INSTITUTE FOR RESOURCE AND SECURITY STUDIES
27 Ellsworth Avenue, Cambridge, Massachusetts 02139, USA
Phone: 617-491-5177 Fax: 617-491-6904
Email: gthompson@irss-usa.org

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Declaration of 2 January 2013 by Gordon R. Thompson: Recommendations for the US Nuclear Regulatory Commission's Consideration of Environmental Impacts of Long-Term, Temporary Storage of Spent Nuclear Fuel or Related High-Level Waste

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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 assist in the preparation of comments invited by the US Nuclear Regulatory Commission (NRC).[1] The NRC has invited comments on the scope of an environmental impact statement (EIS) that the NRC proposes to prepare, which is referred to hereafter as the NRC's "proposed EIS".[2] That EIS would support a rulemaking by the NRC to update the NRC's Waste Confidence Decision and Rule. In this declaration I set forth some recommendations on the scope of the proposed EIS. These recommendations address 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 should be addressed in the proposed EIS.

(I-3) The issues discussed in this declaration are outlined in Section III, below. These issues all pertain to the concept of radiological risk, which is defined in Section IV, below. In brief, in this declaration the term "radiological risk" refers to the potential for harm to humans as a result of unplanned exposure to ionizing radiation.

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[1] These organizations include: Beyond Nuclear; Blue Ridge Environmental Defense League; Citizens Allied for Safe Energy; Ecology Party of Florida; Friends of the Earth; Missouri Coalition for the Environment; Nevada Nuclear Waste Task Force; NC WARN; Nuclear Information and Resource Service; Nuclear Watch South; Public Citizen; Riverkeeper; San Luis Obispo Mothers for Peace; SEED Coalition; and Southern Alliance for Clean Energy.
[2] NRC, 2012.

(I-4) The NRC's invitation to submit comments makes the following statement about scenarios to be considered in the proposed EIS:[3]

> "Possible scenarios to be analyzed in the EIS include temporary spent fuel storage after cessation of reactor operation until a repository is made available in either the middle of the century or at the end of the century, and storage of spent fuel if no repository is made available by the end of the century."

(I-5) The latter part of that statement by the NRC envisions storage of spent fuel for an unspecified period. In that context, it should be noted that the NRC previously embarked on a related EIS, and published a draft document setting forth preliminary assumptions that would apply to that EIS.[4] That document is referred to hereafter as the NRC's "preliminary-assumptions document". The preliminary-assumptions document called for a time horizon of about 2250 in the EIS then under discussion.[5] That document also assumed that a repository would ultimately become available.[6]

(I-6) From the perspective of the radiological risk posed by temporary storage of spent fuel, a time horizon of about 2250 has some logic. A major determinant of the risk, especially in terms of atmospheric release, is the inventory of Cesium-137, which has a half-life of about 30 years.[7] Between 2012 and 2250, a given inventory of Cesium-137 would shrink to a value of about 0.004 (0.4 percent) of its initial value. At that point, the radiological risk posed by storing spent fuel would not disappear, but would be entering a different phase. Moreover, the NRC's preliminary-assumptions document represents a body of work by the NRC staff, and reflects some public input. Accordingly, I recommend as follows:

> **Recommendation #1:** The NRC's preliminary-assumptions document should be a point of departure for determining the scope of the proposed EIS, especially in regard to storage after the end of the 21^{st} century.

(I-7) Spent fuel can more precisely be described as spent nuclear fuel (SNF). I typically use that term hereafter. Also, the NRC's preliminary-assumptions document has introduced the possibility that some SNF discharged from NRC-licensed reactors will be reprocessed in the future.[8] If that outcome were to occur, reprocessing would generate high-level waste (HLW) that would contain most of the radioactivity present in the SNF that is reprocessed.[9] Accordingly, I recommend as follows:

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[3] NRC, 2012, page 65138.
[4] NRC, 2011.
[5] NRC, 2011, Section 7.
[6] NRC, 2011, Section 8.
[7] The inventory of Cesium-137 is an indicator of biological hazard and decay heat production; both properties are determinants of radiological risk.
[8] NRC, 2011, Section 8.
[9] Here, "radioactivity" refers to the inventory of radio-isotopes, measured in Bq.

> **Recommendation #2:** The proposed EIS should not only address the storage of SNF, but also the potential storage of HLW from reprocessing of SNF.

(I-8) It does not follow from my Recommendation #2 that I recommend the future reprocessing of SNF discharged from NRC-licensed reactors, or that I view the future introduction of such reprocessing as likely. Indeed, as discussed in paragraph VI-3, below, trends in the nuclear-power industry over the past two decades suggest that the most likely outcome for that industry over the next few decades is general decline in its activities. Such a future would be inconsistent with reprocessing.

(I-9) The NRC's statement quoted in paragraph I-4, above, refers to "temporary spent fuel storage **after cessation of reactor operation**" [emphasis added]. That statement is imprecise, and could be seriously misleading in regard to the radiological risk posed by storage of SNF. At all contemporary US commercial reactors, SNF assemblies are discharged only when the reactor is shut down. Thereafter, the SNF assemblies may be stored adjacent to an operating reactor from which they were discharged, adjacent to another operating reactor, or at a location not adjacent to an operating reactor. As discussed in Section VIII, below, the radiological risk could be substantially greater if SNF is stored adjacent to an operating reactor. Accordingly, I recommend as follows:

> **Recommendation #3:** The proposed EIS should consider the radiological risk posed by storage of SNF from the moment of its discharge from a reactor.

(I-10) This declaration has the following narrative sections:

(I-11) In addition to the above-named narrative sections, this declaration has two appendices that are an integral part of the declaration. Appendix A is a bibliography. Documents cited in the narrative or in Appendix B are listed in that bibliography unless otherwise identified. Appendix B contains tables and figures that support the narrative.

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.

(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 self-sustaining, exothermic oxidation reactions of fuel cladding in a high-density SNF pool if water is lost from the pool. For simplicity, that event can be referred to as a "pool fire". In examining the potential for a pool fire, I identified partial loss of water 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 SNF was not an acceptable option at Gorleben.[11] As a direct result, policy throughout

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

Germany 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.[12] Also, I co-authored a journal article, on SNF radiological risk, that received considerable attention from relevant stakeholders.[13] The findings in that article were generally confirmed by a subsequent report by the National Research Council.[14] 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]

(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] The time horizon used in my report was, by CORWM's specification, 300 years.

III. Issues Discussed in this Declaration

(III-1) The primary purpose of this declaration is to set forth recommendations regarding the scope of the proposed EIS with respect to the environmental impacts of long-term, temporary storage of SNF or related HLW. My declaration is complementary to the declaration of Dr. Arjun Makhijani, which addresses some SNF storage issues and also some issues of SNF disposal.[17]

(III-2) In this declaration I focus on environmental impacts that are associated with radiological risk, which is defined in Section IV, below. In addressing radiological risk, I focus on the potential for unplanned release of radioactive material, especially atmospheric release. Within that focus, I consider two categories of initiating event – conventional accidents, and attacks.

[12] See, for example: Thompson, 2009.
[13] Alvarez et al, 2003.
[14] National Research Council, 2006.
[15] Thompson, 2008a.
[16] Thompson, 2005.
[17] Makhijani, 2013.

(III-3) Analysts who examine the radiological risk associated with potential attacks affecting nuclear facilities have a double duty. First, they owe the public an accurate assessment of the risk. Second, they should refrain from publishing information that could directly assist a potential attacker. This declaration satisfies both requirements. It does not purport to provide a comprehensive assessment of radiological risk. Instead, it offers recommendations for such an assessment. From that perspective the 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-4) The NRC's preliminary-assumptions document called for a time horizon of about 2250 when considering the environmental impacts of long-term, temporary storage of SNF or HLW. Given such a distant time horizon, a risk assessor should consider the potential for substantial change in the risk environment. In Section V, I outline a process for considering such change.

(III-5) Most stakeholders would agree that the proposed EIS should consider a range of scenarios for the future, and a range of alternative options for storing SNF or HLW. Moreover, I understand that considering these matters is a legal requirement for an EIS. Accordingly, I offer recommendations regarding scenarios and alternative options. I also offer recommendations on improving the state of knowledge about the radiological risk posed by storing SNF or HLW.

IV. 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, risk can be managed. Indeed, as shown in Table IV-1, management of risk could be one of three major pillars of a framework of principles for the design and appraisal of infrastructure projects in the 21st century. Facilities for long-term, temporary storage of SNF or HLW would be appropriate projects for employment of that framework.

(IV-2) Table IV-2 shows some categories of risk that could be posed by a commercial nuclear facility. Radiological risk is defined 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 unplanned release, especially 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) The effects of an unplanned release of radioactive material could be among the most severe impacts that arise from storing SNF or HLW. Thus, assessing radiological risk should be a major function of the proposed EIS. Accordingly, I recommend as follows:

> **Recommendation #4:** Assessment of radiological risk should be a major function of the proposed EIS, this category of risk being defined as the potential for harm to humans as a result of unplanned exposure to ionizing radiation.

(IV-4) Defining radiological risk as "the potential for harm" does not 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. That approach is consistent with my general definition of "risk" as the potential for an unplanned, undesired outcome. The NRC has articulated a similar definition.[18]

(IV-5) In the nuclear industry and elsewhere, one often encounters a more limited definition, in which risk is the arithmetic product of a numerical indicator of harmful impact and a numerical indicator of the impact's probability.[19] That definition is hereafter designated as the "arithmetic" definition of risk. The arithmetic definition can be seriously misleading in two respects. First, the full spectrum of impact and/or probability may not be susceptible to numerical estimation, and numerical estimates may be incomplete or highly uncertain. Second, many subscribers to the arithmetic definition argue that equal levels of the numerically-estimated risk should be equally acceptable to citizens. Their argument may be given a scientific gloss, but is actually a statement laden with subjective values and interests.

(IV-6) Quantitative analysis is essential to science, engineering, and other fields. Yet, the limitations of quantitative analysis should be recognized. Analysts should be especially careful to avoid the intellectual trap of ignoring issues that are difficult to quantify. Many practitioners of radiological risk assessment fall into that trap. Thus, important risk factors are ignored. Examples include: (i) acts of malice or insanity; and (ii) gross errors in design, construction, and operation of facilities. Risk assessments for nuclear facilities routinely ignore these and other factors that may be major determinants of risk.[20]

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[18] The NRC Glossary defines risk as: "The combined answer to three questions that consider (1) what can go wrong, (2) how likely it is, and (3) what its consequences might be. These three questions allow the NRC to understand likely outcomes, sensitivities, areas of importance, system interactions, and areas of uncertainty, which can be used to identify risk-significant scenarios." (See: http://www.nrc.gov/reading-rm/basic-ref/glossary/risk.html, accessed on 16 February 2012.)

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

[20] For example, there is evidence that a major risk factor underlying the 1986 Chernobyl reactor accident was endemic secrecy in the USSR. (See: Shlyakhter and Wilson, 1992.) Also, there is evidence that a major risk factor underlying the 2011 accident at the Fukushima #1 reactor site was collusion among government, the regulators, and the licensee (TEPCO). (See: Diet, 2012, page 16.) Radiological-risk

(IV-7) A nuclear facility typically has the potential to experience unplanned releases of radioactive material across a spectrum ranging from small releases to large releases. Risk analysts who subscribe to the arithmetic definition often conclude that small releases are more probable. With their arithmetic approach, it then appears that large releases with low probability are equivalent to small releases with high probability. Often, these analysts leap to the assumption that the apparent equivalence is "scientific". Thus, they argue, equal levels of the numerically-estimated risk should be equally acceptable to citizens. In fact, the assumption of equivalence lacks a scientific basis. It is a subjective statement that reflects the values and interests of this group of analysts. From the perspective of a citizen, the potential for a large release may be much less acceptable than the potential for a small release, regardless of probability. That perspective could have a solid, rational basis, because a large release could have effects that are qualitatively different from the effects of a small release. Moreover, a prudent citizen will be skeptical of the probability findings generated by arithmetic risk analysts, given the propensity of these analysts to ignore important risk factors.

(IV-8) Radiological risk assessment requires the identification of potential events that could initiate a radiological incident. One category of initiating events, which I categorize as "conventional accidents", encompasses events such as random failure of equipment, random human error, or natural forces such as earthquakes. This category of events has been extensively studied in the context of commercial nuclear facilities.

(IV-9) The NRC's preliminary-assumptions document called for consideration of another category of potential initiating events under the rubric of "terrorism". In discussing such events the document stated:[21]

> "The staff plans to consider the environmental impacts of terrorism related to storage and transportation at a generic level. The terrorism consideration will be developed using available information in agency records and other available information for current facilities, package technologies, and transportation infrastructures; current technologies and reasonably foreseeable technologies that are being explored in depth; mitigation measures; and security arrangements that have a bearing on likely environmental consequences."

(IV-10) I welcome the NRC's willingness to consider initiating events that are beyond the category of conventional accidents. However, I find the above-quoted NRC statement on terrorism to be unsatisfactory. For example, it does not define terrorism or explain why this phenomenon should be considered to the exclusion of other potential events that involve violence.

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studies performed by the nuclear industry and its regulators do not consider secrecy or collusion as risk factors.

[21] NRC, 2011, Section 8.1(9).

(IV-11) Events involving violence could be significant for the radiological risk posed by storing SNF or HLW. My view is that such events should be categorized as "attacks", with the understanding that an attack could adversely affect stored SNF or HLW either directly or indirectly. Accordingly, I recommend as follows:

> **Recommendation #5:** The proposed EIS should assess the radiological risk arising from a range of conventional accidents or attacks that could affect stored SNF or HLW.

(IV-12) Table IV-3 shows that the NRC has publicly examined potential attacks on stored SNF. In that instance, the potential, hypothesized attacks were "sabotage events" at an SNF storage pool.

(IV-13) As discussed in paragraph III-5, above, there is a general expectation and, I understand, a legal requirement that the proposed EIS should consider alternative options and their respective impacts. Accordingly, given that the effects of an unplanned release of radioactive material could be among the most severe impacts that arise from storing SNF or HLW, I recommend as follows:

> **Recommendation #6:** The comparative radiological risk posed by a range of alternative options for storing SNF or HLW should be assessed in the proposed EIS as a major indicator of the comparative impacts of these alternatives.

V. The Future Risk Environment

(V-1) As discussed in paragraph I-4, above, the NRC currently envisions that the proposed EIS will consider scenarios including:

- temporary storage of SNF until a repository is made available in either the middle of the 21^{st} century or at the end of the 21st century
- temporary storage of SNF for an unspecified period if no repository is made available by the end of the 21^{st} century

(V-2) The NRC's preliminary-assumptions document called for consideration of temporary storage of SNF within a time horizon of about 2250. Accordingly, in this declaration I assume that the "unspecified period" mentioned in the second bullet of paragraph V-1 would extend until about 2250.

(V-3) As discussed in Section IV, above, assessment of radiological risk should be one of the major features of the proposed EIS. There is a considerable body of experience with radiological risk assessment. In this instance, however, there are unusual challenges in risk assessment because of the extended time frame. Thus, before attempting to assess the radiological risk posed by storage of SNF or HLW over a period of decades or centuries, a risk assessor should seek to understand the risk environment throughout that period. 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. Therefore, a credible risk assessment would systematically examine the potential for substantial change, over time, in the risk environment.

(V-4) There have been many serious efforts to forecast the future risk environment or factors that could influence that environment. Such efforts find, unsurprisingly, that uncertainty grows as the time horizon of the forecast becomes more distant. Three examples of forecasting are illustrative:

- The World Economic Forum (WEF) has now published seven editions of its "Global Risks" report. The seventh edition, published in 2012, examines fifty global risks across five categories. A 10-year time horizon is employed. Risks were assessed by surveying 469 experts and industry leaders. Five "centers of gravity" of risk are identified: (i) chronic fiscal imbalances; (ii) greenhouse gas emissions; (iii) global governance failure; (iv) unsustainable population growth; and (v) critical systems failure.[22]

- The US National Intelligence Council (NIC) has now published five editions of its "Global Trends" report. The fifth edition, published in December 2012, has a time horizon of 2030.[23] Findings in that report include the statement:[24]

  > "Extrapolations of the megatrends would alone point to a changed world by 2030 – but the world could be transformed in radically different ways. We believe that six key ***game-changers*** – questions regarding the global economy, governance, conflict, regional instability, technology, and the role of the United States – will largely determine what kind of transformed world we will inhabit in 2030."

- The Stockholm Environment Institute (SEI) convened its Global Scenario Group in 1995. The Group's work led to SEI's "Great Transition" report of 2002.[25] The time horizon in that report varied by scenario, extending to 2065 in some cases. The report identified six global scenarios in three categories: (i) conventional worlds; (ii) barbarization; and (iii) great transitions. These scenarios are described further in Table V-1.

(V-5) The forecasting efforts mentioned in the preceding paragraph, and numerous other studies, have identified human abuse of natural resources as a factor that could adversely

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[22] WEF, 2012.
[23] NIC, 2012.
[24] NIC, 2012, page iii.
[25] Raskin et al, 2002.

affect human welfare over the coming decades. For example, a group of authors examining the "safe operating space for humanity" has said:[26]

> "Human activities increasingly influence the Earth's climate (International Panel on Climate Change (IPPC) 2007a) and ecosystems (Millennium Ecosystem Assessment (MEA) 2005a). The Earth has entered a new epoch, the Anthropocene, where humans constitute the dominant driver of change to the Earth System (Crutzen 2002, Steffen et al. 2007). The exponential growth of human activities is raising concern that further pressure on the Earth System could destabilize critical biophysical systems and trigger abrupt or irreversible environmental changes that would be deleterious or even catastrophic for human well-being. This is a profound dilemma because the predominant paradigm of social and economic development remains largely oblivious to the risk of human-induced environmental disasters at continental to planetary scales (Stern 2007)."

(V-6) Societal response to the threats mentioned in the preceding quotation is inhibited by a number of factors, including a widespread lack of recognition of the rapidity of action that is needed to prevent adverse outcomes. For example, government leaders meeting in Copenhagen in 2009 committed their countries to holding the human-caused increase in average global temperature below 2°C. Yet, although accumulating scientific knowledge indicates that a 2°C increase may be dangerously high, current trends in greenhouse gas emissions make it unlikely that the increase can be held below 2°C.[27] Correcting those trends to achieve a 2°C limit would, according to analysis published in November 2012 by Pricewaterhouse Coopers, require an unprecedented reduction in global carbon intensity (CO_2 emissions per unit of economic product) averaging 5.1% per year throughout the period from the present until 2050.[28] There is no international agreement or plan to achieve such reduction.

(V-7) Adverse outcomes for human welfare, as a result of our abuse of natural resources, could include direct effects, such as reduced agricultural yields and increased incidence of infectious diseases. These direct effects could be accompanied and amplified by indirect effects, with the potential for a descending spiral in the human condition. Many analysts have noted that indirect effects could include an increase in violent conflict. For example, the Defense Science Board has examined the implications of climate change for national and international security, and has stated:[29]

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

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[26] Rockstrom et al, 2009.
[27] Anderson and Bows, 2011.
[28] PwC, 2012.
[29] Defense Science Board, 2011, page xi.

(V-8) The NRC envisions storage of SNF until about 2100 if a repository becomes available, or until about 2250 if no repository is available by the end of the 21st century. Both time horizons are considerably more distant than the time horizons of the forecasts outlined in paragraph V-4, above. Those forecasts acknowledge substantial uncertainty in their projections. One could reasonably expect that the NRC would acknowledge a much greater degree of uncertainty, in view of the comparatively distant time horizons it envisions. As discussed below, the NRC's preliminary-assumptions document did not meet that expectation. The proposed EIS should rectify that deficiency.

(V-9) The NRC's preliminary-assumptions document postulated that the risk environment throughout the period ending in 2250 will be little changed from what it is now. Indeed, the document specifically stated that "the EIS will minimize speculation about future conditions".[30] Consistent with that position, the document proposed a range of status quo assumptions. For example, nuclear fission power would continue providing about 20 percent of US electricity production. The SNF generated from that activity would have properties similar to the SNF generated by the present generation of light-water reactors. The NRC or an equivalent governmental entity would provide regulatory oversight that is at least as stringent as present requirements. The responsible entities would continue to fund the storage of SNF, "regardless of cost".[31]

(V-10) The NRC's preliminary-assumptions document acknowledged that a public commenter requested the NRC to "include in the EIS a scenario that accounts for a collapse of society and loss of government institutions, with a resulting lack of control over, and knowledge about, nuclear plants and radioactive waste". The document refused to meet that request, offering the following argument as justification:[32]

> "The request to include a societal-collapse scenario would require an analysis of the impacts of storage under a highly speculative scenario in which societal institutions, knowledge, and controls no longer exist. However, as described above, the trend in modern society is toward more awareness and control over issues that pose a risk to humans and their environment. The staff concludes that a loss of societal structures and the associated knowledge base is not reasonably foreseeable and, in fact, is highly unlikely to occur within the 200-year timeframe to be considered in the EIS. The staff's view, therefore, is that any of the impacts associated with this scenario are also not reasonably foreseeable."

(V-11) The NRC's argument in the preceding quotation fails on at least three grounds, discussed here and in the following two paragraphs. First, the NRC considers only a status-quo scenario and a scenario involving complete collapse of organized society, before excluding the latter scenario. By limiting its view in that manner, the NRC has

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[30] NRC, 2011, Section 8.1.
[31] NRC, 2011, Section 8.1(6).
[32] NRC, 2011, Section 8.1(6).

failed to understand the range of possible societal conditions. Any serious forecast of societal developments over the period ending in 2250 – or in 2100 – would postulate a broad range of possible scenarios.

(V-12) Second, the NRC claims to see a contemporary societal trend "toward more awareness and control over issues that pose a risk to humans and their environment". If that trend were real, it would have limited relevance across the period ending in 2250, but would be more significant across the period ending in 2100. Regrettably, no such trend can be seen in the contemporary United States with any consistency. Improvements in natural-resource management were made in the 20th century, but much of that momentum has been lost. For example, despite the clear and urgent need for rapid reduction of greenhouse-gas emissions, present US policies will not yield that reduction. The Energy Information Administration's latest reference-case forecast is that US energy-related emissions of carbon dioxide will rise continually from 2016 to 2040.[33] Also, the NRC itself is enabling the continued accumulation of SNF without the existence of a repository into which that SNF can be placed, and has indicated a willingness to enable further accumulation until at least 2250.[34] Such a policy places a growing burden on future generations without a commensurate benefit, and is the antithesis of sustainable development. These and other examples show that the contemporary societal trend cited by the NRC is not real.

(V-13) The third ground on which the NRC's argument fails is that it ignores a human history that includes conflict and the degradation of institutions. Looking forward from 2012 to 2250 is analogous to looking forward from 1774 to 2012. Any informed person knows that there have been numerous, major changes in human affairs within the present territory of the USA since 1774. Just from the perspective of large-scale violent conflict, US history has witnessed a Revolutionary War, a Civil War, two World Wars, a Cold War that came close to nuclear-weapon exchange during the Cuban Missile Crisis, and many other wars. With the exception of the Revolutionary War, these precise events could not have been predicted in 1774 although they were, to some degree, foreseeable. Such occurrences demonstrate that it is unreasonable to assume that society and its institutions will remain stable over an extended future period.

(V-14) The NRC's preliminary-assumptions document attempted to argue that its exclusive focus on a status quo scenario represented the only "reasonably foreseeable" outcome until 2250. That is the reverse of the truth. Limiting analysis to a status quo scenario across such a time period is speculative in the extreme. The only way to consider reasonably foreseeable outcomes is to articulate a broad range of possible future scenarios, while acknowledging the uncertainty that inevitably accompanies such an exercise. The uncertainty within a time horizon of 2100 would be large, and within a time horizon of 2250 it would be substantially larger.

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[33] EIA, 2012, Figure 13.

[34] The NRC's preliminary-assumptions document assumed that "spent nuclear fuel and high-level waste **ultimately** [emphasis added] will be transported to a geologic repository for disposal and that at least one repository will need to be constructed". (See: NRC, 2011, Section 8.2.)

(V-15) Drawing from the preceding paragraphs in Section V and other sources with which I am familiar, I recommend in paragraphs V-16 and V-17 a process whereby the proposed EIS could be informed by a forecast of the risk environment during the time period covered by the EIS. Across that period, the EIS should assess risks in all relevant categories, including radiological risk. Those assessments should be done for all the scenarios, and all the SNF and HLW storage options, that are considered in the EIS. The risk environment could vary across scenarios, but would typically not vary across storage options. Characteristics of the risk environment could affect both the likelihood and the magnitude of adverse outcomes.

(V-16) The risk environment can be characterized by a set of indicators that represent an array of natural, technical, and societal factors. At any given time and place, the risk environment is temporarily static. As time and place vary, the risk environment becomes dynamic. Accordingly, I recommend as follows:

> **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.

(V-17) Dynamic aspects of the potential risk environment that are particularly relevant to radiological risk could include:

- <u>Influence of Natural Factors</u>: Global climate change could increase: (i) sea level; (ii) the incidence of high winds and associated surges in coastal water level; (iii) the incidence of drought; and (iv) the incidence of river-basin flooding.

- <u>Influence of Technical Factors</u>: Technological advances could: (i) increase the capabilities and decrease the costs of instruments that could be used to attack SNF or HLW storage facilities; and (ii) provide new design options for protecting stored SNF or HLW against conventional accidents or attacks.

- <u>Influence of Global Societal Factors</u>: Failure to adequately address natural-resource limits and other global challenges could: (i) increase the incidence of violent conflict involving States and non-State actors; (ii) impoverish large numbers of people; (iii) degrade national and international systems of governance; and (iv) degrade the technological capabilities of societies.

- <u>Influence of Societal Factors within US Territory</u>: Global societal factors, as discussed above, could influence the risk environment within US territory either directly or indirectly; indirect impacts could include an increased potential for attack on US assets by non-State actors or States.

VI. Scenarios to be Considered in the Proposed EIS

(VI-1) As shown in Section V, above, if the proposed EIS is to be credible then it must consider a broad range of possible scenarios for the future. Here, in Section VI, I outline the types of scenario that should be considered in order to credibly assess radiological risk.

(VI-2) The future role of nuclear power is one of the issues that should be reflected in the choice of scenarios. As discussed in paragraph V-9, above, the NRC's preliminary-assumptions document postulated that the status quo for nuclear power will persist through all scenarios until 2250, one exception being the possible introduction of reprocessing. From the perspective of 2012, introduction of commercial reprocessing in the USA would be a major policy step. Across the period from 2012 to 2250, however, that step would be only one of numerous possible changes in US energy infrastructure. Scenarios identified in the NRC's preliminary-assumptions document were:[35]

- Scenario 1 – Extended onsite storage at reactor sites and offsite independent spent fuel storage installations
- Scenario 2 – Interim onsite storage and shipment to regional storage facilities
- Scenario 3 – Interim onsite storage and shipment to one centralized storage facility
- Scenario 4 – Interim onsite storage and shipment to at least one reprocessing facility

(VI-3) Trends in the nuclear-power industry over the past two decades suggest that the most likely outcome for that industry over the next few decades is not the status quo, but decline.[36] For example, in the early 1990s the nuclear industry supplied 17 percent of the world's electricity while in 2011 that fraction had fallen to 11 percent. The industry's annual, worldwide production of electricity peaked in 2006 at 2,660 TWh and fell to 2,518 TWh in 2011. The mean age of the world's fleet of operating reactors is now 27 years, and is increasing. The same general picture holds in the USA, where the last completion of a new reactor was in 1996.

(VI-4) A two-decade trend prior to 2012 does not ordain any particular future between 2012 and 2250, but is more significant for the period between 2012 and 2100. Across either time frame, it is clear that reasonably foreseeable outcomes for the US nuclear industry include shrinkage in the number of operating reactors, potentially leading to shutdown of all reactors by the middle of the 21st century. An important implication is that the industry's revenue would decline as reactors close. Payment for the management of the SNF remaining from reactor operation could initially come from funds set aside

[35] NRC, 2011, Section 8.2.
[36] Schneider et al, 2012.

during the years of operation. Over time, those funds could be depleted, at which point the most likely source of payment would be the general funds of the US government. Also, shrinkage of the US reactor fleet would inevitably reduce national capabilities in nuclear engineering.

(VI-5) From the two preceding paragraphs, it is clear that scenarios in the proposed EIS should cover outcomes in which the nuclear-power industry largely disappears, leaving behind a hazardous residue of SNF and HLW. Management of that residue could be a charge on the general public, who would receive no commensurate benefit. Society's remaining capabilities in nuclear engineering could be severely limited. These conditions could apply even if the general society at that time is prosperous and technologically competent. Also, as discussed in Section V, above, reasonably foreseeable factors could lead to prosperity, technological competence, and the quality of governance being at lower levels than in 2012.

(VI-6) Conversely, scenarios in the proposed EIS should also cover outcomes in which the nuclear-power industry employs new technology or expands the scale of its operations. As discussed in paragraphs VI-3 and VI-4, above, such outcomes would be inconsistent with current trends. However, they are as reasonably foreseeable as is a status quo scenario for the industry.

(VI-7) One potential new technology that is relevant to radiological risk is the use of ceramic fuel cladding as a replacement for the zirconium alloy (zircaloy) fuel cladding that is now used in light-water reactors. In situations where the fuel overheats, ceramic cladding may behave better than zircaloy cladding. Experience and analysis show that zircaloy cladding can readily undergo exothermic reaction with air or steam, and a steam-zircaloy reaction can yield a copious amount of hydrogen. These phenomena can greatly exacerbate the severity of a fuel-overheating incident. Currently, efforts to develop ceramic cladding appear to be focused on a "triplex" silicon carbide cladding. The developers hope to begin a prototype test program – in which complete fuel assemblies made with the triplex cladding are placed in commercial reactors – by about 2020.[37]

(VI-8) As mentioned in paragraph VI-2, above, the NRC's preliminary-assumptions document identified a scenario in which SNF is reprocessed. The technology to be employed for reprocessing was not discussed but, given that document's preference for the status quo, would presumably be the prevailing current technology (i.e., PUREX).

(VI-9) Consistent with paragraph VI-6, above, scenarios in the proposed EIS should cover a range of outcomes in which the nuclear-power industry expands the scale of its operations and/or employs technology that is "new" by comparison with the prevailing technology now used in light-water reactors. Potential new technology could include, in addition to ceramic fuel cladding and current-technology reprocessing:

[37] Yueh et al, 2010.

- Mixed-oxide (MOX) fuel
- Burning of light-water SNF in CANDU-type reactors (i.e., the DUPIC cycle)
- Reactors fueled by TRISO particles embedded in pebbles or prismatic blocks
- Sodium-cooled, fast-neutron breeder reactors
- Electrometallurgical pyroprocessing of SNF
- Accelerator-driven subcritical reactors
- Fusion reactors
- Fusion-fission hybrid reactors

(VI-10) Paragraphs VI-2 through VI-9 outline how reasonably foreseeable future roles of nuclear power should be reflected in the proposed EIS. To summarize, I recommend as follows:

> **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.

(VI-11) I pursue a related matter in Section VII, below. That matter is the potential variation, over time, in the inventories and modes of storage of SNF and HLW. In Section VII, I recommend that storage scenarios should be articulated to express a dynamic view of the inventory of stored SNF and HLW.

(VI-12) Other issues are also important in choosing scenarios. Notably, the scenarios should reflect the full range of potential variation of the risk environment, as discussed in Section V, above. Thus, I recommend as follows:

> **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.

(VI-13) The variation mentioned in Recommendation #9 could significantly influence radiological risk. For example, an impoverished society with degraded technological capability and governance might be unable or unwilling to maintain an SNF or HLW storage facility and the associated arrangements for security and emergency response. In that situation, the probability and consequences of a conventional accident or attack could increase.

(VI-14) As a corollary to Recommendation #9, the scenarios considered in the proposed EIS should cover a broad range of situations in which States and non-State actors are involved in violent conflict. During such situations, stored SNF or HLW could be attacked directly or could experience indirect effects of violent conflict. A range of possible attacks is reasonably foreseeable.

(VI-15) Table VI-1 outlines the types of attack that could occur at an SNF storage facility, and the atmospheric releases of radioactive material that could ensue. This table assumes that the stored SNF has zircaloy cladding. The table would apply to high-density pool storage of SNF, or to storage of SNF in dry casks, but the event details would vary across those two cases. The table could also apply to dry-cask transportation of SNF. A somewhat similar table could be prepared for storage of HLW, with details varying according to the mode of storage.

(VI-16) A notable feature of Table VI-1 is that the atmospheric release of volatile radioactive species, including Cesium-137, would not necessarily scale linearly with the apparent violence of the attack. The apparent violence would decrease progressively as one moved from a Type 1 attack to a Type 4 attack. Yet, the release of volatile species from a Type 4 attack could exceed the release from a Type 3 attack or even a Type 2 attack. The reason is that a successful Type 4 attack would exploit the propensity of zircaloy cladding to undergo exothermic reaction. In the case of high-density pool storage of SNF, a Type 4 attacker might rely on self-ignition of the zircaloy, but in the case of dry-cask storage the attacker might use an incendiary device to ignite the zircaloy.

(VI-17) Table VI-1 shows some of the instruments that might be used to attack an SNF storage facility. The instruments that are mentioned have been available since World War II or, in some cases, much earlier. Attack scenarios that are considered in the proposed EIS should consider the use of a range of possible instruments and modes of attack. That range should include all relevant instruments and modes of attack that are now available to States or non-State actors.

(VI-18) The shaped charge can illustrate some of the instruments of attack that are currently available. Table VI-2 outlines the status and potential applications of shaped-charge technology. Table VI-3 and Figures VI-1 through VI-3 provide supporting information. It is clear that an appropriate shaped charge could penetrate the structure of any commercial reactor or SNF storage facility in the USA. The capability to design, build, and use a shaped charge is widely distributed around the world. Many of the non-State actors that have engaged in violent conflict in recent decades could have deployed that capability, and some have done so (e.g., Iraqi insurgents).

(VI-19) Some potential attacks on nuclear facilities would involve the use of general-aviation aircraft. Figure VI-4 illustrates the fact that general-aviation aircraft have been used as instruments of attack. In the context of the proposed EIS, reasonably foreseeable events include attacks in which general-aviation aircraft are equipped with explosive charges, potentially including shaped charges.

(VI-20) Paragraphs VI-14 through VI-19 outline how reasonably foreseeable acts of violence affecting stored SNF or HLW should be considered in the proposed EIS. To summarize, I recommend as follows:

> **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. SNF and HLW Storage Modes and Dynamics to be Considered in the Proposed EIS

(VII-1) The NRC's preliminary-assumptions document envisioned the long-term temporary storage of SNF and related HLW. Subsequently, in the context of the proposed EIS, the NRC introduced the possibility that a repository may affect the need for storage. As discussed in paragraph I-4, above, the NRC envisions the possibility that storage will continue "**until** [emphasis added] a repository is made available". The implication is that the repository would absorb the entire stored inventory of SNF and HLW immediately upon becoming "available". That outcome is impossible. In fact, transfer of stored SNF and HLW would occur over a period of decades.

(VII-2) Table VII-1 shows the estimated duration of phases of implementation of the Yucca Mountain repository. For the case in which the repository would receive 105,000 MTHM of commercial SNF, one sees that the Construction phase would occupy 5 years. Thereafter, emplacement of SNF would occupy an additional 38-51 years. (The Development and Emplacement phases would occur in parallel.) It is notable that legislation limited the amount of SNF that could be placed in Yucca Mountain to 63,000 MTHM, and that the Blue Ribbon Commission published a projection that 133,000 MTHM of SNF will be accumulated in the USA by 2050.[38] The same projection indicates that an increasing fraction of the SNF inventory will be in dry storage.

(VII-3) Thus, a range of reasonably foreseeable situations could unfold over time. For example, the national inventory of stored SNF could rise over several decades, then fall over several more decades while emplacement in a repository is occurring, then resume growing when the repository is full. During that process, there could be significant shifts of SNF from one storage mode to another.

(VII-4) It is clear that, if the proposed EIS is to be credible, it must examine a range of possible trends in SNF and HLW storage over time, throughout the period covered by the EIS. This matter is significant from the perspective of radiological risk, as discussed below. Accordingly, I recommend as follows:

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[38] BRC, 2012, Figure 15.

> **Recommendation #11:** The proposed EIS should take a dynamic view of the potential inventories and modes of storage of SNF and HLW, by considering a range of storage scenarios.

(VII-5) Taking a "dynamic view" would mean that scenarios of the type discussed in Section VI, above, would be accompanied by storage scenarios that account for at least the following factors and their variations over time:

- Discharge of SNF from reactors
- Initial mode of storage of SNF (e.g., high-density pool storage, or low-density pool storage)
- Reprocessing of SNF
- Initial mode of storage of HLW (e.g., liquid in tanks, or vitrified canisters in vaults or dry casks)
- Transfer of SNF or HLW from one storage mode to another (e.g., transfer of SNF from high-density pool storage to dry-cask storage)
- Movement of SNF or HLW from one site to another
- Emplacement of SNF or HLW in a repository

(VII-6) The radiological risk posed by a particular facility for storing SNF or HLW could vary in response to at least five major factors, as follows:

- The threat environment at the facility could change over time.
- The mass of SNF or HLW stored at the facility could change over time.
- The modes of storage could vary in the radiological risk that they pose, for a given mass of SNF or HLW.
- The radiological risk posed by a given mode of storage (e.g., a high-density SNF storage pool) could vary according to the operational status of an adjacent facility (e.g., a reactor).
- The radiological risk posed by a given mass of SNF or HLW tends to decline with age, other factors being equal, because: (i) its radioactive decay heat production declines over time, resulting in a decreased propensity to overheat and release radioactive material to the atmosphere; and (ii) the inventory of radioactive material that is available for release also declines

(VII-7) From paragraph VII-6 it is clear that each storage scenario of the type discussed in paragraph VII-5 would have its own profile of radiological risk over time.

(VII-8) In paragraph VII-6, above, I note that: (i) modes of storage could vary in the radiological risk that they pose, for a given mass of SNF or HLW; and (ii) the radiological risk posed by a given mode of storage (e.g., a high-density SNF storage pool) could vary according to the operational status of an adjacent facility (e.g., a reactor). These observations support a more general point, which is addressed in my Recommendation #6, namely that the comparative radiological risk posed by a range of alternative options for storing SNF or HLW should be assessed in the proposed EIS as a major indicator of the comparative impacts of these alternatives. Accordingly, I recommend as follows:

> **Recommendation #12:** The proposed EIS should use a range of storage scenarios as vehicles to help assess the comparative radiological risk posed by alternative options for storing SNF or HLW.

(VII-9) The comparative radiological risk posed by alternative options for storing SNF or HLW is determined by a number of factors. One factor that can be a significant determinant of comparative risk, other factors being equal, is the extent to which the storage facility is placed below ground level. In illustration, Holtec has developed a design for an SNF dry-cask storage module that is said to be more robust against attack than conventional modules. The module in question is the HI-STORM 100U module, which would employ the same internal canister (MPC) as is used in the conventional Holtec modules. For most of its height, the 100U module would be below ground level. Holtec has described the robustness of the 100U module as follows:[39]

> "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."

(VII-10) In considering the storage of SNF or HLW below ground level, it should be noted that there is considerable discussion about the roles of reversibility and retrievability in the design of repositories for radioactive waste.[40] Indeed, the Yucca Mountain repository was nominally designed for retrievability during the Emplacement and Monitoring phases that are shown in Table VII-1. Reversibility and retrievability at a repository are issues relevant to discussion about the extent to which nuclear power could be compatible with sustainable development. In the context of this declaration, it is notable that retrievable emplacement of SNF or HLW in a repository, deep underground, would be a form of storage that could pose lower radiological risk than would storage at the surface. Accordingly, I recommend as follows:

> **Recommendation #13:** In assessing the comparative radiological risk posed by alternative options for storing SNF or HLW, the proposed EIS should regard retrievable emplacement in a repository as a mode of storage.

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[39] Holtec, 2007.
[40] Nuclear Energy Agency, 2011.

(VII-11) In paragraph II-4, above, I mention the concept of a "pool fire". That term refers to the occurrence of self-sustaining, exothermic oxidation reactions of fuel cladding in a high-density SNF pool if water is lost from the pool. More precisely, a pool fire would involve the following sequence of events:

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

(VII-12) A pool-fire event sequence would unfold over a timeframe ranging from a few hours to a number of days. During this timeframe, there might, in principle, be opportunities for personnel to halt or mitigate the event sequence through actions such as plugging holes in a pool, or adding water. However, addition of water after zircaloy ignites could be counter-productive, because the water could feed combustion. Circumstances accompanying the pool-fire event sequence, such as a core-damage event sequence at an adjacent reactor, could preclude mitigating actions. This matter is discussed in Section VIII, below.

(VII-13) The NRC concedes that a pool fire could occur, but argues that its probability is very low.[41] Nevertheless, the NRC acknowledges this event in its planning for emergencies. For example, a workbook used to train personnel in use of NRC's dose-projection code RASCAL contains an exercise in which trainees are asked to calculate offsite radiation doses in the event of a pool fire. The exercise is introduced with the following description of the event:[42]

> "The plant staff are calling you from San Onofre, Unit 2 because there has been an earthquake in the vicinity. The spent fuel pool has lost much of its water due to a large crack possibly flowing into a sink hole. Due to a malfunctioning pump, it has not been possible to provide enough water to make up for the loss. The water dropped to the top of the fuel at 8:49 A.M., and appears likely to continue dropping. Estimates are that the fuel will be fully uncovered by 11:00 A.M. The pool has high density racking and contains one batch of fuel that was unloaded from the reactor only 2 weeks earlier. (A batch is defined as one-third of a core)

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[41] For example, in a 2008 decision the NRC stated: "Thus, the **very low probability** [emphasis added] of an SFP zirconium fire would result in an SFP risk level less than that for a reactor accident." (See: NRC, 2008, page 46212.)

[42] Athey et al, 2007, page 116.

> Another batch was unloaded about a year before that, and 8 batches have been in the pool for longer than 2 years. The spent fuel building has been severely damaged and is in many places directly open to the atmosphere."

(VII-14) One notable feature of pool fires is that the potential for their occurrence derives almost entirely from the practice of employing high-density racks in SNF pools. That practice is now almost universal at US pools. If the high-density racks were replaced with low-density racks, SNF would not spontaneously ignite across a broad range of water-loss scenarios. The nuclear industry is reluctant to make the change to low-density racks, primarily because of the cost involved. Another notable feature of pool fires is that a pool fire could release a large inventory of radioactive material, especially Cesium-137, creating substantial radiological impact.

(VII-15) SNF stored in a dry cask could, in principle, experience an event analogous to a pool fire. I term that potential event a "cask fire". Occurrence of a cask fire would require that three conditions are satisfied. First, a circulating pathway between SNF and the atmosphere must exist, so that air can reach the SNF and combustion products (and Cesium-137) can reach the atmosphere. Second, circulation of fluid through this pathway must be driven by natural convection. Third, the temperature of the cladding of a portion of the SNF in the cask must be raised to the ignition point, so that a self-sustaining reaction can begin.

(VII-16) A pool fire could be initiated by a conventional accident or by an attack. By contrast, a cask fire could be initiated by an attack, but its initiation by a conventional accident is comparatively unlikely. This matter is addressed further in Section VIII, below. A cask fire could release a substantial fraction of the volatile radioactive material, such as Cesium-137, in the cask. Thus, a cask fire could create substantial radiological impact.

(VII-17) In light of the discussion in paragraphs VII-11 through VII-16, above, I recommend as follows:

> **Recommendation #14:** In assessing the comparative radiological risk posed by alternative options for storing SNF or HLW, the proposed EIS should give special attention to the potential for radioactive release from stored SNF as a result of a pool fire or a cask fire.

(VII-18) My Recommendation #12 is that the proposed EIS should use a range of storage scenarios as vehicles to help assess the comparative radiological risk posed by alternative options for storing SNF or HLW. Two SNF storage scenarios could be particularly useful to illustrate the options available, and their comparative radiological risk. These SNF storage scenarios would be: (i) an Extended Status Quo scenario; and (ii) a Nuclear Power Rundown with SNF Risk Minimization scenario.

(VII-19) The Extended Status Quo storage scenario would involve:

- Production of SNF continues at about the present level
- Newly-discharged SNF is placed in high-density pools adjacent to reactors
- Excess SNF is placed in dry casks on reactor sites
- This situation continues for some number of centuries

(VII-20) The Nuclear Power Rundown with SNF Risk Minimization storage scenario would involve:

- The present reactors shut down at the ends of their license periods or earlier, and no new reactors commence operating
- Newly-discharged SNF is placed in low-density pools adjacent to reactors
- Excess SNF is placed in dry casks on reactor sites, with additional protection (e.g., the HI-STORM 100U system, or placement of casks within berms, robust buildings, or tunnels)
- A repository begins receiving SNF as soon as possible

(VII-21) To summarize the discussion in paragraphs VII-18 through VII-20, above, I recommend as follows:

> **Recommendation #15:** The SNF storage scenarios to be considered in the proposed EIS should include: (i) an Extended Status Quo scenario; (ii) a Nuclear Power Rundown with SNF Risk Minimization scenario; and (iii) a range of other scenarios.

VIII. Phenomena Relevant to Radioactive Release from SNF or HLW

(VIII-1) My Recommendation #14 indicates that the proposed EIS should give special attention to the potential for radioactive release from stored SNF as a result of a pool fire or a cask fire. To date, the phenomena associated with a pool fire or a cask fire have not been adequately examined. I address that matter in the following paragraphs. Section VIII closes with some brief observations on phenomena relevant to radioactive release from HLW.

(VIII-2) As stated in paragraph II-4, above, I publicly identified the potential for a pool fire in 1979, and the Lower Saxony government accepted my findings. Independently, a group at Sandia Laboratories identified the same potential in a report prepared for the NRC.[43] In light of knowledge that has accumulated since 1979, the Sandia report generally stands up well, provided that one reads the report in its entirety. However, the report's introduction contains an erroneous statement that complete drainage of an SNF

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[43] Benjamin et al, 1979.

pool is the most severe situation in the context of a pool fire. The body of the report clearly shows that partial drainage can be a more severe case, as I had previously recognized. Unfortunately, NRC continued, until October 2000, to employ the erroneous assumption that complete drainage is the most severe case.

(VIII-3) After receiving the Sandia report, the NRC conducted and sponsored a number of analyses related to pool fires. Those analyses were published over a period of about two decades. I identified and critiqued that body of work in a February 2009 report, reaching the following conclusion:[44]

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

(VIII-4) After September 2001, the NRC ceased publishing analysis on pool fires, but claims to have done some secret studies. To my knowledge, the NRC has not published any significant analysis on pool fires or cask fires since February 2009. Thus, my conclusion of February 2009, as quoted in paragraph VIII-3, remains valid.

(VIII-5) The US Government Accountability Office (GAO) confirms that the NRC has, indeed, done some secret studies on pool fires. However, according to the GAO, the NRC has lost track of those studies. An August 2012 GAO report states:[45]

> "Because a decision on a permanent means of disposing of spent fuel may not be made for years, NRC officials and others may need to make interim decisions, which could be informed by past studies on stored spent fuel. In response to GAO requests, however, NRC could not easily identify, locate, or access studies it had conducted or commissioned because it does not have an agencywide mechanism to ensure that it can identify and locate such classified studies."

(VIII-6) I identified a similar problem in my February 2009 report, which I discuss in paragraph VIII-3, above. In that report, I examined statements, in two official NRC documents published in 2008, regarding secret studies allegedly conducted or sponsored by the NRC in order to improve technical understanding of pool fires. I concluded:[46]

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[44] Thompson 2009, Section 11, Conclusion C3.
[45] GAO, 2012, Highlights.
[46] Thompson, 2009, Section 5.2, pp 24-25.

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

(VIII-7) The experiences outlined in paragraphs VIII-5 and VIII-6 illustrate the corrosive, counterproductive effects of an entrenched culture of secrecy. Such a culture is not compatible with a clear-headed, science-based approach to the understanding of radiological risk. Entrenched secrecy perpetuates dogma, stifles dissent, encourages conflicts of interest, promotes laziness, and can create a false sense of security. Indeed, secrecy can significantly increase radiological risk. For example, there is evidence that a major risk factor underlying the 1986 Chernobyl reactor accident was endemic secrecy in the USSR.[47]

(VIII-8) There is no justification for secrecy about the phenomena associated with potential pool fires. A pool fire could be initiated by either a conventional accident or an attack. In either case, the phenomena associated with the fire itself would be similar. Effective management of the radiological risk of a potential pool fire, in the context of conventional accidents, demands open, transparent consideration of all associated phenomena. The resulting publication of information would not significantly assist an entity that contemplates an attack on an SNF pool. A capable entity in that category would already possess, or could readily obtain, the information needed to plan an attack. The NRC itself has published sabotage scenarios, as shown in Table IV-3, that could, with modest adaptation, lead to an unstoppable pool fire with severe offsite impacts. In any event, if the NRC determines in future that an attack-initiated pool fire is a significant threat, the mitigation of that threat could be simple. The NRC could order its licensees to re-equip their SNF pools with low-density racks, which could be accomplished comparatively quickly.

(VIII-9) In light of the discussion in paragraphs VIII-2 through VIII-8, above, I recommend as follows:

> **Recommendation #16:** In assessing the potential for radioactive release from stored SNF as a result of a pool fire, the proposed EIS should rely on an updated, transparent, fully published body of analytic and empirical investigation that adequately describes all relevant phenomena, including: (i) the dynamics of cladding self-ignition across a range of water-loss and fuel-loading scenarios; (ii) propagation of exothermic reactions between fuel assemblies; (iii) hydrogen generation; (iv); heat generation; and (v) atmospheric release of radioactive material.

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[47] Shlyakhter and Wilson, 1992.

(VIII-10) My Recommendation #16 addresses phenomena associated with a pool fire, rather than the pre-conditions and initiating events that could cause a pool fire to commence. To date, these matters have not been adequately examined. I address them in the following paragraphs.

(VIII-11) As mentioned in paragraph VII-12, above, a pool-fire event sequence would unfold over a timeframe ranging from a few hours to a number of days. During this timeframe, there might, in principle, be opportunities for personnel to halt or mitigate the event sequence. For a particular event sequence, the timeframe, and the existence of potential opportunities to halt or mitigate the sequence, would reflect factors including: (i) the facility design; (ii) the age and disposition of SNF in the pool; and (iii) the nature of the initiating event, which could be a conventional accident or an attack.

(VIII-12) Although potential opportunities to halt or mitigate a pool-fire event sequence might exist in principle, circumstances accompanying the sequence could prevent personnel from exploiting those opportunities. One category of such circumstances would be the degradation of site conditions caused by an incident at an adjacent facility. For example, that incident could block cooling and water makeup to the pool, and access by personnel to restore those services could be precluded by phenomena such as high radiation fields, fires, explosions, damage to equipment and structures, and release of high-temperature steam and gases. That situation is not speculative, because it occurred at the Fukushima #1 site in 2011. Figure VIII-1 shows Unit 4 at that site during the 2011 accident. A concrete pumping truck is shown, spraying water into the SNF pool. Prior to the arrival of that truck, unsuccessful attempts had been made over a number of days to add water to SNF pools at the site, employing fire trucks, police riot control vehicles, and bags of water suspended from helicopters. Yet, despite this vivid illustration of the threat, the NRC has never published a credible analysis of the potential for degraded-site conditions to enable or exacerbate a pool fire.

(VIII-13) In light of the discussion in paragraphs VIII-11 and VIII-12, above, I recommend as follows:

> **Recommendation #17:** In assessing the potential for initiation of a pool fire at a given facility, the proposed EIS should account for factors including: (i) the potential occurrence of a range of conventional accidents or attacks at the facility; (ii) a range of water-loss and fuel-loading scenarios; and (iii) the potential occurrence of degraded-site conditions due to an incident at an adjacent facility (e.g., a reactor).

(VIII-14) In paragraph VII-15, above, I outline the conditions that must be satisfied for a cask fire to occur. In paragraph VII-16, I note that an attack could satisfy those conditions. The NRC has not yet conceded that an attack could initiate a cask fire. However, the NRC has been reliably informed that a reasonably foreseeable attack could penetrate a cask, damage SNF inside the cask, and cause a release of radioactive material to the atmosphere. That point has been established by a body of empirical work whose findings have been openly published. For example, consider a 2008 Sandia report on tests related to potential sabotage of an SNF storage or transport cask. The report states:[48]

> "In some plausible, intentional sabotage scenarios, such as an attack employing a high energy density device (HEDD), i.e., explosive armor-piercing weapons, it is possible that a cask could be penetrated. Then, a small percentage of aerosolized particles produced within from disrupted fuel rod and pellet materials could be released as a radiological inhalation source hazard. If released to the environment in a significant quantity, the spent fuel respirable particles have the potential to cause radiological consequences."

(VIII-15) From the preceding paragraph, it is clear that attack-induced penetration of an SNF cask, leading to atmospheric release, is a reasonably foreseeable event. With a few additional steps, attackers could initiate a cask fire. I addressed that matter in a 2008 declaration, being careful to avoid disclosing information that could directly assist an attacker.[49] I conclude that an attack-induced cask fire is a reasonably foreseeable event.

(VIII-16) My position on the foreseeability of an attack-induced cask fire differs from the public position of the NRC. The difference boils down to a question: Could attackers who are capable of penetrating an SNF cask take the additional steps needed to initiate a cask fire? That question could be addressed 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.

(VIII-17) Figure VIII-2 shows that the NRC has sponsored a test burn of an SNF assembly. The findings from that test could improve understanding of both pool fires and cask fires. Accordingly, those findings should be published. Findings from similar tests should also be published.

(VIII-18) In light of the discussion in paragraphs VIII-14 through VIII-17, above, I recommend as follows:

> **Recommendation #18:** In assessing the potential for radioactive release from stored SNF as a result of a cask fire, the proposed EIS could rely on a body of analytic and empirical investigation that is not fully published, provided that the

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[48] Molecke et al, 2008, Section 1, page 9.
[49] Thompson, 2008b, Section V.

NRC has engaged an independent Red Team to determine through representative tests whether a cask fire can be initiated and, if so, what release of radioactive material would be likely to occur.

(VIII-19) The preceding paragraphs in Section VIII have addressed phenomena associated with a pool fire or a cask fire. That focus of attention is consistent with my Recommendation #14. However, as stated in my Recommendation #2, the proposed EIS should address the potential storage of HLW as well as SNF. Thus, the proposed EIS should be supported by a thorough examination of phenomena relevant to radioactive release from HLW. I have studied such phenomena in several contexts. One such context is the storage of HLW in liquid form at the Sellafield site in the UK.[50]

IX. Assessing Likelihood and Impacts of Radiological Incidents

(IX-1) My Recommendation #4 is that assessment of radiological risk should be a major function of the proposed EIS. Such assessment will require estimation of the likelihood and the impacts of potential radiological incidents. I address these matters in the following paragraphs.

(IX-2) An analyst who seeks to estimate the likelihood of potential radiological incidents can employ various sources of information and various analytic tools. One of those tools is the art of probabilistic risk assessment (PRA). The high point of PRA practice in the nuclear-power sector to date was the NRC's NUREG-1150 study, which examined the radiological risk posed by five US nuclear power plants, in the context of conventional accidents.[51]

(IX-3) PRA techniques, if judiciously applied, could contribute to an assessment of the likelihood of radiological incidents involving stored SNF or HLW. However, as discussed in paragraph IV-6, above, the limitations of PRA techniques should be recognized.[52] Accordingly, I recommend as follows:

> **Recommendation #19:** In assessing the likelihood of a radiological incident, the proposed EIS should rely on diverse sources of information, and should not rely solely upon the findings of probabilistic risk assessment.

(IX-4) An analyst who seeks to estimate the impacts of potential radiological incidents should consider a range of impacts. In the context of incidents involving atmospheric release, I recommend as follows:

> **Recommendation #20:** In assessing the impacts of a potential radiological incident involving atmospheric release, the proposed EIS should consider types of impact including: (i) plume exposure; (ii) ground contamination and resulting

[50] Thompson, 1998.
[51] NRC, 1990.
[52] For additional information on the limitations of PRA, see: Hirsch et al, 1989.

exposure; (iii) exposure via food and water pathways; (iv) health effects pursuant to total exposure; (v) abandonment of assets; (vi) cleanup costs; (vii) direct and indirect economic impacts; and (viii) social impacts.

(IX-5) In paragraphs (IV-5) through (IV-7), above, I describe the "arithmetic" definition of risk and show how that definition can be seriously misleading. Nevertheless, the NRC is prone to using the arithmetic definition in official documents. Here is an example:[53]

> "Risk is defined as the probability of the occurrence of a given event multiplied by the consequences of that event."

(IX-6) The quoted statement is inconsistent with the NRC's Glossary, as footnoted in my paragraph (IV-4), above. Moreover, the quoted statement is inconsistent with its own footnote, which refers to an ASME standard. In light of these inconsistencies and my finding that the arithmetic definition can be seriously misleading, I recommend as follows:

> **Recommendation #21:** In considering radiological risk, the proposed EIS should repudiate the arithmetic definition of risk.

(IX-7) Radiological risk is one category of potential impacts from storage of SNF or HLW. A related category is the set of implications of storage options for national security. I address that matter in Table IX-1, with a focus on the threat of attack by non-State actors. That table shows how robust and inherently-safer design of infrastructure facilities, such as facilities for storing SNF or HLW, could contribute to a national strategy of protective deterrence. Accordingly, I recommend as follows:

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

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[53] NRC, 2008, page 46207.

X. Summary of Recommendations

(X-1) Numbered recommendations regarding the scope of the proposed EIS are set forth within Sections I through IX of this declaration. Here, the recommendations are repeated, grouped by the sections where they are set forth. Each recommendation should be read within the context of the narrative that surrounds it. The recommendations are:

SECTION I

Recommendation #1: The NRC's preliminary-assumptions document should be a point of departure for determining the scope of the proposed EIS, especially in regard to storage after the end of the 21^{st} century.

Recommendation #2: The proposed EIS should not only address the storage of SNF, but also the potential storage of HLW from reprocessing of SNF.

Recommendation #3: The proposed EIS should consider the radiological risk posed by storage of SNF from the moment of its discharge from a reactor.

SECTION IV

Recommendation #4: Assessment of radiological risk should be a major function of the proposed EIS, this category of risk being defined as the potential for harm to humans as a result of unplanned exposure to ionizing radiation.

Recommendation #5: The proposed EIS should assess the radiological risk arising from a range of conventional accidents or attacks that could affect stored SNF or HLW.

Recommendation #6: The comparative radiological risk posed by a range of alternative options for storing SNF or HLW should be assessed in the proposed EIS as a major indicator of the comparative impacts of these alternatives.

SECTION V

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.

SECTION VI

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.

SECTION VII

Recommendation #11: The proposed EIS should take a dynamic view of the potential inventories and modes of storage of SNF and HLW, by considering a range of storage scenarios.

Recommendation #12: The proposed EIS should use a range of storage scenarios as vehicles to help assess the comparative radiological risk posed by alternative options for storing SNF or HLW.

Recommendation #13: In assessing the comparative radiological risk posed by alternative options for storing SNF or HLW, the proposed EIS should regard retrievable emplacement in a repository as a mode of storage.

Recommendation #14: In assessing the comparative radiological risk posed by alternative options for storing SNF or HLW, the proposed EIS should give special attention to the potential for radioactive release from stored SNF as a result of a pool fire or a cask fire.

Recommendation #15: The SNF storage scenarios to be considered in the proposed EIS should include: (i) an Extended Status Quo scenario; (ii) a Nuclear Power Rundown with SNF Risk Minimization scenario; and (iii) a range of other scenarios.

SECTION VIII

Recommendation #16: In assessing the potential for radioactive release from stored SNF as a result of a pool fire, the proposed EIS should rely on an updated, transparent, fully published body of analytic and empirical investigation that adequately describes all relevant phenomena, including: (i) the dynamics of cladding self-ignition across a range of water-loss and fuel-loading scenarios; (ii) propagation of exothermic reactions between fuel assemblies; (iii) hydrogen generation; (iv); heat generation; and (v) atmospheric release of radioactive material.

Recommendation #17: In assessing the potential for initiation of a pool fire at a given facility, the proposed EIS should account for factors including: (i) the potential occurrence of a range of conventional accidents or attacks at the facility; (ii) a range of water-loss and fuel-loading scenarios; and (iii) the potential occurrence of degraded-site conditions due to an incident at an adjacent facility (e.g., a reactor).

Recommendation #18: In assessing the potential for radioactive release from stored SNF as a result of a cask fire, the proposed EIS could rely on a body of analytic and empirical investigation that is not fully published, provided that the NRC has engaged an independent Red Team to determine through representative tests whether a cask fire can be initiated and, if so, what release of radioactive material would be likely to occur.

SECTION IX

Recommendation #19: In assessing the likelihood of a radiological incident, the proposed EIS should rely on diverse sources of information, and should not rely solely upon the findings of probabilistic risk assessment.

Recommendation #20: In assessing the impacts of a potential radiological incident involving atmospheric release, the proposed EIS should consider types of impact including: (i) plume exposure; (ii) ground contamination and resulting exposure; (iii) exposure via food and water pathways; (iv) health effects pursuant to total exposure; (v) abandonment of assets; (vi) cleanup costs; (vii) direct and indirect economic impacts; and (viii) social impacts.

Recommendation #21: In considering radiological risk, the proposed EIS should repudiate the arithmetic definition of risk.

Recommendation #22: In assessing the overall impacts of storing SNF or HLW, the proposed EIS should consider the implications of alternative storage options for a national strategy of protective deterrence.

****

I declare, under penalty of perjury, that the facts set forth in the foregoing narrative, and in the two 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 2 January 2013.

G.R. Thompson

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Gordon R. Thompson

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APPENDIX B: Tables and Figures

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Table IV-1
A Possible Framework of Sustainable-Development Principles for Design and Appraisal of Infrastructure Projects

Objective	Design Approach Dictated by Objective
#1. Build and preserve assets	Design for preservation and enhancement of: • Human capital • Natural capital • Engineered capital
#2. Create options for the future	Design for: • Reversibility • Resilience • Adaptability • Flexibility
#3. Manage risk	Prepare for unusual events by: • Identifying and characterizing potential events • Designing infrastructure to ride out events or to fail consistent with objectives #1 and #2 • Planning for emergency response

Notes:
(a) This particular framework of principles is attributable to Gordon R. Thompson. Each principle in the framework has been widely discussed by many authors and has, to some extent, been applied to the design of infrastructure. (See, for example: Nuclear Energy Agency, 2000.) However, at present there is no generally accepted framework that integrates these principles.
(b) This framework reflects the definition of sustainable development that was set forth by the World Commission on Environment and Development in 1987, as follows (WCED, 1987, beginning of Chapter 2):

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

(c) Infrastructure should serve a societal purpose. A particular societal purpose could be served by a variety of configurations of infrastructure. A framework such as the one set forth here could be used to appraise the comparative sustainability of proposed configurations, across a range of options.
(d) Logically, the principles used to appraise an infrastructure project should be identical to the principles used to design the project.

Table IV-2
Some Categories of Risk Posed by a Commercial Nuclear Facility

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 conventional 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 IV-3
Potential Sabotage Events at an SNF Storage Pool, as Postulated in the NRC's August 1979 Generic EIS 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 V-1
Future World Scenarios Identified by the Stockholm Environment Institute

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

Source: Raskin et al, 2002

Table VI-1
Potential Types of Attack on an SNF 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-2
The Shaped Charge as a Potential Instrument of Attack

Category of Information	Selected Information in Category
General information	• Shaped charges have many civilian and military applications, and have been used for decades • Applications include human-carried demolition charges or warheads for anti-tank missiles • Construction and use does not require assistance from a government or access to classified information
Use in World War II	• The German MISTEL, designed to be carried in the nose of an un-manned bomber aircraft, is the largest known shaped charge • Japan used a smaller version of this device, the SAKURA bomb, for kamikaze attacks against US warships
A large, contemporary device	• Developed by a US government laboratory for mounting in the nose of a cruise missile • Described in detail in an unclassified, published report (citation is voluntarily withheld here) • Purpose is to penetrate large thicknesses of rock or concrete as the first stage of a "tandem" warhead • Configuration is a cylinder with a diameter of 71 cm and a length of 72 cm • When tested in November 2002, created a hole of 25 cm diameter in tuff rock to a depth of 5.9 m • Device has a mass of 410 kg; would be within the payload capacity of many general-aviation aircraft
A potential delivery vehicle	• A Beechcraft King Air 90 general-aviation aircraft 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-3
Performance of US Army Shaped Charges, M3 and M2A3

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

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

Table VII-1
Estimated Duration of Phases of Implementation of the Yucca Mountain Repository

Phase of Repository Implementation		**Duration of Phase (years)**	
		If Yucca Mountain total inventory of commercial spent fuel = 63,000 MTHM	**If Yucca Mountain total inventory of commercial spent fuel = 105,000 MTHM**
Construction phase		5	5
Operation and monitoring phases	Development	22	36
	Emplacement	24-50	38-51
	Monitoring	76-300	62-300
Closure phase		10-17	12-23

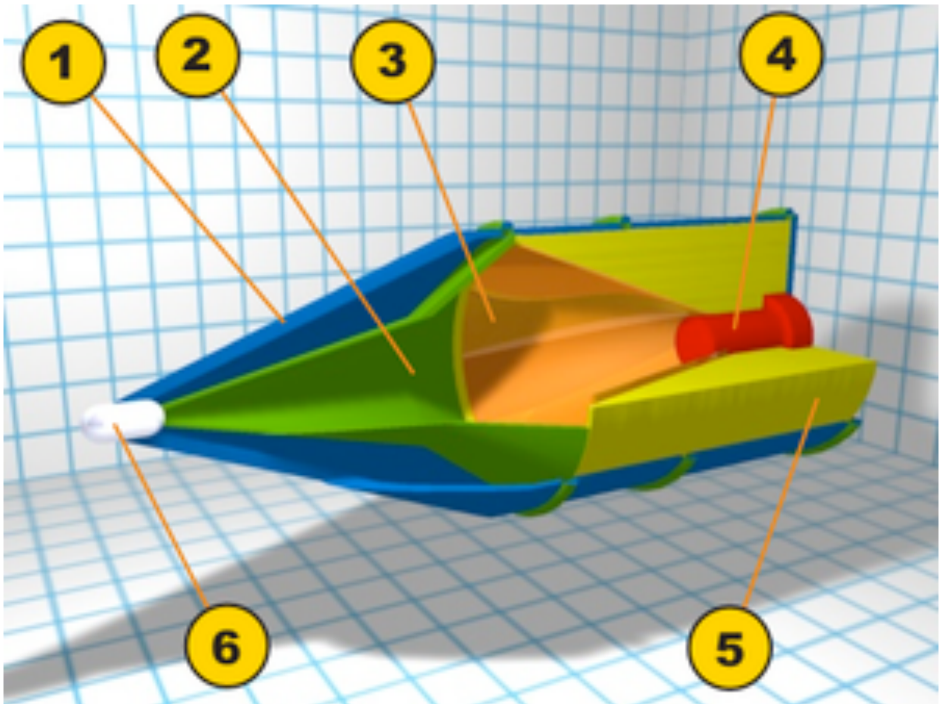
Notes:
(a) These estimates are from: DOE, 2002, Volume I, pages 8-8 and 2-18.
(b) The Development and Emplacement phases would begin on the same date. Other phases would be sequential.
(c) The Construction phase would begin with issuance of construction authorization, and end with issuance of a license to receive and dispose of radioactive waste.

Table IX-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".

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

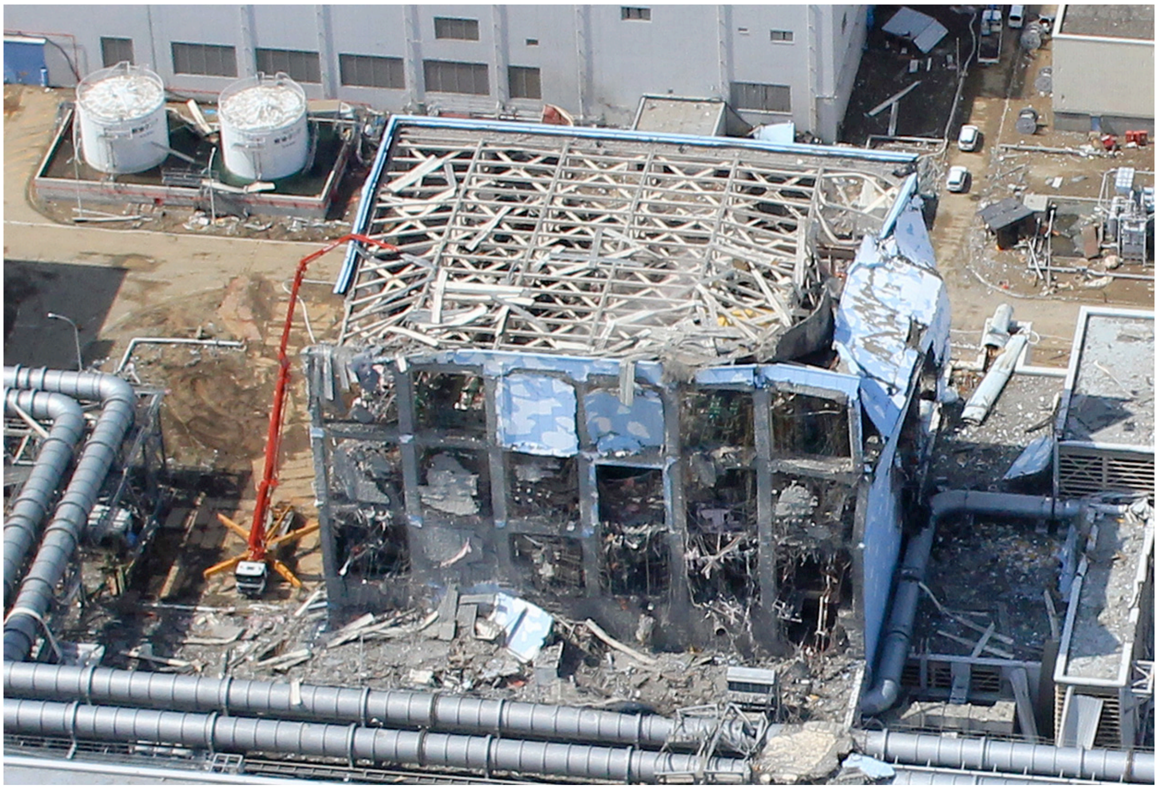
After Test (viewed from the attacked face)

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
Outcome of Test Burn of a BWR Fuel Assembly

Notes:
(a) This figure is from: Weber, 2011.
(b) The figure shows the outcome of a test to investigate the burning of SNF. An inactive 9x9 BWR fuel assembly with zircaloy-2 cladding was burned in air. The assembly was at reactor scale although not all rods were full length. The assembly was electrically heated (via 74 electric heater rods) at a rate of 5 kW.
(c) The fuel assembly was surrounded by thermal insulation – the white material in the photograph.
(d) This test did not attempt to simulate the release of Cesium or other materials from the damaged fuel.