-1 shows the importance of taking this broad view. The table shows how wise design of critical infrastructure can enhance protective deterrence and substitute for defense measures that are less effective and/or have significant adverse impacts. The NIPP has outlined appropriate design principles.

Options for reducing the risk of a pool fire

Table 8-2 shows some options that could reduce the risk of a fire in a spent-fuel pool. The option that is most compatible with protective deterrence and the NIPP is to re-equip the pool with low-density, open-frame racks, as was planned when the existing commercial reactors were designed. That option would dramatically reduce the probability of a pool fire, and would substantially reduce the inventory of radioactive material available for release if a fire did occur.

Table 7-9 shows that the present value of cost risk for a fire at an Indian Point pool would be about $28 million for a conventional accident (assuming probability as in NUREG-1353) and $500 million for a malice-induced accident (assuming a probability of 1 per 10,000 reactor-years). Those values are calculated according to standard practice for SAMA analyses. In that paradigm, a SAMA would be cost-effective if its benefit (reduction in the present value of cost risk) exceeds its cost.

Table 8-3 provides an estimate of the incremental cost of using low-density racks in the pool associated with a new commercial reactor. With these racks in place, SNF assemblies would be transferred to dry storage after about 5 years of cooling in the pool. An incremental cost of $3.2 million per year (equivalent to 0.04 cent per kWh of nuclear generation) would arise, beginning in the 11th year of plant operation. That incremental cost would cease at a later point, around the 30th year of plant operation, when the pool inventory of SNF would have approached the pool's capacity if high-density racks had been used. The total, undiscounted incremental cost up to that point would be about $64 million. Viewed over the entire operating life of the reactor, the total, undiscounted incremental cost would actually be zero, assuming that all SNF remaining in the pool after permanent shut-down of the reactor would be moved to dry storage.

Use of low-density racks would dramatically reduce the risk of a pool fire. Thus, the benefit of this SAMA at Indian Point would be a large fraction of the present value of cost risk shown in Table 7-9 for a pool fire. Comparison with the cost estimate in Table 8-3 shows that this SAMA would be cost-effective by a large margin, in the context of malice-induced accidents.

A more complete discussion of SAMAs related to pool fires is provided in another report by this author.[141] That discussion relates directly to the Indian Point site, but also has general application.

Options for reducing the risk of release from an ISFSI

The overall risk of a radioactive release from an ISFSI is dominated by the risk of a malice-induced accident. Options for reducing the latter risk include active defense of the site and preparations for damage control.[142] Here, we focus on design options for enhancing the robustness of the ISFSI.

Options for designing an ISFSI to resist attack have been identified by this author, as follows:[143] "re-design of the ISFSI to use thick-walled metal casks, dispersal of the casks,

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[141] Thompson, 2007c.
[142] Thompson, 2007b.
[143] Thompson, 2002, paragraph XI-5.

and protection of the casks by berms or bunkers in a configuration such that pooling of aircraft fuel would not occur in the event of an aircraft impact". Elsewhere, the author has provided a more detailed discussion about designing an ISFSI to be more robust against attack.[144] A factor addressed in that discussion is the possibility that society will extend the life of ISFSIs until they become, by default, repositories for spent fuel. Consideration of that possibility could favor an above-ground ISFSI whose robustness would be enhanced through a combination of the design options described above.

Holtec has developed a design for a new ISFSI storage module that is said to be more robust against attack than present modules. The new module is the HI-STORM 100U module, which would employ the same MPC as is used in the present Holtec modules. For most of its height, the 100U module would be underground. Holtec has described the robustness of the 100U module as follows:[145]

> "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."

9. NRC Regulation of Spent-Fuel Storage

9.1 NRC's Approach to Regulating Spent-Fuel Storage

As shown in Section 2, above, NRC has enabled and encouraged the development of a de facto, national strategy for storing SNF from existing commercial reactors. This strategy is likely to persist at existing reactors until 2055, and appears poised to continue into the 22nd century at new reactors. As shown in Section 5, above, NRC has known since 1979 that the strategy creates the potential for a fire in a spent-fuel pool, and that the environmental impacts of such a fire would be severe. The Draft Update agrees that a pool fire could occur, but argues that the probability of this event has been limited by secret studies and secret actions.

Options are available for reducing the risk of a pool fire, as shown in Section 8, above. One option – use of low-density racks – would almost eliminate the risk, at a comparatively modest cost. Yet, NRC has never prepared an EIS that assesses the risk of a pool fire and the options for reducing that risk.

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[144] Thompson, 2003.
[145] Holtec, 2007.

Published NRC documents that address pool fires

Section 5, above, describes various documents published by NRC that are relevant to pool fires. One document is a 1979 GEIS on SNF handling and storage (NUREG-0575), which failed to identify the risk of a pool fire. Another document is an initial technical report (NUREG/CR-0649) published in 1979, whose introduction mis-characterized its content by erroneously stating that complete drainage of a pool is the most severe case. All subsequent documents published by NRC until October 2000 employed the erroneous assumption that complete drainage is the most severe case. For that and other reasons, none of those documents provides a credible assessment of pool-fire risk or risk-reducing options.

The October 2000 document (published in February 2001 as NUREG-1738) addressed nuclear power plants undergoing decommissioning. At such plants, the risk of a pool fire is qualitatively different, and quantitatively lower, than at operating plants. Thus, NRC should have taken the technical understanding that it had belatedly achieved in NUREG-1738, and applied that understanding to operating plants. Instead, NUREG-1738 was the last technical document published by NRC that addressed pool fires.

Secret NRC studies that address pool fires

Since September 2001, NRC has stated on various occasions that it has conducted secret studies addressing the risk of pool fires. The Draft Update, published in October 2008, mentions secret studies of this type.[146] An August 2008 decision by the NRC Commissioners to deny two rulemaking petitions also mentions secret studies of this type.[147] As shown in Section 5.2, above, the two sets of secret studies are clearly different. It appears that NRC is either confused or careless in attributing its position on pool fires to secret studies.

NRC actions to reduce the risk of pool fires

Prior to September 2001, NRC required no specific action to reduce the risk of a pool fire. Since September 2001, NRC has required licensees to take actions with the specific purpose of reducing the risk of a pool fire, while simultaneously claiming that the risk was overstated in published documents such as NUREG-1738. The new, risk-reducing actions are secret. From the Draft Update, they appear to include security measures and damage-control preparations.[148]

The NRC Commissioners' August 2008 decision to deny two rulemaking petitions mentions "internal and external strategies" for the supply of emergency water makeup or

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[146] NRC, 2008a.
[147] NRC, 2008d.
[148] NRC, 2008a.

spray to spent-fuel pools. These strategies were proposed by the nuclear industry in 2006, and NRC has "approved license amendments and issued safety evaluations to incorporate these strategies into the plant licensing bases of all operating nuclear power plants in the United States". The external strategy involves the use of an "independently-powered, portable" pumping system.[149]

Adoption of these secret strategies shows that the nuclear industry and NRC are aware of the potential for a pool fire, despite their numerous claims that the risk of such a fire is very low. However, the strategies have been implemented in secrecy, without any assessment of their effectiveness and cost by an EIS or equivalent study. A credible assessment would be likely to show that these strategies would be ineffective following a well-executed attack that targets a reactor and its adjacent pool, as discussed in Section 7.5, above.

Regulation of ISFSIs

An ISFSI poses a radiological risk that is lower than the risk posed by a spent-fuel pool packed at high density. Nevertheless, options are available for reducing the risk associated with malice-induced accidents at an ISFSI, as discussed in Section 8, above. NRC refuses to consider these options in an EIS. Also, NRC attempts to hide the vulnerabilities of existing ISFSIs under a veil of secrecy.

9.2 Impacts of NRC's Regulatory Approach

The preceding discussion identifies four notable features of NRC's approach to regulating SNF storage. First, NRC has not performed any credible EIS to assess the risk of a pool fire caused by a conventional accident. Second, NRC refuses to perform any EIS that assesses the risk associated with malice-induced accidents at any nuclear facility. Third, NRC relies heavily on secrecy as a protective measure. Fourth, under the veil of secrecy, NRC has cooperated with the nuclear industry to adopt measures to reduce the risk of a pool fire, without assessing the effectiveness and costs of these measures by conducting an EIS or equivalent study.

These features of NRC's regulatory approach yield significant, adverse impacts on the environment in the following respects. First, NRC's secrecy is likely to be counterproductive, suppressing a true understanding of risk and discouraging the use of appropriate measures of risk reduction. Second, secretive behavior by a governmental agency has adverse impacts on society and the economy. Third, NRC's secrecy and refusal to prepare an EIS undermine the potential to enhance protective deterrence by implementing protective measures of the type called for in the National Infrastructure Protection Plan.

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[149] NRC, 2008d, Section VI (B) (3).

The potential for secrecy to be counterproductive

An entrenched culture of secrecy will adversely affect the safety and security of nuclear facilities. Such a culture is not compatible with a clear-headed, science-based approach to the understanding of risk. Entrenched secrecy perpetuates dogma, stifles dissent, and can create a false sense of security. In illustration, the culture of secrecy in the former USSR was a major factor contributing to the occurrence of the 1986 Chernobyl reactor accident.[150]

Moreover, secrecy is limited in its effectiveness. Nuclear fission power is a mature technology based on science from the mid-20th century. Detailed information about nuclear technology and individual nuclear facilities is archived at many locations around the world, and large numbers of people have worked in nuclear facilities. Similarly, information about weapons and other devices that could be used to attack nuclear facilities is widely available. Large numbers of people have been trained to use such devices in a military context. Thus, it would be prudent to assume that sophisticated sub-national groups can identify and exploit vulnerabilities in US nuclear facilities.

The costs of secrecy

Secrecy is antithetical to US traditions and inconsistent with long-term national prosperity. Thus, when an EIS is conducted to assess design options for a nuclear facility, the EIS should consider the social and economic impacts of secrecy. That consideration would tend to favor options involving features such as hardening, resiliency and passive protection. Secrecy can be reduced or eliminated if such features are employed. In considering the impacts of secrecy, it should be remembered that nuclear facilities exist to serve society, rather than vice versa.[151]

NRC's undermining of protective deterrence

Section 7, above, discusses the role of protective deterrence as part of a balanced policy for homeland security. That role is illustrated by Table 8-1, which shows the strengths and weaknesses of options for protecting critical infrastructure from attack by sub-national groups. Table 8-1 shows the benefits that could flow from adoption of resilient design, passive defense, and other protective measures for infrastructure elements such as SNF or HLW storage facilities. The NIPP envisions the use of such measures. Yet, NRC does not require such measures, and refuses to allow their identification and assessment in an EIS. Moreover, NRC attempts to hide the true characteristics of existing nuclear facilities under a veil of secrecy. In effect, NRC endorses the use of offensive military

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[150] Thompson, 2002, Section X.

[151] NRC's Principles of Good Regulation state, in the context of openness: "Nuclear regulation is the public's business, and it must be transacted publicly and candidly". See: Principles of Good Regulation, accessed at the NRC web site (www.nrc.gov) on 20 November 2007.

operations, surveillance of the domestic population, and related measures as the primary means of protecting critical infrastructure. NRC appears to be willing to sustain that preference into the 22nd century.

An opportunity to eliminate secrecy regarding spent-fuel pools

Secrecy and its adverse impacts could be quickly eliminated in the context of spent-fuel pools. As discussed in Section 8, above, the pools could be re-equipped with low-density, open-frame racks, as was planned when the existing commercial reactors were designed. That option would dramatically reduce the probability of a pool fire, and would substantially reduce the inventory of radioactive material available for release if a fire did occur. There would no longer be any reasonable basis for secrecy regarding spent-fuel pools.

10. A NEPA-Compliant Approach to Regulation of SNF and HLW Storage

The National Environmental Policy Act (NEPA) requires, for US government actions that significantly affect the environment, systematic consideration of impacts and alternatives in an EIS. Licensing of a facility for storage of SNF or HLW is such an action, especially given the modes of storage that NRC has licensed.

This report shows that an SNF storage facility can pose a significant radiological risk, which is a form of environmental impact. Also, deficiencies in NRC regulation of the facility can cause other, significant impacts on the environment, as discussed in Section 9, above. This combined set of impacts could be considered in an EIS without any conceptual difficulty. If NRC were to perform such an EIS, NRC would be obliged to accurately assess the impacts of its own regulatory approach.

Consideration of malice-induced accidents in an EIS would pose two challenges. First, the probabilities of such accidents cannot be quantitatively estimated. Second, some analyses related to such accidents contain sensitive information and are therefore not appropriate for general publication.

Both challenges could be readily overcome. The probabilities of malice-induced accidents could be estimated qualitatively, and a numerical range could be used for illustrative calculations. NRC has well-established procedures for handling sensitive information, including procedures whereby intervenors in a licensing process that involves sensitive information can be represented by persons with security clearances.

If necessary, an EIS could have classified appendices. However, an EIS that is consistent with the purposes of NEPA would use secrecy sparingly, not as a veil to hide inconvenient information. Notably, such an EIS would explicitly identify and examine alternatives whose assessment does not require the use of sensitive information.

11. Conclusions

C1. NRC has enabled and encouraged the development of a de facto, national strategy for storing spent fuel from existing commercial reactors. Major elements of the strategy are: (i) storage of spent fuel, after discharge from a reactor, in a high-density pool; (ii) placement of the pool in close proximity to the reactor, with sharing of systems; (iii) accumulation of spent fuel in the pool until the pool is packed nearly to full capacity, followed by periodic offloading of older fuel from the pool to an on-site ISFSI in order to make room for newly-discharged fuel; and (iv) after permanent shut-down of the reactor, transfer of the remaining fuel from the pool to the ISFSI.

C2. The strategy described in conclusion C1 creates a substantial risk of radiological harm and, therefore, has severe, adverse impacts on the environment. The dominant component of the radiological risk arises from the potential for a fire in a spent-fuel pool following a loss of water from the pool. That event could be caused by a conventional accident or a malice-induced accident. The potential for a pool fire is exacerbated by the presence of an operating reactor in close proximity to a pool. Among other components of the radiological risk, the most significant component arises from the potential for a malice-induced accident to release radioactive material from an ISFSI.

C3. NRC has conducted some analyses related to the radiological risk described in conclusion C2. The analyses that have been published, taken together, provide an incomplete and inaccurate assessment of the risk. None of the published analyses meets the standards of an EIS prepared under NEPA. NRC has issued statements about the radiological risk associated with malice-induced accidents affecting spent fuel, but has neither published any technical analysis of that risk, nor published any citation to a secret analysis that could meet the standards of an EIS prepared under NEPA.

C4. NRC has conceded, in the Draft Update and other documents, that a fire could occur in a spent-fuel pool following a loss of water. NRC has also conceded that radioactive material released during a pool fire would have significant, adverse impacts on the environment. To offset those concessions, NRC argues that the probability of a pool fire is very low. NRC attributes the alleged low probability, in part, to unspecified, secret security measures and damage-control preparations that have been implemented at commercial reactors. NRC further attributes the alleged low probability, in part, to unspecified, secret studies that find that a fire would not break out in certain scenarios for loss of water from a pool. None of the arguments advanced by NRC to support its claim of low probability cites or provides an analysis that could meet the standards of an EIS prepared under NEPA.

C5. Options are available for reducing the radiological risk now associated with storage of spent fuel. Some of those options are entirely passive, and do not rely on active systems or human action. Options of that type are especially suitable for spent-fuel storage. Notably, spent-fuel pools could be re-equipped with low-density racks, as was intended when the existing reactors were designed, the excess fuel being moved to ISFSIs. That option would be entirely passive, and would dramatically reduce the potential for a pool fire. Also, the spent-fuel storage modules that are deployed at ISFSIs could be protected from attack by berming, underground placement, and/or stronger outer containers. Those options would be entirely passive, and would significantly reduce the risk of a malice-induced release of radioactive material from an ISFSI. Passive, robust options for risk reduction, such as the options outlined here for spent-fuel pools and ISFSIs, are protective measures of the type called for in the National Infrastructure Protection Plan.

C6. NRC has published some analyses of options for reducing the radiological risk associated with storage of spent fuel. None of those analyses considers the potential for malice-induced accidents. Nor does any of those published analyses meet the standards of an EIS prepared under NEPA. Also, NRC has never published any citation to a secret analysis, meeting the standards of an EIS prepared under NEPA, that examines options for reducing the radiological risk associated with storage of spent fuel.

C7. NRC has not required the use of risk-reducing options of the type outlined in conclusion C5. Nor has NRC analyzed risk-reducing options in the manner required by NEPA, as pointed out in conclusion C6. Instead, NRC claims that the radiological risk associated with spent-fuel storage is limited by secret studies and secret actions, in the following respects. First, says NRC, secret studies show that many accident scenarios would not lead to a large release of radioactive material. Second, says NRC, secret actions significantly reduce the probability of occurrence of accident scenarios that would lead to a large release of radioactive material. NRC takes that position in regard to pool fires, as mentioned in conclusion C4, and in regard to radioactive releases from ISFSIs. NRC appears to be unaware that the use of passive, robust options for risk reduction, of the type discussed in conclusion C5, could reduce or eliminate any need for secrecy.

C8. Conclusion C7 shows that NRC relies on secrecy as a primary measure for limiting the radiological risk associated with spent-fuel storage. NRC's heavy reliance on secrecy, and its refusal to perform risk analyses that meet the standards of an EIS prepared under NEPA, are significant deficiencies in NRC's approach to regulating the storage of spent fuel. NRC's reliance on secrecy has adverse impacts on the environment in two respects. First, secrecy is likely to be counterproductive, suppressing a true understanding of risk and discouraging the use of appropriate measures of risk reduction. Second, secretive behavior by a governmental agency has adverse impacts on society and the economy. In addition, NRC's overall regulatory approach, which combines secrecy with a lack of NEPA compliance, has adverse impacts on the defense and security of the USA. NRC's approach undermines the potential to enhance protective deterrence by implementing protective measures of the type called for in the National Infrastructure Protection Plan.

C9. The de facto, national strategy for storing spent fuel, as described in conclusion C1, creates the substantial risk of radiological harm that is described in conclusion C2. In addition, NRC's approach to the regulation of spent-fuel storage exacerbates the radiological risk and has adverse impacts on society, the economy, national defense and security, as summarized in conclusion C8. Taken together, the national strategy and NRC's regulatory approach have significant, adverse impacts on the environment. In the context of a particular reactor, the combined impacts are at a comparatively high level when the reactor is in its operational period, because the potential for a pool fire is the dominant component of radiological risk, and that potential is exacerbated by reactor operation. The combined impacts then continue at a lower level after permanent shut-down of the reactor, during any remaining period of ISFSI operation.

C10. Likely trends in the operation of existing reactors show a substantial part of the fleet operating into the 2040s, with the last reactor shutting down in 2055. The combined impacts described in conclusion C9 would continue at a comparatively high level during that period, and at a lower level thereafter. If new reactors commence operating and the present fuel-storage strategy continues, the combined impacts associated with that strategy could be expected to continue at a comparatively high level into the latter part of the 21st century and, potentially, into the 22nd century.

C11. Findings 3, 4 and 5 of NRC's Waste Confidence Decision should account for the environmental impacts summarized in conclusion C9, and for likely trends in those impacts as discussed in conclusion C10. No such accounting is provided in the 1990 version of the Decision or in the Draft Update. Finding 3 states that spent fuel "will be managed in a safe manner", the proposed Finding 4 states that spent fuel "can be stored safely without significant environmental impacts", and Finding 5 states that "safe" storage of spent fuel in an ISFSI will be provided if needed. None of those statements has a basis in credible analysis by NRC. The statement in proposed Finding 4 might be shown to be correct, with an emphasis on the word "can", if risk-reducing options of the type discussed in conclusion C5 were considered through analysis that meets the standards of NEPA.

C12. NRC's Proposed Rule should account for the environmental impacts summarized in conclusion C9, and for likely trends in those impacts as discussed in conclusion C10. No such accounting is provided. The Proposed Rule's statement that spent fuel "can be stored safely and without significant environmental impacts" has no basis in credible analysis by NRC. The statement might be shown to be correct, with an emphasis on the word "can", if risk-reducing options of the type discussed in conclusion C5 were considered through analysis that meets the standards of NEPA.

C13. The US government is pursuing, through the GNEP program at DOE, the development of alternative nuclear fuel cycles. Those cycles would involve the processing of spent fuel in facilities that would produce streams of HLW. The HLW waste forms would require storage prior to their placement in a repository. The storage period could be long. For example, some fuel cycles would involve the separation of cesium and strontium isotopes from the other constituents of spent fuel. The cesium and strontium isotopes would be incorporated into an HLW waste form that would be stored for about 300 years.

C14. NRC's present approach to the regulation of spent-fuel storage could set a precedent for regulation of the storage of HLW waste forms in the future. NRC currently allows spent fuel to be stored in a manner that creates significant, adverse impacts on the environment, and appears willing to allow these impacts to continue through the 21st century. The Draft Update and the Proposed Rule do not acknowledge the potential for NRC's present regulatory approach to set a precedent for regulating the storage of HLW waste forms that are produced in the future.

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Table 1-1
NRC Waste Confidence Findings, 1990 Version and Version Now Proposed by NRC

1990 Version	Proposed Version
Finding 1: The Commission finds reasonable assurance that safe disposal of high-level radioactive waste and spent fuel in a mined geologic repository is technically feasible.	Unchanged
Finding 2: The Commission finds reasonable assurance that at least one mined geologic repository will be available within the first quarter of the twenty-first century, and that sufficient repository capacity will be available within 30 years beyond the licensed life for operation (which may include the term of a revised or renewed license) of any reactor to dispose of the commercial high-level radioactive waste and spent fuel originating in such reactor and generated up to that time.	Finding 2: The Commission finds reasonable assurance that sufficient mined geologic repository capacity can reasonably be expected to be available within 50-60 years beyond the licensed life for operation (which may include the term of a revised or renewed license) of any reactor to dispose of the commercial high-level radioactive waste and spent fuel originating in such reactor and generated up to that time.
Finding 3: The Commission finds reasonable assurance that HLW and spent fuel will be managed in a safe manner until sufficient repository capacity is available to assure the safe disposal of all HLW and spent fuel.	Unchanged
Finding 4: The Commission finds reasonable assurance that, if necessary, spent fuel generated in any reactor can be stored safely and without significant environmental impacts for at least 30 years beyond the licensed life for operation (which may include the term of a revised or renewed license) of that reactor at its spent fuel storage basin, or at either onsite or offsite independent spent fuel storage installations.	Finding 4: The Commission finds reasonable assurance that, if necessary, spent fuel generated in any reactor can be stored safely without significant environmental impacts for at least 60 years beyond the licensed life for operation (which may include the term of a revised or renewed license) of that reactor in a combination of storage in its spent fuel storage basin and either onsite or offsite independent spent fuel storage installations.
Finding 5: The Commission finds reasonable assurance that safe independent onsite spent fuel storage or offsite spent fuel storage will be made available if such storage capacity is needed.	Unchanged

Source:
NRC, 2008a

Table 3-1
Cesium-137 Inventories and Other Indicators for Reactors, Spent-Fuel Pools and the ISFSI at Indian Point

Indicator	Indian Point 2	Indian Point 3
Rated power of reactor	3,216 MWt	3,216 MWt
Number of fuel assemblies in reactor core	193 assemblies	193 assemblies
Mass of uranium in reactor core	87 Mg	87 Mg
Typical period of full-power exposure of a fuel assembly (assuming refueling outages of 2-month duration at 24-month intervals, discharging 72 assemblies, capacity factor of 0.9 between outages)	4.4 yrs (during 5.4 calendar years)	4.4 yrs (during 5.4 calendar years)
Typical burnup of fuel assembly at discharge	59,370 MWt-days/MgU	59,370 MWt-days/MgU
Typical Cs-137 inventory in fuel assembly at discharge (assuming steady-state fission at 0.9x22/24 power for 5.4 yrs with an energy yield of 200 MeV per fission and a Cs-137 fission fraction of 6.0 percent)	0.082 MCi	0.082 MCi
Approx. Cs-137 inventory in reactor core (assuming 193 fuel assemblies with av. burnup = 50% of discharge burnup)	7.9 MCi	7.9 MCi
Cs-137 inventory in reactor core according to License Renewal Application	11.2 MCi	11.2 MCi
Capacity of spent-fuel pool	1,376 assemblies	1,345 assemblies
Cs-137 inventory in spent-fuel pool (assuming space for full-core unloading, av. assembly age after discharge = 15 yrs	68.6 MCi	66.8 MCi
Cs-137 inventory in one ISFSI module (assuming 32 fuel assemblies, av. age after discharge = 30 yrs)	1.3 MCi	

Source:
This table is adapted from Table 2-1 of: Thompson, 2007c.

Table 3-2
Illustrative Inventories of Cesium-137

Case	Inventory of Cesium-137
Produced during detonation of a 10-kilotonne fission weapon	0.002 MCi
Released to atmosphere during Chernobyl reactor accident of 1986	2.4 MCi
Released to atmosphere during nuclear-weapon tests, primarily in the 1950s and 1960s (Fallout was non-uniformly distributed across the planet, mostly in the Northern hemisphere.)	20 MCi
In Indian Point 2 spent-fuel pool during period of license extension	68.6 MCi
In Indian Point 3 spent-fuel pool during period of license extension	66.8 MCi
In IP2 or IP3 reactor core	11.2 MCi
In one storage module at the Indian Point ISFSI	1.3 MCi

Source:
This table is adapted from Table 2-2 of: Thompson, 2007c.

Table 5-1
Estimated Present Value of Cost Risk Associated with Atmospheric Releases from Conventional Accidents: Full Spectrum of Releases from a Core-Damage Event at the IP2 or IP3 Reactor; Fire in the IP2 or IP3 Spent-Fuel Pool

Indicator	**Affected Facility**		
	Indian Point 2 Reactor	**Indian Point 3 Reactor**	**Spent-Fuel Pool at the IP2 or IP3 Plant**
Type of radioactive release	Full spectrum of releases from core damage	Full spectrum of releases from core damage	Fire in the pool, following water loss
Present value of offsite cost risk, for internal + external initiating events	$3,635,924 (as in License Renewal Application)	$6,048,060 (as in License Renewal Application)	$9,923,394 (probability from NUREG-1353, offsite cost from study by Beyea et al)
Present value of onsite cost risk, for internal + external initiating events	$1,448,245 (as in License Renewal Application)	$1,351,583 (as in License Renewal Application)	Not estimated in this table
Total present value of cost risk, for internal + external initiating events	$5,084,168	$7,399,643	$9,923,394

Notes:
(a) This table is adapted from Table 6-3 of: Thompson, 2007c.
(b) The full spectrum of releases from each of the two reactors includes accident sequences in which the containment does not fail.
(c) Uncertainty in probability, and the potential for malice-induced accidents, are not considered in this table.
(d) Annual cost risk ($ per year) is converted to the present values shown here by accumulating the annual value over 20 years with a discount rate of 7 percent per year.

Table 6-1
Estimated Atmospheric Release of Radioactive Material and Downwind Inhalation Dose for Blowdown of the MPC in a Spent-Fuel-Storage Module

Indicator		**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		6.3 rem	48 rem	79 rem

Notes:

(a) Estimates are from: Gordon Thompson, *Estimated Downwind Inhalation Dose for Blowdown of the MPC in a Spent Fuel Storage Module*, IRSS, June 2007.
(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 6-2
Illustrative Calculation of Heat-Up of a Fuel Rod in a PWR Fuel Assembly Due to Combustion in Air

Indicator	**Affected Material**	
	Zircaloy Cladding	**UO_2 Pellets**
Solid volume, per m length	1.90E-05 cub. m (OD = 1.07 cm; thickness = 0.06 cm)	6.36E-05 cub. m (OD = 0.9 cm)
Mass, per m length	0.124 kg (@ 6.55 Mg per cub. m)	0.700 kg (@ 11.0 Mg per cub. m)
Heat output from combustion of material in air, per m length	1.48 MJ (@ 2,850 cal per g Zr)	Neglected
Equilibrium temperature rise if material receives 50% of heat output from adjacent combustion, and if heat loss from material is neglected	Neglected	approx. 2,700 deg. C (Note: The enthalpy rise if UO_2 temp. rises from 300 K to 3,000 K = 1,052 kJ per kg UO_2)

Notes:
(a) Data shown in table are from: Nero, 1979, Table 5-1; Powers et al, 1994, Table 4; and files accessed at International Nuclear Safety Center (INSC), Argonne National Laboratory, <http://www.insc.anl.gov/>, in March 2008.
(b) Melting point of UO_2 is 2,850 deg. C (from INSC files).
(c) Boiling point of elemental cesium is 685 deg. C (from: Thompson and Beckerley, 1973, Volume 2, page 527).
(d) 1 cal = 4.184 J

Table 7-1
Public Opinion in Four Muslim Countries Regarding the US "War on Terrorism"

Country	**Percentage of Respondents Who Think that the Primary Goal of What the US Calls "the War on Terrorism" is to:**		
	Weaken and Divide the Islamic Religion and its People	**Achieve Political and Military Domination to Control Middle East Resources**	**Protect Itself from Terrorist Attacks**
Morocco	33	39	19
Egypt	31	55	9
Pakistan	42	26	12
Indonesia	29	24	23

Notes:
(a) Data are from: Steven Kull et al, *Muslim Public Opinion on US Policy, Attacks on Civilians and al Qaeda*, Program on International Policy Attitudes, University of Maryland, 24 April 2007.
(b) Percentages not shown in each row are "do not know" or "no response".

Table 7-2
Opinions of Selected Experts Regarding the Probability of Another 9/11-Type Attack in the United States

Time Horizon for Potential Attack	**Fraction of Interviewed Experts Holding Position (percent)**	
	Attack has No Chance or is Unlikely	**Attack is Likely or Certain**
Within 6 months	80	20
Within 5 years	30	70
Within 10 years	17	83

Notes:
(a) These and other survey data are discussed in: "The Terrorism Index", *Foreign Policy*, September/October 2007, pp 60-67. The underlying data are from: "Terrorism Survey III", June 2007, accessed from the website of the Center for American Progress <www.americanprogress.org> on 21 August 2007.
(b) The following question was posed to 108 US-based experts in international security: "What is the likelihood of a terrorist attack on the scale of the 9/11 attacks occurring again in the United States in the following time frames?"

Table 7-3
Future World Scenarios Identified by the Stockholm Environment Institute

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

Source:
Paul Raskin et al, *Great Transition: The Promise and Lure of the Times Ahead*, Stockholm Environment Institute, 2002.

Table 7-4
Some Potential Modes and Instruments of Attack on a US Nuclear Power Plant

Attack Mode/Instrument	Characteristics	Present Defense
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
Anti-tank missile	• 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:
This table is adapted from Table 7-4 of: Thompson, 2007c. Sources supporting this table include:
(a) Jim Wells, US Government Accountability Office, testimony before the Subcommittee on National Security, Emerging Threats and International Relations, US House Committee on Government Reform, 4 April 2006.
(b) Marvin Fertel, Nuclear Energy Institute, testimony before the Subcommittee on National Security, Emerging Threats and International Relations, US House Committee on Government Reform, 4 April 2006.
(c) Danielle Brian, Project on Government Oversight, letter to NRC chair Nils J. Diaz, 22 February 2006.
(d) National Research Council, *Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report*, National Academies Press, 2006.

Table 7-5
Potential Sabotage Events at a Spent-Fuel-Storage Pool, as Postulated in NRC's August 1979 GEIS on Handling and Storage of Spent LWR Fuel

Event Designator	General Description of Event	Additional Details
Mode 1	• Between 1 and 1,000 fuel assemblies undergo extensive damage by high-explosive charges detonated under water • Adversaries commandeer the central control room and hold it for approx. 0.5 hr to prevent the ventilation fans from being turned off	• One adversary can carry 3 charges, each of which can damage 4 fuel assemblies • Damage to 1,000 assemblies (i.e., by 83 adversaries) is a "worst-case bounding estimate"
Mode 2	• Identical to Mode 1 except that, in addition, an adversary enters the ventilation building and removes or ruptures the HEPA filters	
Mode 3	• Identical to Mode 1 within the pool building except that, in addition, adversaries breach two opposite walls of the building by explosives or other means	• Adversaries enter the central control room or ventilation building and turn off or disable the ventilation fans
Mode 4	• Identical to Mode 1 except that, in addition, adversaries use an additional explosive charge or other means to breach the pool liner and 5-ft-thick concrete floor of the pool	

Notes:
(a) Information in this table is from Appendix J of: USNRC, *Generic EIS on Handling and Storage of Spent Light Water Power Reactor Fuel, NUREG-0575*, August 1979.
(b) The postulated fuel damage ruptures the cladding of each rod in an affected fuel assembly, releasing "contained gases" (gap activity) to the pool water, whereupon the released gases bubble to the water surface and enter the air volume above that surface.

Table 7-6
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 an unclassified, published report (citation is voluntarily withheld here) • Purpose is to penetrate large thicknesses of rock or concrete as the first stage of a "tandem" warhead • Configuration is a cylinder with a diameter of 71 cm and a length of 72 cm • When tested in November 2002, created a hole of 25 cm diameter in tuff rock to a depth of 5.9 m • Device has a mass of 410 kg; would be within the payload capacity of many general-aviation aircraft
A potential delivery vehicle	• A Beechcraft King Air 90 general-aviation aircraft will carry a payload of up to 990 kg at a speed of up to 460 km/hr • A used King Air 90 can be purchased in the US for $0.4-1.0 million

Source:
This table is adapted from Table 7-6 of: Thompson, 2007c.

Table 7-7
Performance of US Army Shaped Charges, M3 and M2A3

Target Material	**Indicator**	**Type of Shaped Charge**	
		M3	**M2A3**
Reinforced concrete	Maximum wall thickness that can be perforated	60 in	36 in
	Depth of penetration in thick walls	60 in	30 in
	Diameter of hole	• 5 in at entrance • 2 in minimum	• 3.5 in at entrance • 2 in minimum
	Depth of hole with second charge placed over first hole	84 in	45 in
Armor plate	Perforation	At least 20 in	12 in
	Average diameter of hole	2.5 in	1.5 in

Notes:
(a) Data are from: Army, 1967, pp 13-15 and page 100.
(b) The M2A3 charge has a mass of 12 lb, a maximum diameter of 7 in, and a total length of 15 in including the standoff ring.
(c) The M3 charge has a mass of 30 lb, a maximum diameter of 9 in, a charge length of 15.5 in, and a standoff pedestal 15 in long.

Table 7-8
Types of Atmospheric Release from a Spent-Fuel-Storage Module at an ISFSI as a Result of a Potential Attack

Type of Event	Module Behavior	Relevant Instruments and Modes of Attack	Characteristics of Atmospheric Release
Type I: Vaporization	• Entire module is vaporized	• Module is within the fireball of a nuclear-weapon explosion	• Radioactive content of module is lofted into the atmosphere and amplifies fallout from nuc. explosion
Type II: Rupture and Dispersal (Large)	• MPC and overpack are broken open • Fuel is dislodged from MPC and broken apart • Some ignition of zircaloy fuel cladding may occur, without sustained combustion	• Aerial bombing • Artillery, rockets, etc. • Effects of blast etc. outside the fireball of a nuclear weapon explosion	• Solid pieces of various sizes are scattered in vicinity • Gases and small particles form an aerial plume that travels downwind • Some release of volatile species (esp. cesium-137) if incendiary effects occur
Type III: Rupture and Dispersal (Small)	• MPC and overpack are ruptured but retain basic shape • Fuel is damaged but most rods retain basic shape • No combustion inside MPC	• Vehicle bomb • Impact by commercial aircraft • Perforation by shaped charge	• Scattering and plume formation as for Type II event, but involving smaller amounts of material • Little release of volatile species
Type IV: Rupture and Combustion	• MPC is ruptured, allowing air ingress and egress • Zircaloy fuel cladding is ignited and combustion propagates within the MPC	• Missiles with tandem warheads • Close-up use of shaped charges and incendiary devices • Thermic lance • Removal of overpack lid	• Scattering and plume formation as for Type III event • Substantial release of volatile species, exceeding amounts for Type II release

Table 7-9
Estimated Present Value of Cost Risk of a Potential Atmospheric Release from a Reactor or Spent-Fuel Pool at Indian Point, Including a Release Caused by an Attack

<table>
<tr><th rowspan="2">Type of Event</th><th colspan="3">Estimated Present Value of Cost Risk for Affected Facility</th></tr>
<tr><th>Indian Point 2 Reactor</th><th>Spent-Fuel Pool at the IP2 or IP3 Plant</th><th>Indian Point 3 Reactor</th></tr>
<tr><td>Full spectrum of releases from reactor core damage, for internal + external initiating events (excluding attack) plus uncertainty</td><td>$10.7 million (as in License Renewal Application)</td><td>Not applicable</td><td>$10.7 million (as in License Renewal Application)</td></tr>
<tr><td>Fire in pool, for internal + external initiating events (excluding attack) plus uncertainty</td><td>Not applicable</td><td>$27.7 million (assuming probability as in NUREG-1353)</td><td>Not applicable</td></tr>
<tr><td>Attack on reactor assuming probability of 1 per 10,000 reactor-years</td><td>$73.2 million</td><td>Not applicable</td><td>$62.4 million</td></tr>
<tr><td>Attack on pool assuming probability of 1 per 10,000 reactor-years</td><td>Not applicable</td><td>$498 million</td><td>Not applicable</td></tr>
<tr><td>Attack on IP2 reactor and pool assuming probability of 1 per 10,000 reactor-years</td><td colspan="2">$569 million</td><td>Not applicable</td></tr>
<tr><td>Attack on IP3 reactor and pool assuming probability of 1 per 10,000 reactor-years</td><td>Not applicable</td><td colspan="2">$559 million</td></tr>
</table>

(Notes for this table are on the following page.)

Notes for Table 7-9:

(a) This table is adapted from Table 7-7 of: Thompson, 2007c.

(b) In the second row, the probability of a pool fire is assumed, following NUREG-1353, to be 2.0E-06 per reactor-year adjusted by an uncertainty multiplier (the ratio of 95th percentile to mean probability) of 2.78. That multiplier is taken from Table 4.6.8 of NUREG-1353, for a 99% cutoff value. The fire is assumed to yield an atmospheric release of 35 MCi of Cs-137, with accompanying offsite costs of $461 billion as estimated by Beyea et al.

(c) An attack on a reactor is assumed here to yield an atmospheric release and accompanying offsite costs as estimated in the License Renewal Application for an Early High release.

(d) An attack on a spent-fuel pool is assumed here to initiate a fire that yields an atmospheric release of 35 MCi of Cs-137, with accompanying offsite costs of $461 billion as estimated by Beyea et al.

(e) A core-damage event and/or a spent-fuel-pool fire at each unit is assumed here to yield onsite costs of $2 billion, as estimated in the License Renewal Application for a core-damage event at IP2 or IP3.

(f) Present value is determined by accumulating annual value over 20 years with a discount rate of 7 percent per year.

Table 8-1
Selected Approaches to Protecting US Critical Infrastructure From Attack by Sub-National Groups, and Some of the 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 USA	• Could promote growth of sub-national groups hostile to the USA, and build sympathy for these groups in foreign populations • Could be costly in terms of lives, money and national reputation
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
Resilient design, passive defense, and related protective measures for infrastructure facilities (as envisioned in the NIPP)	• 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

Table 8-2
Selected Options to Reduce the Risk of a Spent-Fuel-Pool Fire at a Commercial Reactor

Option	Passive or Active?	Does Option Address Fire Scenarios Arising From:		Comments
		Malice?	Other Events?	
Re-equip pool with low-density, open-frame racks	Passive	Yes	Yes	• Will substantially reduce pool inventory of radioactive material • Will 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 can feed Zr-steam reaction
Mix hotter (younger) and colder (older) fuel in pool	Passive	Yes	Yes	• Can delay or prevent auto-ignition in some cases • Will be ineffective if debris or residual water block air flow • Can promote fire propagation to older fuel
Minimize movement of spent-fuel cask over pool	Active	No (Most cases)	Yes	• Can conflict with adoption of low-density, open-frame racks
Deploy air-defense system (e.g., Sentinel and Phalanx) at site	Active	Yes	No	• Implementation requires presence of US military at site
Develop enhanced onsite capability for damage control	Active	Yes	Yes	• Requires new equipment, staff and training • Personnel must function in extreme environments

Table 8-3
Estimation of Incremental Cost if Spent Fuel from a New PWR is Transferred from the Spent-Fuel Pool to Dry Storage After 5 Years of Storage in the Pool

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

Notes:
(a) This calculation employs data that apply to the Indian Point 2 nuclear power plant. Similar data apply to other US plants.
(b) Data in this table are from Tables 2-1 and 9-2 of: Thompson, 2007c.
(c) The capital cost begins in the 11th year of plant operation, and continues while the plant operates.