INSTITUTE FOR RESOURCE AND SECURITY STUDIES
27 Ellsworth Avenue, Cambridge, Massachusetts 02139, USA

Declaration of 19 December 2013
by Gordon R. Thompson:

Comments on the US Nuclear Regulatory Commission's
Waste Confidence Generic Environmental Impact Statement,
Draft Report for Comment (September 2013)

I, Gordon R. Thompson, declare as follows:

I. Introduction

(I-1) I am the executive director of the Institute for Resource and Security Studies (IRSS), a nonprofit, tax-exempt corporation based in Massachusetts. Our office is located at 27 Ellsworth Avenue, Cambridge, MA 02139. IRSS was founded in 1984 to conduct technical and policy analysis and public education, with the objective of promoting peace and international security, efficient use of natural resources, and protection of the environment. My professional qualifications are discussed in Section II, below.

(I-2) I have been retained by a group of environmental organizations to prepare this declaration.[1] This declaration provides comments invited by the US Nuclear Regulatory Commission (NRC).[2] NRC has invited comments on a September 2013 draft version of a generic environmental impact statement (GEIS) that addresses the subject of "waste confidence".[3] In the remainder of this declaration I refer to that document as the "draft GEIS". The stated objective of the draft GEIS is to:[4] "examine the potential environmental impacts that could occur as a result of the continued storage of spent

[1] These organizations include: Alliance to Halt Fermi 3, Beyond Nuclear, Blue Ridge Environmental Defense League, Center for a Sustainable Coast, Citizens Allied for Safe Energy, Citizens' Environmental Coalition, Don't Waste Michigan, Ecology Party of Florida, Friends of the Coast, Friends of the Earth, Georgia Women's Action for New Directions, Green States Solutions, Hudson River Sloop Clearwater, Missouri Coalition for the Environment, NC WARN, Nevada Nuclear Waste Task Force, New England Coalition, No Nukes Pennsylvania, Northwest Environmental Advocates, Nuclear Energy Information Service, Nuclear Information and Resource Service, Nuclear Watch South, Physicians for Social Responsibility, Public Citizen, Promoting Health and Sustainable Energy, Radiation and Public Health Project, Riverkeeper, SEED Coalition, San Clemente Green, San Luis Obispo Mothers for Peace, Sierra Club Nuclear Free Campaign, Snake River Alliance, Southern Alliance for Clean Energy, and Vista 360.
[2] NRC, 2013a.
[3] NRC, 2013b.
[4] NRC, 2013b, page iii.

nuclear fuel (spent fuel) at at-reactor and away-from-reactor sites until a repository is available."

(I-3) NRC states that it has prepared the draft GEIS to support a proposed rule.[5] The proposed rule is the most recent of a sequence of formal NRC findings, over several decades, about waste confidence. In this context, the term "waste" refers to spent nuclear fuel (SNF) or other forms of high-level radioactive waste (HLW) arising from the operation of commercial nuclear reactors.

(I-4) In a declaration dated 2 January 2013, I set forth 22 recommendations for the scope of the draft GEIS, together with information and analysis to support those recommendations.[6] Hereafter, I refer to that declaration as the "Thompson scoping declaration". It accompanies this declaration as Exhibit #1. In the present declaration, I incorporate by reference the information, analysis, and recommendations provided in the Thompson scoping declaration.

(I-5) This declaration addresses selected issues. Absence of discussion of an issue in this declaration does not imply that I view the issue as insignificant, or that I have no professional opinion on the manner in which the issue has been addressed in the draft GEIS.

(I-6) The issues discussed in this declaration are outlined in Section III, below. These issues all pertain to the concept of radiological risk, whose definition is discussed in Section IV, below. In this declaration the term "radiological risk" refers to the potential for harm to humans as a result of unplanned exposure to ionizing radiation. The consequences of this exposure could be direct or indirect. In the context of the draft GEIS, the set of direct and indirect consequences constitutes a set of environmental impacts.

(I-7) When spent fuel is discharged from a reactor of the type now used in the USA, it is initially stored under water in a pool adjacent to the reactor. The fuel assemblies are held upright in racks sitting on the floor of the pool. At each commercial reactor in the USA, the adjacent pool is now equipped with high-density, closed-frame racks. The nuclear industry began installing these racks in the 1970s, to replace the low-density, open-frame racks previously used. The high-density racks offered a comparatively cheap option for storing a growing nationwide inventory of spent fuel.

(I-8) At each commercial reactor in the USA, fuel takes the form of long, narrow tubes made of zirconium alloy (i.e., zircaloy), containing uranium oxide pellets. A group of these tubes makes up a fuel assembly. The zircaloy tubes are often referred to as fuel "cladding". Zircaloy has the property that at a comparatively high temperature (e.g.,

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[5] NRC, 2013c.
[6] Thompson, 2013b.

about 900 °C) it can begin reacting exothermically (i.e., with production of heat) with either air or steam.

(I-9) Spent fuel generates internal heat from decay of radioactive isotopes. When the fuel is under water in a normally functioning pool, the decay heat enters the surrounding water, which is in turn cooled by pumping it through heat exchangers. However, if the water level were to fall below the top of the fuel, the fuel temperature would begin to rise. This temperature rise would be exacerbated by storage of spent fuel in high-density, closed-frame racks, as is now universally practiced in the USA. The fuel temperature could continue rising to the point at which an exothermic reaction of zircaloy with air or steam would begin. That reaction could then accelerate, in a runaway process. In this manner, loss of water from a pool could lead to a self-propagating exothermic reaction of zircaloy cladding with air or steam. That phenomenon is often referred to as a "pool fire". Conditions determining the onset and progression of a pool fire would include the timing of water loss and the level of decay heat production in the fuel. The level of decay heat production declines with increasing age of the fuel after discharge from a reactor.

(I-10) As part of its consideration of radiological risk, the draft GEIS considers the potential for a pool fire. Later in this declaration, I show that the draft GEIS is deficient in its examination of both the probability and the consequences of a pool fire. In examining these matters, the draft GEIS cites a number of studies that NRC has performed in the context of pool fires.

(I-11) In June 2013, NRC published a draft version of a pool-fire study that is not cited in the draft GEIS. That study is titled "Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a US Mark I Boiling Water Reactor".[7] Hereafter, I refer to that study as "NRC's draft consequence study". It accompanies this declaration as Exhibit #2. In a declaration dated 1 August 2013, I provided a critical review of NRC's draft consequence study, with recommendations for further NRC investigation in this area.[8] Hereafter, I refer to that declaration as the "Thompson draft consequence declaration". It accompanies this declaration as Exhibit #3. In the present declaration, I incorporate by reference the information, analysis, and recommendations provided in the Thompson draft consequence declaration. NRC's draft consequence study was re-published in final form in October 2013, with no substantial change.[9] Thus, my critical review of the draft study had no effect on the final study. I assume that the technical parts of the draft and final versions are identical. Thus, the Thompson draft consequence declaration applies equally to both.

[7] Barto et al, 2013a.
[8] Thompson, 2013a.
[9] The October 2013 version is: Barto et al, 2013b. It was published as an enclosure under the SECY memo: Satorius, 2013a. That memo stated: "None of the comments or responses [i.e., on the draft version of the study] has necessitated making substantial changes to the report." (See: Satorius, 2013a, page 3.)

(I-12) The draft GEIS assumes that spent fuel will be stored initially in pools and subsequently in dry casks. The potential for a pool fire has been mentioned above. There is also a potential for a "cask fire". Such an event could occur if a malevolent actor gains access to a dry cask containing spent fuel and attacks the cask in a manner that produces a self-propagating reaction between air and zircaloy fuel cladding. Later in this declaration, I address the probability and consequences of a cask fire.

(I-13) As mentioned in paragraph I-6, above, the issues discussed in this declaration all pertain to radiological risk. Accordingly, I focus my comments on the draft GEIS on selected portions of that document. Portions of the draft GEIS that I address include, but are not limited to:

- Section 4.18 – Environmental Impacts of Postulated Accidents
- Section 4.19 – Potential Acts of Sabotage or Terrorism
- Appendix F – Spent Fuel Pool Fires

(I-14) As mentioned in paragraph I-2, above, this declaration has been prepared on behalf of a group of environmental organizations. This declaration complements three other declarations – by Arjun Makhijani, David Lochbaum, and Mark Cooper – prepared on behalf of the same group of environmental organizations.

(I-15) This declaration has the following narrative sections:

I. Introduction
II. My Professional Qualifications
III. Issues Discussed in this Declaration
IV. Definition of Radiological Risk
V. Estimation of Radiological Risk
VI. Malevolent Acts and Radiological Risk
VII. The Future Risk Environment
VIII. Linkage of Pool Risk and Reactor Risk
IX. Risk Implications of Nuclear-Power Scenarios
X. Pool Fire: Probability and Consequences
XI. Cask Fire: Probability and Consequences
XII. Risk-Reducing Options
XIII. Conclusions

(I-16) In addition to the above-named narrative sections, this declaration has four appendices that are an integral part of the declaration. Appendix A contains tables and figures that support the narrative. Appendix B is a bibliography. Documents cited in the narrative or in Appendix A are listed in Appendix B unless otherwise identified. Appendix C is a list of exhibits that accompany this declaration. Each exhibit is a document that is listed in Appendix B. My curriculum vitae is provided in Appendix D.

II. My Professional Qualifications

(II-1) As stated in paragraph I-1, above, I am the executive director of the Institute for Resource and Security Studies. In addition, I am a senior research scientist at the George Perkins Marsh Institute, Clark University. My curriculum vitae is provided here in Appendix D.

(II-2) I received an undergraduate education in science and mechanical engineering at the University of New South Wales, in Australia, and practiced engineering in Australia in the electricity sector. Subsequently, I pursued graduate studies at Oxford University and received from that institution a Doctorate of Philosophy in mathematics in 1973, for analyses of plasma undergoing thermonuclear fusion. During my graduate studies I was associated with the fusion research program of the UK Atomic Energy Authority. My undergraduate and graduate work provided me with a rigorous education in the methodologies and disciplines of science, mathematics, and engineering.

(II-3) My professional work involves technical and policy analysis in the fields of energy, environment, sustainable development, human security, and international security. Since 1977, a significant part of my work has consisted of analyses of the radiological risk posed by commercial and military nuclear facilities. These analyses have been sponsored by a variety of non-governmental organizations and local, state and national governments, predominantly in North America and Western Europe. Drawing upon these analyses, I have provided expert testimony in legal and regulatory proceedings, and have served on committees advising US government agencies.

(II-4) To a significant degree, my work has been accepted or adopted by relevant governmental agencies. During the period 1978-1979, for example, I served on an international review group commissioned by the government of Lower Saxony (a state in Germany) to evaluate a proposal for a nuclear fuel cycle center at Gorleben. I led the subgroup that examined radiological risk and identified alternative options with lower risk.[10] One of the risk issues that I personally identified and analyzed was the potential for a pool fire. In examining that potential, I identified partial loss of water from a pool as a more severe condition than total loss of water. I identified a variety of events that could cause loss of water from a pool, including aircraft crash, sabotage, neglect, and acts of war. Also, I identified and described alternative SNF storage options with lower risk; these lower-risk options included design features such as spatial separation, natural cooling, and underground vaults. The Lower Saxony government accepted my findings about the risk of a pool fire, and ruled in May 1979 that high-density pool storage of spent fuel was not an acceptable option at Gorleben.[11] That ruling accompanies this declaration as Exhibit #4. As a direct result of that ruling, policy throughout Germany

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[10] Beyea et al, 1979.
[11] Albrecht, 1979.

has been to use dry storage in casks, rather than high-density pool storage, for away-from-reactor storage of SNF.

(II-5) Since 1979, I have been based in the USA. During the subsequent years, I have been involved in a number of NRC regulatory proceedings related to the radiological risk posed by storage of SNF. In that context I have prepared a number of declarations and expert reports. For example, in 2009 I prepared a report that critiqued proposed NRC findings on waste confidence.[12] That report accompanies this declaration as Exhibit #5. Also, I co-authored a 2003 journal article, on SNF radiological risk, that received considerable attention from relevant stakeholders.[13] That article accompanies this declaration as Exhibit #6. The findings in that article were generally confirmed by a subsequent report by the National Research Council.[14] That report accompanies this declaration as Exhibit #7. As a result of my cumulative experience, I am generally familiar with: (i) US practices for managing SNF; (ii) the radiological risk posed by those practices; (iii) NRC regulation of that risk; and (iv) alternative options for reducing that risk. Also, I am familiar with the US effort since the 1950s to implement final disposal of SNF and HLW, and have written a review article on that subject.[15] That article accompanies this declaration as Exhibit #8.

(II-6) I have performed a number of studies on the potential for commercial or military nuclear facilities to be attacked directly or to experience indirect effects of violent conflict. A substantial part of that work relates to the radiological risk posed by storage of SNF or HLW. For example, in 2005 I was commissioned by the UK government's Committee on Radioactive Waste Management (CORWM) to prepare a report on reasonably foreseeable security threats to options for long-term management of UK radioactive waste.[16] That report accompanies this declaration as Exhibit #9. The time horizon used in that report was, by CORWM's specification, 300 years.

(II-7) On behalf of the Nautilus Institute, I prepared a handbook that analysts in various countries could use to support their assessment of radiological risk arising from management of spent fuel.[17] That handbook accompanies this declaration as Exhibit #10.

III. Issues Discussed in this Declaration

(III-1) The primary purpose of this declaration is to provide comments on the draft GEIS, regarding selected issues. These issues all pertain to radiological risk, with a focus on the potential for a pool fire or a cask fire. The definition of radiological risk may appear to be an academic matter, but it has substantial practical implications. I discuss this matter in Section IV, below, explaining why I reject the definition employed in the

[12] Thompson, 2009.
[13] Alvarez et al, 2003.
[14] National Research Council, 2006.
[15] Thompson, 2008.
[16] Thompson, 2005.
[17] Thompson, 2013c.

draft GEIS. In addressing radiological risk in this declaration, I focus on the potential for an unplanned release of radioactive material, especially an atmospheric release. Within that focus, I consider two categories of initiating event for the release: (i) accidents; and (ii) attacks. Accidents would involve events such as equipment failure, human error, or natural forces (e.g., earthquake). Attacks would involve deliberate, malevolent acts or the collateral effects of such acts. Accidents and attacks have features in common. Therefore, they should be considered in parallel, which is the approach I take in this declaration.

(III-2) Analysts who examine the radiological risk associated with potential attacks affecting nuclear facilities have a double duty. First, they owe the public an accurate, general picture of the risk. Second, they should refrain from publishing information that could directly assist a potential attacker. This declaration is designed to meet both requirements. Also, this declaration does not purport to provide an assessment of radiological risk. Instead, it comments on the risk assessment provided in the draft GEIS. From that perspective this declaration is, I believe, accurate and reasonably complete. At the same time, this declaration does not provide information that could directly assist an attack on a particular nuclear facility. Accordingly, this declaration is appropriate for general distribution.

(III-3) After radiological risk is properly defined, one can identify quantitative and qualitative indicators that, taken together, describe the risk in a particular situation. Then, analysts can seek to estimate values for those indicators. The resulting set of values constitutes a risk assessment. Section V, below, discusses approaches that can be used to estimate the values of relevant indicators. In that discussion I describe the strengths and limitations of probabilistic risk assessment (PRA), which provides the basis for the draft GEIS's estimation of radiological risk.

(III-4) Section VI, below, provides some background discussion on the contribution of malevolent acts (i.e., attacks) to radiological risk. Section VII provides some background discussion on the "risk environment", a term that refers to the array of societal, technical, and natural factors that, taken together, have significant influence on the radiological risk posed by a particular facility. Those discussions inform this declaration's critique, in Sections X and XI and elsewhere, of risk assessment in the draft GEIS.

(III-5) The potential for a pool fire can be affected by the potential for a radioactive release from a nearby, operational reactor, and vice versa. In other words, the radiological risks associated with a pool and with a nearby reactor can be linked. Section VIII discusses the nature and significance of this linkage, and its neglect in the draft GEIS. The linkage is discussed further in Section X.

(III-6) The development of waste-related radiological risk over future decades would be affected by the nature and scale of activity in the country's nuclear-power sector during that period. Section IX discusses the risk implications of nuclear-power scenarios, and NRC's neglect of this issue in the draft GEIS.

(III-7) Section X provides a critical review of the assessment of pool-fire risk in the draft GEIS, in terms of probability and consequences. Section XI discusses the probability and consequences of a cask fire, and NRC's neglect of this threat in the draft GEIS.

(III-8) Section XII discusses options for reducing waste-related radiological risk, and NRC's neglect of these options in the draft GEIS.

(III-9) Conclusions are presented in Section XIII.

IV. Definition of Radiological Risk

(IV-1) In this declaration, I define the general term "risk" as the potential for an unplanned, undesired outcome. Risk, so defined, is an inevitable part of human existence. However, many aspects of risk can be managed. That is especially true when the risk arises from a technological project. In such a case, the first step in risk management is to understand, as deeply as possible, the risk arising from the project. The second step is to identify and characterize a range of options for reducing the risk. The remaining steps are to choose, implement, and follow up a set of risk-reducing options.

(IV-2) Table IV-1 shows some categories of risk that could be posed by a commercial nuclear facility. I define radiological risk as the potential for harm to humans as a result of unplanned exposure to ionizing radiation. The exposure could arise from unplanned release of radioactive material, or from line-of-sight exposure to unshielded radioactive material or a criticality event. In this declaration I focus on exposure arising from an unplanned release, especially an atmospheric release. That mode of exposure would typically dominate the radiological risk posed by storage of SNF or HLW, at least during the first few centuries of storage.

(IV-3) By defining radiological risk as "the potential for harm", I do not mean to imply that any single indicator can adequately describe this risk. To the contrary, assessment of radiological risk requires the compiling of a set of qualitative and quantitative information about the likelihood and characteristics of the unplanned exposure and resulting harm. The required information can be expressed as values of qualitative and quantitative indicators.

(IV-4) NRC has articulated several, inconsistent definitions of risk. The definition in the NRC Glossary is, on its face, similar to my definition. Other NRC definitions, discussed below, deviate from the NRC Glossary to the point where they become fundamentally flawed. The NRC Glossary defines risk as:[18]

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[18] NRC website, http://www.nrc.gov/reading-rm/basic-ref/glossary/risk.html, accessed on 21 October 2013.

> "The combined answer to three questions that consider (1) what can go wrong, (2) how likely it is, and (3) what its consequences might be. These three questions allow the NRC to understand likely outcomes, sensitivities, areas of importance, system interactions, and areas of uncertainty, which can be used to identify risk-significant scenarios."

(IV-5) In the draft GEIS, the concept of risk is first introduced using a definition close to, but not identical with, the definition in NRC's Glossary. The Executive Summary of the draft GEIS says:[19]

> "NRC's concept of risk combines the *probability* of an accident with the *consequences of that accident.* In other words, the NRC examines the following questions:
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> - What can go wrong?
> - How likely is it?
> - What would be the consequences?"

(IV-6) Later in the draft GEIS, the definition of risk deviates further from NRC's Glossary and becomes fundamentally flawed. In Section 4 of the draft GEIS, this later definition is embedded in an instructive paragraph. The paragraph is:[20]

> "The consequences of a severe (or beyond-design-basis) accident, if one occurs, could be significant and destabilizing. The impact determinations for these accidents, however, are made with consideration of the low probability of these events. The environmental impact determination with respect to severe accidents, therefore, is based on the **risk, which the NRC defines as the product of the probability and the consequences of an accident**. This means that a high-consequence low-probability event, like a severe accident, could still result in a small impact determination, if the risk is sufficiently low."

(IV-7) Through this deviation, NRC has ended up with a particular, limited definition of risk, as the arithmetic product of a numerical indicator of harmful consequences and a numerical indicator of the probability that those consequences will occur.[21] I refer to that definition hereafter as the "arithmetic" definition of risk. The arithmetic definition is flawed from several perspectives, as discussed below. It is, however, used extensively in the nuclear industry.

(IV-8) The above-quoted paragraph from the draft GEIS suggests a powerful motive for use of the arithmetic definition of risk. Consider the following situation. The consequences of a potential event could be severe; indeed, they could be "significant and

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[19] NRC, 2013b, page xxx.
[20] NRC, 2013b, pages 4-68 and 4-69 (emphasis added).
[21] Often, the arithmetic product is calculated for each of a range of scenarios, and these products are summed across the scenarios to yield an overall "risk".

destabilizing", to use the words of the draft GEIS. Yet, if the event has, allegedly, a sufficiently low probability, then its "risk", arithmetically defined, would be very low. A devotee of the arithmetic definition could then argue that no action is required to mitigate the risk. In that way, the cost of mitigating actions would be avoided.

(IV-9) In the context of radiological risk in the commercial nuclear sector, the arithmetic definition of risk is flawed from at least four overlapping perspectives:

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

(IV-10) I address the first and second of these four perspectives in Section V, below, and elsewhere in this declaration. I address the third and fourth perspectives in the remainder of Section IV, and elsewhere in this declaration.

(IV-11) The third perspective is that larger consequences can be qualitatively different than smaller consequences. There is ample evidence to support this proposition. For example, analysts at the French government's Institut de Radioprotection et de Surete Nucleaire (IRSN) have found a qualitative difference between larger and smaller radiological consequences. The IRSN analysts estimated the costs (i.e., economic damage) that would arise from an accidental, atmospheric release of radioactive material from the Dampierre nuclear generating station in France. They considered two types of release – a "controlled" (smaller) and a "massive" (larger) release. A paper summarizing their findings was presented at the 2012 Eurosafe conference.[22] That paper accompanies this declaration as Exhibit #11.

(IV-12) The IRSN analysts concluded that the costs arising from a massive release would differ "profoundly" from the costs arising from a controlled release, in terms of both qualitative and quantitative factors. Indeed, they described the massive release as "an unmanageable European catastrophe". Their paper concluded with the statement: [23]

> "Safety decisions may also be informed by this picture, in particular if it is realized that the most severe cases actually carry huge stakes for the nation and

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[22] Pascucci-Cahen and Patrick, 2012.
[23] Pascucci-Cahen and Patrick, 2012.

> therefore that their lower probability may not balance their catastrophic potential."

(IV-13) To illustrate the potential for qualitative difference between larger and smaller consequences, consider the IRSN description of a massive release as "an unmanageable European catastrophe". Underlying that description is the potential for major socio-political impacts that would, in Europe, have substantial trans-boundary dimensions. The European Union might not survive the political stress arising from this event.

(IV-14) There is strong evidence that the 1986 Chernobyl accident was a principal cause of the dissolution of the Soviet Union. Political unrest related to the accident was noted in a 1987 paper by the US Central Intelligence Agency. That paper accompanies this declaration as Exhibit #12. The paper's concluding statement was:[24]

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

(IV-15) Public dissatisfaction did indeed grow, and the Warsaw Pact and the Soviet Union dissolved in 1991. Mikhail Gorbachev, the last head of state of the Soviet Union, confirmed in a 2006 essay that the Chernobyl accident was a principal cause of the Union's dissolution. That essay accompanies this declaration as Exhibit #13. Gorbachev's essay began with the statement:[25]

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

(IV-16) The full array of consequences of a large, atmospheric release of radioactive material from a nuclear facility in the United States is difficult to predict. The nature and scale of those consequences would vary according to the characteristics of the release and other factors. It is clear, however, that there are unresolved socio-political tensions in this country. Thus, the consequences of a large release could include substantial political stress. It is unlikely that aggrieved citizens would be comforted if they learned that NRC had determined, at a prior time, that the release was a low-risk event.

(IV-17) As mentioned above, the arithmetic definition of risk is used extensively in the nuclear industry, despite its flaws. It is also used in other contexts. One manifestation of this definition is the "probability-threshold position" on risk. Supporters of that position

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[24] CIA, 1987.
[25] Gorbachev, 2006.

argue that levels of risk below some numerical threshold can be ignored. That position means, in effect, that risks below the threshold are assigned a value of zero. The threshold might be, for example, an average probability of human fatality of 1×10^{-6} per annum. The probability-threshold position has been critiqued in a paper by the philosopher Kristin Shrader-Frechette.[26] That paper accompanies this declaration as Exhibit #14. Shrader-Frechette found that arguments for the probability-threshold position are fundamentally flawed.

(IV-18) Devotees of the arithmetic definition of risk often claim that their position is "scientific" and "rational". It is neither. The arithmetic definition is laden with subjective values and interests, and is prone to abuse. It is given a scientific gloss because it is expressed in numbers. However, the neatness of its numerical expression is achieved by ignoring significant factors that are not susceptible to numerical assessment. Ignoring such factors is the antithesis of a scientific approach. Moreover, the arithmetic definition pre-empts important ethical considerations, such as the tolerability of large consequences. Accordingly, the Thompson scoping declaration offered the following recommendation, which I continue to endorse:[27]

> "**Recommendation #21:** In considering radiological risk, the proposed EIS [i.e., the draft GEIS] should repudiate the arithmetic definition of risk."

V. Estimation of Radiological Risk

(V-1) For many societal hazards, such as automobile accidents, there is a rich body of data on actual incidents. In these cases, statistical methods can be used to predict probability. Also, in cases where the consequences are well defined, as is true for most automobile accidents, statistics can be used to predict consequences.

(V-2) The hazard of interest in this declaration is an unplanned release of radioactive material from a commercial nuclear facility. More specifically, the unplanned release contemplated here would be substantially larger than the authorized, routine release from a facility over a period of a year or so. There is, fortunately, a limited body of experience with unplanned releases of this nature. Thus, statistics cannot be used to predict probability or consequences.

(V-3) In the absence of reliable statistics, other approaches to radiological risk assessment must be taken. Three approaches are discussed here:

- Probabilistic risk assessment
- Direct experience
- Insurers' judgment

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[26] Shrader-Frechette, 1985.
[27] Thompson, 2013b, Sections IX and X.

(V-4) The great majority of experience with radiological risk assessment for commercial nuclear facilities is for reactors. Thus, I provide here a discussion of reactor risk assessment. This discussion shows the strengths and limitations of PRA, which provides the basis for estimation of radiological risk in the draft GEIS. Moreover, spent-fuel-pool risk is strongly linked with reactor risk, as shown in Section VIII, below.

(V-5) Figures V-1 through V-3 show PRA findings for two commercial reactors – a pressurized-water reactor (PWR) at the Surry site, and a boiling-water reactor (BWR) at the Peach Bottom site. Figures V-1 and V-2 show the estimated probability of an accident involving substantial damage to the reactor core. Such damage would involve melting of some or all of the fuel in the core. The probability is expressed as core damage frequency (CDF) per reactor-year (RY). Figure V-3 shows the estimated conditional probability (i.e., probability given core damage) of various types of containment failure. A failure of containment would lead to a release of radioactive material to the atmosphere. The earlier the failure, the larger the release, other factors being equal.

(V-6) The findings shown in Figures V-1 through V-3 are from NRC's NUREG-1150 study.[28] That study was the high point of PRA practice worldwide. The study was well funded, involved many experts, was conducted in an open and transparent manner, was done at Level 3 (i.e., with estimation of offsite consequences), 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. While there are deficiencies in the NUREG-1150 findings, these could 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.

(V-7) PRA practice in the USA has degenerated since the NUREG-1150 study. Now, PRAs or similar studies are conducted mostly by the nuclear industry, with limited transparency. NRC formerly sponsored independent reviews of industry PRAs, but no longer does so. Recent NRC work on PRA has not attained the scope, quality of review, and other aspects of NUREG-1150 that are mentioned in paragraph V-6.

(V-8) The first reactor PRA was the NRC's Reactor Safety Study (RSS).[29] NRC set up a group of experts, chaired by the physicist Harold Lewis, to review the RSS. Their report accompanies this declaration as Exhibit #15. In their report, the review group succinctly described the challenge of developing a credible PRA as follows:[30]

> "RSS was faced with the problem of estimating the probability of occurrence of an extremely rare event – core melt – in a system of great complexity, a nuclear power reactor. Since the event has never occurred in a commercial reactor, there

[28] NRC, 1990.
[29] NRC, 1975.
[30] Lewis et al, 1978, page 6.

> are no direct experimental data on which to base an estimate. The only datum that exists is the observation that there have been no core melts [as of 1978] in several hundred reactor-years of light water power reactor operation, and this fact provides at best an upper bound on the probability to be estimated. Therefore, it is necessary to resort to a theoretical calculation of the probability. But since the system is so complex, a complete and precise theoretical calculation is impossibly difficult. It is consequently necessary to invoke simplified models, estimates, engineering opinion, and in the last resort, subjective judgments."

(V-9) The preparation of a "complete and precise theoretical calculation" of core damage frequency remains "impossibly difficult" today, just as it was when Lewis and his colleagues wrote in 1978. This difficulty is intrinsic to the complexity of a reactor and the large number of potential failure modes. The difficulty is compounded when PRA analysts move from estimation of CDF (Level 1) to estimation of radioactive release (Level 2) and to estimation of offsite consequences (Level 3). At Level 2 there are many phenomenological uncertainties and variabilities. At Level 3 there is great variation in a variety of factors, such as atmospheric characteristics, and basic difficulties in characterizing indirect consequences. Thus, the radiological risk posed by a reactor is much more uncertain than other technological risks that are readily susceptible to actuarial analysis (e.g., automobile accidents).

(V-10) The complexity of a reactor is not the only reason why PRA findings are uncertain. Another reason is that a PRA examines an idealized system. The idealized system is properly designed, properly built, properly operated, and composed of independent components that typically fail randomly. PRA analysts have recognized that component failures may not always be independent. In response, they have developed analytic techniques to account for "common mode" failures that are attributable to influences (e.g., an earthquake, or a maintenance error) that can simultaneously affect more than one component. Although these techniques are useful, they leave some significant threats unaddressed.

(V-11) Three exemplary threats show how the idealized system examined in a PRA can be an incomplete representation of reality. First, a PRA cannot account for gross errors in design, construction, or operation. Second, it cannot account for malevolent acts. Third, it cannot account for deficiencies in institutional culture and practice. Each threat is significant. All three threats can lead to common mode failures. PRA's inability to account for malevolent acts is notable because a malevolent human intellect can identify weak points in a system, and can exploit destructive forces that are latent in the system.

(V-12) Reactor core-melt accidents have occurred at the Three Mile Island (TMI) site in 1979, the Chernobyl site in 1986, and the Fukushima #1 site in 2011. In each instance, retrospective investigations identified dominant risk factors that were non-quantifiable and could not have been accounted for in a PRA. These factors reflected, in differing ways, substantial deficiencies in institutional culture and practice. The three instances are discussed in the following three paragraphs.

(V-13) A commission, chaired by John Kemeny, was established by US President Carter to investigate the TMI accident. The commission's report accompanies this declaration as Exhibit #16. The commission concluded that systemic deficiencies in human behavior and organization were the dominant causes of the accident. To illustrate, their report included the statement:[31]

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

(V-14) Two Harvard University physicists, one of whom had previously worked in a reactor physics group in the USSR, published a paper in 1992 that examined the Chernobyl accident. Their paper accompanies this declaration as Exhibit #17. The abstract of their paper stated:[32]

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

(V-15) The National Diet (i.e., parliament) of Japan established an independent commission to investigate the Fukushima accident. The executive summary of their report accompanies this declaration as Exhibit #18. The commission's principal conclusion was:[33]

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

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[31] Kemeny et al, 1979, page 8.
[32] Shlyakhter and Wilson, 1992.
[33] Diet, 2012, page 16.

(V-16) The combined experience of these three incidents strongly suggests that a non-quantifiable factor, which cannot be accounted for in a PRA, will be a major or dominant risk factor underlying the next core melt at a commercial nuclear reactor. Thus, reliance on PRA to estimate the probability of the next core melt would be neither reasonable nor prudent.

(V-17) One might expect that responsible authorities would learn from these three incidents, and ensure that hitherto neglected risk factors are considered in future assessments of radiological risk. However, a paper by the sociologist John Downer shows that entrenched institutional cultures in the nuclear industry can suppress learning and promote the continuation of favored narratives. Downer's paper accompanies this declaration as Exhibit #19. The paper's conclusion begins with the statement:[34]

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

(V-18) Another approach to assessing radiological risk is to examine direct experience. In the case of a reactor, the most relevant experience consists of incidents in which a reactor core suffered severe damage. The next most relevant experience consists of incidents in which the core could have suffered severe damage if the incident had continued to develop. NRC categorizes incidents of the second type as accident sequence precursors (ASPs).

(V-19) Testimony to the US Senate by Thomas Cochran, soon after the Fukushima accident, listed twelve incidents involving severe damage to fuel in the core of a power reactor.[35] Cochran's testimony accompanies this declaration as Exhibit #20. His list of incidents excludes similar incidents at non-power reactors. For example, it excludes the core fire and radioactive release experienced in 1957 by a reactor at the Windscale site in the UK. That reactor was used to produce plutonium and other materials for nuclear weapons.

(V-20) Of the twelve core-damage incidents at power reactors, five have both: (i) occurred at a Generation II commercial reactor; and (ii) involved substantial fuel melting. These five incidents were at TMI Unit 2 (a PWR) in 1979, Chernobyl Unit 4 (an RBMK) in 1986, and Fukushima #1 Units 1 through 3 (BWRs) in 2011. These incidents occurred

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[34] Downer, 2013, page 17.
[35] Cochran, 2011.

in a worldwide fleet of commercial reactors. About 430 reactors are currently operable, although none of Japan's 50 nominally operable reactors is actually operating at present. Currently-operating reactors and previous reactors in the worldwide fleet had accrued 14,760 RY of operating experience as of February 2012.[36] Thus, about 15,500 RY of experience will be accrued through 2013.

(V-21) These five core-melt incidents provide a data set that is comparatively sparse and therefore does not provide a statistical basis for a high-confidence estimate of CDF. Nevertheless, this data set does provide a reality check for PRA estimates of CDF. From this data set – five core-melt incidents over a worldwide experience base of about 15,500 RY – one observes a CDF of 3.2×10^{-4} per RY (1 event per 3,100 RY). This value can be regarded as a "simple" estimate of CDF.

(V-22) A PRA analyst employed by NRC, Raymond Gallucci, has written a paper that develops CDF estimates based on direct experience.[37] Gallucci's paper accompanies this declaration as Exhibit #21. The paper considers both reactor core-melt and ASP experience, leading to a "simple" CDF estimate of 6.0×10^{-4} per RY (1 event per 1,700 RY). The paper does not adopt that estimate. Instead, it makes some analytic assumptions, and ultimately concludes that CDF, worldwide and in the USA, is in the range 0.7×10^{-4} to 4.0×10^{-4} per RY (between 1 event per 14,300 RY and 1 event per 2,500 RY). I question the assumptions underlying this downward adjustment of the "simple" CDF estimate. However, Gallucci's analysis deserves careful consideration in view of his professional expertise. On another note, Gallucci ends his paper by expressing his personal willingness to tolerate a CDF of the level that he has identified. On that matter, his opinion has no more weight than the opinion of any citizen.

(V-23) As shown in the preceding paragraphs, direct experience suggests a CDF as high as 6.0×10^{-4} per RY. The lowest value in the range suggested by Gallucci is 0.7×10^{-4} per RY. It is instructive to compare these numbers with the CDF estimates shown in Figures V-1 and V-2. The only CDF estimates in those figures that approach direct-experience levels are the upper-bound (95th percentile) levels of earthquake-caused CDF using Livermore seismic estimates. Thus, direct experience indicates that NUREG-1150 substantially under-estimated CDF. This finding does not mean that NUREG-1150 was a bad study. On the contrary, as stated above, NUREG-1150 was the high point of PRA practice. My finding simply confirms that PRA cannot account for all of the factors that determine the probability component of radiological risk.

(V-24) CDF estimates are typically presented as the number of incidents per RY. These estimates could also be presented as the cumulative number of incidents across a fleet of reactors, during a calendar year or some other time interval. At present, there are 100

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

licensed commercial reactors in the USA. Thus, a CDF of 3.2×10^{-4} per RY would be equivalent to a nationwide core-damage probability of 3.2×10^{-2} per calendar year (i.e., 3.2 percent per year). If that probability were sustained over decades, the occurrence of one or more core-damage incidents would become almost certain.

(V-25) Estimating the probability of core damage is just one step in assessing the radiological risk posed by a commercial reactor. Another step is to estimate the potential release of radioactive material to the environment. Figure V-3 illustrates a part of that step – estimating the conditional probability of failure of containment, given core damage. Additional steps include estimation of the movement of radioactive material in the environment, and estimation of the resulting consequences. As mentioned above, assessment of radiological risk involves the compiling of a set of qualitative and quantitative information about both probability and consequences.

(V-26) Direct experience provides some evidence regarding the release of radioactive material, its movement in the environment, and its impacts. Table V-1 shows estimated amounts of the radioactive isotope Cs-137 that were released to the atmosphere during the Chernobyl and Fukushima accidents. Figure V-4 shows the distribution of Cs-134 and Cs-137 isotopes deposited on Japan after being released to the atmosphere during the Fukushima accident. Table V-2 shows an estimate, by the US Department of Energy, of radiation dose commitment from the Chernobyl release.

(V-27) A paper by Sornette et al reveals the limitations of PRA findings by comparing them with lessons from direct experience.[38] That paper accompanies this declaration as Exhibit #22. The paper considers monetized losses from nuclear-facility incidents, using two sources of information. One source is a reactor PRA. The other source is a compilation of data on actual incidents at nuclear facilities. Figure V-5 of this declaration reproduces a figure from Sornette et al. That figure shows that the PRA substantially under-estimates the probability of a monetized loss. The under-estimation grows as losses become larger. In other words, the PRA findings show a thin-tail probability distribution, whereas the empirical data show a fat-tail distribution.

(V-28) Two approaches to radiological risk assessment are discussed above – PRA, and direct experience. A third approach is to examine the judgment of nuclear-facility insurers. Such an examination is set forth in Tables V-3 and V-4. Table V-3 shows insurance premiums for the Darlington nuclear generating station in Canada, to cover liability for bodily injury or property damage at offsite locations. Table V-4 calculates an "implied probability of event", which represents the insurers' assessment of the probability of a claim up to the liability limit, arising from an accident at Darlington.[39] (Events caused by malevolent acts are not considered in Table V-4.) If, for example, the liability limit is $1 billion, the implied probability of a claim up to that limit ranges from 6.4×10^{-4} to 1.0×10^{-3} per RY.

[38] Sornette et al, 2013.
[39] A claim up to the liability limit means that monetized impact exceeds the liability limit.

(V-29) The calculations presented in Table V-4 show that, in the judgment of the Canadian nuclear insurers, the probability distribution of the monetized impact of an accident at Darlington is close to the distribution shown by the "Empirical Records" curve in Figure V-5. Evidently, the insurers are not persuaded by PRA findings, which show much lower probabilities. In 2012, Ontario Power Generation, the owner/operator of the Darlington station, published the findings of a PRA it conducted for the station.[40] Those findings accompany this declaration as Exhibit #23. Findings of a previous PRA for Darlington were published in 1987.[41] The 2012 PRA estimated the probability of a large, atmospheric release as 9.5×10^{-6} per RY, while the 1987 PRA estimated that probability as 8.2×10^{-7} per RY. The Canadian nuclear insurers have access to these PRA studies, but choose to set premiums at much higher levels than the PRAs would imply.

(V-30) At this point in Section V, I have shown that reactor PRAs typically yield estimates of probability (i.e., the probability of accident outcomes) that are substantially lower than is implied by direct experience and insurers' judgment. This finding carries over to PRAs for non-reactor facilities, because it arises from limitations in the art of PRA itself. Those limitations are significant for the draft GEIS, because the draft GEIS relies upon PRA findings for estimation of radiological risk.

(V-31) In 1989 I was a co-author of a critical review of the state of the art of PRA.[42] The findings of that review remain generally valid today. One of the review's conclusions, with some reframing and updating to match the context of this declaration, provides a useful way to summarize the role of PRA in radiological risk assessment. The reframed and updated conclusion, which refers to a commercial reactor or to various other types of nuclear facility, is:

Actual probability of event = (PRA finding)x(Reality factor #1) + (Reality factor #2)

Where the variables in this equation are as follows:

- "Actual probability of event" refers to the real-world numerical probability of an outcome such as: reactor core damage; release of a specified amount of radioactive material; contamination of a specified area of land above a specified dose threshold; or accrual of a specified collective dose to people offsite.
- "PRA finding" refers to a PRA estimate of the probability of the outcome in question – this could be a mean, median, or other representation of a probability distribution.
- "Reality factor #1" is a number, typically greater than 1, that represents influences that are within the paradigm of PRA but are not properly accounted for in contemporary PRAs – these influences include: complexity; inadequate data; and deficiencies in institutional culture and practice.

[40] OPG, 2012.
[41] Ontario Hydro, 1987.
[42] Hirsch et al, 1989.

- "Reality factor #2" is a number that represents influences outside the paradigm of PRA – these influences include: gross errors in design, construction, or operation; and malevolent acts.

And the following observations apply:

- Experience suggests that Reality factor #1 for severe accidents may have a value that exceeds 1 by several orders of magnitude (i.e., factors of 10).
- Reality factor #2 has two numerical components: (i) a retrospective component that can be determined empirically based on the occurrence of events; and (ii) a prospective component that will remain unknown for the foreseeable future.
- Both Reality factors may vary significantly in response to variations in the future risk environment, as discussed in Section VII, below.
- This version of the equation is applicable when the values of "PRA finding" and "Actual probability of event" are both less than 1. At higher values, the term "probability" would be replaced by the term "frequency".

(V-32) The two Reality factors cannot be fully estimated by PRA techniques, although they may have components that can be estimated in that way. In cases where there is a record of direct experience – such as the occurrence of reactor core damage or the occurrence of ASPs – one can infer a range of values for the Reality factors, drawing upon PRA findings. If there is no record of direct experience of a hypothesized event, PRA findings can provide a kernel of information that can be adjusted by Reality factors that are judged appropriate to the situation. Thus, PRA findings can be valuable items of information. They are, however, only a guide to the assessment of probability, and are not definitive statements of that probability.

VI. Malevolent Acts and Radiological Risk

(VI-1) The draft GEIS makes assertions about the environmental impacts of malevolent acts affecting stored spent fuel. Later in Section VI, I identify those assertions. Then, in Sections X and XI, below, I critically review those assertions in the contexts of pool fires and cask fires. I begin Section VI by providing some background information about malevolent acts.

(VI-2) In the context of this declaration, it is noteworthy that NRC explicitly considered the impacts of malevolent acts in its 1979 GEIS on Handling and Storage of Spent Light Water Power Reactor Fuel, which was designated NUREG-0575.[43] Potential malevolent acts were described in Appendix J of that GEIS. Appendix J accompanies this declaration as Exhibit #24. NRC stated its rationale for considering malevolent acts as follows:[44]

[43] NRC, 1979.
[44] NRC, 1979, Appendix J, pages J-2 and J-3.

> "The NRC staff is unable to determine the quantitative likelihood of a hypothetical malevolent act being successfully performed by an adversary group. Instead, a group of selected reference events have been assumed to occur in order to establish a range of potential effects that might be caused by deliberate acts. The consequences corresponding to these reference events were calculated on a per-fuel-element basis, thus allowing the results to be extrapolated to possibly include massive destructive acts and thereby develop an upper bound on estimates of potential consequences, regardless of the plausibility of the attempted acts."

(VI-3) To implement that rationale in NUREG-0575, NRC considered four types of "sabotage" event at a spent-fuel pool. Table VI-1 summarizes NRC's description of these types of event. One sees from Table VI-1 that NRC envisioned an attack by up to 83 adversaries. The attackers could hold the control room for about one half hour. They could use explosive charges to breach the walls of the pool building or the floor of the pool itself.

(VI-4) NUREG-0575 did not consider the environmental impact of pool fires. It dismissed the potential for a pool fire with the brief statement:[45]

> "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".

(VI-5) The citation for the "calculations" mentioned in that statement was to a report prepared by Sandia Laboratories for NRC, under the designation NUREG/CR-0649.[46] That report accompanies this declaration as Exhibit #25. Careful examination of NUREG/CR-0649 shows that it did not support the interpretation placed upon it by NUREG-0575. In fact, NUREG/CR-0649 showed that partial loss of water from a spent-fuel pool could lead to a pool fire.[47] The significance of partial loss of water is discussed further in Section X, below.

(VI-6) Thus, the authors of NUREG-0575 did not properly understand the potential for a pool fire. Accordingly, they failed to understand that the malevolent acts they postulated in Appendix J could, with slight adjustment, readily initiate a pool fire, as discussed in Section X, below. Nevertheless, NRC did postulate this set of malevolent acts in its 1979 GEIS. To my knowledge, NRC has never repudiated its postulation of these acts.

(VI-7) Since the 1970s, I have written numerous reports, declarations, and other documents that address malevolent acts as potential contributors to the radiological risk posed by reactors, spent-fuel-storage facilities, and other nuclear facilities. Documents in

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[45] NRC, 1979, page 4-21.
[46] Benjamin et al, 1979.
[47] See, for example, the "blocked inlets" curve in Figure 26 (at page 77) of: Benjamin et al, 1979.

this category that are mentioned up to this point in this declaration include: (i) a January 2013 declaration[48] (Exhibit #1); (ii) an August 2013 declaration[49] (Exhibit #3); (iii) a February 2009 report[50] (Exhibit #5); (iv) a November 2005 report[51] (Exhibit #9); and (v) a January 2013 handbook[52] (Exhibit #10). Here, I introduce two additional documents I have written that address malevolent acts at nuclear facilities. One document is a November 2007 report that discusses continued operation of the Indian Point nuclear power plants.[53] That report accompanies this declaration as Exhibit #26. The second document is a January 2003 report that discusses threats to spent fuel as a neglected issue of homeland security.[54] That report accompanies this declaration as Exhibit #27. Each of the documents listed in this paragraph cites numerous documents prepared by diverse authors.

(VI-8) An August 2012 report prepared at the Congressional Research Service provides a succinct overview of policy, law, and regulation in the United States regarding the threat of malevolent acts at nuclear facilities.[55] That report accompanies this declaration as Exhibit #28. A February 2012 report on the future of nuclear power in the United States, by authors including former NRC chair John Ahearne, contains an instructive chapter on the threat of malevolent acts.[56] That report accompanies this declaration as Exhibit #29. Also instructive is a 2007 journal article by staff of the US Environmental Protection Agency, on the sabotage vulnerability of nuclear power plants.[57] That article accompanies this declaration as Exhibit #30. Computer models have been developed to help assess the vulnerability of nuclear facilities to malevolent acts, as discussed in a 2006 journal article by Morris et al.[58] That article accompanies this declaration as Exhibit #31.

(VI-9) For convenience, this declaration includes some tables and figures that appear in one or more of the documents listed in paragraph VI-7, above. I refer here to Tables VI-2 through VI-5, and Figures VI-1 through VI-4. These tables and figures provide clear evidence that reactors and spent-fuel-storage facilities are vulnerable to attack, including attack by non-State actors. I could explain this evidence in detail, but choose not to provide that explanation in a document that is intended for general distribution.

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[48] Thompson, 2013b.
[49] Thompson, 2013a.
[50] Thompson, 2009.
[51] Thompson, 2005.
[52] Thompson, 2013c.
[53] Thompson, 2007.
[54] Thompson, 2003.
[55] Holt and Andrews, 2012.
[56] Ahearne et al, 2012.
[57] Honnellio and Rydell, 2007.
[58] Morris et al, 2006.

(VI-10) The documents listed in paragraphs VI-7 and VI-8, the numerous citations within those documents, and the tables and figures identified in paragraph VI-9, provide a thoroughly documented basis for the following conclusions:

1. A reactor, spent-fuel-storage facility, or other nuclear facility in the United States could be attacked by a State or by a non-State actor.
2. A non-State actor could acquire the capability to execute an attack that releases to the environment a large amount of radioactive material from a reactor core or from stored spent fuel.
3. Storage of spent fuel at high density in a pool adjacent to an operating reactor is advantageous to an attacker, because this arrangement would help the attacker to obtain a large, radioactive release from the reactor and the pool.
4. The amount of radioactive material that would be released by an attack could exceed the amount that would be released by an accident.
5. NRC requires licensees to implement only a "light" defense of a nuclear facility, namely a defense that is designed to resist attacks within the lower end of the spectrum of severity of potential attacks.
6. NRC does not require any defense against attack from the air, although a non-State actor could execute such an attack.
7. Licensees routinely lobby NRC to reduce the scale of threat against which licensees are required to mount a defense.
8. Measures deployed by licensees to mitigate the effects of potential accidents would be ineffective in many scenarios of potential attack.
9. The probability of a successful attack cannot be estimated by statistical methods or by analytic arts such as probabilistic risk assessment.
10. In light of human history, observation of the contemporary world, and consideration of possible societal trends, a prudent decision maker would conclude that a successful attack on a reactor or spent-fuel-storage facility in the United States over the coming decades is as likely to occur as are major national challenges that are planned for, such as severe natural disasters or engagement in wars.
11. Options are available to reduce radiological risk arising from potential attacks.
12. The attack-related risk of storing spent fuel could be dramatically reduced by re-equipping spent-fuel pools with low-density, open-frame racks, and by otherwise storing spent fuel in protected dry casks.
13. Requiring licensees to implement options that substantially reduce the attack-related risk at nuclear facilities would enhance protective deterrence as a national strategy, with substantial benefits.

(VI-11) The draft GEIS addresses the potential for malevolent acts in its Section 4.19, titled Potential Acts of Sabotage or Terrorism. The Executive Summary of the draft GEIS addresses this potential in its Section ES.13.1.19, also titled Potential Acts of Sabotage or Terrorism. In its Section 4.19, the draft GEIS has separate sub-sections that address attacks on spent-fuel pools, and attacks on independent spent fuel storage installations (ISFSIs). The draft GEIS summarizes its findings on the potential for malevolent acts as follows:[59]

> "The NRC finds that even though the environmental consequences of a successful attack on a spent fuel pool beyond the licensed life for operation of a reactor are large, the very low probability of a successful attack ensures that the environmental risk is SMALL. Similarly, for an operational ISFSI during continued storage, the NRC finds that both the probability and consequences of a successful attack are low, and therefore, the environmental risk is SMALL. Therefore, the storage of spent fuel during continued storage will not constitute an unreasonable risk to the public health and safety from acts of radiological sabotage, theft, or diversion of special nuclear material. The environmental impacts of terrorism are an area of particular controversy."

(VI-12) In addressing an attack on a spent-fuel pool, this statement in the draft GEIS acknowledges that the consequences of an attack could be "large". In Section X, below, I provide further evidence about the meaning of that term. Then, the statement asserts that the probability of a successful attack is "very low". Elsewhere, the draft GEIS says that this probability is "numerically indeterminable".[60] I agree with the latter statement, but do not agree that the probability is very low. As summarized in paragraph VI-10, above, there is an extensive, thoroughly documented body of evidence showing that a successful attack on a reactor or pool is as likely to occur as are major national challenges that are planned for, such as severe natural disasters or engagement in wars.

(VI-13) The draft GEIS notes that, after loss of cooling at a pool, some days would pass before water boiled away to the point where fuel would be exposed. For a pool containing PWR fuel, the draft GEIS cites boil-away times exceeding 4 to 11 days, depending upon the age of the fuel. The draft GEIS asserts that such a time period would allow the implementation of mitigating actions that would prevent a pool fire.[61] In Section VIII, below, I show that NRC has neglected to consider pool-reactor risk linkage that could hinder or preclude mitigating actions. Pool-reactor risk linkage could preclude mitigating actions during either an accident or an attack. Also, a malevolent actor could preclude mitigating actions directly, and/or could cause a loss of water by mechanisms other than boil-away. I address these matters in Section X, below.

(VI-14) The draft GEIS asserts that additional security measures implemented after the 11 September 2001 attacks reduced the probability of a pool fire.[62] Presumably, the draft GEIS is referring to attack-induced pool fires. However, even with the additional security measures, NRC requires licensees to implement only a light defense of a nuclear

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[59] NRC, 2013b, Executive Summary, page xiiv. A briefer statement to the same general effect appears at: NRC, 2013b, pp 4-89 to 4-90.
[60] NRC, 2013b, page 4-85.
[61] NRC, 2013b, Appendix F, page F-11.
[62] NRC, 2013b, Appendix F, page F-11.

facility. The conclusions that I set forth in paragraph VI-10, above, take account of that defense.

(VI-15) As discussed in paragraphs VI-11 and VI-12, above, the draft GEIS identifies "large" but vaguely specified consequences of an attack-induced pool fire, and "very low" but numerically indeterminable probability. The draft GEIS proceeds to multiply these indicators together in some unspecified manner, concluding that the risk of an attack on a pool is "SMALL". In effect, the draft GEIS uses the "arithmetic" definition of risk that I discuss in Section IV, above. That definition is fundamentally flawed for the reasons I set forth in Section IV. In this instance, application of the arithmetic definition is additionally flawed because the indicators that are multiplied together are nebulous.

(VI-16) In addressing an attack on an ISFSI, the statement in the draft GEIS that is quoted in paragraph VI-11 asserts that both the probability and consequences of a successful attack are "low". I discuss this probability and these consequences in Section XI, below. That discussion addresses, among other matters, the role of protective deterrence. The statement quoted in paragraph VI-11 goes on to assert that the risk of a successful attack on an ISFSI is "SMALL". That assertion reflects use of the arithmetic definition of risk. As stated in paragraph VI-15, above, that definition is fundamentally flawed, and its application in the draft GEIS is additionally flawed because the indicators that are multiplied together are nebulous.

VII. The Future Risk Environment

(VII-1) The draft GEIS examines storage of spent fuel over three timeframes.[63] The "short-term storage" timeframe is for 60 years beyond licensed life for reactor operations. The "long-term storage" timeframe is for 100 years beyond the short-term timeframe. The "indefinite storage" timeframe extends into the indefinite future.

(VII-2) Assessing radiological risk over such long timeframes poses a daunting challenge to risk assessors. A competent risk assessor would immediately acknowledge that the risk environment could change substantially during the short- and long-term timeframes, and even more so during the indefinite timeframe. In this declaration, the term "risk environment" refers to the array of societal, technical, and natural factors that, taken together, have significant influence on risk. Over a period of decades and centuries, these factors, and their interactions with each other, could change substantially. Moreover, the risk environment could change non-uniformly across the United States.

(VII-3) Section V of the Thompson scoping declaration discussed the future risk environment. That discussion culminated in my recommendation:[64]

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[63] NRC, 2013b, page 1-12.
[64] Thompson, 2013b, Section V and Section X.

> "**Recommendation #7:** Risk assessment in the proposed EIS should be supported by a set of indicators that express the dynamic aspects of the potential risk environment across the time period and suite of scenarios considered in the EIS."

(VII-4) A report from Argonne National Laboratory examines the challenge of safeguarding spent fuel during very long-term storage (VLTS), which it defines as above-ground, interim, dry storage for a period of more than 50 years.[65] That report accompanies this declaration as Exhibit #32. The challenges identified in the report arise partly from potential changes in the risk environment. Thus, the report illustrates the significance of a potentially changing risk environment for the assessment of radiological risk. The report makes the following statement:[66]

> "Safeguarding a VLTS facility with nuclear material for 50, 100, or 200 years will present many challenges. First of all, the integrity of the fuel or cask may deteriorate. The radioactive signature of the fuel will also change. As the fuel cools, it may become more attractive for diversion. Even though the State has the means to handle very radioactive spent fuel, cooler spent fuel will still be more attractive to divert because it is easier to handle and reprocess. Keeping data on the facility for that long may also be a challenge. If the past 50 years are any indication of the future, it is difficult to predict what the safeguards challenges and needs will be in just the next 50 years."

(VII-5) The draft GEIS does consider one aspect of potential change in the risk environment over coming decades. In its Section 4.18, it discusses the influence of climate change on design-basis accidents or severe accidents at spent-fuel pools or at dry cask storage facilities (i.e., ISFSIs). It acknowledges various potential outcomes of climate change, such as increased intensity and frequency of severe weather events, sea level rise, increased storm surges, shoreline retreat, and inland flooding. It assumes, however, that mitigating actions could prevent significant increase in radiological risk as a result of climate change, that NRC will continue to exist and will require the necessary mitigating actions, and that licensees will be willing and able to implement these actions.

(VII-6) Section 1.8.3 of the draft GEIS, titled Analysis Assumptions, sets forth a highly optimistic view of the future conditions that will affect stored spent fuel. It assumes that institutional controls will remain operative into the indefinite future, arguing that this assumption "avoids unreasonable speculation regarding what might happen in the future regarding Federal actions to provide for the safe storage of spent fuel".[67] It further assumes that each ISFSI will be replaced on a 100-year cycle, into the indefinite future.

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[65] Kollar et al, 2013.
[66] Kollar et al, 2013, page 6.
[67] NRC, 2013b, page 1-14.

(VII-7) For the reasons set forth in Section V of the Thompson scoping declaration, the highly optimistic assumptions used in the draft GEIS are neither reasonable nor prudent. Moreover, assuming static conditions is speculative in the extreme, and shows a profound ignorance of human history. Given the long timeframes envisioned in the draft GEIS, the only reasonable approach is to consider a broad range of scenarios. Section VI of the Thompson scoping declaration discussed this approach. That discussion yielded three recommendations, each of which is pertinent to radiological risk, as follows:[68]

> "**Recommendation #8:** The scenarios considered in the proposed EIS should cover a range of potential outcomes regarding the role of nuclear power, including: (i) shrinkage in the number of operating reactors, with potential shutdown of all reactors by the middle of the 21st century; (ii) expansion in the number of operating reactors; and (iii) introduction of new technology."
>
> "**Recommendation #9:** The scenarios considered in the proposed EIS should cover future societies exhibiting a range of variation in prosperity, technological capability, and the quality of governance."
>
> "**Recommendation #10:** The scenarios considered in the proposed EIS should cover a range of potential future outcomes regarding the propensity for violent conflict, and should cover situations in which stored SNF or HLW would experience attacks involving States or non-State actors."

(VII-8) The draft GEIS does not implement any of my Recommendations #7 through #10. Instead, the draft GEIS takes the unreasonable, imprudent, and highly speculative position that the risk environment will remain unchanged into the indefinite future.

VIII. Linkage of Pool Risk and Reactor Risk

(VIII-1) The radiological risk posed by a spent-fuel pool is significantly increased if that pool is located near an operational reactor, and vice versa. This linkage of pool risk and reactor risk is discussed below. Before embarking on that discussion, however, I explain why this linkage is significant in the context of the draft GEIS.

(VIII-2) The hazard posed by a nuclear fuel assembly begins at the moment when the assembly first undergoes nuclear fission, which occurs inside a reactor. That moment would be the logical starting point for any GEIS that addresses spent fuel. A less logical, but perhaps plausible, starting point would be the moment when the fuel assembly is discharged from a reactor and placed in a nearby pool. The draft GEIS uses a much later and entirely illogical starting point. The draft GEIS considers the environmental impacts of storing spent fuel during a period that begins when the reactor that discharged the fuel is no longer licensed for operation.

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[68] Thompson, 2013b, Section VI and Section X.

(VIII-3) By adopting this later starting point, the draft GEIS excludes from consideration a set of significant environmental impacts that arise in earlier phases of the life of a fuel assembly. That exclusion is illogical. It deserves examination from a legal perspective, but that examination is outside the scope of this declaration.

(VIII-4) For the remainder of this declaration, I adopt the starting point used in the draft GEIS. That adoption does not mean that I endorse this starting point. Discussion in the following paragraphs shows that, even if one adopts the starting point used in the draft GEIS, linkage of pool risk and reactor risk is a significant factor in the radiological risk of storing spent fuel.

(VIII-5) Let us consider spent fuel that has been discharged from a reactor that is no longer operational, and that is currently in the pool into which it was discharged. Let us designate the US inventory of this spent fuel, at any given time, as "draft GEIS fuel in pools" (DGFIP). It turns out, as shown below, that a significant fraction of DGFIP could be located near operational reactors. This finding could hold for a significant period even if nuclear power continues to decline as a US energy source. The same finding could hold for a much longer period if nuclear power revives as a US energy source. Both outcomes for nuclear power are encompassed by the draft GEIS. Later in this declaration, I discuss the implications of nuclear-power scenarios for the radiological risk of storing spent fuel. That discussion is in Section IX, below.

(VIII-6) Currently, 100 commercial reactors are licensed to operate in the United States, at 62 sites. At 35 of these sites, there are multiple (i.e., two or three) licensed reactors.[69] During future decades, all of the currently licensed reactors will shut down permanently. However, there is no NRC requirement or expectation that all of the reactors at a particular site will permanently shut down at the same moment. Thus, there could be, and probably will be, significant periods when a significant fraction of DGFIP is located near operational reactors. Moreover, there are 9 sites where two reactors share a single pool, and 8 other sites where the pools serving two adjacent reactors are connected by a transfer canal.[70] At these 17 sites, any fuel in a pool is intimately associated with two adjacent reactors.

(VIII-7) If nuclear power revives as a US energy source, where might a new fleet of reactors be constructed? This question has been addressed by nuclear industry consultant Karl Fleming in a paper supporting his presentation to NRC commissioners in July 2011. That paper accompanies this declaration as Exhibit #33. The paper states:[71]

> "It is likely that most if not all of the next fleet of new reactors will be built on one or more of the existing licensed reactor sites in view of the additional costs

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[69] NRC, 2013d. There are 25 sites with multiple PWRs, and 10 sites with multiple BWRs. There are 13 sites with one PWR, and 14 sites with one BWR.
[70] Satorius, 2013b, Enclosure 1, Table 72.
[71] Fleming, 2011.

and effort that will be required to approve new sites."

(VIII-8) Thus, if nuclear power revives, a significant fraction of DGFIP could be located near new operational reactors, for a period of many years. That finding, combined with my finding in paragraph VIII-6 for the case of continued decline of nuclear power, shows that a significant fraction of DGFIP could be located near operational reactors for a significant period, regardless of future trends in US nuclear power.

(VIII-9) At this point, I have established that pool storage of spent fuel, as considered in the draft GEIS, could occur, and probably will occur, at locations near operational reactors. It follows that the draft GEIS should have carefully considered the potential linkage of pool risk and reactor risk.

(VIII-10) PRA practice has neglected linkage of risk among multiple reactors at a site. That neglect is summarized in Karl Fleming's paper, discussed above. The paper says:[72]

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

(VIII-11) In a 2013 journal article, Schroer and Modarres proffer an event classification schema for applying PRA to multiple reactors at a site.[73] That article accompanies this declaration as Exhibit #34. At the time of publication, co-author Suzanne Schroer was a member of the NRC staff. The article says:[74]

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

[72] Fleming, 2011.
[73] Schroer and Modarres, 2013.
[74] Schroer and Modarres, 2013, page 49.

> class, independent events, was only marginally discussed because it does not address dependencies between the units."

(VIII-12) From the two preceding paragraphs and the documents cited therein, one sees that linkage of risk among multiple reactors at a site has been long neglected, but is beginning to receive some attention from NRC and licensees. Linkage of pool risk and reactor risk at a site has been similarly neglected, but has not been properly addressed by NRC or licensees.

(VIII-13) Although NRC has not properly addressed the linkage of pool risk and reactor risk, NRC has taken a small, initial step in that direction. This step was taken in a pool-fire study that NRC published in 2013. As discussed in paragraph I-11, above, NRC published a draft version of the pool-fire study in June 2013.[75] The study was re-published in final form in October 2013, with no substantial change.[76] The October 2013 version, with its cover memo, accompanies this declaration as Exhibit #35. Hereafter, I refer to it as "NRC's consequence study". I assume that the technical parts of the June 2013 and October 2013 version are identical. Thus, the Thompson draft consequence declaration applies equally to both.

(VIII-14) NRC's consequence study took a small step toward addressing the linkage of pool risk and reactor risk in the sense that it identified aspects of that linkage. It did not proceed to analyze those aspects. The identification occurred under the rubric, Multi-Unit Considerations, via the following statement:[77]

> "<u>Observations Regarding a Concurrent Reactor Event</u>:
>
> There are four broad interplays that can be defined between the SFP [spent fuel pool] and the reactor:
>
> 1. an initiating event that directly affects both the reactor and the SFP
> 2. a reactor accident that prevents accessibility to the SFP for a prolonged period of time (e.g., due to high radiation fields), leading to a SFP accident
> 3. a reactor accident that includes ex-containment energetic events (e.g., a hydrogen combustion event) or other ex-containment interplays (e.g., steaming through the drywell head that affects refuel floor combustible gas mixtures) and creates a hazard to the SFP (e.g., by causing debris to fall in to the pool) or otherwise changes the SFP event progression
> 4. an SFP accident that prevents accessibility to key reactor systems and components for a prolonged period of time or which creates a hazard for

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[75] Barto et al, 2013a.
[76] The October 2013 version is: Barto et al, 2013b. It was published as an enclosure under the SECY memo: Satorius, 2013a. That memo stated: "None of the comments or responses [i.e., on the draft version of the study] has necessitated making substantial changes to the report." (See: Satorius, 2013a, page 3.)
[77] Barto et al, 2013b, Section 2.2, pp 28-29.

> equipment used to cool the reactor (e.g., the flooding of low elevations of the reactor building due to a leak in the pool or excessive condensation from continuous boiling of SFP water), leading to a reactor accident
>
> For each of these interplays, large seismic events and severe weather SBO [station blackout] events are logically the most relevant initiators, as they are the type of initiators that are most likely to initiate an accident at the reactor and SFP, while simultaneously hampering further accessibility to key areas, key systems and components, and key resources. To the extent practicable, this study has attempted to qualitatively account for some of these effects. For example, when the reactor and SFP are hydraulically connected (during refueling), the decay heat and water volumes from both sources are considered. The study also explores these effects on mitigation (Section 8), and addresses some aspects of the uncertainty associated with this treatment (Section 9). However, explicitly modeling multiunit effects was not a focus of this study, because of the existing limitations with the available computational tools. An ongoing project described in SECY-11-0089 will attempt to more rigorously address these effects in the framework of a multiunit Level 3 PRA for Vogtle Electric Generating Plant Units 1 and 2."

(VIII-15) The four "interplays" described in this statement are far from the final word about linkage of pool risk and reactor risk, but they would provide a useful starting point for technical analysis on that linkage. These interplays could occur in situations where pool storage of spent fuel, as considered in the draft GEIS, occurs at a location near an operational reactor. Thus, the draft GEIS should have carefully considered the implications of these interplays for the environmental impacts of storing spent fuel in pools. Unfortunately, the draft GEIS failed to consider those implications.

(VIII-16) The second half of the statement quoted in paragraph VIII-14 shows clearly that NRC's consequence study does not provide credible technical analysis of the pool-reactor interplays that it identifies. Instead, it says that another project "will attempt" to address these interplays at some future date. Until that work is done properly, NRC will not be able to complete an adequate GEIS on the environmental impacts of storing spent fuel.

(VIII-17) The 2011 Fukushima accident illustrated the potential for risk linkages among facilities at a nuclear site. Figure VIII-1 shows how that potential was manifested at Unit 4. The Unit 4 reactor building suffered a violent explosion of hydrogen that reportedly originated from reactor core damage at Unit 3.[78] That hydrogen explosion, and other influences at the site, hindered mitigating actions at Unit 4. Those actions were needed to keep the Unit 4 spent-fuel pool in a safe state, because normal systems that provide cooling and makeup to the pool were disabled by the earthquake and tsunami that

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[78] The reactor core of Unit 4 had been removed and placed in the adjacent pool prior to the accident.

afflicted the site. Eventually, water makeup was provided to the pool by the concrete-pumping truck that appears in Figure VIII-1. That truck was brought to the site after several other methods of providing water makeup had failed.

(VIII-18) Figure VIII-2 illustrates how intimately a spent-fuel pool can be associated with the reactor it serves. Moreover – as discussed in paragraph VIII-6, above – at 17 sites in the United States, any fuel in a pool is intimately associated with two adjacent reactors. In other instances, the association between a pool and a different, nearby reactor may not be quite so intimate. Nevertheless, physical proximity, sharing of buildings, and/or sharing of support systems could establish a strong linkage of pool risk and reactor risk. One concern is that a release of radioactive material from a reactor could create a radiation field that precludes personnel access needed to keep a nearby spent-fuel pool in a safe state. Lack of that access could lead to a pool fire.

(VIII-19) One potential manifestation of risk linkage among facilities at a nuclear site would be the occurrence of a cascading sequence of incidents. To illustrate, consider the potential impact of a large aircraft on a reactor. That event could be an accident or a malevolent act. The successful use of a large aircraft as an instrument of attack is, of course, not theoretical. It occurred in the United States three times on 11 September 2001.

(VIII-20) Morris et al describe the use of the VISAC code to analyze the impact of a large aircraft on the containment of a reactor.[79] They note that the hard parts of the aircraft – notably, the jet engine rotors – might not fully penetrate the containment. They consider, however, the entry of a small fraction (apparently, 1 percent) of the aircraft's jet fuel into the annular space between the inner and outer walls of the containment. Perusal of Figure VIII-2 shows analogous spaces in that reactor design. Vaporization and ignition of the jet fuel in this confined space would, with high conditional probability, lead to a violent fuel-air explosion. Morris et al describe VISAC analyses that show, in all cases, significant damage to the containment from this explosion, with holes in both the inner and outer walls. They go on to say:[80]

> "While the damage is significant, subsequent events are most likely responsible for most of the radioactive release predicted. It is unlikely that the staff inside the control room adjacent to the containment building will survive the smoke and toxic fumes resulting from the fire, even if they managed to survive the direct consequences of the crash of the airplane. In view of the fire engulfing the containment building and adjacent structures, it seems unlikely that the separately located auxiliary control room could be reached by the staff members originally located in the main control room. Therefore, even if those in the control room should be unaffected by the air fuel explosion, the additional fire hazard outdoors will prohibit the surviving operators from shutting down the plant in a controlled

[79] Morris et al, 2006.
[80] Morris et al, 2006, page 206.

> manner from the auxiliary control room."

(VIII-21) The potential events that Morris et al describe can be viewed as stages in a cascading sequence of incidents. First, the aircraft strikes the containment. Second, some jet fuel enters a confined space. Third, a fuel-air explosion breaches the containment and causes other damage. At some point during stages 1-3, or subsequently, the control room, the auxiliary control room, and their personnel are rendered non-functional. Fourth, radioactive material is released from the reactor to the interior of the containment, or directly to the external environment. Fifth, radioactive material passes from the interior of the containment to the external environment. Sixth, the cascade could proceed to one or more pool fires, as discussed in the following paragraph.

(VIII-22) The spent-fuel pool that serves the afflicted reactor, and the cooling and water makeup systems that serve that pool, could be damaged by the aircraft impact or by the fuel-air explosion. That damage could be sufficient to initiate a zircaloy fire in the pool. A nearby spent-fuel pool, built to serve another reactor, could suffer similar damage, resulting in a zircaloy fire in that pool. Deposition of radioactive material released from the afflicted reactor would create an intense radiation field around the reactor. The radiation field could extend in all directions, because the fire accompanying this disaster would create intense turbulence in the local atmosphere. The radiation field could preclude personnel access for days or weeks, thereby precluding mitigating actions that might prevent the initiation of zircaloy fires in the affected pools. In that situation, a nearby pool that was not affected directly by the aircraft impact could boil dry, leading to a fire in that pool.

(VIII-23) NRC has never, to my knowledge, published a credible technical analysis of a cascading sequence of incidents of this type. Nor, to my knowledge, has NRC ever publicly stated that it has performed such analysis in secret. Until such analysis is done, and done properly, NRC will not be able to complete an adequate GEIS on the environmental impacts of storing spent fuel.

IX. Risk Implications of Nuclear-Power Scenarios

(IX-1) Section 1.8.6 of the draft GEIS, titled Issues Eliminated from Review in this GEIS, contains the statement:[81]

> "The NRC is evaluating the continued storage of commercial spent fuel in this draft GEIS. Thus, certain topics are not addressed because they are not within the scope of this review. These topics include:
>
> - noncommercial spent fuel (e.g., defense waste)
> - commercial high level waste generated from reprocessing
> - greater-than-class-C LLW
> - advanced reactors (e.g., high-temperature and gas-cooled reactors)

[81] NRC, 2013b, pages 1-23 and 1-24.

- foreign spent fuel
- nonpower reactor spent fuel (e.g., test and research reactors)
- need for nuclear power
- reprocessing of commercial spent fuel"

(IX-2) By excluding from consideration the "need for nuclear power", the draft GEIS cripples its ability to assess the environmental impacts of storing spent fuel. Nowhere in the draft GEIS is this grave deficiency corrected. The draft GEIS does not set forth any scenario for the future use of nuclear power or, more specifically, for the future creation of spent fuel. Thus, in the draft GEIS, the timeframe for creation of spent fuel spans an unknown but potentially vast range, as does the quantity of spent fuel created in that timeframe.

(IX-3) At the lower end of its range, the timeframe for creation of spent fuel will end when the last of the currently licensed reactors ceases to operate. However, since the draft GEIS sets no upper limit on the time period that it considers, the creation of spent fuel could continue ad infinitum. Thus, the upper end of the range of timeframes is undefined.

(IX-4) At the lower end of its range, the quantity of spent fuel that is created will be the quantity that is discharged from the currently licensed reactors. However, since the draft GEIS says nothing about the future use of nuclear power, it sets no upper limit to the quantity of spent fuel that will be created. Consider a simple, illustrative example. Suppose that nuclear power soon revives in the United States, leading to a tenfold increase in annual creation of spent fuel by the mid-21st century. Further suppose that this rate of creation continues for a few centuries. At the end of that period, the cumulative quantity of spent fuel that has been created would far exceed the quantity that is discharged from the currently licensed reactors.

(IX-5) If the total quantity of spent fuel that is created were at the lower end of its range, the radiological risk posed by storing this fuel would be bounded. As the inventory of fuel aged, its radiological risk would decline, other factors being equal. Moreover, the inventory would gradually move from pools to ISFSIs, which would reduce its risk. In principle, one could assess the cumulative radiological risk of storing spent fuel, from the present until the moment when the last fuel assembly in the inventory is emplaced in a repository.

(IX-6) If, however, the total quantity of spent fuel that is created is unbounded, then the radiological risk posed by storing this fuel would be similarly unbounded.[82] The draft GEIS allows for this outcome. Thus, the draft GEIS has denied itself the ability to assess the long-term radiological risk of storing spent fuel. One cannot assess a quantity that is unbounded.

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[82] This statement holds at any given time, and cumulatively.

(IX-7) In Sections VI and VII of the Thompson scoping declaration, I set forth a number of recommendations for the use of scenarios.[83] These recommendations could have helped the framers of the draft GEIS to avoid the self-crippling of the draft GEIS that I have described in the preceding paragraphs. The framers ignored my recommendations. Those recommendations would, in principle, have allowed the draft GEIS to bound the radiological risk of storing spent fuel. Moreover, those recommendations would have allowed the draft GEIS to compare the risk posed by different scenarios and different options for managing spent fuel.

X. Pool Fire: Probability and Consequences

(X-1) The draft GEIS concedes that a pool fire could occur. More precisely, it concedes that zircaloy combustion could occur in a spent-fuel pool following loss of water from the pool. Here, in Section X, I address five aspects of the draft GEIS's consideration of pool fires, with an emphasis on the probability and consequences of a pool fire. The draft GEIS's consideration of pool fires is deficient in regard to each aspect. As a result, the draft GEIS makes an incorrect determination of the environmental impact of pool fires. The five aspects are:

- Documents cited in the draft GEIS
- NRC's understanding of relevant phenomena
- Probability of a pool fire
- Consequences of a pool fire
- Determination of radiological risk and environmental impact

Documents cited in the draft GEIS

(X-2) The draft GEIS provides technical discussions of pool fires in its Sections 4.18 and 4.19 and Appendix F. To support those discussions, the draft GEIS cites a number of documents. However, some relevant documents are not cited. In paragraphs X-3 through X-6, below, I discuss three examples of documents whose omission from the citations in the draft GEIS is significant.

(X-3) In paragraph VI-2, above, I note that NRC explicitly considered the impacts of malevolent acts in its 1979 GEIS on Handling and Storage of Spent Light Water Power Reactor Fuel, which was designated NUREG-0575.[84] Potential malevolent acts were described in Appendix J of that document. NUREG-0575 is not cited in Sections 4.18 and 4.19 and Appendix F of the draft GEIS. That omission is significant because the malevolent acts postulated in Appendix J of NUREG-0575 could, with slight adjustment, readily initiate a pool fire. I discuss that matter below.

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[83] Thompson, 2013b, Sections VI, VII, and X.
[84] NRC, 1979.

(X-4) In paragraph VIII-13, above, and elsewhere in this declaration, I discuss NRC's consequence study.[85] That study, published in draft form in June 2013 and final form in October 2013, is NRC's most recent technical analysis of pool fires. Yet, that study is not cited in Sections 4.18 and 4.19 and Appendix F of the draft GEIS, which was published in September 2013. That omission is significant from several perspectives. For example, as discussed in paragraphs VIII-14 through VIII-16, above, NRC's consequence study identified an important issue that has not been considered in the draft GEIS. That issue is the linkage of pool risk and reactor risk.

(X-5) The NRC staff incorporated the findings of NRC's consequence study into a staff recommendation regarding the expedited transfer of spent fuel from pools to dry storage. The staff recommended against expedited transfer in a November 2013 document that I refer to hereafter, following NRC practice, as the "Tier 3 analysis".[86] That document accompanies this declaration as Exhibit #36. The Tier 3 analysis describes its connection to the draft GEIS as follows:[87]

> "Within this Tier 3 analysis, the staff has considered the agency's activities on the waste confidence generic environmental impact statement (GEIS) and rulemaking, and it has ensured that the availability of these documents and interactions with stakeholders are coordinated to facilitate the public's involvement in these activities. Although this Tier 3 analysis was not specifically referenced in the draft GEIS, those who prepared the draft GEIS were aware of the conclusions in this Tier 3 analysis, and the staff has coordinated this activity with the relevant sections of the draft GEIS. To facilitate the public's ability to provide input, a draft of the October 2013 SFP study was released for public review and comment on July 1, 2013. Additionally, the draft evaluation of this Tier 3 issue was released to the public on September 26, 2013, well before the draft GEIS public comment period ends on December 20, 2013."

(X-6) Omission of the Tier 3 analysis from the citations in the draft GEIS is significant because the Tier 3 analysis sets forth an NRC staff position on the radiological risk of pool fires. The draft GEIS does not address that position. Yet, according to the statement quoted in the preceding paragraph, the preparers of the draft GEIS were aware of the conclusions in the Tier 3 analysis, and the two documents were "coordinated" in some manner. Thus, the Tier 3 analysis had a substantial but undocumented influence on the draft GEIS.[88] The lack of documentation of this influence handicaps those who seek to comment on the draft GEIS.

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[85] Barto et al, 2013b.
[86] Satorius, 2013b.
[87] Satorius, 2013b, page 9.
[88] One illustration of a likely influence is the draft GEIS's assertion that air cooling of spent fuel would prevent a pool fire at a point much earlier following fuel offload from a reactor than was considered in the study NUREG-1738. (See: NRC, 2013b, Appendix F, page F-11.) The Tier 3 analysis and NRC's consequence study represent NRC's most recent analysis of pool-fire issues such as the role of air cooling, but are not cited in the draft GEIS.

NRC's understanding of relevant phenomena

(X-7) I now turn to addressing NRC's understanding of phenomena relevant to a pool fire. I show that NRC's understanding of these phenomena is deficient, and that the NRC staff seeks to close off further inquiry that could correct the deficiencies. The first phenomenon that I address is the connection between: (i) the presence of residual water in the lower part of a pool that has experienced water loss; and (ii) the initiation of zircaloy combustion. NRC failed to understand this connection for more than two decades, and that misunderstanding continues to influence NRC's current analysis on pool fires.

(X-8) As discussed in paragraph I-7, above, the pool serving each commercial reactor in the USA is now equipped with high-density, closed-frame racks. The nuclear industry began installing these racks in the 1970s, to replace the low-density, open-frame racks previously used. The high-density racks offered a comparatively cheap option for storing a growing nationwide inventory of spent fuel. Figure X-1 shows the configurations of the two types of rack.

(X-9) If water were lost from a pool equipped with high-density racks, the racks would inhibit heat transfer from the exposed fuel. Thus, spent fuel in the pool would increase in temperature, potentially leading to ignition and sustained combustion of zircaloy cladding in air or steam. To a technically trained observer, it should be obvious that ignition could be more likely if residual water were present in the pool, other factors being equal. Residual water would block the flow of air from below, thus reducing heat transfer from the exposed portion of the fuel. Figure X-2 illustrates this phenomenon. As a result, spent fuel with a comparatively high age after discharge from a reactor could burn if residual water were present. The initial phase of "burning" would, in this case, be a steam-zircaloy reaction.

(X-10) As discussed in paragraph VI-4, above, NUREG-0575 dismissed the potential for a pool fire, arguing that spent fuel aged more than one year would not burn if water were lost from a pool.[89] NUREG-0575 was published by NRC in 1979. NRC held a similar position in 1989, when it published the pool-fire study NUREG-1353.[90] That study accompanies this declaration as Exhibit #37. NUREG-1353 stated:[91]

> "A typical spent fuel storage pool with high density storage racks can hold roughly five times the fuel in the core. However, since reloads typically discharge one third of the core, much of the spent fuel stored in the pool will have had considerable decay time. This reduces the radioactive inventory somewhat. More importantly, **after roughly three years of storage, spent fuel can be air-**

[89] NRC, 1979, page 4-21.
[90] Throm, 1989.
[91] Throm, 1989, page 1-1 (emphasis added).

> **cooled**. The spent fuel need not be submerged to prevent melting, although submersion is still desirable for shielding and to reduce airborne activity."

(X-11) Thus, from 1979 to 1989, NRC failed to understand the significance of residual water for zircaloy ignition. NRC's belief that comparatively old fuel would not ignite derived from NRC's mistaken assumption that the worst case of water loss from a pool would be total, instantaneous drainage. This erroneous belief continued into 1999 and 2000, while NRC was preparing a pool-fire study that was eventually published, in February 2001, as NUREG-1738.[92] That study accompanies this declaration as Exhibit #38. Preliminary versions of NUREG-1738 were published by NRC in June 1999 and February 2000.

(X-12) In 1999 and 2000, I was a technical adviser and expert witness for Orange County, North Carolina, supporting the County's intervention in a license proceeding before NRC's Atomic Safety and Licensing Board. The proceeding addressed a proposed expansion of spent-fuel storage capacity at the Shearon Harris nuclear power plant. In a March 2000 filing in that proceeding, the NRC staff disputed my position that comparatively old fuel could ignite if water were lost from a pool. That filing accompanies this declaration as Exhibit #39. In its filing, the NRC staff stated:[93]

> "However, although Dr. Thompson states that for "scenarios which involve partial uncovery of fuel, the reaction could affect fuel aged 10 or more years," he offers no authority to support this conclusion. **Dr. Thompson's is the only opinion of which the Staff is aware that holds that fuel five years or more out of the reactor is susceptible to zircaloy fire/exothermic reaction**. *See, e.g.,* NUREG/CR-0649, Spent Fuel Heatup Following Loss of Water During Storage, at 85-87 (1979) (Exhibit B)."

(X-13) Later in 2000, NRC corrected its erroneous belief, held since 1979, that comparatively old fuel could not ignite in the event of water loss. The Thompson draft consequence declaration describes the circumstances in which NRC made this correction.[94] In brief, NRC made the correction because its representatives were required, for the first time in decades, to justify their technical position in a public setting in which they could be challenged. The correction was acknowledged in NUREG-1738, which stated:[95]

> "The analyses in Appendix 1A determined that the amount of time available (after complete fuel uncovery) before a zirconium fire depends on various factors, including decay heat rate, fuel burnup, fuel storage configuration, building ventilation rates and air flow paths, and fuel cladding oxidation rates. While the

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92 Collins and Hubbard, 2001.
93 NRC, 2000, page 21 (emphasis added).
94 Thompson, 2013a, paragraphs III-12 to III-13 and III-23 to III-24.
95 Collins and Hubbard, 2001, pages 2-1 and 2-2 (emphasis added).

February 2000 study indicated that for the cases analyzed a required decay time of 5 years would preclude a zirconium fire, **the revised analyses show that it is not feasible, without numerous constraints, to define a generic decay heat level (and therefore decay time) beyond which a zirconium fire is not physically possible**. Heat removal is very sensitive to these constraints, and two of these constraints, fuel assembly geometry and spent fuel pool rack configuration, are plant specific. Both are also subject to unpredictable changes as a result of the severe seismic, cask drop, and possibly other dynamic events which could rapidly drain the pool. Therefore, since the decay heat source remains nonnegligible for many years and since configurations that ensure sufficient air flow for cooling cannot be assured, a zirconium fire cannot be precluded, although the likelihood may be reduced by accident management measures."

(X-14) Paragraphs X-7 through X-13, above, yield a significant finding. They show that NRC failed to understand a comparatively simple technical issue for more than two decades. NRC's misunderstanding persisted for this long period because its staff were shielded from public challenge and did not engage in the open discourse that is essential to scientific inquiry. With some limited exceptions, that situation has continued until the present.

(X-15) Before publishing NUREG-1738 in February 2001, NRC had published several studies related to pool fires. These studies, like NUREG-1353, contained erroneous statements about the potential for ignition of comparatively old fuel. They also contained other substantial deficiencies.[96] For example, NUREG-1353 did not consider storage of BWR spent fuel in high-density racks, even though such storage has been common practice for many years.[97] Yet, NRC has neither retracted nor repudiated NUREG-1353, despite its clear obsolescence. Indeed, the draft GEIS cites NUREG-1353 as a major source of information on the probability and consequences of a pool fire.[98]

(X-16) The potential for a pool fire became clear in 1979. From the beginning, the means of addressing this threat was also clear. The radiological risk of a pool fire could be dramatically reduced by abandoning the use of high-density racks in pools, and reverting to low-density, open-frame racks.[99] Figure X-1 shows the two types of rack. Since 1979, numerous parties have intervened in license proceedings and pursued other avenues, seeking to persuade NRC to order the elimination of high-density racks. A corollary of that action would be the transfer of a substantial portion of the US inventory of spent fuel from pools to dry casks. NRC has consistently and vigorously opposed the elimination of high-density racks.

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[96] Thompson, 2009, Section 5.
[97] Throm, 1989, pages 4-9 and 4-10.
[98] NRC, 2013b, Table F-1 (page F-4).
[99] In the case of BWR spent fuel, removal of channel boxes from the fuel could also be appropriate.

(X-17) Now, in its Tier 3 analysis, the NRC staff seeks to close off any further inquiry into the risk of a pool fire. The staff recommends:[100]

> "The staff's assessment concludes that the expedited transfer of spent fuel to dry cask storage would provide only a minor or limited safety benefit, and that its expected implementation costs would not be warranted. Therefore, the staff recommends that no further generic assessments be pursued related to possible regulatory actions to require the expedited transfer of spent fuel to dry cask storage and that this Tier 3 Japan lessons-learned activity be closed."

(X-18) The Tier 3 analysis relies heavily upon NRC's consequence study.[101] I provided a critical review of that study in the Thompson draft consequence declaration.[102] I concluded that NRC's consequence study is fundamentally and irredeemably flawed, and recommended:[103]

> "(VIII-7) NRC's Draft Consequence Study should be scrapped.
> (VIII-8) In addressing the pool-fire issue, NRC should focus its initial attention exclusively on establishing a solid technical understanding of phenomena directly related to a potential pool fire. To do this, NRC would start with a clean slate and use the best available modeling capability backed up by experiment. This modeling and experimental work would be done according to scientific principles. Further recommendations regarding such work are provided in Section IV, above."

(X-19) I recommend additional investigation of pool-fire phenomena because, more than three decades after the potential for a pool fire was recognized, NRC has not yet established a solid technical understanding of relevant phenomena. Thus, the NRC staff's recommendation to cease investigation of pool-fire issues is imprudent. Apparently, the NRC staff believes that acquisition of a solid understanding of pool-fire phenomena is unnecessary. The staff has not articulated a clear position on this matter. Such a position has, however, been articulated by Dr. Dana Powers, a member of NRC's Advisory Committee on Reactor Safeguards (ACRS), in a written commentary on the Thompson draft consequence declaration.[104] That commentary, with associated documents, accompanies this declaration as Exhibit #40. Dr. Powers' commentary includes the statement:[105]

> "Much of Section IV of Dr. Thompson's report is devoted to outlining an extensive study of accident phenomenology for spent fuel events. The intent seems to be to establish a very comprehensive understanding to a scientific

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[100] Satorius, 2013b, page 10.
[101] Barto et al, 2013b.
[102] Thompson, 2013a.
[103] Thompson, 2013a, Section VIII.
[104] Armijo, 2013, Enclosure 3.
[105] Armijo, 2013, Enclosure 3, page 4 (emphasis added).

> certainty in this phenomenology. Dr. Thompson does not make it clear why this should be done if, in fact, it can be shown that partial drain events are easily remediated with high confidence and that complete drain events are highly improbable. Nor does he provide a ranking of the use of resources for the purposes of studying spent fuel pools in preference to other safety issues. On the basis of results presented to ACRS thus far, it would appear that a systems engineering evaluation would suggest **the best use of available resources would be to assure that mitigation of partial drain events was assured and that complete drain events were highly improbable. This would obviate the need for a detailed understanding of accident phenomenology**. Should a decision be made to conduct confirmatory research, examination of the Dr. Thompson's list of topics might be useful starting point in the identification of possible avenues of investigation."

(X-20) Dr. Powers' statement is instructive. He and I view the pool-fire problem from opposite perspectives. His confidence regarding the efficacy of mitigating measures, and the validity of probability estimates, is such that he sees no need for a thorough understanding of relevant phenomena. In my judgment, however, there is compelling evidence that: (i) mitigation of loss of water from a pool could not be assured in many potential situations; and (ii) complete or partial loss of water from a pool has a significant probability. Moreover, the consequences of a pool fire could be severe. Accordingly, given present knowledge of pool-fire phenomena, prudence dictates a high-priority action – the rapid elimination of high-density racks from all pools. A thorough investigation of pool-fire phenomena, conducted in parallel with that action, might yield knowledge that somewhat reduces the urgency and scope of the action, thus reducing its cost. I recommend such an investigation.

(X-21) Later in Section X, I discuss the compelling evidence mentioned in the preceding paragraph. Here, I close my discussion of pool-fire phenomena by briefly discussing the influence of two factors on zircaloy ignition and combustion. The two factors are: (i) accumulation of zirconium hydrides in the cladding of high-burnup fuel; and (ii) the ballooning and burst of fuel cladding at temperatures above the normal operating level.

(X-22) In April 2000, the Chairman of ACRS wrote a letter to the Chairman of NRC, discussing some pool-fire phenomena.[106] That letter accompanies this declaration as Exhibit #41. The letter discussed a number of phenomenological issues that had not been properly considered by NRC. I focus here on one of those issues. That issue is the influence of zirconium hydrides on the ignition of exposed spent fuel. As part of its discussion of that issue, the ACRS letter said:[107]

> "We also have difficulties with the analysis performed to determine the time at which the risk of zirconium fires becomes negligible. In previous interactions

[106] Powers, 2000.
[107] Powers, 2000, page 3 (emphasis added).

> with the staff on this study, we indicated that there were issues associated with the formation of zirconium-hydride precipitates in the cladding of fuel especially when that fuel has been taken to high burnups. Many metal hydrides are spontaneously combustible in air. Spontaneous combustion of zirconium-hydrides would render moot the issue of "ignition" temperature that is the focus of the staff analysis of air interactions with exposed cladding. **The staff has neglected the issue of hydrides** and suggested that uncertainties in the critical decay heat times and the critical temperatures can be found by sensitivity analyses. Sensitivity analyses with models lacking essential physics and chemistry would be of little use in determining the real uncertainties."

(X-23) Given the trend of driving nuclear fuel to ever-higher burnups, one could reasonably expect that NRC would seriously address the concern expressed by ACRS. The ACRS letter did stimulate the preparation of an NRC internal memorandum.[108] That memorandum, with its attached draft report, accompanies this declaration as Exhibit #42. The memorandum and its attached draft report discussed factors that could influence the ignition of zircaloy when exposed to air or steam. Those factors included the presence of hydrides. They also included the ballooning and burst of fuel cladding, a matter I return to below. The draft report attached to the memorandum contained the statement:[109]

> "It would be necessary to **conduct actual ignition tests on either spent fuel or pre-oxidized and hydrided cladding** to generate experimental data to understand these various effects and to determine unambiguously the potential for autoignition. For lack of such experimental data, the potential for autoignition after ballooning and burst cannot be ruled out at this time."

(X-24) Ignition tests on actual spent fuel would be problematic because the fuel's large inventory of radioactive material would have to be shielded and contained. NRC did sponsor ignition tests on pre-oxidized cladding, as described in the report NUREG/CR-6846, published in 2004.[110] That report accompanies this declaration as Exhibit #43. At the time of publication of NUREG/CR-6846, NRC had not sponsored tests on hydrided cladding. Those tests were promised at some future time, as follows:[111]

> "The effect of pre-existing hydrides, formed on the cladding surface during in-reactor operation and relevant, in particular, for high burnup operation, is being investigated under a follow-on program at the Argonne National Laboratory. This latter study will be reported separately."

(X-25) NRC's consequence study was published in 2013. In that study, the theoretical model used to represent zircaloy ignition and combustion is drawn directly from

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[108] Eltawila, 2001.
[109] Eltawila, 2001, attached draft report by Chung and Basu, page 9 (emphasis added).
[110] Natesan and Soppet, 2004.
[111] Natesan and Soppet, 2004, Foreword (by Farouk Eltawila), page xvii.

NUREG/CR-6846. The model reflects the ignition tests on pre-oxidized cladding that are mentioned in the preceding paragraph. The study notes that this model shows accelerated combustion compared with previous models, and that this effect is confirmed by experiment.[112] Thus, the tests on pre-oxidized cladding that are described in NUREG/CR-6846 were a useful step toward simulating the ignition and combustion of actual spent fuel. Moreover, this step revealed that combustion would be more vigorous than previously expected. Yet, NRC's consequence study does not mention the effects of hydrides on cladding ignition and combustion, despite ACRS's highlighting of this issue in 2000 and NRC's promise in 2004 to sponsor appropriate tests. Thus, it seems that a key aspect of the ignition and combustion behavior of actual spent fuel, arising from the presence of hydrides, has been ignored by NRC. Moreover, accumulation of hydrides increases with burnup, and there is a trend of driving nuclear fuel to ever-higher burnups.

(X-26) As discussed in paragraph X-23, above, factors that could influence the ignition of zircaloy include the ballooning and burst of fuel cladding. It is well known that cladding can balloon (i.e., swell) and ultimately burst at temperatures substantially above the normal operating temperature. During the ballooning phase, the cross-sectional area for axial fluid flow through a fuel assembly could be reduced, thereby reducing heat transfer from the fuel. At the time of burst, unoxidized cladding would be exposed to air or steam, which could promote zircaloy ignition. The MELCOR code used in NRC's consequence study lacks a capability to model the ballooning and burst of fuel cladding.[113] MELCOR has been "benchmarked" against tests involving the ignition of electrically heated structures simulating fuel assemblies, as described in the report NUREG/CR-7143.[114] That report accompanies this declaration as Exhibit #44. Apparently, the tests did not involve ballooning and burst of cladding, perhaps because the simulated fuel rods were not sealed. Thus, neither MELCOR nor these tests provides any information about the implications of cladding ballooning and burst for zircaloy ignition. NRC's consequence study alludes to secret studies that address this matter, but provides no citation.[115]

(X-27) An April 2003 accident at the Paks-2 nuclear power plant in Hungary shows how overheated nuclear fuel will balloon and then burst. The accident and a subsequent simulation are described in a 2007 conference paper that accompanies this declaration as Exhibit #45.[116] The accident occurred while fuel was undergoing chemical cleaning inside a tank submerged in the plant's spent-fuel pool. Cooling water was supplied to the tank by a pump submerged in the pool. On this occasion, the water flow was inadequate, reportedly due to design defects and operating deficiencies. As a result, a steam bubble formed in the tank and fuel temperature began to rise. The zircaloy fuel cladding experienced extensive ballooning, followed by cladding burst and zirconium-steam

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[112] Barto et al, 2013b, pages 93 and 94.
[113] Barto et al, 2013b, Table 3, page 26.
[114] Lindgren and Durbin, 2013.
[115] Barto et al, 2013b, Table 3 (page 26).
[116] Windberg and Hozer, 2007.

combustion. This accident did not lead to a substantial release of radioactive material to the atmosphere, because it occurred inside a closed tank submerged in a pool. Nevertheless, this accident provides real-world evidence of the significance of phenomena such as cladding ballooning and burst. Regrettably, NRC's consequence study has not accounted for all relevant phenomena.

(X-28) Paragraphs X-7 through X-27, above, address various aspects of phenomena relevant to a pool fire. The Thompson draft consequence declaration contains a further critique of NRC's consideration of such phenomena.[117] Taken together, those sources support the following findings:

- NRC failed to understand a comparatively simple technical issue for more than two decades, because its staff were shielded from public challenge and did not engage in the open discourse that is essential to scientific inquiry.
- With limited exceptions, NRC staff remain shielded from public challenge and scientific discourse.
- NRC's latest analysis of pool fires (i.e., NRC's consequence study) ignores a number of technical issues that are significant to a determination of pool-fire risk.
- The NRC staff proposes to close off further inquiry into pool-fire risk.
- Apparently, the NRC staff believes that the acquisition of a thorough understanding of pool-fire phenomena is unnecessary because the probability of unmitigated partial or total loss of water from a pool is, in their view, negligible.

(X-29) NRC's deficient understanding of pool-fire phenomena is significant for the draft GEIS's determination of the environmental impact of pool fires, because that determination relies heavily on the judgment of NRC staff, especially in the context of malevolent acts. In many instances that reliance is undocumented or poorly documented.

Probability of a pool fire

(X-30) I now turn to discussing the probability of a pool fire. In this discussion I generally use the term "frequency" instead of "probability", because in some situations this indicator could have a value exceeding 1. A pool fire could be caused by an accident or a malevolent act. In the context of accidents, I have always been concerned about potential situations in which a radioactive release occurs at a reactor near to a pool. Given such a situation, the radiation field created by the reactor release, and other influences, could preclude mitigating actions needed to keep the pool in a safe state. In the context of malevolent acts, an analogous situation could arise. Additionally, a malevolent actor could preclude pool-related mitigating actions in ways that did not rely on obtaining a radioactive release from a nearby reactor.

(X-31) The draft GEIS relies upon the findings of PRA-type studies for its estimation of the frequency of accident-induced pool fires. Drawing upon such studies, the draft GEIS asserts that the frequency of a pool fire, caused by an accident, is in the range 5.8×10^{-7} to

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[117] Thompson, 2013a.

$2.4x10^{-6}$ per year.[118] Although not explicitly stated as such, this assertion refers to a frequency per pool-year. A pool-year is analogous to the concept of a reactor-year, which is introduced in paragraph V-5, above. Note that a frequency of $2.4x10^{-6}$ per pool-year, which is low, would become a much higher value if accumulated across many pools over many years. I address that matter below.

(X-32) The discussion in Section V, above, regarding the limitations of PRA, suggests that the actual frequency of a pool fire may be substantially higher than is asserted in the draft GEIS. Here, I focus on an issue that reinforces that suggestion. That issue is the linkage of pool risk and reactor risk. As discussed in Section VIII, above, NRC has never done a credible analysis of this linkage. Moreover, there is persuasive evidence, including the Fukushima accident, that a reactor accident could be part of a cascading sequence of incidents that preclude mitigating actions needed to maintain nearby pools in a safe state. Finally, as discussed in Section VIII, pool storage of spent fuel, as considered in the draft GEIS, will probably occur at locations near operational reactors.

(X-33) As discussed in paragraph V-21, above, direct experience of reactor accidents suggests that the frequency of accident-induced severe core damage may be in the vicinity of $3.2x10^{-4}$ per reactor-year. Let us now consider the conditional probability of a pool fire, given severe core damage at a nearby reactor. Experience suggests that this conditional probability is less than 1, because there have been 5 core melts and 0 pool fires at commercial facilities. Given the present state of knowledge, selecting a value of 0.1 for this conditional probability is prudent. Thus, a reasonable estimate for the frequency of an accident-induced pool fire, associated with an accident at a nearby reactor, is $0.1x3.2x10^{-4} = 3.2x10^{-5}$ per pool-year.[119] That value is 13 times higher than the pool-fire frequency (i.e., $2.4x10^{-6}$ per pool-year) at the upper end of the range asserted by the draft GEIS, and 55 times higher than the frequency (i.e., $5.8x10^{-7}$ per pool-year) at the lower end of the range.

(X-34) The discussion in the three preceding paragraphs can be structured in terms of the equation that is set forth in paragraph V-31, above. In that context, "PRA finding" is the pool-fire frequency asserted by the draft GEIS. The present state of knowledge suggests that "Reality factor #1" has a value of about one order of magnitude (i.e., factor of 10) at the upper end of the draft GEIS's frequency range. That value reflects the fact that the PRA-type analyses cited in the draft GEIS did not account for linkage of pool risk and reactor risk.

(X-35) As discussed in paragraph VI-11, above, the draft GEIS asserts that the probability of an attack-induced pool fire is "very low". In Section VI, however, I present evidence to the contrary. In my judgment, a prudent decision maker would

[118] NRC, 2013b, Appendix F, Table F-1 (page F-4). Also see: Collins and Hubbard, 2001, Table 3.1 (page 3-9).
[119] Here, I make the simplifying assumption that each reactor has a risk linkage with one nearby pool other than its own pool, and vice versa.

conclude from this evidence that a successful attack on a reactor or spent-fuel-storage facility in the United States over the coming decades is as likely to occur as are major national challenges that are planned for, such as severe natural disasters or engagement in wars.

(X-36) Here, I expand slightly upon the discussion in Section VI, while being careful to not disclose information that would assist a potential attacker. First, consider a potential situation in which a malevolent actor creates a cascading sequence of incidents that includes a radioactive release from a reactor. Given such a situation, the radiation field created by the reactor release, and other influences, could preclude mitigating actions needed to keep nearby pools in a safe state.

(X-37) In paragraphs VIII-19 through VIII-22, above, I draw from analysis by Morris et al to discuss a potential situation in which a large aircraft strikes a reactor. That event could be a malevolent act. I show that the aircraft impact could be part of a cascading sequence of incidents that includes a pool fire. Since the attacks of 11 September 2001 in New York and Washington, acquisition of a large aircraft by a malevolent actor has become more difficult. Also, precise aiming of a large aircraft at low altitude is difficult. However, a malevolent actor has other options. That actor might, for example, employ a comparatively small aircraft equipped with explosive devices.

(X-38) Now, consider a situation in which a malevolent actor has direct access to a pool. NUREG-0575 postulated such a situation, as discussed in paragraphs VI-2 through VI-6, above. The malevolent acts postulated in NUREG-0575 are summarized in Table VI-1. In the Mode 4 case, adversaries are assumed to temporarily take command of a spent-fuel pool while deploying an explosive device that could breach the floor of the pool. In that situation, as a slight adjustment of the Mode 4 case, the adversaries could use the explosive device to breach a wall of the pool, causing rapid drainage of water. The adversaries could ensure that some residual water is present. The exposed portion of the fuel would begin to heat up. Without prompt implementation of mitigating actions, a pool fire could follow. The adversaries could, in various ways, hinder or preclude mitigating actions.

(X-39) NRC proffers two, mutually inconsistent narratives about the threat of an attack on a spent-fuel pool. In one narrative, the pools are safe and secure, and no further action is needed to reduce the risk of a pool fire. In the other narrative, information about the potential for a pool fire must remain secret, because that information could be useful to an adversary.[120] Both narratives cannot be true. Apparently, NRC recognizes that the pools are vulnerable to attack, but believes that hiding that vulnerability under a veil of secrecy will eliminate the potential for attack. That belief is imprudent. Non-State

[120] NRC's consequence study mentions "security assessments" that were completed in 2006-2008, and further states that the results of these studies are not publicly available because they contain "sensitive information that could be useful to an adversary". (See: Barto et al, 2013b, page 14.)

adversaries of the United States have repeatedly demonstrated a level of technical knowledge such that they could readily understand the mechanisms underlying a pool fire, without recourse to NRC's secret studies. Thus, NRC's secrecy does not provide protection. Instead, it denies US citizens a full accounting of the risk of a pool fire.

Consequences of a pool fire

(X-40) I now turn to discussing the consequences of a pool fire. The draft GEIS provides two types of quantitative estimate of the consequences of a pool fire. One type is the value of an outcome per event (i.e., per pool fire). The second type is the frequency-weighted value of the outcome, which is calculated by multiplying the value per event by the supposed frequency of the event. The supposed frequency is expressed on a per-pool-year basis. The draft GEIS takes the position that the frequency-weighted value is the appropriate indicator of an environmental impact. I reject that position, as discussed below. Here, I discuss consequences on a per-event basis.

(X-41) The draft GEIS sets forth the following estimates of quantitative outcomes of a pool fire, on a per-event basis, in its Table F-1:[121]

- Collective radiation dose ranging from 47,000 person-Sv to 260,000 person-Sv across the population living within 50 miles, with no accounting of collective dose at greater distances.
- Latent fatalities (i.e., deaths occurring months or years after the event) ranging from 20,000 to 27,000, across the population residing at distances up to 500 miles.
- Onsite and offsite economic damage ranging from $56 billion to $58 billion (in 2010 dollars).

(X-42) NRC's consequence study, which is not cited in the draft GEIS, provides some quantitative estimates of pool-fire consequences.[122] These estimates do not appear in the draft GEIS. I discuss these estimates because they help to show that the draft GEIS substantially under-estimates the potential consequences of a pool fire. These estimates are specific to a potential fire at the Peach Bottom site in Pennsylvania. The particular estimates shown below are for an atmospheric release containing 330 PBq (i.e., 8.8 MCi) of the radioactive isotope Cs-137. That is a minor fraction of the inventory available for release. There are two operational reactors at the Peach Bottom site. Each reactor has its own spent-fuel pool, and each pool now contains about 2,180 PBq (i.e., 59 MCi) of Cs-137.[123] The quantity (i.e., mass) of fuel in each pool is equivalent to 5 reactor cores. For

[121] NRC, 2013b, Table F-1 (page F-4).
[122] The pool fire considered in NRC's consequence study would begin in recently-discharged fuel. In this declaration, I consider older spent fuel that falls under the ambit of the draft GEIS. However, the consequences that I discuss would be determined primarily by the magnitude of release of comparatively long-lived radio-isotopes, principally Cs-137. Thus, the consequences predicted by NRC's consequence study are applicable to the situation that I consider.
[123] Satorius, 2013b, Enclosure 1, Table 72 (page 133).

a postulated release of 330 PBq of Cs-137, NRC's consequence study predicts the following average outcomes of a pool fire, on a per-event basis:[124]

- Collective radiation dose of 350,000 person-Sv across a population living within an unspecified distance.
- Land area interdicted (i.e., rendered unfit for habitation) of 24,300 square km (i.e., 9,400 square miles).[125]
- Long-term displacement of 4.1 million people.[126]

(X-43) The numbers shown in paragraphs X-41 and X-42 begin to show the scale of the national disaster that could arise from a pool fire. Long-term displacement of 4.1 million people, which is an average case and not a worst case, would be a disaster of historic magnitude.[127] As discussed in paragraph IV-16, above, this event would cause substantial political stress and other adverse consequences. The social, political, and economic consequences would be diverse and difficult to predict, but would undoubtedly be severe. Moreover, the estimates described in paragraph X-42 assume a release of only 7% of the inventory of Cs-137 in the two pools at the Peach Bottom site. A larger release could occur.

(X-44) The estimate of economic damage that is set forth in the draft GEIS, and is shown in paragraph X-41, above, is much lower than other, more credible, estimates. Here, I discuss two estimates of this kind. One estimate is set forth in a 2004 journal article by Beyea et al.[128] That article accompanies this declaration as Exhibit #46. The second estimate is set forth in a 2007 report by the French government agency IRSN.[129] That report accompanies this declaration as Exhibit #47. A related paper by IRSN analysts is discussed in paragraphs IV-11 through IV-13, above.

(X-45) Beyea et al considered two potential, atmospheric releases. One release would consist of 130 PBq (i.e., 3.5 MCi) of Cs-137, and the other release would consist of 1,300 PBq (i.e., 35 MCi) of Cs-137. These releases represent two possible outcomes of a pool fire. The larger release would represent 60% of the Cs-137 inventory now in each of the two pools at the Peach Bottom site. Beyea et al estimated offsite economic damage for the two releases, at each of five nuclear-power-plant sites. For the 130 PBq release, the estimated offsite economic damage, averaged across the five sites, was $91 billion. For

[124] Barto et al, 2013b, Table 33 (page 162).
[125] The relationship between the estimated average area of interdicted land and distance is as follows: 1,200 square miles within a 50-mile distance; 3,100 square miles within a 100-mile distance; and 9,400 square miles within a 500-mile distance. (See: Barto et al, 2013b, Table 35.)
[126] The relationship between the estimated average number of displaced people and distance is as follows: 780,000 people within a 50-mile distance; 2.0 million people within a 100-mile distance; and 4.1 million people within a 500-mile distance. (See: Barto et al, 2013b, Table 36.)
[127] For a given atmospheric release, the estimated number of displaced people varies with wind direction, atmospheric stability, precipitation, and other factors. NRC's consequence study presents an average case.
[128] Beyea et al, 2004.
[129] IRSN, 2007.

the 1,300 PBq release, the estimated offsite economic damage, averaged across the five sites, was $385 billion.[130] Both values are substantially higher than the economic-damage estimate of $56 billion to $58 billion, covering both onsite and offsite damage, that is set forth in the draft GEIS. Yet, Beyea et al did not consider a full range of contributors to offsite economic damage. Nor did they consider onsite economic damage.

(X-46) A more comprehensive set of contributors to economic damage was considered by IRSN. Their findings are set forth in Table X-1, drawing from IRSN's 2007 report. That report was secret when first prepared, but was leaked to the press in early 2013 and, soon thereafter, was published by IRSN. The report considered an atmospheric release from a reactor at the Dampierre site in France. Economic damage was attributed primarily to the presence of 100 PBq of Cs-137 in the release. Thus, IRSN's findings are applicable to a pool fire. This pool fire would not be a worst-case event. A release of 100 PBq of Cs-137 would represent only 5% of the Cs-137 inventory now in each of the two pools at the Peach Bottom site.

(X-47) The cost (i.e., economic damage) estimates shown in Table X-1 are in Euro. Here, I use a currency conversion of US$1.40 per Euro. With that conversion, Table X-1 shows that IRSN's base-case estimate of economic damage from a release of 100 PBq of Cs-137 in France is $1,060 billion (760 billion Euro). The low-case estimate is $410 billion (290 billion Euro), and the high-case estimate is $8,060 billion (5,760 billion Euro). For comparison, the GDP of the United States in 2012 was $15,700 billion.[131]

(X-48) A cost study of the type done by IRSN would yield different results if done for a US nuclear site. There is no reason to expect, however, that the estimated economic damage would be substantially lower in the US case. The damage could be higher. Thus, IRSN's 2007 analysis provides, until a better estimate becomes available, a reasonable default estimate of economic damage from a pool fire in the United States that would release 100 PBq (2.7 MCi) of Cs-137. I am not aware of any other analysis that considers all of the cost contributors that are considered in the IRSN analysis. The draft GEIS's estimation of economic damage, as shown in paragraph X-41, is derived from analysis that is substantially inferior to the IRSN analysis.

(X-49) The economic damage estimated by IRSN would be only part of the consequences of a pool fire. The accompanying social and political consequences would be diverse and difficult to predict, but would undoubtedly be severe. Thus, a pool fire could be a national disaster of historic dimensions. That is why IRSN analysts, whose work is described in paragraphs IV-11 through IV-13, above, said in their 2012 paper that a massive release of radioactive material would be "an unmanageable European catastrophe".[132] In their 2012 paper, these analysts did not disclose the magnitude of a

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[130] Beyea et al, 2004, Table 3 (page 131).
[131] World Bank website, "GDP (current US$)", accessed on 13 December 2013 at: http://data.worldbank.org/indicator/NY.GDP.MKTP.CD
[132] Pascucci-Cahen and Patrick, 2012.

"massive" release. I assume that this release would contain no more than 100 PBq of Cs-137, the amount considered in IRSN's 2007 report. That report was secret when the IRSN analysts presented their 2012 paper.

(X-50) Japan's experience with fallout from the 2011 Fukushima accident is instructive. The pattern of radioactive fallout across Japan is complex, as shown in Figure V-4. That fallout contained about 6 PBq of Cs-137, as shown in Table V-1. This amount of Cs-137 is comparatively small in the context of a potential release from a pool fire. Yet, the impacts of the Fukushima fallout on Japan are diverse and significant. For example, it is reported that 160,000 people were displaced from land contaminated by the Fukushima accident, and about one-third of this population remains in temporary housing. There is considerable uncertainty about the number of people who may be able to return to their homes.[133] Also, all of Japan's nuclear power plants remain shut down, due to public concern about their operation.

Determination of radiological risk and environmental impact

(X-51) I now turn to the final subject I address in Section X, namely the determination of radiological risk and environmental impact. As discussed in Section IV, above, NRC employs what I describe as an "arithmetic" definition of risk. That definition is fundamentally flawed for the reasons I set forth in Section IV.

(X-52) The flawed nature of the arithmetic definition of risk is clearly evident in the draft GEIS, NRC's consequence study, and the NRC staff's Tier 3 analysis. Each of those documents uses frequency-weighted consequences, as discussed in paragraph X-40, above, as a measure of environmental impact. In that manner, disastrous consequences of a potential pool fire, such as the long-term displacement of 4.1 million people, are made to appear small by multiplying the consequences by a supposedly low frequency.

(X-53) Also, NRC focuses on each facility in isolation. That focus is evident in NRC's discussion of frequency in terms of occurrence per reactor-year or per pool-year. For some, limited, technical purposes, this single-facility focus is appropriate. It is, however, inappropriate when considering the risk experienced by a citizen. The United States currently has 100 operational, commercial reactors, roughly the same number of spent-fuel pools, and various other nuclear facilities.[134] A citizen is exposed to the radiological risk associated with a number of facilities. This point is illustrated by NRC's finding, as discussed in paragraph X-42, above, that a pool fire at the Peach Bottom site could lead to the long-term displacement of 4.1 million people. About 800,000 of those people would have resided within 50 miles of the site, while about 1.2 million would have resided between 50 and 100 miles from the site, and about 2.1 million would have resided

[133] Knight and Slodkowski, 2013.
[134] An operational reactor is a reactor that is normally in operation except when shut down for refueling, maintenance, or repair.

between 100 and 500 miles from the site.[135] Clearly, this event would have long-range consequences, extending far beyond the vicinity of the afflicted site. A citizen at a given location could be vulnerable to impacts of this nature originating at any of a number of sites.[136]

(X-54) Moreover, if such an event occurred, citizens would experience significant consequences even if they did not suffer from substantial, immediate injury such as displacement from their homes. The economic, social, and political consequences of this event would be felt by everyone residing in the United States, and by many people outside its borders. This pool fire would be a national disaster with international implications.

(X-55) Thus, in considering the probability of a pool fire, an appropriate indicator would be the frequency of the event occurring anywhere in the United States during a specified time period. Given the existence of operational reactors in Canada and Mexico, the geographic perimeter might logically be extended to North America. For the purposes of this declaration, however, I set that option aside because it would be legally and politically difficult to implement.

(X-56) What would be the appropriate time period for a determination of frequency? Given that a pool fire could be a national disaster of historic dimensions, a reasonable time period would be a century. If that time period were employed in the context of the United States as a geographic unit, then the frequency of a pool fire would be expressed in terms of the number of occurrences per century, where the occurrence could be at any location within the United States. This concept of frequency would be compatible with the particular characteristics of pool-fire risk. Hereafter, I refer to this concept as "cumulative frequency". Note, as discussed previously, that this indicator could have a value greater than 1.

(X-57) There are now 100 operational reactors in the United States. As discussed in Section IX, above, the draft GEIS allows for the continuation of this situation indefinitely. Thus, for the purpose of illustrating pool-fire risk, it is reasonable to consider a scenario in which 100 reactors are operational throughout a period of 100 years. In this scenario, each reactor has a risk linkage with one nearby pool other than its own pool, and vice versa. Each of these nearby pools is assumed to fall under the ambit of the draft GEIS because the reactor that it served is no longer licensed for operation. I assume that each nearby pool is equipped with high-density racks, and that the risk posed by each reactor-pool linkage is uniform across the fleet and constant over time. This "status quo" scenario is entirely compatible with the draft GEIS.

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[135] Barto et al, 2013b, Table 36 (page 169).

[136] The flexRISK project in Austria developed a computer-model capability to assess the radiological risk, at any location in Europe, that arises from operation of all nuclear facilities across Europe. That capability could be applied to the United States. An overview of the flexRISK project was accessed on 14 December 2013 from: http://flexrisk.boku.ac.at/en/index.html

(X-58) For this illustrative scenario, the cumulative frequency of a pool fire can be determined by simple extrapolation of current estimates of pool-fire frequency, which are expressed on a per-pool-year basis. Consider first the frequency estimate of 2.4×10^{-6} per pool-year that is set forth in the draft GEIS in the context of an accident-induced pool fire, as discussed in paragraph X-31, above. In that case, the cumulative frequency would be $100 \times 100 \times 2.4 \times 10^{-6} = 0.024$ events per century. Now, consider the revised frequency estimate of 3.2×10^{-5} per pool-year that is set forth in paragraph X-33. This revised estimate accounts for linkage of pool risk and reactor risk, still in the context of an accident-induced pool fire. In this case, the cumulative frequency would be $100 \times 100 \times 3.2 \times 10^{-5} = 0.32$ events per century.

(X-59) At this point in Section X, I am ready to evaluate the draft GEIS's assessment of the environmental impact of pool fires. I provide this evaluation in paragraph X-60, addressing accident-induced pool fires, and in paragraph X-61, addressing attack-induced pool fires. In both cases, I find that the draft GEIS's assessment of environmental impact is incorrect. Paragraphs X-60 and X-61 provide my evaluation and its underlying rationale.

(X-60) The draft GEIS asserts that the environmental impact of accident-induced pool fires is SMALL.[137] However, as shown above, the draft GEIS indicates that the cumulative frequency of such fires could be 0.024 events per century. Also, NRC's consequence study shows that the consequences of a pool fire could be severe, with outcomes such as the long-term displacement of 4.1 million people. IRSN's analysis shows that outcomes could include economic damage measured in trillions of dollars. Therefore, the environmental impact of accident-induced pool fires is not SMALL. Instead, it is LARGE. This finding does not account for linkage of pool risk and reactor risk. If that linkage is accounted for, as is appropriate, the cumulative frequency of accident-induced pool fires could be 0.32 events per century. In that case, it is even more evident that the environmental impact of accident-induced pool fires is not SMALL. Instead, it is LARGE. Thus, the draft GEIS substantially under-estimates the environmental impact of accident-induced pool fires. Also, the draft GEIS ignores the possibility that the risk environment will become more adverse in the future. In addition, the draft GEIS uses a flawed definition of risk – the arithmetic definition.

(X-61) The draft GEIS further asserts that the environmental impact of attack-induced pool fires is SMALL.[138] However, from the discussions in Section VI and paragraphs X-35 through X-39, above, it is clear that the cumulative frequency of attack-induced pool fires could be substantial. Also, NRC's consequence study shows that the consequences of a pool fire could be severe, with outcomes such as the long-term displacement of 4.1 million people. IRSN's analysis shows that outcomes could include economic damage measured in trillions of dollars. Therefore, the environmental impact of attack-induced

[137] NRC, 2013b, Table 4-2 (page 4-91).
[138] NRC, 2013b, Table 4-2 (page 4-91).

pool fires is not SMALL. Instead, it is LARGE. Thus, the draft GEIS substantially under-estimates the environmental impact of attack-induced pool fires. Also, the draft GEIS ignores the possibility that the risk environment will become more adverse in the future. In addition, the draft GEIS uses a flawed definition of risk – the arithmetic definition. Moreover, application of the arithmetic definition is additionally flawed in this instance because the indicators that are multiplied together are nebulous.

XI. Cask Fire: Probability and Consequences

(XI-1) The draft GEIS assumes that spent fuel will be stored initially in pools and subsequently in dry casks. A group of dry casks will constitute an ISFSI. During cask storage there is a potential for a "cask fire". That event could occur if a malevolent actor gains access to a dry cask containing spent fuel and attacks the cask in a manner that produces a self-propagating reaction between air and zircaloy fuel cladding, leading to a substantial atmospheric release of radio-isotopes including Cs-137. An accident could conceivably cause a cask fire at a storage facility, but I do not consider that possibility here. The draft GEIS does not consider the occurrence of a cask fire caused by either accident or attack.

(XI-2) In the Thompson scoping declaration, I outlined the potential for an attack-induced cask fire.[139] I first discussed a potential precursor to a cask fire – a reasonably foreseeable attack that would penetrate a cask, damage fuel inside the cask, and cause a release of radioactive material to the atmosphere. The feasibility of such an attack has been demonstrated in tests whose findings have been openly published. In my judgment, an attacker could, with a few additional steps, readily initiate a cask fire. NRC has not conceded that an attacker could take these additional steps and initiate a cask fire.

(XI-3) The difference between my position and that of NRC could be resolved by commissioning an independent "Red Team" of persons who have relevant experience in practice and research. That team could conduct tests at a national laboratory or military base, to determine how readily a cask fire could be initiated. The tests could involve the use of tracer materials, thereby contributing to estimation of the radioactive release that could result from a cask fire. The general findings of the tests should be published, but some details of the tests may not be appropriate for publication. Until such tests are done, NRC will not be able to complete an adequate GEIS on the environmental impacts of storing spent fuel.

(XI-4) The probability and impacts of an attack-induced cask fire are interrelated. Also, the relationship between probability and impacts is influenced by the extent to which casks are protected from attack. Moreover, the difference between the risk of attack-induced pool fires and the risk of attack-induced cask fires is a significant issue in the context of national security. The concept of protective deterrence provides a useful perspective on that difference. These matters are discussed below.

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[139] Thompson, 2013b, paragraphs VII-15 through VII-16 and VIII-14 through VIII-18.

(XI-5) The effort needed to successfully attack an ISFSI and produce a cask fire could be roughly the same as the effort needed to successfully attack a spent-fuel pool and produce a pool fire. Let us examine the implications of that finding during a future period when pools and ISFSIs coexist. As discussed in paragraph VI-10 and elsewhere in this declaration, there is persuasive evidence that an attack-induced pool fire is as likely to occur as are major national challenges that are planned for, such as severe natural disasters or engagement in wars. An identical statement could be made about a cask fire, if two provisos were satisfied. The <u>first proviso</u> is that attackers would be able to achieve roughly the same outcomes by attacking a pool or an ISFSI. If that proviso were not satisfied, and the attack on the ISFSI would achieve a lower outcome, the attackers would have a reduced incentive to attack the ISFSI. The <u>second proviso</u> is that the casks sit on concrete pads in the open air without additional protection, which is current practice. If that proviso were not satisfied, and additional protection was provided, the attackers would have to expend greater effort to achieve the same outcome, which would reduce their incentive to attack.

(XI-6) These provisos show how probability and impacts are interrelated. If the expected outcome of an attack on an ISFSI would be smaller than the outcome of an attack on a pool, other factors being equal, then a malevolent actor would be less likely to attack the ISFSI. The probability of the attack would decrease even further if the casks in the ISFSI were provided with additional protection against attack. Thus, either decreasing the expected outcome of an attack, or increasing the effort required to achieve a given outcome, would decrease the probability of attack. In the context of national security, that effect is encompassed within the concept of protective deterrence. Implementation of that concept could benefit the nation. Accordingly, the Thompson scoping declaration made the following recommendation:[140]

> "**Recommendation #22:** In assessing the overall impacts of storing SNF or HLW, the proposed EIS [i.e., the draft GEIS] should consider the implications of alternative storage options for a national strategy of protective deterrence."

(XI-7) Table XI-1 shows how the United States could benefit from policies that ensured that critical infrastructure is designed to be robust and inherently safer. The benefits could include, for example, a reduction in the federal government's perceived need to conduct surveillance of the domestic population. That matter is a subject of current debate. Designing critical infrastructure to be robust and inherently safer would be part of a national strategy of protective deterrence.

(XI-8) Nuclear facilities – including reactors, pools, and ISFSIs using dry casks – are components of critical infrastructure. In the context of storing spent fuel, a dry cask is more robust and inherently safer than is a pool equipped with high-density racks. A dry cask in an ISFSI with enhanced protection would be even more robust and inherently

[140] Thompson, 2013b, Section IX and Section X.

safer. Thus, the aspects of radiological risk that I discuss in this declaration are significant for national security, and could be productively addressed within the context of protective deterrence. The draft GEIS is oblivious to this matter, and does not respond to my recommendation as quoted in paragraph XI-6, above. More generally, NRC appears oblivious to its potential ability to benefit the nation by implementing principles of protective deterrence.

(XI-9) The first step in assessing potential consequences of an attack-induced cask fire is to determine the inventory of radioactive material that is in the cask and available for release. Here, I focus on the radio-isotope Cs-137. I consider, as an illustrative example, a cask holding 32 PWR fuel assemblies. With reasonable assumptions, one can readily calculate that the cask contains 67 PBq (i.e., 1.8 MCi) of Cs-137.[141]

(XI-10) A successful attack on an ISFSI, in which attackers expended an effort roughly the same as the effort needed to successfully attack a spent-fuel pool and cause a pool fire, could cause a cask fire in one or perhaps two casks. For illustration, let us assume that two casks would experience a fire and the fractional release of Cs-137 to the atmosphere would be 50%. In that case, the total atmospheric release from two typical casks holding 32 PWR fuel assemblies per cask would contain 67 PBq of Cs-137. That would be a substantial release, with a magnitude between the Fukushima release (36 PBq) and the Chernobyl release (85 PBq), as shown in Table V-1.

(XI-11) Section X, above, discusses the consequences of atmospheric releases of various amounts of Cs-137. For example, as discussed in paragraph X-42, release of 330 PBq of Cs-137 could lead to severe consequences including long-term displacement of 4.1 million people. Also, as discussed in paragraphs X-46 through X-48, release of 100 PBq of Cs-137 could create economic damage of about $1 trillion in the "base" case and $8 trillion in the "high" case. In addition, there would be severe consequences of a social and political nature.

(XI-12) Thus, it is clear that a release of 67 PBq of Cs-137 during a cask-fire incident could lead to severe consequences. Yet, a pool fire could lead to a much larger release, with correspondingly greater consequences. For example, as noted in paragraph X-42, each of the two pools at the Peach Bottom site now contains about 2,180 PBq of Cs-137. The fractional release of Cs-137 during a pool fire could be substantial, potentially exceeding 50%. At Peach Bottom, where two pools are in close proximity, an attack on one pool could ultimately lead to fires in both pools. Thus, a pool-fire release exceeding 2,000 PBq of Cs-137 is entirely credible.

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[141] Assumptions in the calculation are: (i) there are 32 PWR spent fuel assemblies in the cask; (ii) each fuel assembly has a mass of 0.45 Mg HM; (iii) the fuel has a burnup of 50 GWt-days per Mg HM; (iv) the fuel is aged 10 years after discharge from a reactor; and (v) 1 GWt-day of fission energy yields 1.17×10^{14} Bq of Cs-137.

(XI-13) The effort needed to successfully attack an ISFSI and produce an atmospheric release of 67 PBq of Cs-137 could be roughly the same as the effort needed to successfully attack a spent-fuel pool and produce a pool fire. However, the pool-fire release could be much larger than 67 PBq of Cs-137. As discussed above, at Peach Bottom a pool-fire release could exceed 2,000 PBq of Cs-137. Informed attackers would be aware of this discrepancy in potential outcomes. Accordingly, they would tend to target a pool rather than an ISFSI, other factors being equal. If the ISFSI were provided with enhanced protection, the comparative attractiveness of the ISFSI as a target would be even lower. Section XII, below, discusses some options for providing ISFSIs with enhanced protection.

(XI-14) At present, pools and ISFSIs coexist in the United States. Thus, given the comparative attractiveness of pools and ISFSIs as targets, a successful attack on a pool is currently more likely than a successful attack on an ISFSI. However, the draft GEIS contemplates a future in which there would be ISFSIs and no pools. That situation could continue into the indefinite future. Diminution of radioactive decay heat in spent fuel over time would be irrelevant to the creation of a cask fire. The risk environment could become more adverse over time. For example, security measures at ISFSIs could degrade over time. Also, an increased propensity for violent conflict could find expression through attacks on ISFSIs. Thus, the frequency of successful attacks on ISFSIs could be much greater in the future than it is today.

(XI-15) The findings set forth in Section XI, up to this point, support three conclusions about the environmental impact of attacks on ISFSIs. Here, I use the creation of one or more cask fires as an indicator of the success of an attack on an ISFSI.

(XI-16) The first conclusion is as follows. As discussed in paragraph VI-11, above, the draft GEIS asserts that the environmental impact of attacks on ISFSIs is SMALL. However, the cumulative frequency of successful attacks on ISFSIs could be substantial. Also, the consequences of a successful attack could be severe. Therefore, the environmental impact of attacks on ISFSIs is not SMALL. Instead, it is LARGE. Thus, the draft GEIS substantially under-estimates the environmental impact of attacks on ISFSIs. Also, the draft GEIS ignores the possibility that the risk environment will become more adverse in the future. In addition, the draft GEIS uses a flawed definition of risk – the arithmetic definition. Moreover, application of the arithmetic definition is additionally flawed in this instance because the indicators that are multiplied together are nebulous.

(XI-17) The second conclusion is as follows. While pools and ISFSIs coexist, as is true today, the cumulative frequency of successful attacks on pools is likely to exceed the cumulative frequency of successful attacks on ISFSIs. However, the draft GEIS contemplates a future in which there would be ISFSIs and no pools. In that case, the cumulative frequency of successful attacks on ISFSIs could be comparable to the currently-applicable cumulative frequency of successful attacks on pools, if there were no change in the risk environment. Whether or not pools coexist with ISFSIs in the future, the risk environment could become more adverse, leading to an increase in the cumulative frequency of successful attacks on ISFSIs.

(XI-18) The third conclusion is as follows. The cumulative frequency of successful attacks on ISFSIs, now and in the future, could be decreased by providing ISFSIs with enhanced protection against attack.

XII. Risk-Reducing Options

(XII-1) There are numerous options for reducing the radiological risk arising from management of spent fuel and other radioactive waste produced by the nuclear fuel cycle. The draft GEIS does not discuss any options of this type. Here, I provide a brief discussion of a few options. This discussion does not purport to be comprehensive.

(XII-2) Table XII-1 outlines some options for reducing the risk of a pool fire at a nuclear power plant. This table was prepared in the context of a spent-fuel pool that serves an operational reactor. A similar table could be prepared for a pool that no longer serves an operational reactor.

(XII-3) The most effective option in Table XII-1 is to re-equip the pool with low-density, open-frame racks. In the case of BWR fuel, a corollary action could be the removal of channel boxes from the fuel. When nuclear power plants in the present US fleet first entered service, their spent-fuel pools were equipped with low-density, open-frame racks. The margin of safety provided by this configuration was lost when the nuclear industry adopted high-density racks as a way to minimize short-term costs.

(XII-4) Over a period of decades, pursuit of short-term cost minimization has increased the radiological risk of nuclear power production in various respects. This pursuit influenced the design of the nuclear power plants that participated in the Fukushima accident of 2011. Other manifestations of this pursuit include reactor power uprates, use of higher-burnup fuel, shorter refueling periods, and use of high-density racks in spent-fuel pools.

(XII-5) Section XI, above, discusses some of the implications of providing enhanced protection of ISFSIs. In the United States, a typical ISFSI consists of dry casks sitting on a concrete pad in the open air. Other countries provide greater protection.

(XII-6) Sweden has taken an interesting approach to ISFSI design. The Swedes have built the Clab facility, in which spent-fuel pools are located in underground caverns excavated in rock. The Clab facility has been described in a brochure published by SKB, the company that manages Sweden's radioactive waste.[142] That brochure accompanies this declaration as Exhibit #48. One sees from the brochure that the ceiling of each cavern is 32 m below the surface. The intervening rock is granite.

[142] SKB, 2006.

(XII-7) The Clab facility will probably not be replicated in the United States. It represents a comparatively expensive approach to managing spent fuel. Also, although Clab is not designed as a repository, there might be political pressure to employ such a facility as a repository if repeated efforts to build a repository were to fail. For that reason, I recommend that interim storage of spent fuel be done at the surface, to reduce the likelihood that an interim storage facility could become a repository by default.

(XII-8) The German approach to ISFSI design is to store spent fuel in dry casks that are, with one exception, located within buildings at the surface.[143] The design of these buildings is described in a conference paper by Thomauske.[144] That paper accompanies this declaration as Exhibit #49. Two basic designs are used. One design is by STEAG, and the other by WTI. Cross-sectional drawings in Thomauske's paper suggest that the STEAG design would be more robust against attack. That observation is confirmed by analyses showing that the STEAG design would be more robust against impact by a large aircraft.

(XII-9) Holtec is a US-based vendor of dry casks used for storing spent fuel at ISFSIs. The Holtec design approach is modular. Fuel is sealed inside a multi-purpose canister (MPC) that is designed to be placed inside overpacks of various types. Holtec has developed an overpack, known as the HI-STORM 100U, that would be more robust against attack than present overpacks. A standard MPC would be placed, in a vertical-axis position, inside the 100U overpack. The 100U overpack would be sunk below ground except for its lid. Holtec has described the robustness of the 100U system 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."

(XII-10) Paragraphs XII-6 through XII-9 show that options are available for providing enhanced protection of ISFSIs. Use of such options at ISFSIs across the United States would support a national strategy of protective deterrence.

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[143] The exception is the Neckarwestheim ISFSI, which consists of two concrete-lined tunnels in the wall of a quarry.
[144] Thomauske, 2003.
[145] Holtec, 2007. A current description of the 100U system was accessed on 15 December 2013 from: http://www.holtecinternational.com/productsandservices/wasteandfuelmanagement/hi-storm/

XIII. Conclusions

(XIII-1) I provide conclusions in two categories. The first category is "reference conclusions". These are set forth at some length, linked consecutively to the portions of this declaration from which they were derived. The second category is "summary conclusions". These are expressed concisely, and are arranged to support a coherent argument.

(XIII-2) The reference conclusions, and the body of this declaration, represent my definitive findings. The summary conclusions may be less exact.

(XIII-3) My reference conclusions are set forth below. The heading for each conclusion shows the portion of this declaration from which the conclusion was principally derived. These conclusions are:

<u>Reference Conclusion #1 (derived from Section IV)</u>

The draft GEIS defines radiological risk as the numerical product of the probability and the consequences of an event, and further argues that a high-consequence, low-probability event, such as a severe accident, could be determined to have a small environmental impact if the risk is sufficiently low. In the context of the draft GEIS, that definition of radiological risk, and the associated determination of environmental impact, are fundamentally flawed from at least four overlapping perspectives:

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

<u>Reference Conclusion #2 (derived from Section V)</u>

The draft GEIS relies on PRA-type studies for its estimation of radiological risk. Studies of this type can provide useful information about radiological risk, for certain purposes. However, these studies cannot provide a credible estimate of the probability of a radiological event such as a pool fire. The relationship between a PRA finding and reality can be represented as follows:

Actual probability of event = (PRA finding)x(Reality factor #1) + (Reality factor #2)

Where the variables in this equation are as follows:

- "Actual probability of event" refers to the real-world numerical probability of an outcome such as: fuel damage; release of a specified amount of radioactive material; contamination of a specified area of land above a specified dose threshold; or accrual of a specified collective dose to people offsite.
- "PRA finding" refers to a PRA estimate of the probability of the outcome in question – this could be a mean, median, or other representation of a probability distribution.
- "Reality factor #1" is a number, typically greater than 1, that represents influences that are within the paradigm of PRA but are not properly accounted for in contemporary PRAs – these influences include: complexity; inadequate data; and deficiencies in institutional culture and practice.
- "Reality factor #2" is a number that represents influences outside the paradigm of PRA – these influences include: gross errors in design, construction, or operation; and malevolent acts.

And the following observations apply:

- Experience suggests that Reality factor #1 for severe accidents may have a value that exceeds 1 by several orders of magnitude (i.e., factors of 10).
- Reality factor #2 has two numerical components: (i) a retrospective component that can be determined empirically based on the occurrence of events; and (ii) a prospective component that will remain unknown for the foreseeable future.
- Both Reality factors may vary significantly in response to variations in the future risk environment.
- This version of the equation is applicable when the values of "PRA finding" and "Actual probability of event" are both less than 1. At higher values, the term "probability" would be replaced by the term "frequency".

<u>Reference Conclusion #3 (derived from Section VI)</u>

In light of human history, observation of the contemporary world, and consideration of possible societal trends, a prudent decision maker would conclude that a successful attack on a reactor or spent-fuel-storage facility in the United States over the coming decades is as likely to occur as are major national challenges that are planned for, such as severe natural disasters or engagement in wars.

<u>Reference Conclusion #4 (derived from Section VII)</u>

The draft GEIS sets forth a highly optimistic view of the future conditions that will affect stored spent fuel. It assumes that institutional controls will remain operative into the indefinite future, arguing that this assumption "avoids unreasonable speculation regarding what might happen in the future". This assumption, like other optimistic assumptions in the draft GEIS, is neither reasonable nor prudent. Moreover, assuming static conditions is speculative in the extreme, and shows a profound ignorance of human history. Given the long timeframes envisioned in the draft GEIS, the only reasonable approach is to consider a broad range of scenarios. Those scenarios would encompass substantial changes in the risk environment over time. The changes could be non-uniform across the United States.

<u>Reference Conclusion #5 (derived from Section VIII)</u>

Pool storage of spent fuel, as considered in the draft GEIS, could occur, and probably will occur, at locations near operational reactors. Accordingly, the draft GEIS should have carefully considered the potential linkage of radiological risk among pools and operational reactors at each site. The draft GEIS has not considered this matter.

<u>Reference Conclusion #6 (derived from Section VIII)</u>

Risk linkages among spent-fuel pools and operational reactors at a site could be manifested in a cascading sequence of incidents that preclude mitigating actions needed to maintain pools in a safe state. Mitigating actions could be precluded by, for example, a radiation field arising from the release of radioactive material. NRC has never, to my knowledge, published a credible technical analysis of a cascading sequence of incidents of this type, or publicly stated that it has performed such analysis in secret. Until such analysis is done properly, NRC will not be able to complete an adequate GEIS on the environmental impacts of storing spent fuel.

<u>Reference Conclusion #7 (derived from Section IX)</u>

The draft GEIS does not set forth any scenario for the future use of nuclear power or, more specifically, for the future creation of spent fuel. Thus, in the draft GEIS, the timeframe for creation of spent fuel spans an unknown but potentially vast range, as does the quantity of spent fuel created in that timeframe. Accordingly, the radiological risk posed by storing spent fuel is unbounded. In this manner, the draft GEIS has denied itself the ability to assess the long-term radiological risk of storing spent fuel. One cannot assess a quantity that is unbounded. This grave deficiency could have been avoided by judicious use of scenarios. A scenario-based approach could, in principle, have allowed the draft GEIS to bound the radiological risk of storing spent fuel. Moreover, such an approach could have allowed the draft GEIS to compare the risk posed by different scenarios and different options for managing spent fuel.

<u>Reference Conclusion #8 (derived from Section X)</u>

The draft GEIS fails to cite a number of documents that are relevant to its findings about the risk of pool fires. Moreover, some recently published documents in this category had a substantial but undocumented influence on the draft GEIS. The lack of documentation of this influence handicaps those who seek to comment on the draft GEIS. Documents not cited in the draft GEIS that are particularly significant include:

- Appendix J of NUREG-0575.[146]
- NRC's consequence study. [147]
- The NRC staff's Tier 3 analysis.[148]

<u>Reference Conclusion #9 (derived from Section X)</u>

The draft GEIS reflects NRC's present understanding of phenomena relevant to a pool fire. That understanding is deficient from the following perspectives:

- NRC failed to understand a comparatively simple technical issue for more than two decades, because its staff were shielded from public challenge and did not engage in the open discourse that is essential to scientific inquiry.
- With limited exceptions, NRC staff remain shielded from public challenge and scientific discourse.
- NRC's latest analysis of pool fires (i.e., NRC's consequence study) ignores a number of technical issues that are significant to a determination of pool-fire risk.
- The NRC staff proposes to close off further inquiry into pool-fire risk.
- Apparently, the NRC staff believes that the acquisition of a thorough understanding of pool-fire phenomena is unnecessary because the probability of unmitigated partial or total loss of water from a pool is negligible.

<u>Reference Conclusion #10 (derived from Section X)</u>

The draft GEIS significantly under-estimates the probability of an accident-induced pool fire, in part because it does not consider the linkage of pool risk and reactor risk. The present state of knowledge suggests that the under-estimate is by at least one order of magnitude (i.e., factor of 10).

<u>Reference Conclusion #11 (derived from Section X)</u>

The draft GEIS significantly under-estimates the probability of an attack-induced pool fire. That probability cannot be determined quantitatively. My qualitative assessment is provided in Conclusion #3, above.

<u>Reference Conclusion #12 (derived from Section X)</u>

The draft GEIS substantially under-estimates the consequences of a pool fire. Those consequences could include the long-term displacement of millions of people, economic damage measured in trillions of dollars, and adverse social and political outcomes. A pool fire yielding these consequences would be a national disaster of historic dimensions.

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[146] NRC, 1979.
[147] Barto et al, 2013b.
[148] Satorius, 2013b.

Reference Conclusion #13 (derived from Section X)

The draft GEIS considers the risk of a pool fire in terms of the probability of its occurrence at a particular pool within a 1-year timeframe. That approach to risk assessment does not account for the potential magnitude and scope of the consequences of a pool fire. Instead, the radiological risk of a pool fire should be considered in terms of the cumulative frequency of its occurrence, over a period of a century, at any location within the United States.

Reference Conclusion #14 (derived from Section X)

The draft GEIS asserts that the environmental impact of accident-induced pool fires is SMALL. However, the cumulative frequency of such fires is substantial, and the consequences of a pool fire could be severe. Therefore, the environmental impact of accident-induced pool fires is not SMALL. Instead, it is LARGE. Thus, the draft GEIS substantially under-estimates the environmental impact of accident-induced pool fires. Also, the draft GEIS ignores the possibility that the risk environment will become more adverse in the future. In addition, the draft GEIS uses a flawed definition of risk – the arithmetic definition.

Reference Conclusion #15 (derived from Section X)

The draft GEIS asserts that the environmental impact of attack-induced pool fires is SMALL. However, the cumulative frequency of such fires is substantial, and the consequences of a pool fire could be severe. Therefore, the environmental impact of accident-induced pool fires is not SMALL. Instead, it is LARGE. Thus, the draft GEIS substantially under-estimates the environmental impact of attack-induced pool fires. Also, the draft GEIS ignores the possibility that the risk environment will become more adverse in the future. In addition, the draft GEIS uses a flawed definition of risk – the arithmetic definition. Moreover, application of the arithmetic definition is additionally flawed in this instance because the indicators that are multiplied together are nebulous.

Reference Conclusion #16 (derived from Section XI)

The draft GEIS asserts that the environmental impact of attacks on ISFSIs is SMALL. However, the cumulative frequency of successful attacks on ISFSIs could be substantial. Also, the consequences of a successful attack could be severe. Therefore, the environmental impact of attacks on ISFSIs is not SMALL. Instead, it is LARGE. Thus, the draft GEIS substantially under-estimates the environmental impact of attacks on ISFSIs. Also, the draft GEIS ignores the possibility that the risk environment will become more adverse in the future. In addition, the draft GEIS uses a flawed definition of risk – the arithmetic definition. Moreover, application of the arithmetic definition is additionally flawed in this instance because the indicators that are multiplied together are nebulous.

Reference Conclusion #17 (derived from Section XI)

While pools and ISFSIs coexist, as is true today, the cumulative frequency of successful attacks on pools is likely to exceed the cumulative frequency of successful attacks on ISFSIs. However, the draft GEIS contemplates a future in which there would be ISFSIs and no pools. In that case, the cumulative frequency of successful attacks on ISFSIs could be comparable to the currently-applicable cumulative frequency of successful attacks on pools, if there were no change in the risk environment. Whether or not pools coexist with ISFSIs in the future, the risk environment could become more adverse, leading to an increase in the cumulative frequency of successful attacks on ISFSIs.

Reference Conclusion #18 (derived from Section XI)

The cumulative frequency of successful attacks on ISFSIs, now and in the future, could be decreased by providing ISFSIs with enhanced protection against attack.

Reference Conclusion #19 (derived from Section XII)

The draft GEIS does not consider options for reducing the radiological risk arising from management of spent fuel. However, numerous options of this kind are available. For example, options are available for providing enhanced protection of ISFSIs. Use of such options at ISFSIs across the United States would support a national strategy of protective deterrence.

(XIII-4) My summary conclusions are set forth below. They are:

Summary Conclusions

1. The draft GEIS asserts that the environmental impact of accident-induced or attack-induced pool fires is SMALL in both cases. That assertion is incorrect. The environmental impact is LARGE in both cases.
2. The draft GEIS asserts that the environmental impact of attacks on ISFSIs is SMALL. That assertion is incorrect. The environmental impact is LARGE.
3. The draft GEIS's assertions regarding the environmental impacts of pool fires and attacks on ISFSIs are incorrect because the draft GEIS: (i) employs an inappropriate definition of radiological risk; (ii) inappropriately assesses radiological risk on a single-facility basis over a one-year period; and (iii) under-estimates the probability and consequences of radiological incidents at pools and ISFSIs.
4. An appropriate definition of radiological risk would: (i) account for qualitative factors affecting probability and consequences; (ii) recognize qualitative differences between small and large consequences; and (iii) repudiate the idea that large consequences are tolerable if their supposed probability is low.

5. An appropriate assessment of radiological risk at pools and ISFSIs would examine cumulative risk across all US facilities over a period of a century, and would account for potential changes in the risk environment.
6. The draft GEIS under-estimates the probability and consequences of radiological incidents at pools and ISFSIs because: (i) NRC has not conducted the comprehensive empirical and analytic inquiry needed to thoroughly understand probability and consequences in this context; (ii) NRC staff are shielded from public challenge and scientific discourse; and (iii) NRC inappropriately assumes that the risk environment will remain static.
7. The NRC staff proposes to close off further inquiry into the probability and consequences of radiological incidents at pools.
8. NRC has ignored my recommendation to conduct further inquiry into the probability and consequences of cask fires.
9. Options are available to reduce the probability and consequences of radiological incidents at pools and ISFSIs, with collateral benefits to the nation via enhancement of protective deterrence, but these options are ignored in the draft GEIS.

****

I declare, under penalty of perjury, that the facts set forth in the foregoing narrative, and in the four appendices below, are true and correct to the best of my knowledge and belief, and that the opinions expressed therein are based on my best professional judgment.

Executed on 19 December 2013.

G. R. Thompson

Gordon R. Thompson

APPENDIX A: Tables and Figures

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List of Figures

Table IV-1
Some Categories of Risk Posed by a Commercial Nuclear Facility: Author's Definitions

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

Notes:
(a) In this declaration, the general term "risk" is defined as the potential for an unplanned, undesired outcome. There are various categories of risk, including the three categories in this table.
(b) In the case of radiological risk, the events leading to unplanned exposure to radiation could be accidents or attacks.
(c) The term "proliferation risk" is often used to refer to the potential for diversion of fissile material, for use in nuclear weapons. Here, the term also covers the potential for diversion of radioactive material, for use in radiological weapons.

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

Category	Amount of Cesium-137 (PBq)
Chernobyl release to atmosphere (1986)	85
Fukushima #1 release to atmosphere (2011)	36
Deposition on Japan due to the Fukushima #1 atmospheric release	6.4
Pre-release inventory in reactor cores of Fukushima #1, Units 1-3 (total for 3 cores)	940
Pre-release inventory in spent-fuel pools of Fukushima #1, Units 1-4 (total for 4 pools)	2,200

Notes:
(a) This table shows estimated amounts of Cesium-137 from: Stohl et al, 2011. The estimates for release from Fukushima #1 and deposition on Japan may change as new information becomes available.
(b) Stohl et al, 2011, provide the following data and estimates for Fukushima #1, Units 1-4, just prior to the March 2011 accident:

Indicator	Unit 1	Unit 2	Unit 3	Unit 4
Number of fuel assemblies in reactor core	400	548	548	0
Number of fuel assemblies in reactor spent-fuel pool	392	615	566	1,535
Cesium-137 inventory in reactor core (Bq)	2.40E+17	3.49E+17	3.49E+17	0
Cesium-137 inventory in reactor pool (Bq)	2.21E+17	4.49E+17	3.96E+17	1.11E+18

(The core capacity of Unit 4 was 548 assemblies. The core of Unit 3 contained some MOX fuel assemblies at the time of the accident.)
(c) Assuming a total Cesium-137 release to atmosphere of 36 PBq, originating entirely from the reactor cores of Units 1, 2, and 3, which contained 940 PBq, the overall release fraction to atmosphere for Cesium-137 was 36/940 = 0.038 = 3.8 percent.

Table V-2
Estimated Human Dose Commitment from the Chernobyl Release of Radioactive Material to Atmosphere in 1986

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

Notes:
(a) These estimated doses are whole-body doses, from: DOE, 1987, Table 5.16, "preferred estimate".
(b) Most of the dose is attributable to Cesium-137 (see: DOE, 1987, page x).
(c) Estimates for non-USSR countries show that, on average, about 50% of the collective dose is attributable to external exposure, and about 50% is attributable to ingestion (see: DOE, 1987, Table 5.14). Uncertainty in these estimates is greater for ingestion than for external exposure.
(d) In this instance, 1 Gy is equivalent to 1 Sv.

Table V-3
Insurance Premiums Paid by Ontario Power Generation (OPG) for Nuclear Liability and Terrorism Coverage of the Darlington Station, 2005-2012

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

Notes:
(a) Premium data were obtained from copies of annual invoices from Marsh Canada Limited to OPG. These copies were provided by OPG to Shawn-Patrick Stensil of Greenpeace Canada in February 2013, pursuant to a request by Stensil under the Freedom of Information and Protection of Privacy Act.
(b) Marsh Canada received the premium payments on behalf of the Nuclear Insurance Association of Canada (NIAC) and other insurance pools, which may have included British Nuclear Insurers and American Nuclear Insurers.
(c) In addition to paying the amounts shown to Marsh Canada, OPG also paid an 8% sales tax on each amount to the province of Ontario.
(d) The components of the total premium (i.e., nuclear liability, and terrorism) are available, for the years shown, only for 2005. In that year, the terrorism premium was $88,086 (12.3% of the total premium) and the nuclear liability premium was $626,287 (87.7% of the total premium).
(e) Prior to 2005, a combined premium payment was made for the Darlington and Pickering stations and, in earlier years, for the Bruce station as well.

Table V-4
Accident-Probability Implications of Insurance Premiums Paid by OPG for Coverage Associated with Operation of the Darlington Station

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

Notes:
(a) Table V-3 shows gross, pre-tax insurance premiums paid by OPG for nuclear liability and terrorism coverage of the 4-unit Darlington station, over the period 2005-2012. The annual average gross premium for the station during that period was $727,853. In 2005, the terrorism premium accounted for 12.3% of the gross premium. Here, it is assumed that 30% of the gross premium is allocated to: (i) terrorism premium; (ii) administration; (iii) contingency; (iv) reinsurance premium paid to the Canadian government; and (v) profit. Thus, 70% of the gross premium is assumed here to be the net premium that supports offsite Coverage A (i.e., legal liability for bodily injury or property damage) through the private insurers in the NIAC pool, for an accident not involving a malevolent act. Throughout the period 2005-2012 and currently, the limit on that liability is $75 million. Thus, the net premium per RY for a $75 million maximum liability = $727,853 x 0.7 x 0.25 = $127,000 per RY.
(b) Dermot Murphy of NIAC has said that increasing the liability limit from $75 million to $650 million would require a premium increase by a factor of approximately 4 to 6, while a limit of $1,000 million would require a premium increase by a factor of approximately 5 to 8. (See: Murphy, 2009.) These factors are applied in the second column of the table.
(c) The "implied probability of event", in the third column, is calculated by dividing the amount in the second column by the amount in the first column, for each row. This implied probability represents NIAC's assessment of the probability of a claim up to the liability limit.
(d) As indicated in note (a), above, the "implied probability of event" that is calculated here applies to an accident in which offsite damage (i.e., bodily injury or property damage) arises from a release of radioactive material at Darlington. The calculation shown here does not apply to a release caused by a malevolent act.

Table VI-1
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 1.5 m-thick concrete floor of the pool	

Notes:
(a) Information in this table is from Appendix J of: NRC, 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 VI-2
Potential Types of Attack on a Reactor or Spent-Fuel Storage Facility, Leading to Atmospheric Release of Radioactive Material

Type of Event	Facility Behavior	Some Relevant Instruments and Modes of Attack	Characteristics of Atmospheric Release
Type 1: Vaporization or Pulverization	• All or part of facility is vaporized or pulverized	• Facility is within the fireball of a nuclear-weapon explosion	• Radioactive material in facility is lofted into the atmosphere and amplifies fallout from nuc. explosion
Type 2: Rupture and Dispersal (Large)	• Facility structures are broken open • Fuel is dislodged from facility and broken apart • Some ignition of zircaloy fuel cladding may occur, typically without sustained combustion	• 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 zirc. combustion occurs
Type 3: Rupture and Dispersal (Small)	• Facility structures are penetrated but retain basic shape • Fuel may be damaged but most rods retain basic shape • Damage to cooling systems could lead to zirc. combustion	• Vehicle bomb • Impact by commercial aircraft • Perforation by shaped charge	• Scattering and plume formation as in Type 2 event, but involving smaller amounts of material • Substantial release of volatile species if zirc. combustion occurs
Type 4: Precise, Informed Targeting	• Facility structures are penetrated, creating a release pathway • Zirc. combustion is initiated indirectly by damage to cooling systems, or by direct ignition	• Missiles (military or improvised) with tandem warheads • Close-up use of attack instruments (e.g., shaped charge, incendiary, thermic lance)	• Scattering and plume formation as in Type 3 event • Substantial release of volatile species, potentially exceeding amount in Type 3 release

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

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

Notes:
(a) This table is adapted from: Thompson, 2007, Table 7-4. Further citations are provided in that table and its supporting narrative. For additional, supporting information of more recent vintage, see: Ahearne et al, 2012, Chapter 5.
(b) Defenses at nuclear power plants around the world are typically no more robust than at US plants.

Table VI-4
The Shaped Charge as a Potential Instrument of Attack

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

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

Table VI-5
Performance of US Army Shaped Charges, M3 and M2A3

Target Material	Indicator	Value for Stated Type of Shaped Charge	
		Type: M3	**Type: M2A3**
Reinforced concrete	Maximum wall thickness that can be perforated	150 cm	90 cm
	Depth of penetration in thick walls	150 cm	75 cm
	Diameter of hole	• 13 cm at entrance • 5 cm minimum	• 9 cm at entrance • 5 cm minimum
	Depth of hole with second charge placed over first hole	210 cm	110 cm
Armor plate	Perforation	At least 50 cm	30 cm
	Average diameter of hole	6 cm	4 cm

Notes:
(a) Data are from US Army Field Manual FM 5-25: Army, 1967, pp 13-15 and page 100.
(b) The M2A3 charge has a mass of 5 kg, a maximum diameter of 18 cm, and a total length of 38 cm including the standoff ring.
(c) The M3 charge has a mass of 14 kg, a maximum diameter of 23 cm, a charge length of 39 cm, and a standoff pedestal 38 cm long.

Table X-1
IRSN Estimates of Costs Arising from a "Massive" Atmospheric Release of Radioactive Material from a French 900 MWe PWR

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

Notes:
(a) Data are from: IRSN, 2007, Tables A4.4.4 and A4.4.5.
(b) The assumed release would be from the Dampierre nuclear generating station, which has four 900 MWe PWR units and is located on the Loire River south of Paris. The release is described (IRSN, 2007, page 37) as follows: "Par simplification, le scenario considere la dispersion en deux heures d'un tiers de l'inventaire du coeur, ce qui est le bon ordre de grandeur pour le cesium, contributeur preponderant des couts." Thus, the release apparently includes one-third of one reactor's core inventory of Cesium isotopes, which are said to be the major contributors to the estimated costs. The many radio-isotopes in a reactor core have widely varying volatilities and chemical properties. Thus, their release fractions will vary. The IRSN text, quoted above, does not address this matter.
(c) An estimate of the core inventory of Cs-137 in a 900 MWe PWR can be made by assuming: (i) total fuel mass = 75 Mg HM; (ii) average fuel burnup at discharge = 50 GWt-days per Mg HM; (iii) Cs-137 yield = 1.17E+14 Bq per GWt-day of fission; and (iv) one-third of the core is discharged at each refueling, and a refueling outage is imminent, so that average fuel burnup in the core = (2/3) x discharge burnup. With those assumptions, the core inventory of Cs-137 = 1.17E+14 x 75 x (2/3) x 50 = 2.9E+17 Bq. One-third of that inventory = 9.7E+16 Bq = 97 PBq.
(d) IRSN used the COSYMA code to estimate plume behavior and radiological impacts for 144 weather conditions. The "base case" estimates shown in the table are said to reflect median results. The "low case" (scenario favorable) and "high case" (scenario defavorable) estimates reflect non-median results and, apparently, changes in analytic assumptions.

Table XI-1
Selected Approaches to Protecting Critical Infrastructure in the USA From Attack by Non-State Actors, and Some Strengths and Weaknesses of these Approaches

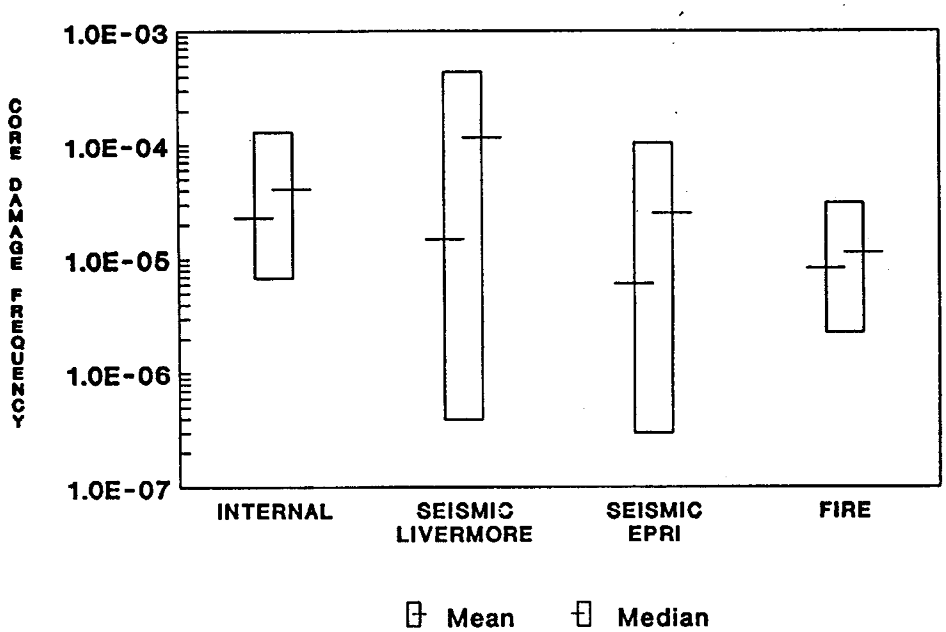
Approach	Strengths	Weaknesses
Approach #1: Offensive military operations internationally	• Could deter or prevent governments from supporting non-State actors hostile to the USA	• Could promote growth of non-State groups hostile to the USA, and build sympathy for these groups in foreign populations • Could be costly in terms of lives, money, etc.
Approach #2: International police cooperation within a legal framework	• Could identify and intercept potential attackers	• Implementation could be slow and/or incomplete • Requires ongoing international cooperation
Approach #3: Surveillance and control of the domestic population	• Could identify and intercept potential attackers	• Could destroy civil liberties, leading to political, social, and economic decline of the USA
Approach #4: 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
Approach #5: 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
Approach #6: Robust and inherently-safer design of infrastructure facilities (**Note:** This approach could be part of a "protective deterrence" strategy for the USA.)	• Could allow target to survive attack without damage, thus contributing to 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

Notes:
(a) These approaches could be used in parallel, with differing weightings.
(b) Approach #6 would contribute to "protective deterrence", which is distinct from "counter-attack deterrence".

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

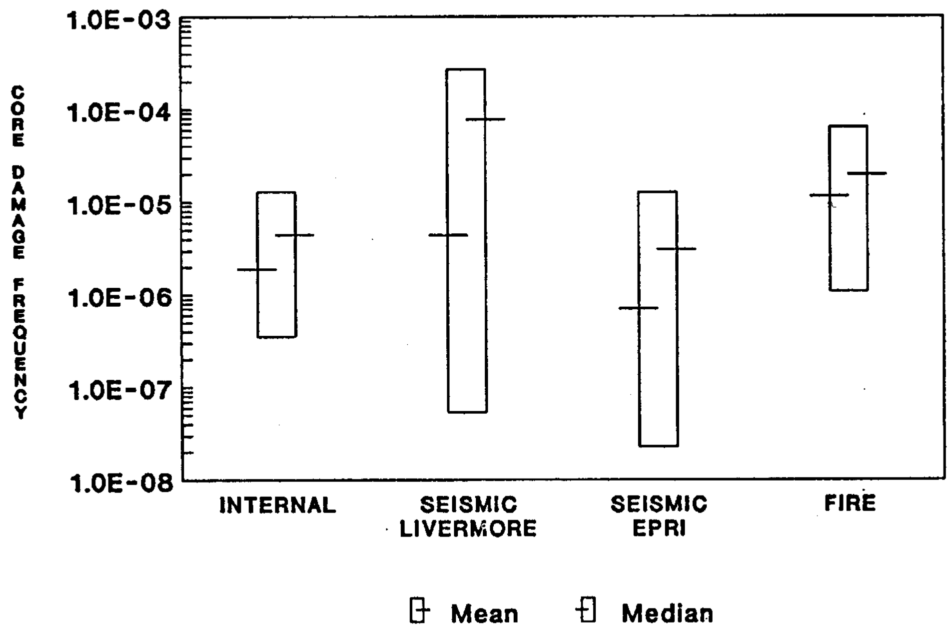
Option	Passive or Active?	Does Option Address Fire Scenarios Arising From:		Comments
		Attack?	Other Events?	
Re-equip pool with low-density, open-frame racks	Passive	Yes	Yes	• Would substantially reduce pool inventory of radioactive material • Would prevent auto-ignition of fuel in almost all cases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

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



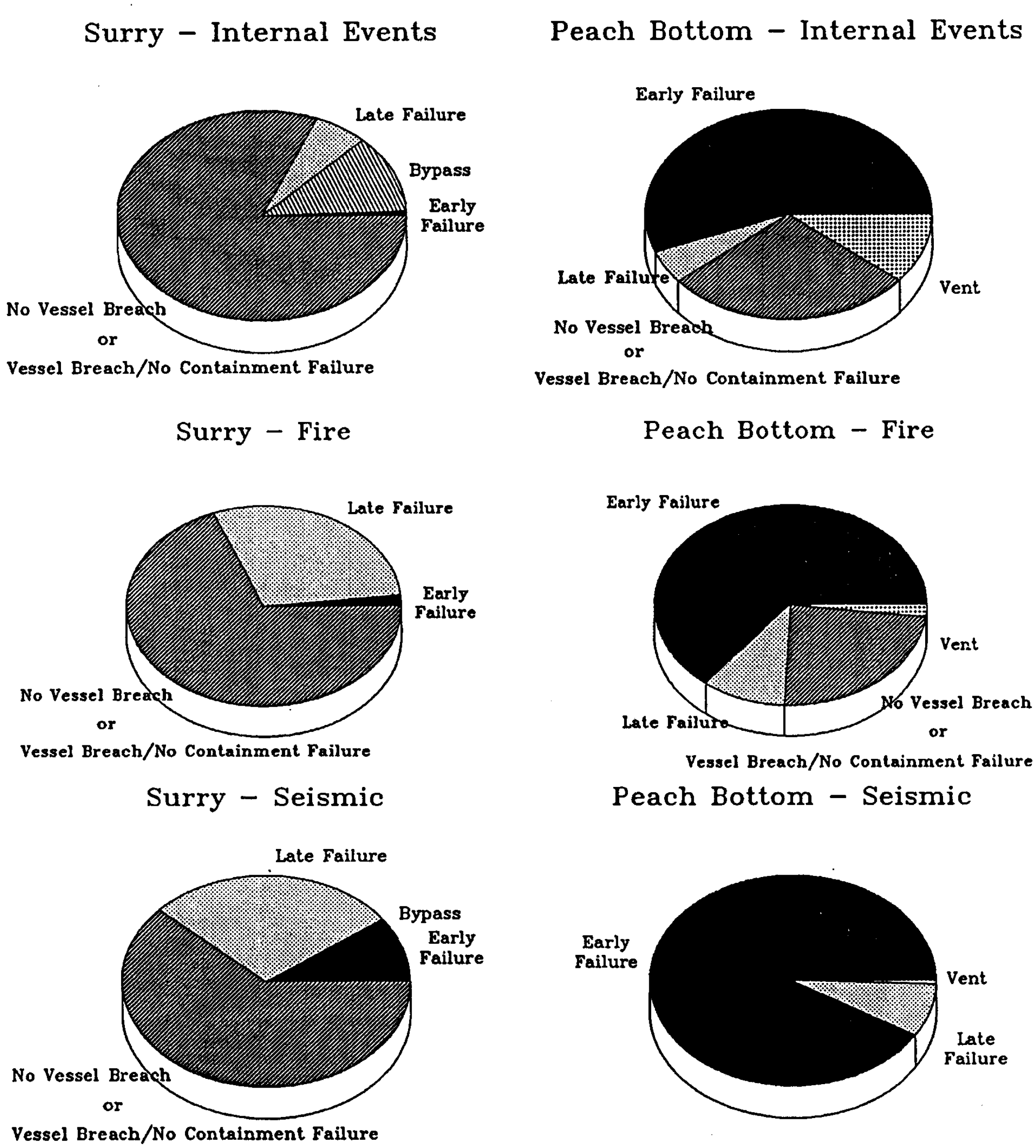
Notes:
(a) This figure is adapted from Figure 8.7 of: NRC, 1990.
(b) The bars range from the 5th percentile (lower bound) to the 95th percentile (upper bound) of the estimated core damage frequency (CDF). CDF values shown are per reactor-year (RY).
(c) "Internal" initiating events encompass equipment failure, human error, etc. "External" initiating events encompass earthquake, flood, strong wind, fire, etc.
(d) Two estimates are shown for the CDF from earthquakes (seismic effects). One estimate derives from seismic predictions done at Lawrence Livermore National Laboratory (Livermore), the other from predictions done at the Electric Power Research Institute (EPRI).
(e) CDFs were not estimated for external initiating events other than earthquake and fire.
(f) Malevolent acts were not considered.

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



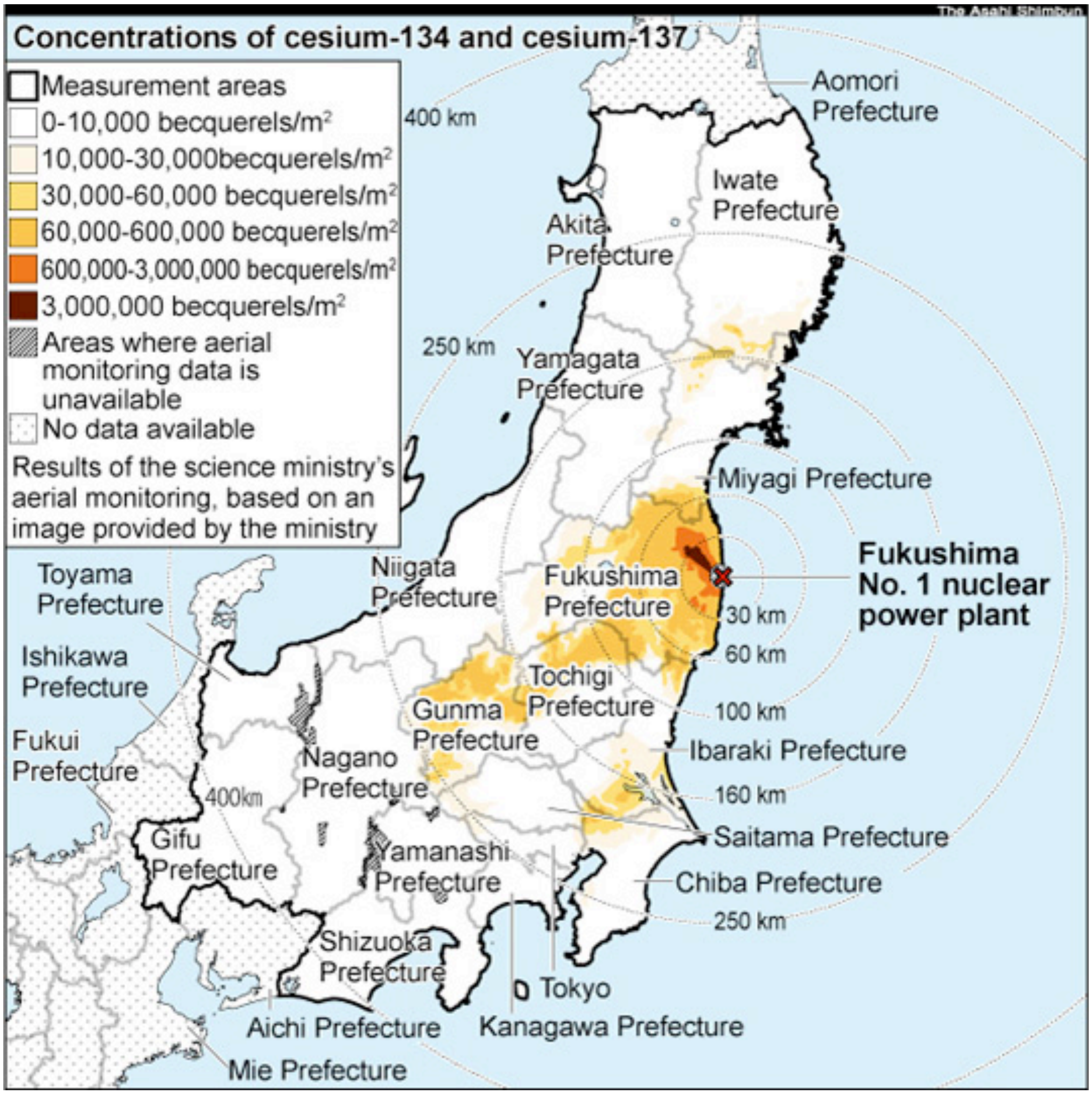
Notes:
(a) This figure is adapted from Figure 8.8 of: NRC, 1990.
(b) Notes (b) through (f) of Figure V-1 also apply here.

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



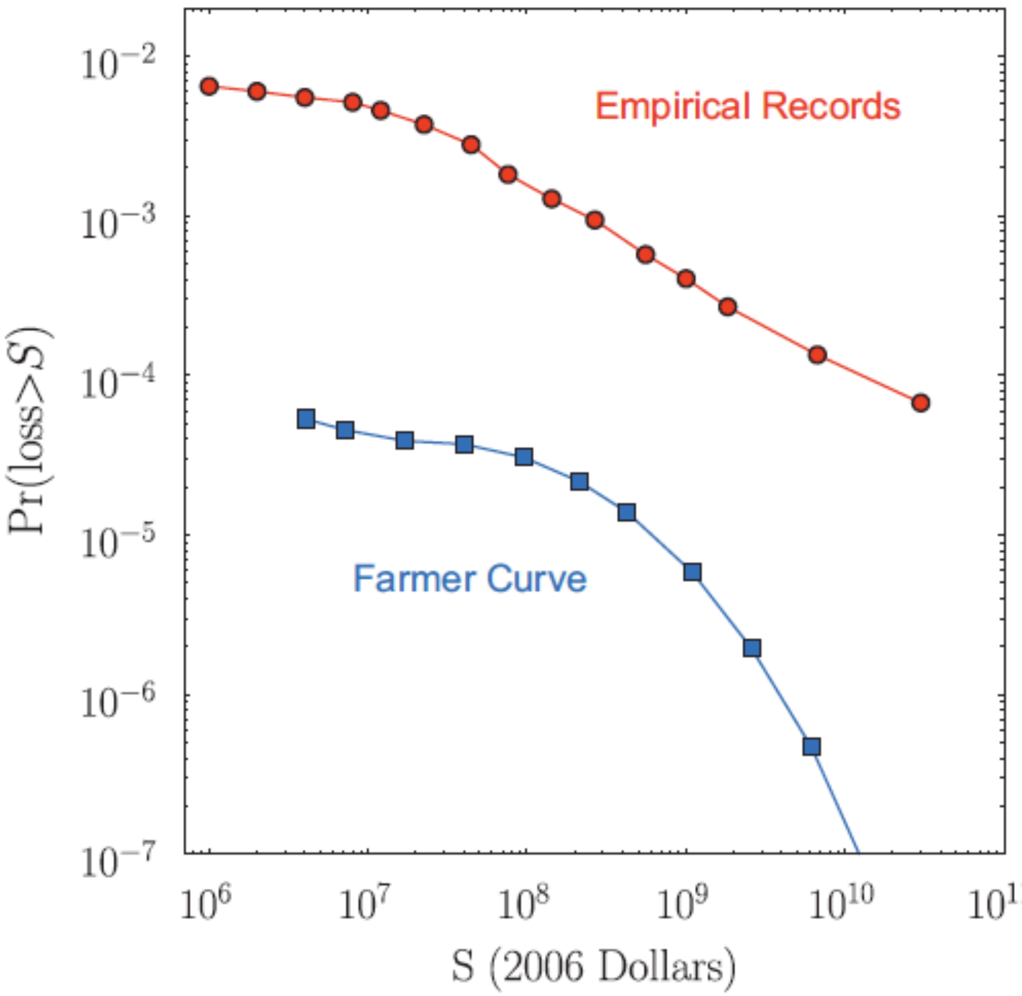
Note:
This figure is adapted from Figure 9.5 of: NRC, 1990.

Figure V-4
Contamination of Land in Japan by Radioactive Cesium Released to Atmosphere During the Fukushima #1 Accident of 2011



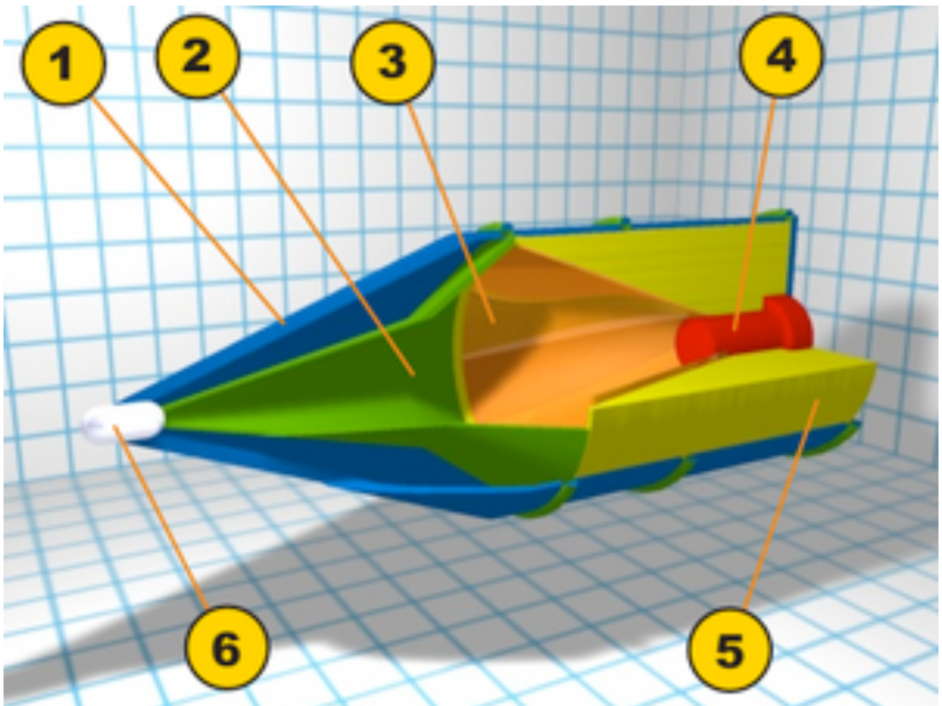
Source:
Asahi Shimbun, 2011.

Figure V-5
Probability Distribution of Monetized Losses from Nuclear-Facility Incidents: Sornette et al's Comparison of Empirical Data with PRA Estimates



Notes:
(a) This figure is a reproduction of Figure 1 from: Sornette et al, 2013.
(b) The curves shown are complementary cumulative distribution functions.
(c) The vertical axis is probability per reactor-year (or facility-year).
(d) The "Farmer Curve" is based on findings from NRC's Reactor Safety Study, which was the first reactor PRA. In this curve, monetized losses are associated with radiological impacts.
(e) The "Empirical Records" curve is based on Sovacool's compilation of data on 99 incidents at nuclear facilities. In this curve, monetized losses may, or may not, be associated with radiological impacts.

Figure VI-1
Schematic View of a Generic Shaped-Charge Warhead



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

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

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

Figure VI-2
MISTEL System for Aircraft Delivery of a Shaped Charge, World War II

Notes:
(a) Photograph accessed on 5 March 2012 from:
http://www.historyofwar.org/Pictures/pictures_Ju_88_mistel.html
(b) A shaped-charge warhead can be seen at the nose of the lower (converted bomber) aircraft, replacing the cockpit. The aerodynamic cover in front of the warhead would have a contact fuse at its tip, to detonate the shaped charge at the appropriate standoff distance.
(c) A human pilot in the upper (fighter) aircraft would control the entire rig, and would point it toward the target. Then, the upper aircraft would separate and move away, and the lower aircraft would be guided to the target by an autopilot.

Figure VI-3
January 2008 Test of a Raytheon Shaped Charge, Intended as the Penetration (Precursor) Stage of a Tandem Warhead System

Before Test

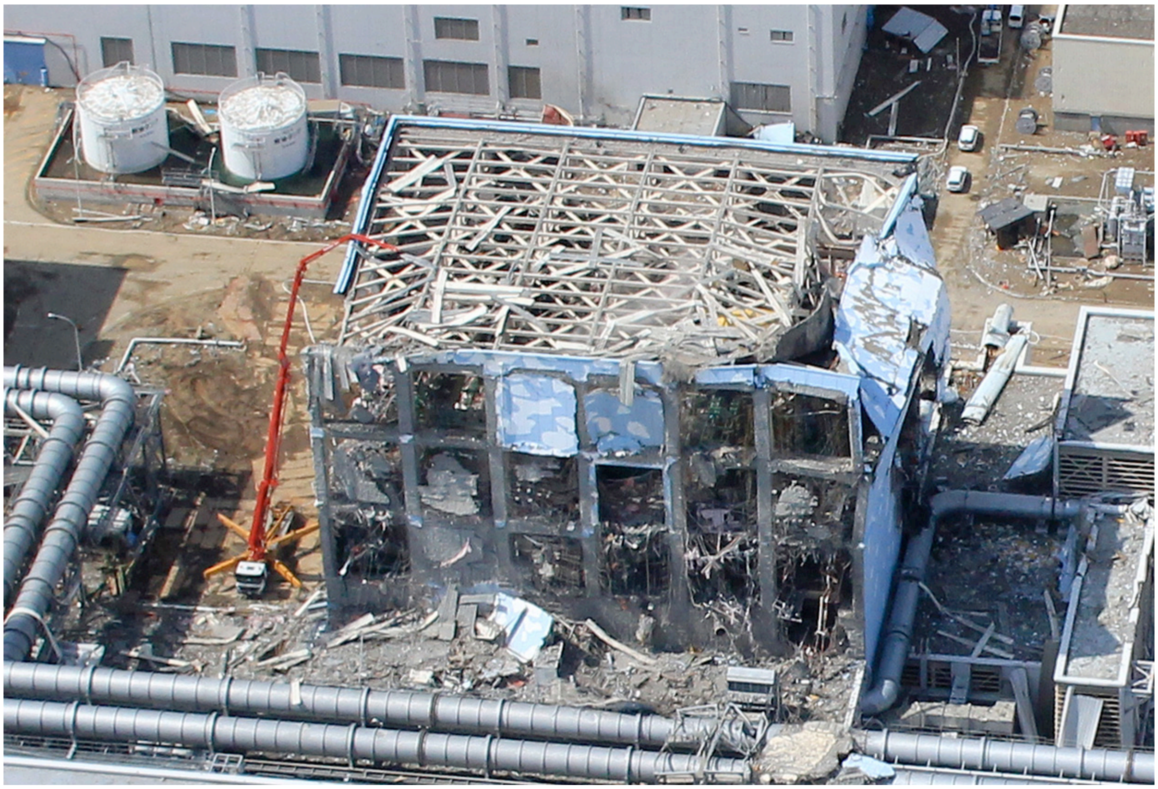
After Test (viewed from the attacked face)

Notes:
(a) These photographs are from: Raytheon, 2008. For additional, supporting information, see: Warwick, 2008.
(b) The shaped-charge jet penetrated about 5.9 m into a steel-reinforced concrete block with a thickness of 6.1 m. Although penetration was incomplete, the block was largely destroyed, as shown. Compressive strength of the concrete was 870 bar.
(c) The shaped charge had a diameter of 61 cm and contained 230 kg of high explosive. It was sized to fit inside the US Air Force's AGM-129 Advanced Cruise Missile.

Figure VI-4
Aftermath of a Small-Aircraft Suicide Attack on an Office Building in Austin, Texas, February 2010

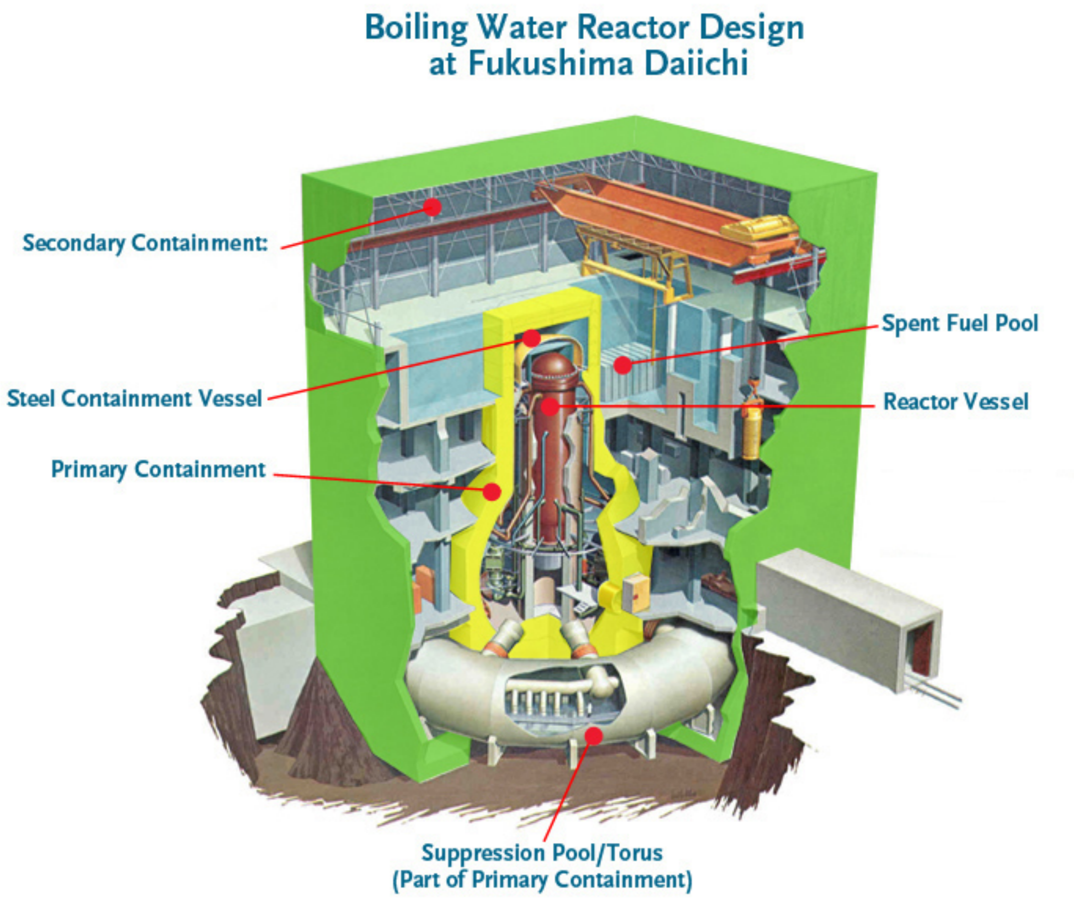
Notes:
(a) Photograph and information in these notes are from: Brick, 2010.
(b) A major tenant of the building was the Internal Revenue Service (IRS).
(c) The aircraft was a single-engine, fixed-wing Piper flown by its owner, Andrew Joseph Stack III, an Austin resident who worked as a computer engineer.
(d) A statement left by Mr Stack indicated that a dispute with the IRS had brought him to a point of suicidal rage.

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



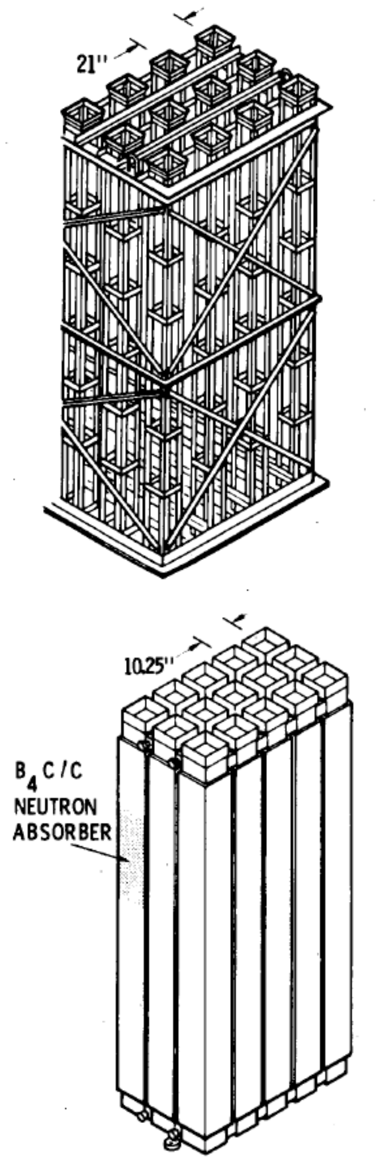
Source:
Accessed on 20 February 2012 from Ria Novosti at:
http://en.rian.ru/analysis/20110426/163701909.html; image by Reuters Air Photo Service.

Figure VIII-2
Schematic View of a BWR Reactor with a Mark I Containment, as Used at the Fukushima #1 Site and Elsewhere



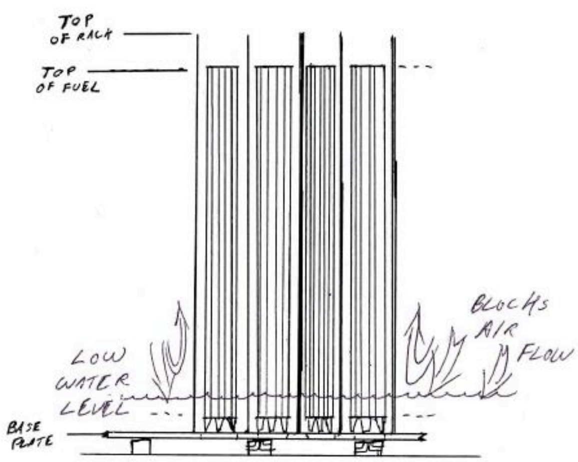
Notes:
(a) This figure accessed on 24 February 2012 from:
http://safetyfirst.nei.org/japan/background-on-fukushima-situation/
(b) All BWR reactors with Mark I containments have the same basic configuration. Details vary for specific reactors.

Figure X-1
PWR Spent Fuel Storage Racks: Low-Density and High-Density Designs



Notes:
(a) These drawings are from: Benjamin et al, 1979, page 18.
(b) The upper drawing shows a low-density, open-frame rack, and the lower drawing shows a high-density, closed-frame rack.

Figure X-2
An Argonne Analyst's Illustration of the Effect of Residual Water on Heat Transfer from Spent Fuel in a Partially Drained Pool Equipped with High-Density Racks



<u>Water addition:</u> adding water to the bottom of an empty spent fuel pool can damage an assembly with a heat rate of 7kw or less that has reached equilibrium in air! -- *The water can block the circulation of air and cause the fuel assembly to overheat. The heat removed by the low level of water is insufficient to cool the assembly.*

Notes:
(a) Figure and accompanying text are from: Braun, 2010.
(b) Braun considers, as a typical example, a fuel assembly that would generate 10 MWt in a reactor at full power. According to Braun, at a time point after reactor shutdown of 1.0×10^7 sec (116 days), the assembly would produce 7.8 kW of decay heat.
(c) Braun goes on to discuss a related situation in which water level descends slowly from the top of the rack by boiling off due to decay heat. He says:

- "As the levels drop, steam from the boil-off will cool the uncovered parts of the fuel.
- At some point, the rising steam will be insufficient to cool the uncovered fuel and clad temperatures will rise until they reach the "ignition" point.
- Where is this level? Detailed calculations are needed. Experts suggest that it is somewhere between 20 and 80% of assembly height, possibly around the mid-point.
- When the water is at the bottom of the fuel, say about the 20% level, the steaming rate is probably insufficient to cool the rest of the assembly, and air circulation is not possible. So fuel assemblies that may be safe in air are likely to melt with a low water level.
- Detailed calculations are needed to address specific issues of geometry and heat transfer."

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APPENDIX C: List of Exhibits

Exhibit #1
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Exhibit #2
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Exhibit #23
Ontario Power Generation, *Darlington NGS Risk Assessment Summary Report* (Toronto: Ontario Power Generation, 29 May 2012).

Exhibit #24
Appendix J of: US Nuclear Regulatory Commission, *Generic Environmental Impact Statement on Handling and Storage of Spent Light Water Power Reactor Fuel, NUREG-0575* (Washington, DC: Nuclear Regulatory Commission, August 1979).

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Andrew Barto and nine other authors, *Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a US Mark I Boiling Water Reactor* (Washington, DC: US Nuclear Regulatory Commission, October 2013). This document is provided here with its cover memo: Mark A. Satorius, memo to NRC Commissioners, "SECY-13-0112: Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a US Mark I Boiling Water Reactor", 9 October 2013.

Exhibit #36
Mark A. Satorius, memo to NRC Commissioners, "COMSECY-13-0030: Staff Evaluation and Recommendation for Japan Lessons-Learned Tier 3 Issue on Expedited Transfer of Spent Fuel", 12 November 2013.

Exhibit #37
E. D. Throm, *Regulatory Analysis for the Resolution of Generic Issue 82, "Beyond Design Basis Accidents in Spent Fuel Pools", NUREG-1353* (Washington, DC: US Nuclear Regulatory Commission, April 1989).

Exhibit #38
T. E. Collins and G. Hubbard, *Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants, NUREG-1738* (Washington, DC: US Nuclear Regulatory Commission, February 2001).

Exhibit #39
US Nuclear Regulatory Commission Staff, "NRC Staff Response to Intervenor's Request for Admission of Late-Filed Environmental Contentions", Docket No. 50-400-LA, ASLBP No. 99-762-02-LA, 3 March 2000.

Exhibit #40
J. Sam Armijo (Chairman, NRC Advisory Committee on Reactor Safeguards), letter and enclosures to Ms. Diane Curran, Esq., 20 November 2013.

Exhibit #41
Dana A. Powers (Chairman, NRC Advisory Committee on Reactor Safeguards), letter to Richard A. Meserve (Chairman, NRC), "Subject: Draft Final Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants", 13 April 2000.

Exhibit #42
Farouk Eltawila (Office of Nuclear Regulatory Research, NRC), memorandum to Gary Holahan (Office of Nuclear Reactor Regulation, NRC), "RES Review of and Response to ACRS Comments on Spent Fuel Cladding Behavior Following a Loss-of-Water Accident During Pool Storage", 15 May 2001. Attached to this memorandum is an undated draft report: H. M. Chung (Argonne) and S. Basu (NRC), "Spent Fuel Cladding Behavior Following Loss-of-Water Accident During Pool Storage".

Exhibit #43
K. Natesan and W.K. Soppet, *Air Oxidation Kinetics for Zr-Based Alloys, NUREG/CR-6846* (Washington, DC: NRC, June 2004).

Exhibit #44
E.R. Lindgren and S.G. Durbin, *Characterization of Thermal-Hydraulic and Ignition Phenomena in Prototypic, Full-Length Boiling Water Reactor Spent Fuel Assemblies After a Postulated Complete Loss-of-Coolant Accident, NUREG/CR-7143* (Washington, DC: NRC, March 2013).

Exhibit #45
Peter Windberg and Zoltan Hozer, "CODEX-CT-1 and CT-2 Integral Tests: Two Possible Scenarios of the Paks-2 Incident", paper presented at the international conference: Nuclear Energy for New Europe 2007, Slovenia, 10-13 September 2007.

Exhibit #46
Jan Beyea, Ed Lyman, and Frank von Hippel, "Damages from a Major Release of Cs-137 into the Atmosphere of the United States", *Science and Global Security*, Volume 12, 2004, pp 125-136.

Exhibit #47
Institut de Radioprotection et de Surete Nucleaire, *Examen de la methode d'analyse cout-benefice pour la surete, Rapport DSR No. 157, Annex du Chapitre 4, Evaluation Economique des Consequences d'Accidents Graves et Enseignements* (France: IRSN, 5 July 2007).

Exhibit #48
Svensk Karnbranslehantering AB, "Clab", a brochure about Sweden's interim storage facility for spent nuclear fuel, published in 2006, accessed on 15 December 2013 at: http://www.skb.se/Templates/Standard____25480.aspx

Exhibit #49
Bruno Thomauske, "Realization of the German Concept for Interim Storage of Spent Nuclear Fuel – Current Situation and Prospects", paper presented at the WM'03 Conference, Tucson, Arizona, 23-27 February 2003.

APPENDIX D: Curriculum Vitae

Curriculum Vitae for Gordon R. Thompson
June 2011

Professional expertise

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

Current appointments

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

Education

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

Project sponsors and tasks (selected)

• Nautilus Institute and RMIT University, 2009-2011: conduct policy and technical analysis on transfer of nuclear power plant technology to consumer countries.
• Attorney General of Massachusetts, 2006-2008 and 2011: analyze risk issues and prepare expert testimony associated with the Pilgrim and Vermont Yankee nuclear power plants; current analysis addresses lessons learned from the Fukushima accident of 2011.
• CharityHelp International and other sponsors, 2009-2011: co-convene the Connectivity to Enhance Global Human Security initiative.
• US Institute of Peace and other sponsors, 2005-2011: co-convene the Working Group on US-Iran Health Science Cooperation.
• Texans for a Sound Energy Policy, 2009: review of the US Nuclear Regulatory Commission's Draft Waste Confidence Decision.
• Green Energy Coalition, Pembina Institute, and Ontario Sustainable Energy Association, 2008: prepared testimony for submission to the Ontario Energy Board.
• Greenpeace Canada, 2007-2011: conduct technical and policy analysis on risk and sustainability issues related to the use of nuclear energy.
• World Health Organization, 2006-2007: conducted policy analysis on the potential for "health-bridge" programs to improve cooperation within and between nations.

• Sierra Club of Canada, 2006-2007: prepared a strategy for development of planning and public-engagement tools to facilitate action on climate change.
• Mothers for Peace, California, 2002-2009: analyzed risk issues and prepared expert testimony associated with the Diablo Canyon nuclear power plants.
• Riverkeeper, New York, 2007-2008: analyzed risk issues and prepared expert testimony associated with the Indian Point nuclear power plants.
• Minnesota Center for Environmental Advocacy, and Minnesotans for an Energy Efficient Economy, 2005-2006: conducted technical analysis and provided expert testimony regarding the Monticello nuclear power plant.
• California Energy Commission, 2005: conducted technical analysis and participated in an expert workshop regarding safety and security of commercial nuclear facilities.
• Committee on Radioactive Waste Management (a committee appointed by the UK government), 2005: provided expert advice and technical analysis on long-term safety and security of radioactive waste management.
• Legal Resources Centre, Cape Town, South Africa, 2004-2007: conducted technical analysis regarding the proposed South African pebble bed modular nuclear reactor.
• STAR Foundation, New York, 2002-2004: reviewed planning and actions for decommissioning of research reactors at Brookhaven National Laboratory.
• Attorney General of Utah, 2003: conducted technical analysis and provided expert testimony regarding a proposed national storage facility for spent nuclear fuel.
• Citizens Awareness Network, Massachusetts, 2002-2003: conducted analysis on robust storage of spent nuclear fuel.
• Tides Center, California, 2002-2004: conducted analysis for the Santa Susana Field Laboratory (SSFL) Advisory Panel regarding the history of releases of hazardous material from the SSFL.
• Orange County, North Carolina, 1999-2002: assessed risk issues associated with the Harris nuclear power plant, identified risk-reduction options, and prepared expert testimony.
• William and Flora Hewlett Foundation and other sponsors, 1999-2009: performed research and project development for conflict-management projects, through IRSS's International Conflict Management Program.
• STAR Foundation, New York, 2000-2001: assessed risk issues associated with the Millstone nuclear power plant, identified risk-reduction options, and prepared expert testimony.
• Massachusetts Water Resources Authority, 2000: evaluated risks associated with water supply and wastewater systems that serve greater Boston.
• Canadian Senate, Energy & Environment Committee, 2000: reviewed risk issues associated with the Pickering Nuclear Generating Station.
• Greenpeace International, Amsterdam, 2000: reviewed impacts associated with the La Hague nuclear complex in France.
• Government of Ireland, 1998-2001: developed framework for assessment of impacts and alternative options associated with the Sellafield nuclear complex in the UK.
• Clark University, Worcester, Massachusetts, 1998-1999: participated in confidential review of outcomes of a major foundation's grants related to climate change.

• UN High Commissioner for Refugees, 1998: co-developed a strategy for conflict management in the CIS region.
• General Council of County Councils (Ireland), W. Alton Jones Foundation (USA), and Nuclear Free Local Authorities (UK), 1996-2000: assessed environmental and economic issues of nuclear fuel reprocessing in the UK; assessed alternative options.
• Environmental School, Clark University, Worcester, Massachusetts, 1996: session leader at the Summer Institute, "Local Perspectives on a Global Environment".
• Greenpeace Germany, Hamburg, 1995-1996: performed a study on war, terrorism and nuclear power plants.
• HKH Foundation, New York, and Winston Foundation for World Peace, Washington, DC, 1994-1996: studies and workshops on preventive action and its role in US national security planning.
• Carnegie Corporation of New York, Winston Foundation for World Peace, Washington, DC, and others, 1995: collaboration with the Organization for Security and Cooperation in Europe to facilitate improved coordination of activities and exchange of knowledge in the field of conflict management.
• World Bank, 1993-1994: a study on management of data describing the performance of projects funded by the Global Environment Facility (joint project of IRSS and Clark University).
• International Physicians for the Prevention of Nuclear War, 1993-1994: a study on the international control of weapons-usable fissile material.
• Government of Lower Saxony, Hannover, Germany, 1993: analysis of standards for radioactive waste disposal.
• University of Vienna (using funds supplied by the Austrian government), 1992: review of radioactive waste management at the Dukovany nuclear power plant, Czech Republic.
• Sandia National Laboratories, 1992-1993: advice to the US Department of Energy's Office of Foreign Intelligence.
• US Department of Energy and Battelle Pacific Northwest Laboratories, 1991-1992: advice for the Intergovernmental Panel on Climate Change regarding the design of an information system on technologies that can limit greenhouse gas emissions (joint project of IRSS, Clark University and the Center for Strategic and International Studies).
• Winston Foundation for World Peace, Boston, Massachusetts, and other funding sources, 1992-1993: development and publication of recommendations for strengthening the International Atomic Energy Agency.
• MacArthur Foundation, Chicago, Illinois, W. Alton Jones Foundation, Charlottesville, Virginia, and other funding sources, 1984-1993: policy analysis and public education on a "global approach" to arms control and disarmament.
• Energy Research Foundation, Columbia, South Carolina, and Peace Development Fund, Amherst, Massachusetts, 1988-1992: review of the US government's tritium production (for nuclear weapons) and its implications.
• Coalition of Environmental Groups, Toronto, Ontario (using funds supplied by Ontario Hydro under the direction of the Ontario government), 1990-1993: coordination and conduct of analysis and preparation of testimony on accident risk of nuclear power plants.
• Greenpeace International, Amsterdam, Netherlands, 1988-1990: review of probabilistic risk assessment for nuclear power plants.

• Bellerive Foundation, Geneva, Switzerland, 1989-1990: planning for a June 1990 colloquium on disarmament, and editing of proceedings.
• Iler Research Institute, Harrow, Ontario, 1989-1990: analysis of regulatory response to boiling-water reactor accident potential.
• Winston Foundation for World Peace, Boston, Massachusetts, and other funding sources, 1988-1989: analysis of future options for NATO (joint project of IRSS and the Institute for Peace and International Security).
• Nevada Nuclear Waste Project Office, Carson City, Nevada (via Clark University), 1989-1990: analyses of risk aspects of radioactive waste management and disposal.
• Ontario Nuclear Safety Review (conducted by the Ontario government), Toronto, Ontario, 1987: review of safety aspects of CANDU reactors.
• Washington Department of Ecology, Olympia, Washington, 1987: analyses of risk aspects of a proposed radioactive waste repository at Hanford.
• Natural Resources Defense Council, Washington, DC, 1986-1987: preparation of expert testimony on hazards of the Savannah River Plant, South Carolina.
• Lakes Environmental Association, Bridgton, Maine, 1986: analysis of federal regulations for disposal of radioactive waste.
• Greenpeace Germany, Hamburg, 1986: participation in an international study on the hazards of nuclear power plants.
• Three Mile Island Public Health Fund, Philadelphia, Pennsylvania, 1983-1989: studies related to the Three Mile Island nuclear power plant and emergency response planning.
• Attorney General, Commonwealth of Massachusetts, 1984-1989: analyses of the safety of the Seabrook nuclear power plant, and preparation of expert testimony.
• Union of Concerned Scientists, Cambridge, Massachusetts, 1980-1985: studies on energy demand and supply, nuclear arms control, and the safety of nuclear installations.
• Conservation Law Foundation of New England, Boston, Massachusetts, 1985: preparation of expert testimony on cogeneration potential at a Maine paper mill.
• Town & Country Planning Association, London, UK, 1982-1984: coordination and conduct of a study on safety and radioactive waste implications of the proposed Sizewell nuclear power plant, and testimony to the Sizewell Public Inquiry.
• US Environmental Protection Agency, Washington, DC, 1980-1981: assessment of the cleanup of Three Mile Island Unit 2 nuclear power plant.
• Center for Energy & Environmental Studies, Princeton University, Princeton, New Jersey, and Solar Energy Research Institute, Golden, Colorado, 1979-1980: studies on the potentials of renewable energy sources.
• Government of Lower Saxony, Hannover, Federal Republic of Germany, 1978-1979: coordination and conduct of studies on safety and security aspects of the proposed Gorleben nuclear fuel cycle center.

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

• Principal investigator, project on "Exploring the Role of 'Sustainable Cities' in Preventing Climate Disruption", involving IRSS and three other organizations, 1990-1991.
• Visiting fellow, Peace Research Centre, Australian National University, 1989.

• Principal investigator, Three Mile Island emergency planning study, involving IRSS, Clark University and other partners, 1987-1989.
• Co-leadership (with Paul Walker) of a study group on nuclear weapons proliferation, Institute of Politics, Harvard University, 1981.
• Foundation (with others) of an ecological political movement in Oxford, UK, which contested the 1979 Parliamentary election.
• Conduct of cross-examination and presentation of expert testimony, on behalf of the Political Ecology Research Group, at the 1977 Public Inquiry into proposed expansion of reprocessing capacity at Windscale, UK.
• Conduct of research on plasma theory (while a D.Phil candidate), as an associate staff member, Culham Laboratory, UK Atomic Energy Authority, 1969-1973.
• Service as a design engineer on coal-fired power plants, New South Wales Electricity Commission, Sydney, Australia, 1968.

<u>Publications (selected)</u>

• *New and Significant Information from the Fukushima Daiichi Accident in the Context of Future Operation of the Pilgrim Nuclear Power Plant*, a report for the Attorney General, Commonwealth of Massachusetts, June 2011.
• *Outline of a Code of Conduct for Transfer of Nuclear Power Plant Technology to Consumer Countries*, a report for Nautilus Institute and RMIT University, April 2011.
• *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*, a report for Texans for a Sound Energy Policy, Victoria, Texas, February 2009.
• *Scope of the EIS for New Nuclear Power Plants at the Darlington Site in Ontario: Accidents, Malfunctions and the Precautionary Approach*, a report for Greenpeace Canada, November 2008.
• *Cost Implications of the Residual Radiological Risk of Nuclear Generation of Electricity in Ontario*, a report for the Green Energy Coalition et al, July 2008.
• "The US Effort to Dispose of High-Level Radioactive Waste", *Energy and Environment*, Volume 19, Numbers 3 and 4 (joint issue), 2008, pp 391-412.
• *Design and Siting Criteria for Nuclear Power Plants in the 21st Century*, a report for Greenpeace Canada, January 2008.
• *Risk-Related Impacts from Continued Operation of the Indian Point Nuclear Power Plants*, a report for Riverkeeper, Tarrytown, New York, November 2007.
• *Assessing Risks of Potential Malicious Actions at Commercial Nuclear Facilities: The Case of a Proposed Independent Spent Fuel Storage Installation at the Diablo Canyon Site*, a report for San Luis Obispo Mothers for Peace, California, June 2007.
• *Health as a Bridge for Peace: Achievements, Challenges, and Opportunities for Action by WHO* (with Paula Gutlove), a report for the Department for Health Action in Crises, World Health Organization, Geneva, December 2006.
• "Using Psychosocial Healing in Postconflict Reconstruction" (with Paula Gutlove), in Mari Fitzduff and Chris E. Stout (eds), *The Psychology of Resolving Global Conflicts: From War to Peace*, Praeger Security International, 2006.

• "What Role for Nuclear Power in a Sustainable Civilization?", *The Green Cross Optimist*, Spring 2006, pp 28-30.
• *Radiological Risk of Homeport Basing of a Nuclear-Propelled Aircraft Carrier in Yokosuka, Japan*, a report for the Citizens Coalition Concerning the Homeporting of a CVN in Yokosuka, June 2006.
• *Risks and Risk-Reducing Options Associated with Pool Storage of Spent Nuclear Fuel at the Pilgrim and Vermont Yankee Nuclear Power Plants*, a report for the Attorney General, Commonwealth of Massachusetts, May 2006.
• *Reasonably Foreseeable Security Events: Potential threats to options for long-term management of UK radioactive waste*, a report for the UK Committee on Radioactive Waste Management, November 2005.
• "Plasma, policy and progress", *The Australian Mathematical Society Gazette*, Volume 32, Number 3, 2005, pp 162-168.
• "A Psychosocial-Healing Approach to Post-Conflict Reconstruction" (with Paula Gutlove), *Mind & Human Interaction*, Volume 14, Number 1, 2005, pp 35-63.
• "Designing Infrastructure for New Goals and Constraints", Proceedings of the conference, *Working Together: R&D Partnerships in Homeland Security*, Boston, Massachusetts, 27-28 April 2005, sponsored by the US Department of Homeland Security. (A version of this paper has also been published as CRS Discussion Paper 2005-02, Center for Risk and Security, George Perkins Marsh Institute, Clark University, Worcester, Massachusetts.)
• "Potential Radioactive Releases from Commercial Reactors and Spent Fuel", Proceedings of the conference, *Working Together: R&D Partnerships in Homeland Security*, Boston, Massachusetts, 27-28 April 2005, sponsored by the US Department of Homeland Security. (A version of this paper has also been published as CRS Discussion Paper 2005-03, Center for Risk and Security, George Perkins Marsh Institute, Clark University, Worcester, Massachusetts.)
• *Safety of the Proposed South African Pebble Bed Modular Reactor*, a report for the Legal Resources Centre, Cape Town, South Africa, 12 January 2005.
• *Releases of Hazardous Material from the Santa Susana Field Laboratory: A Retrospective Review*, a report for the SSFL Advisory Panel, June 2004.
• *Decommissioning of Research Reactors at Brookhaven National Laboratory: Status, Future Options and Hazards*, a report for STAR Foundation, East Hampton, New York, April 2004.
• "Psychosocial Healing and Post-Conflict Social reconstruction in the Former Yugoslavia" (with Paula Gutlove), *Medicine, Conflict and Survival*, Volume 20, Number 2, April-June 2004, pp 136-150.
• "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States" (with Robert Alvarez, Jan Beyea, Klaus Janberg, Jungmin Kang, Ed Lyman, Allison Macfarlane and Frank N. von Hippel), *Science and Global Security*, Volume 11, 2003, pp 1-51.
• "Health, Human Security, and Social Reconstruction in Afghanistan" (with Paula Gutlove and Jacob Hale Russell), in John D. Montgomery and Dennis A. Rondinelli (eds), *Beyond Reconstruction in Afghanistan*, Palgrave Macmillan, 2004.

• *Psychosocial Healing: A Guide for Practitioners, based on programs of the Medical Network for Social Reconstruction in the Former Yugoslavia* (with Paula Gutlove), IRSS, Cambridge, Massachusetts and OMEGA Health Care Center, Graz, Austria, May 2003.
• *A Call for Action to Protect the Nation Against Enemy Attack on Nuclear Power Plants and Spent Fuel*, and a Supporting Document, San Luis Obispo Mothers for Peace, California, April 2003 and May 2003.
• "Human Security: Expanding the Scope of Public Health" (with Paula Gutlove), *Medicine, Conflict and Survival*, Volume 19, 2003, pp 17-34.
• *Social Reconstruction in Afghanistan through the Lens of Health and Human Security* (with Paula Gutlove and Jacob Hale Russell), IRSS, Cambridge, Massachusetts, May 2003.
• *Robust Storage of Spent Nuclear Fuel: A Neglected Issue of Homeland Security*, a report for Citizens Awareness Network, Shelburne Falls, Massachusetts, January 2003.
• *Medical Network for Social Reconstruction in the Former Yugoslavia: A Survey of Participants' Views on the Network's Goals and Achievements*, IRSS, Cambridge, Massachusetts, September 2001.
• *The Potential for a Large, Atmospheric Release of Radioactive Material from Spent Fuel Pools at the Harris Nuclear Power Plant: The Case of a Pool Release Initiated by a Severe Reactor Accident*, a report for Orange County, North Carolina, November 2000.
• *A Review of the Accident Risk Posed by the Pickering 'A' Nuclear Generating Station,* a report for the Standing Committee on Energy, Environment and Natural Resources, Canadian Senate, August 2000.
• *High-Level Radioactive Liquid Waste at Sellafield: An Updated Review*, a report for the UK Nuclear Free Local Authorities, June 2000.
• *Hazard Potential of the La Hague Site: An Initial Review*, a report for Greenpeace International, May 2000.
• *A Strategy for Conflict Management: Integrated Action in Theory and Practice* (with Paula Gutlove), IRSS, Cambridge, Massachusetts, March 1999.
• *Risks and Alternative Options Associated with Spent Fuel Storage at the Shearon Harris Nuclear Power Plant*, a report for Orange County, North Carolina, February 1999.
• *High Level Radioactive Liquid Waste at Sellafield: Risks, Alternative Options and Lessons for Policy*, IRSS, Cambridge, Massachusetts, June 1998.
• "Science, democracy and safety: why public accountability matters", in F. Barker (ed), *Management of Radioactive Wastes: Issues for local authorities*, Thomas Telford, London, 1998.
• "Conflict Management and the OSCE" (with Paula Gutlove), *OSCE/ODIHR Bulletin*, Volume 5, Number 3, Fall 1997.
• *Safety of the Storage of Liquid High-Level Waste at Sellafield* (with Peter Taylor), Nuclear Free Local Authorities, UK, November 1996.
• *Assembling Evidence on the Effectiveness of Preventive Actions, their Benefits, and their Costs: A Guide for Preparation of Evidence*, IRSS, Cambridge, Massachusetts, August 1996.
• *War, Terrorism and Nuclear Power Plants,* Peace Research Centre, Australian National University, Canberra, October 1996.

• "The Potential for Cooperation by the OSCE and Non-Governmental Actors on Conflict Management" (with Paula Gutlove), *Helsinki Monitor*, Volume 6 (1995), Number 3.
• "Potential Characteristics of Severe Reactor Accidents at Nuclear Plants", "Monitoring and Modelling Atmospheric Dispersion of Radioactivity Following a Reactor Accident" (with Richard Sclove, Ulrike Fink and Peter Taylor), "Safety Status of Nuclear Reactors and Classification of Emergency Action Levels", and "The Use of Probabilistic Risk Assessment in Emergency Response Planning for Nuclear Power Plant Accidents" (with Robert Goble), in D. Golding, J. X. Kasperson and R. E. Kasperson (eds), *Preparing for Nuclear Power Plant Accidents*, Westview Press, Boulder, Colorado, 1995.
• *A Data Manager for the Global Environment Facility* (with Robert Goble), Environment Department, The World Bank, June 1994.
• *Preventive Diplomacy and National Security* (with Paula Gutlove), Winston Foundation for World Peace, Washington, DC, May 1994.
• *Opportunities for International Control of Weapons-Usable Fissile Material*, International Physicians for the Prevention of Nuclear War, Cambridge, Massachusetts, January 1994.
• "Article III and IAEA Safeguards", in F. Barnaby and P. Ingram (eds), *Strengthening the Non-Proliferation Regime*, Oxford Research Group, Oxford, UK, December 1993.
• *Risk Implications of Potential New Nuclear Plants in Ontario* (prepared with the help of eight consultants), a report for the Coalition of Environmental Groups, Toronto, submitted to the Ontario Environmental Assessment Board, November 1992 (3 volumes).
• *Strengthening the International Atomic Energy Agency*, IRSS, Cambridge, Massachusetts, September 1992.
• *Design of an Information System on Technologies that can Limit Greenhouse Gas Emissions* (with Robert Goble and F. Scott Bush), Center for Strategic and International Studies, Washington, DC, May 1992.
• *Managing Nuclear Accidents: A Model Emergency Response Plan for Power Plants and Communities* (with six other authors), Westview Press, Boulder, CO, 1992.
• "Let's X-out the K" (with Steven C. Sholly), *Bulletin of the Atomic Scientists*, March 1992, pp 14-15.
• "A Worldwide Programme for Controlling Fissile Material", and "A Global Strategy for Nuclear Arms Control", in F. Barnaby (ed), *Plutonium and Security*, Macmillan Press, UK, 1992.
• *No Restart for K Reactor* (with Steven C. Sholly), IRSS, Cambridge, Massachusetts, October 1991.
• *Regulatory Response to the Potential for Reactor Accidents: The Example of Boiling-Water Reactors,* IRSS, Cambridge, Massachusetts, February 1991.
• *Peace by Piece: New Options for International Arms Control and Disarmament*, IRSS, Cambridge, Massachusetts, January 1991.
• *Developing Practical Measures to Prevent Climate Disruption* (with Robert Goble), CENTED Research Report No. 6, Clark University, Worcester, Massachusetts, August 1990.
• "Treaty a Useful Relic", *Bulletin of the Atomic Scientists*, July/August 1990, pp 32-33.

• "Practical Steps for the 1990s", in Sadruddin Aga Khan (ed), *Non-Proliferation in a Disarming World*, Proceedings of the Groupe de Bellerive's 6th International Colloquium, Bellerive Foundation, Geneva, Switzerland, 1990.
• *A Global Approach to Controlling Nuclear Weapons*, IRSS, Cambridge, Massachusetts, October 1989.
• *IAEA Safety Targets and Probabilistic Risk Assessment* (with three other authors), Greenpeace International, Amsterdam, August 1989.
• *New Directions for NATO* (with Paul Walker and Pam Solo), published jointly by IRSS and the Institute for Peace and International Security (both of Cambridge, Massachusetts), December 1988.
• "Verifying a Halt to the Nuclear Arms Race", in F. Barnaby (ed), *A Handbook of Verification Procedures*, Macmillan Press, UK, 1990.
• "Verification of a Cutoff in the Production of Fissile Material", in F.Barnaby (ed), *A Handbook of Verification Procedures*, Macmillan Press, UK, 1990.
• "Severe Accident Potential of CANDU Reactors," Consultant's Report in *The Safety of Ontario's Nuclear Power Reactors*, Ontario Nuclear Safety Review, Toronto, February 1988.
• *Nuclear-Free Zones* (edited with David Pitt), Croom Helm Ltd, Beckenham, UK, 1987.
• *Risk Assessment Review For the Socioeconomic Impact Assessment of the Proposed High-Level Nuclear Waste Repository at Hanford Site, Washington* (edited; written with five other authors), prepared for the Washington Department of Ecology, December 1987.
• *The Nuclear Freeze Revisited* (with Andrew Haines), Nuclear Freeze and Arms Control Research Project, Bristol, UK, November 1986. Variants of the same paper have appeared as Working Paper No. 18, Peace Research Centre, Australian National University, Canberra, February 1987, and in *ADIU Report*, University of Sussex, Brighton, UK, Jan/Feb 1987, pp 6-9.
• *International Nuclear Reactor Hazard Study* (with fifteen other authors), Greenpeace, Hamburg, Federal Republic of Germany (2 volumes), September 1986.
• "What happened at Reactor Four" (the Chernobyl reactor accident), *Bulletin of the Atomic Scientists*, August/September 1986, pp 26-31.
• *The Source Term Debate: A Report by the Union of Concerned Scientists* (with Steven C. Sholly), Union of Concerned Scientists, Cambridge, Massachusetts, January 1986.
• "Checks on the spread" (a review of three books on nuclear proliferation), *Nature*, 14 November 1985, pp 127-128.
• Editing of *Perspectives on Proliferation*, August 1985, published by the Proliferation Reform Project, IRSS.
• "A Turning Point for the NPT ?", *ADIU Report*, University of Sussex, Brighton, UK, Nov/Dec 1984, pp 1-4.
• "Energy Economics", in J. Dennis (ed), *The Nuclear Almanac*, Addison-Wesley, Reading, Massachusetts, 1984.
• "The Genesis of Nuclear Power", in J. Tirman (ed), *The Militarization of High Technology*, Ballinger, Cambridge, Massachusetts, 1984.
• *A Second Chance: New Hampshire's Electricity Future as a Model for the Nation* (with Linzee Weld), Union of Concerned Scientists, Cambridge, Massachusetts, 1983.

• *Safety and Waste Management Implications of the Sizewell PWR* (prepared with the help of six consultants), a report to the Town & Country Planning Association, London, UK, 1983.
• *Utility-Scale Electrical Storage in the USA: The Prospects of Pumped Hydro, Compressed Air, and Batteries*, Princeton University report PU/CEES #120, 1981.
• *The Prospects for Wind and Wave Power in North America*, Princeton University report PU/CEES # 117, 1981.
• *Hydroelectric Power in the USA: Evolving to Meet New Needs*, Princeton University report PU/CEES # 115, 1981.
• Editing and part authorship of "Potential Accidents & Their Effects", Chapter III of *Report of the Gorleben International Review*, published in German by the Government of Lower Saxony, FRG, 1979; Chapter III published in English by the Political Ecology Research Group, Oxford, UK.
• *A Study of the Consequences to the Public of a Severe Accident at a Commercial FBR located at Kalkar, West Germany*, Political Ecology Research Group, 1978.

<u>Expert presentations and testimony (selected)</u>

• Egyptian Council for Foreign Affairs, Cairo, May 2011: presentation, "Nuclear Technology and Global Child Health: Threats and Opportunities".
• Bibliotecha Alexandrina, Egypt, April 2011: presentation, "Accelerating a Green-Technology Transition: A Leading Role for the BA".
• Conference, *Prospects for Nuclear Non-Proliferation and Disarmament*, Cairo, October 2010: presentation (with Paula Gutlove), "The Potential for Near-Term Confidence-Building Measures and Cooperative Actions for an Eventual Middle East NWFZ, Promoting the 2012 Conference".
• Blue Ribbon Commission on America's Nuclear Future, Washington, DC, September 2010: presentation to the Subcommittee on transportation & storage of radioactive waste.
• Green Cross Strategy Workshop, Geneva, May 2010: presentation, "Nuclear Weapons and Power: Issues and Opportunities".
• Munk Centre for International Studies, University of Toronto, March 2010: presentation (with Paula Gutlove), "Demonstrating a New Approach to Stability in Afghanistan: Remote Engagement for Community Empowerment and Rural Development".
• Maxwell School, Syracuse University, February 2009: presentation, "A Second Track for Climate Negotiations: The Biosphere as Common Property".
• Marsh Institute, Clark University, February 2009: presentation, "Green Energy, Economic Renewal and Societal Learning: Research/Action Opportunities for Academia".
• Society for Risk Analysis annual meeting, Boston, Massachusetts, December 2008: presentation, "Multi-Criteria Frameworks for Considering Diverse Risks in Infrastructure Design".
• Institute of Environmental Studies, University of New South Wales, Sydney, Australia, April 2008: presentation, "Citizen Engagement for Sustainable Society".
• Department of Urban and Regional Planning, Shaheed Beheshti University, Tehran, April 2008: presentation, "Sustainable Cities: Challenges and Opportunities".

• National Academy of Sciences, Washington, DC, January 2008: presentation, "What do interested parties think about the expansion of nuclear energy?"
• Abt Associates, Cambridge, Massachusetts, March 2007: presentation, "Creating Informed Action on Climate Change".
• Universities of Medical Science in Tabriz and Isfahan, Iran, April 2007: presentation, "Healthy Design of the Built Environment".
• Minnesota Public Utilities Commission, 2006: testimony regarding trends, risks and costs associated with management of spent fuel from the Monticello nuclear power plant.
• Presentation, "Are Nuclear Installations Terrorist Targets?", at the conference, *Nuclear Energy: Does it Have a Future?*, Drogheda, County Louth, Ireland, 10-11 March 2005.
• Presentation at the session, "UN Security Council Resolution 1244 and Final Status for Kosovo", at the conference, *Lessons Learned from the Balkan Conflicts*, Boston College, Chestnut Hill, Massachusetts, 16-17 October 2004.
• California Public Utilities Commission, 2004: testimony regarding the nature and cost of potential measures for enhanced defense of the Diablo Canyon nuclear power plant.
• European Parliament, 2003: invited presentation to EP members regarding safety and security issues at the Sellafield nuclear site in the UK, and broader implications.
• US Congress, 2002 and 2003: invited presentations at member-sponsored staff briefings on vulnerabilities of nuclear-power facilities to attack and options for improved defenses.
• Numerous public forums in the USA, 2001-2006: invited presentations to public officials and general audiences regarding vulnerabilities of nuclear-power facilities to attack and options for improved defenses.
• UK Consensus Conference on Radioactive Waste Management, 1999: invited testimony on information and decision-making.
• Joint Committee on Public Enterprise and Transport, Irish Parliament, 1999: invited testimony on nuclear fuel reprocessing and international security.
• UK and Irish Parliaments, 1998: invited presentations to members on risks and alternative options associated with nuclear fuel reprocessing in the UK.
• Center for Russian Environmental Policy, Moscow, 1996: invited presentation at a forum in parallel with the G-7 Nuclear Safety Summit.
• Lacey Township Zoning Board, New Jersey, 1995: testimony regarding radioactive waste management.
• Ontario Court of Justice, Toronto, Ontario, 1993: testimony regarding Canada's Nuclear Liability Act.
• Oxford Research Group, seminar on "The Plutonium Legacy", Rhodes House, Oxford, UK, 1993: invited presentation on nuclear safeguards.
• Defense Nuclear Facilities Safety Board, Washington, DC, 1991: testimony regarding the proposed restart of K-reactor, Savannah River Site.
• Conference to consider amending the Partial Test Ban Treaty, United Nations, New York, 1991: presentation on a global approach to arms control and disarmament.
• US Department of Energy, hearing on draft EIS for new production reactor capacity, Columbia, South Carolina, 1991: testimony on tritium need and implications of tritium production options.

• Society for Risk Analysis, 1990 annual meeting, New Orleans, special session on nuclear emergency planning: presentation on real-time techniques for anticipating emergencies.
• Parliamentarians' Global Action, 11th Annual Parliamentary Forum, United Nations, Geneva, 1990: invited presentation on the potential for multilateral nuclear arms control.
• Advisory Committee on Nuclear Facility Safety, Washington, DC, 1989: testimony on public access to information and on government accountability.
• Peace Research Centre, Australian National University, seminar on "Australia and the Fourth NPT Review Conference", Canberra, 1989: invited presentation regarding a universal nuclear weapons non-proliferation regime.
• Carnegie Endowment for International Peace, Conference on "Nuclear Non-Proliferation and the Role of Private Organizations", Washington, DC, 1989: invited presentation on options for reform of the non-proliferation regime.
• US Department of Energy, EIS scoping hearing, Columbia, South Carolina, 1988: testimony on appropriate scope of an EIS for new production reactor capacity.
• International Physicians for the Prevention of Nuclear War, 6th and 7th Annual Congresses, Koln, FRG, 1986 and Moscow, USSR, 1987: invited presentations on relationships between nuclear power and the threat of nuclear war.
• County Council, Richland County, South Carolina, 1987: testimony on implications of severe reactor accidents at the Savannah River Plant.
• Maine Land Use Regulation Commission, 1985: testimony on cogeneration potential at facilities of Great Northern Paper Company.
• Interfaith Hearings on Nuclear Issues, Toronto, Ontario, 1984: invited presentations on options for Canada's nuclear trade and Canada's involvement in nuclear arms control.
• Sizewell Public Inquiry, UK, 1984: testimony on safety and radioactive waste implications of the proposed Sizewell nuclear power plant.
• New Hampshire Public Utilities Commission, 1983: testimony on electricity demand and supply options for New Hampshire.
• Atomic Safety & Licensing Board, US Nuclear Regulatory Commission, 1983: testimony on use of filtered venting at the Indian Point nuclear power plant.
• US National Advisory Committee on Oceans and Atmosphere, 1982: testimony on implications of ocean disposal of radioactive waste.
• Environmental & Energy Study Conference, US Congress, 1982: invited presentation on implications of radioactive waste management.