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Declaration of 1 August 2013
by Gordon R. Thompson:

Comments on the US Nuclear Regulatory Commission's
Draft Consequence Study of a Beyond-Design-Basis
Earthquake Affecting the Spent Fuel Pool
for a US Mark I Boiling Water Reactor

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] Specifically, NRC has invited comments on a draft technical study, dated June 2013, that NRC staff has prepared.[2] The draft study is titled "Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a US Mark I Boiling Water Reactor".[3] Hereafter, in this declaration, I refer to that study as "NRC's Draft Consequence Study" or "the Study".

(I-3) On 2 January 2013, I completed a declaration that set forth recommendations for NRC's consideration of environmental impacts of long-term, temporary storage

[1] These organizations include: Beyond Nuclear, Blue Ridge Environmental Defense League, Center for a Sustainable Coast, Citizens Allied for Safe Energy, Don't Waste Michigan, Ecology Party of Florida, Friends of the Coast, Friends of the Earth, Georgia Women's Action for New Directions, Green States Solutions, Hudson River Sloop Clearwater, Missouri Coalition for the Environment, NC WARN, Nevada Nuclear Waste Task Force, New England Coalition, No Nukes Pennsylvania, Nuclear Energy Information Service, Nuclear Information and Resource Service, Nuclear Watch South, Physicians for Social Responsibility, Public Citizen, Riverkeeper, SEED Coalition, San Luis Obispo Mothers for Peace, Sierra Club Nuclear Free Campaign, and Southern Alliance for Clean Energy.
[2] *Federal Register*, Volume 78, Number 127, Tuesday 2 July 2013, pp 39781-39782.
[3] Barto et al, 2013.

of spent nuclear fuel (SNF) or related high-level waste (HLW).[4] Those recommendations would apply to NRC's Waste Confidence Generic Environmental Impact Statement (GEIS), which has been issued as a preliminary draft report for comment dated August 2013.[5] Some issues addressed in my 2 January 2013 declaration are relevant to NRC's Draft Consequence Study. Accordingly, I incorporate here by reference the findings and recommendations in my 2 January 2013 declaration.

(I-4) Here, I comment on selected aspects of NRC's Draft Consequence Study. The scope of my comments is constrained by time and budget limitations. Absence of discussion of an issue in this declaration does not imply that I view the issue as insignificant, or that I have no professional opinion on the manner in which the issue has been addressed in NRC's Draft Consequence Study. Although I comment only on selected aspects of the Study, these aspects have comparatively high significance for public health and safety. Moreover, my review of the Study is sufficient to support the findings presented here.

(I-5) NRC's Draft Consequence Study examines, among other matters, the potential for self-sustaining, exothermic oxidation reaction of fuel cladding in a spent-fuel pool if water is lost from the pool. For simplicity, that event can be referred to as a "pool fire".

(I-6) A pool fire is a potential event at every nuclear power plant in the USA. That is so because the spent-fuel pools at all plants are equipped with high-density, closed-frame racks. The nuclear industry began installing these racks in the 1970s, to replace the low-density, open-frame racks previously used. The high-density racks offered a comparatively cheap option for storing a growing inventory of spent fuel.

(I-7) This declaration has the following narrative sections:

I. Introduction
II. My Professional Qualifications
III. A Brief History of Pool-Fire Analysis
IV. What Pool-Fire Analysis Should NRC Have Published Now?
V. NRC's Draft Consequence Study: Structure, Apparent Scope, and Messages
VI. NRC's Draft Consequence Study: Actual Scope, and Credibility
VII. NRC's Use of the MELCOR Code
VIII. Conclusions and Recommendations

(I-8) In addition to the above-named narrative sections, this declaration has two appendices that are an integral part of the declaration. Appendix A contains tables and figures that support the narrative. Appendix B is a bibliography. Documents cited in the narrative or in Appendix A are listed in that bibliography unless otherwise identified.

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[4] Thompson, 2013.
[5] NRC, 2013.

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.[6] One of the risk issues that I personally identified and analyzed was the potential for self-sustaining, exothermic oxidation reaction of fuel cladding in a high-density SNF pool if water is lost from the pool. That event is referred to here 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.[7] As a direct result, policy throughout Germany has been to use dry storage in casks, rather than high-density pool storage, for away-from-reactor storage of SNF.

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[6] Beyea et al, 1979.
[7] Albrecht, 1979.

(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.[8] Also, I co-authored a journal article, on SNF radiological risk, that received considerable attention from relevant stakeholders.[9] The findings in that article were generally confirmed by a subsequent report by the National Research Council.[10] 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.[11]

(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.[12]

III. A Brief History of Pool-Fire Analysis

(III-1) Any review of the merit of NRC's Draft Consequence Study should be informed by the history of analysis regarding the potential for a pool fire. Here, I provide a brief history from March 1979 through May 2013 (i.e., just prior to publication of NRC's Draft Consequence Study in June 2013). This history does not purport to be exhaustive. Instead, it addresses some important highlights.

(III-2) Two studies completed in March 1979 independently identified the potential for a pool fire. One study was by members of an international review group commissioned by the government of Lower Saxony, as discussed in paragraph II-4, above. That study was done under time and budget constraints, so it used simple, scoping analysis to address pool-fire phenomena. The second study was done by Sandia Laboratories for NRC.[13] In light of knowledge that has accumulated since 1979, the Sandia report generally stands up well, provided that one reads the report in its entirety. However, the report's introduction contains an erroneous statement that complete drainage of the pool would be the most severe mode of water loss.[14] The body of the report clearly shows that partial loss of water could be a more severe case, as was recognized in the Lower Saxony study.

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[8] See, for example: Thompson, 2009.
[9] Alvarez et al, 2003.
[10] National Research Council, 2006.
[11] Thompson, 2008.
[12] Thompson, 2005.
[13] Benjamin et al, 1979.
[14] Benjamin et al, 1979, page 11.

(III-3) The 1979 Sandia report explicitly recognized a point that was obvious then and has remained so. The point is that the pool-fire issue became salient when the nuclear industry abandoned the use of low-density, open-frame storage racks and switched to high-density, closed-frame racks. The nuclear industry made this switch, beginning in the 1970s, because high-density racks offered a comparatively cheap option for storing a growing inventory of spent fuel. Figure III-1 shows a low-density, open-frame rack for pressurized-water-reactor (PWR) fuel. If water were lost from a pool equipped with such racks, fuel would be readily cooled by three-dimensional, natural convective circulation of air and steam. Human intervention would not be required. Contemporaneous racks used for boiling-water-reactor (BWR) fuel were not as fully open to three-dimensional convective circulation of air and steam, in the event of water loss, as would be the rack shown in Figure III-1. However, a BWR rack could be constructed with a configuration similar to that in Figure III-1. If necessary, channel boxes could be removed from BWR fuel assemblies before their placement in that rack, as discussed in the following paragraph.

(III-4) If low-density, open-frame racks were used, water loss from a pool would lead to fuel ignition only in very rare circumstances. These circumstances might include deformation and coverage of racks by a falling object, and/or the presence in the pool of fuel assemblies from a reactor shut down a short time previously. A thorough investigation of pool-fire risk would identify and characterize such circumstances. Also, such an investigation would determine the potential for ignition and fire propagation for cases in which channel boxes were, or were not, removed from BWR fuel. Convective circulation of air and steam, in the event of water loss, would be enhanced if the channel boxes had been removed. Overall, it is clear that re-equipping the present high-density pools with low-density, open-frame racks would dramatically reduce the risk of a pool fire. In the case of BWR fuel, removal of channel boxes might be an appropriate adjunct step.

(III-5) By the latter part of 1979, at least six points about potential pool fires were clear to any technically-competent person who was paying attention to this issue. First, loss of water from a pool with high-density racks could lead to exothermic air-zircaloy or steam-zircaloy reactions under some conditions. Second, the intensity of exothermic reactions could lead to propagation of ignition to some fuel assemblies that had not initially ignited. Third, a water-loss case involving the presence of residual water would be a more severe case than one involving total drainage, other factors being equal, because the residual water would inhibit convective heat transfer. Fourth, a pool-fire scenario would develop more slowly than a reactor core melt, because the output of decay heat would be smaller in the pool situation. Fifth, the fire threat could be dramatically reduced by reverting to low-density, open-frame racks. Sixth, the fire threat can be roughly characterized using simple, scoping analysis, but developing a thorough understanding would require sophisticated modeling backed up by experiment.

(III-6) Given these six points, one can easily identify a water-loss scenario that represents a test of the credibility of an analysis of pool-fire risk. Any such analysis fails if it does not characterize this scenario. This scenario is not necessarily the "worst" case of water loss from a pool. It does, however, capture the role of residual water in the pool. I refer to it here as the "Severe Reference" scenario of water loss. In the basic version of this scenario, water level would fall rapidly (i.e., within a few minutes) to about mid-height of the fuel. Variants of the scenario would explore the implications of different timing and magnitude for the initial fall of water level, and different outputs of decay heat.[15] After the initial fall of water level, water loss would be evaporative, driven by decay heat. There would be no water makeup. The exposed portion of the fuel would gradually increase in temperature. Eventually, a zircaloy-steam reaction could begin in this portion, commencing first in fuel assemblies with the highest decay heat. The availability of steam would initially limit the rate of this reaction. The fire could propagate across the pool. Over time, fuel and rack degradation, and evaporation of residual water, would alter the fire characteristics. Outcomes could include the initiation of a zircaloy-air reaction.

(III-7) A thorough and comprehensive investigation of pool-fire risk would begin by characterizing the Severe Reference scenario, its variants, and a range of other water-loss scenarios, in terms of phenomena related to zircaloy ignition, fire dynamics, and radioactive release. Then, and only then, would the investigators be ready to move to the next analytic step. That step would be to identify and characterize a full range of event sequences that involve water loss and could lead to a pool fire. The need to work in this manner – completing phenomenological analysis before proceeding to event analysis – has been clear to any technically-competent pool-fire analyst since 1979. I address this matter further in Section IV, below.

(III-8) A credible analysis of event sequences would certainly consider earthquake as a potential initiating event. However, other pool-fire initiating events, including accidents and attacks, would receive at least equal attention. Notably, a credible analysis would thoroughly examine potential situations in which a reactor adjacent to a spent-fuel pool experiences core melt and a substantial release of radioactive material. The onsite impacts of that release and associated phenomena (e.g., hydrogen explosion) could preclude actions, such as water makeup, that could prevent a pool fire.

(III-9) The physical proximity of spent-fuel pools to operating reactors, and their sharing of safety systems, means that the use of high-density racks creates strong linkages between reactor risk and pool risk. A reactor core melt – a comparatively fast-developing event – could enable a pool fire – a slower-developing event. This coupling could be manifested through an accident or an attack. The potential for pool-reactor linkages has, since 1979, been clear to any technically-competent person who was paying attention to the pool-fire issue. The Severe Reference scenario for water loss, as articulated in paragraph III-6, above, is particularly pertinent to these linkages.

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[15] Some variants would include a zero magnitude for the initial fall of water level (i.e., water would be lost only by evaporation).

(III-10) NRC has publicly postulated an attack on a spent-fuel pool, in its August 1979 GEIS on Handling and Storage of Spent LWR Fuel.[16] Table III-1 summarizes the nature of the postulated attack. NRC did not examine the potential for this attack to cause a pool fire. However, the adversary capabilities and other assumptions reflected in Table III-1 would be consistent with an attack that causes a linked core melt and pool fire as outlined in paragraph III-9, above. NRC is currently reluctant to discuss the threat of attack on a pool and/or reactor, but has not repudiated its discussion of attack in the August 1979 GEIS.

(III-11) After receiving the 1979 Sandia report described in paragraph III-3, NRC conducted and sponsored a number of studies related to pool-fire risk, which were published over a period of two decades. Unfortunately, those studies employed the erroneous assumption that complete drainage is the most severe case of water loss, until NRC indirectly corrected this error in October 2000. Thus, for two decades NRC personnel failed to acknowledge the effect of residual water on heat transfer, which is the third of six points I articulate in paragraph III-5, above. The studies also had other deficiencies. I provided a critical review of the various NRC studies in a February 2009 report.[17] In short, those studies did not provide a credible technical basis for assessing the risk of a pool fire.

(III-12) NRC's belated acknowledgment of the effect of residual water on heat transfer came indirectly. It came in the context of determining the maximum age of spent fuel at which the fuel could ignite if water were lost from a pool equipped with high-density racks.[18] If residual water were present, heat transfer from the exposed portion of the fuel would be comparatively feeble.[19] Thus, in the absence of sophisticated modeling of heat transfer, a prudent analyst would assume that the exposed portion of the fuel would be in an approximately adiabatic situation. It follows that comparatively old fuel – perhaps as old as 10 years – could ignite. This issue arose during a license-amendment proceeding in regard to the expansion of spent-fuel-pool capacity at the Harris nuclear power plant. I served as a technical adviser for Orange County, North Carolina, the intervenor in that proceeding. In filings during March and April 2000, the NRC staff repeatedly disparaged my statements that comparatively old fuel could ignite. A few months later, however, the staff adopted my position. NRC staff members stated that loss of water from pools containing fuel aged less than 5 years "would almost certainly result in an exothermic reaction", and also stated: "Precisely how old the fuel has to be to prevent a fire is still not resolved."[20] Moreover, the staff assumed that a fire would be inevitable if the water level fell to the top of the racks.

(III-13) In October 2000, NRC released a study, which was formally published in February 2001, that addressed the potential for a pool fire at a nuclear power plant

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[16] NRC, 1979.
[17] Thompson, 2009.
[18] Here, "age" refers to time since the fuel experienced fission.
[19] Colleagues and I have addressed this heat-transfer situation in various documents. See, for example: Alvarez et al, 2003.
[20] Parry et al, 2000, paragraph 29.

undergoing decommissioning.[21] The study – NUREG-1738 – was in some respects an improvement on previous NRC studies that addressed pool fires. It reversed NRC's longstanding, erroneous position that total drainage of a pool is the most severe case of water loss. However, it did not consider attack. Nor did it add significantly to the weak base of technical knowledge regarding the propagation of a fire from one fuel assembly to another. Its focus was on a plant undergoing decommissioning. Therefore, it did not address potential risk linkages between pools and operating reactors, as mentioned in paragraphs III-8 and III-9, above.

(III-14) The preceding two paragraphs show that, in October 2000, NRC suddenly reversed an erroneous technical position it had held for two decades. The context in which this reversal occurred is significant today. I return to this matter in paragraphs III-23 and III-24, below.

(III-15) After publishing NUREG-1738, NRC ceased publishing analysis on pool-fire risk, but claims to have done some secret studies. The US Government Accountability Office (GAO) confirms that NRC has, indeed, done some secret studies on pool fires. However, according to GAO, the NRC has lost track of those studies. An August 2012 GAO report stated:[22]

> "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."

(III-16) I identified a similar problem in a February 2009 report that I mention in paragraph III-11, above. In that report, I examined statements, in two official NRC documents published in 2008, regarding secret studies allegedly conducted or sponsored by NRC in order to improve technical understanding of pool fires. I concluded:[23]

> "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."

(III-17) Since 1979, NRC has consistently and unequivocally argued, in many contexts and with somewhat varying language, that high-density storage of spent fuel in pools protects public health and safety.[24] Yet, after the attacks of 11 September 2001 on New York and Washington, NRC placed its work on pool-fire risk behind a veil of secrecy.

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[21] Collins and Hubbard, 2001.
[22] GAO, 2012, Highlights.
[23] Thompson, 2009, Section 5.2, pp 24-25.
[24] For example, NRC's Draft Consequence Study says (Barto et al, 2013, page iv): "The NRC continues to believe, based on this study and previous studies that spent fuel pools protect public health and safety."

The lengths to which NRC would go to preserve this secrecy were evident from its confrontation with the National Academy of Sciences (NAS).

(III-18) In 2003, eight authors, of which I was one, published a paper on the radiological risk of pool fires and the options for reducing this risk.[25] That paper aroused vigorous comment, and its findings were disputed by NRC officials and others. Critical comment was also directed to a related report I had prepared.[26] In an effort to resolve this controversy, the US Congress requested NAS to conduct a study on the safety and security of spent-fuel storage. NAS submitted a classified report to Congress in July 2004, and released an unclassified version in April 2005.[27] Press reports described considerable tension between NAS and NRC regarding the inclusion of material in the unclassified NAS report.[28] NRC was the party demanding greater secrecy.

(III-19) NRC has never explained how its ongoing statement that high-density pools protect public health and safety could be reconciled with its vigorous efforts to hide pool-fire risk behind a veil of secrecy. An adequate explanation is hard to imagine. If the pools truly posed an insignificant risk, then spent fuel in the pools would not ignite in the event of water loss, regardless of how that water loss proceeded or what was its cause. In that case, there would be no need for secrecy.

(III-20) Assessing the radiological risk posed by a reactor or spent-fuel pool involves science that was at the cutting edge a comparatively long time ago – mostly in the first half of the 20th century or earlier. Nevertheless, a risk assessment must conform to scientific principles if it is to be credible. Those principles include transparency, accountability, openness, support for independent teams of investigators who can critique each other's work, peer review, and opportunities for open dialogue among investigators.

(III-21) In theory, NRC has processes available to it that would allow some of the principles of scientific discourse to be applied to radiological risk assessment. One such process is an evidentiary hearing. Although that process is more legalistic than a scientist would prefer, it does allow for the public cross-examination of expert witnesses under oath. That cross-examination can help to elucidate the scientific reality underlying a contentious issue.

(III-22) Since the 1980s, I have been a technical adviser to various entities – state and local governments, and citizen groups – that have sought to intervene before NRC regarding pool-fire risk. These entities have repeatedly requested the holding of an evidentiary hearing, in the full knowledge that their own expert witnesses would be subjected to rigorous, public cross-examination. NRC has consistently denied these requests, on legalistic grounds.

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[25] Alvarez et al, 2003.
[26] Thompson, 2003.
[27] The unclassified version was ultimately published as: National Research Council, 2006.
[28] Wald, 2005.

(III-23) Over this period of three decades, I have had one opportunity to present my findings on pool-fire risk at an NRC-sponsored event that approximated the characteristics of a scientific dialogue. That opportunity came when I asked NRC's Advisory Committee on Reactor Safeguards (ACRS) if I could present my findings to them. ACRS agreed, and I presented my findings at two public meetings of ACRS in the latter part of 2000. A remarkable feature of the first meeting was that NRC staff members who made presentations at the meeting suddenly reversed NRC's longstanding, erroneous position that total loss of water from a pool would be the most serious case of water loss. That reversal then made its way into the NRC staff position in the Harris license proceeding, and into NRC's report NUREG-1738, as discussed in paragraphs III-12 and III-13, above.

(III-24) This interaction before ACRS, unique in my experience with NRC, clearly demonstrated the efficacy of scientific discourse. NRC staff members, required for the first time in decades to justify their technical position in a public setting where they could be challenged, suddenly changed that position. Regrettably, however, NRC never repudiated the bad analysis it had done over the preceding two decades, based on its misunderstanding of the 1979 Sandia report. Also, from my observation, NRC has subsequently been careful to avoid placing itself in a similar public setting in which it could be challenged.

(III-25) As stated in paragraph III-5, above, it was clear in 1979 that the threat of a pool fire can be roughly characterized using simple, scoping analysis, but developing a thorough understanding would require sophisticated modeling backed up by experiment. When did NRC acquire the capability to perform such modeling and experiment? A reasonable case can be made that NRC had acquired an appropriate capability by the time of its work on reactor risk that led to publication of the NUREG-1150 study in 1990.[29] Regrettably, however, the NUREG-1150 work did not address pool fires.

(III-26) The history described in paragraphs III-1 through III-25 began in March 1979 and ended just prior to publication of NRC's Draft Consequence Study in June 2013. To summarize, at the end of that period NRC's technical credibility on the pool-fire issue was low. NRC had done demonstrably bad analysis that it never repudiated. NRC had claimed that high-density pool storage protects public health and safety while simultaneously demonstrating the falsity of that claim by hiding pool-fire risk behind a veil of secrecy since 2001. NRC had avoided scientific settings in which its technical position could be publicly challenged. When obliged by ACRS to appear in such a setting in 2000, NRC suddenly changed its position. NRC failed to conduct sophisticated modeling and supporting experiments that could have resolved technical issues central to pool-fire risk, despite having an appropriate capability prior to 1990.

[29] NRC, 1990.

IV. What Pool-Fire Analysis Should NRC Have Published Now?

(IV-1) As summarized in paragraph III-26, above, in May 2013 NRC's technical credibility on the pool-fire issue was low. If NRC had made a serious commitment to begin restoring its credibility, and to provide the public with useful information about pool-fire risk, what technical analysis would NRC have published in June 2013? This question assumes, of course, that NRC would have made its commitment well in advance of June 2013 and would have done the appropriate work before that date.

(IV-2) The answer to the question in paragraph IV-1 is that NRC should have focused its initial attention exclusively on establishing a solid technical understanding of phenomena directly related to a potential pool fire. To do this, NRC would have started with a clean slate and used the best available modeling capability backed up by experiment. This modeling and experimental work would have been done according to scientific principles that I discuss further in paragraph IV-3, below. Tasks in the investigation would have included:

1. <u>Identify a range of rack and pool configurations</u>: The key point here would be to compare a pool with high-density racks to a pool with open-frame, low-density racks. (See paragraph III-3, above.)
2. <u>Identify a range of rack loadings</u>: In the high-density cases, the range of rack loadings would include different phases of the reactor operating cycle, and different distributions of younger and older spent fuel across the pool. In the low-density, open-frame cases, the range of rack loadings would include removal of fuel from the pool if above a certain age, such as five years.
3. <u>Identify a range of water-loss scenarios</u>: Mechanisms for water loss could include various combinations of: leakage; evaporation; sloshing; displacement; siphoning; pumping; and tipping of the pool. To reflect the various combinations and their timeframes, the investigation would identify a range of water-loss scenarios. These scenarios would include, but would not be limited to, situations in which leakage occurred through a hole at the level of the pool floor. The scenarios would include the Severe Reference scenario, and its variants, as discussed in paragraph III-6, above.
4. <u>Identify collateral conditions that could affect fuel ignition or fire dynamics</u>: The potential for fuel ignition, in the event of water loss, could be affected by collateral conditions. Those conditions could also affect the development and propagation of a fire. Relevant conditions could include: the presence of extraneous objects in the pool (e.g., transfer cask, fuel-handling machinery, overhead crane, debris from the upper portion of the pool building); the ventilation status of the pool building; and deformation of racks.
5. <u>Determine combinations of conditions that would lead to fuel ignition</u>: Tasks 1 through 4, above, would identify ranges of rack/pool configurations, rack loadings, water-loss scenarios, and collateral conditions. The various combinations of conditions could be grouped where appropriate. Then, each

combination would be examined to determine if, and with what timing, it would lead to fuel ignition.

6. Predict fire behavior: For each instance where Task 5 determined that ignition would occur, the development and propagation of the resulting fire would be predicted. Relevant fire characteristics would include the production of hydrogen and its behavior in the pool building.
7. Estimate the atmospheric release: For each fire sequence examined in Task 6, the resulting release of radioactive material to the external atmosphere would be estimated in terms of isotopic magnitudes, timing, and other relevant characteristics.

(IV-3) If NRC were truly committed to restoring its credibility and providing useful information, it would have performed Tasks 1 through 6 according to generally accepted scientific principles. As discussed in paragraph III-20, above, those principles include transparency, accountability, openness, support for independent teams of investigators who can critique each other's work, peer review, and opportunities for open dialogue among investigators. To satisfy those principles, NRC would have funded independent investigators and made its models available to them for their own use. NRC would have financed independently-run workshops where NRC investigators and independent investigators could engage in open, scientific discourse. NRC would have provided full documentation of all supporting experiments.

(IV-4) Further to paragraph IV-3, NRC would have performed Tasks 1 through 6 with explicit treatment of uncertainties. Also, NRC would have done sensitivity analyses to test the implications of changing modeling assumptions or input conditions. At this stage of risk assessment, however, modeling of mitigating actions would have been premature.

(IV-5) Completing Tasks 1 through 6, consistent with paragraphs IV-3 and IV-4, would have involved the publication of a number of documents, including NRC analyses, independent analyses, peer reviews, and responses to those reviews. The issues addressed would be purely technical, pertaining to Tasks 1 through 6 as described above. When all issues had been resolved to a reasonable scientific standard, a summary document would be published. Then, and only then, would NRC have been ready to move to the next analytic step.

(IV-6) The next analytic step would have been to identify and characterize a full range of event sequences that could lead to the combinations of conditions that would, according to the analysis done in Tasks 1 through 6, be associated with a significant radioactive release. Hereafter, for simplicity, I refer to this step as "event analysis". If assessment of pool-fire risk is to be done properly, it is essential that event analysis be preceded by acquisition of a thorough understanding of pool-fire phenomena. Otherwise, analysts would lack essential knowledge about how particular combinations of conditions could affect fuel ignition and fire dynamics. In the absence of such knowledge, it is likely that analysts would ignore or misunderstand some event sequences that are significant to pool-fire risk.

(IV-7) The event sequences addressed in a properly-executed event analysis would include a range of potential accidents and attacks. Earthquake would certainly be considered as a possible initiating event, but other types of credible initiating event would receive at least equal attention. Careful attention would be given to potential risk linkages between reactors and pools, as discussed in paragraphs III-8 and III-9, above. In this context, the 2011 Fukushima accident was a wake-up call. Figure IV-1 illustrates two aspects of such linkages. First, the Unit 4 building at Fukushima was badly damaged by explosion of hydrogen that has been attributed to core damage in Unit 3. Second, a concrete-pumping truck was, at the time of this photograph, providing makeup water to the Unit 4 pool, reminding us of several days of futile attempts, earlier in the accident, to provide makeup water to Units 1 through 4 by other means.

(IV-8) Fortunately, the Fukushima accident did not proceed to a pool fire. However, any competent analyst who thinks about the Fukushima accident could readily identify a range of event sequences in which a core melt would be linked to a pool fire. Such an event sequence need not involve an earthquake or tsunami. The key point is that the event sequence would involve a timeframe such that a portion of the fuel in the pool would be above water, in a situation involving limited heat transfer, for a period long enough that the youngest fuel would heat up to its ignition temperature. The Severe Reference scenario for water loss, as articulated in paragraph III-6, above, addresses this point.

(IV-9) This declaration is intended for general distribution. Accordingly, it does not contain any information that would assist persons who could plausibly attack a US nuclear power plant. A large body of information of this type is already in the public domain. Moreover, many persons in the USA and worldwide have already acquired, through military experience or otherwise, the knowledge and practical skills that would be needed to mount a plausible attack. At any given time, some persons in that group may have motivation and resources sufficient to mount an attack with a substantial conditional probability of causing a reactor core melt and/or pool fire. The feasibility of such an attack is illustrated by the publicly-available information presented in Tables IV-1 through IV-3 and Figures IV-2 through IV-5. The probability of such an attack is cumulative across the population of nuclear power plants and the years of their operation.

V. NRC's Draft Consequence Study: Structure, Apparent Scope, and Messages

(V-1) Section IV, above, explains why any NRC study on pool-fire risk that is published now (i.e., mid-2013) should have focused exclusively on establishing a solid technical understanding of phenomena directly related to a potential pool fire. Such a study, done appropriately, could potentially have established NRC as a credible source of information about pool-fire risk. NRC did not follow that path. Indeed, NRC took a radically different approach. It published a study that is misleading, incomplete in its examination of risk, and designed to support pre-determined conclusions.

(V-2) NRC's Draft Consequence Study is structured as though it were a comprehensive assessment of the risk of a pool fire. It begins by identifying a single threat – an earthquake – and proceeds through a series of steps that end with a "regulatory analysis" (Appendix D) to determine if the threat justifies expedited transfer of spent fuel to dry storage. The scope of the Study is actually much narrower than would be the case in a comprehensive assessment, as discussed in Section VI, below. The Study itself acknowledges this fact in its interior sections. However, the Study's initial sections – Foreword, Abstract, and Executive Summary – propagate a different story. As NRC personnel undoubtedly know, many readers of the Study will never penetrate beyond these initial sections. Such readers will receive strong messages that the risk of a pool fire is very low, that expedited transfer of spent fuel to dry storage is not necessary, and that further analysis would not alter these findings.

(V-3) One of the messages in the Study's initial sections is that, by considering a particular earthquake threat, the Study has addressed the major source of risk of a pool fire. In this context, the Study says:[30]

> "Previous studies have shown that earthquakes present the dominant risk for spent fuel pools, so this analysis considered a severe earthquake with ground motion stronger than the maximum earthquake reasonably expected to occur for the reference plant."

(V-4) To complement that message, the Study provides strong messages that the risk of a pool fire is very low, and expedited transfer of spent fuel is not necessary. In those contexts, the Study says:[31]

> "This study's results are consistent with earlier research studies' conclusions that spent fuel pools are robust structures that are likely to withstand severe earthquakes without leaking cooling water and potentially uncovering the spent fuel. The study shows the likelihood of a radiological release from the spent fuel after the analyzed severe earthquake at the reference plant to be about one time in 10 million years or lower. In addition, the regulatory analysis included with this study does not support accelerated spent fuel transfer to casks for the reference plant."

(V-5) Expedited transfer of spent fuel to dry storage would allow a pool to be re-equipped with low-density, open-frame racks. As discussed in paragraphs I-6 and III-3, above, the pool-fire issue became salient in the 1970s when the nuclear industry abandoned the use of low-density, open-frame racks and switched to high-density, closed-frame racks. Thus, if a concerned citizen learns that NRC is now studying the merit of a switch to low-density pool storage, that citizen could reasonably assume that NRC is considering the use of low-density, open-frame racks. Such a citizen, reading only the initial sections of NRCs Draft Consequence Study, would not encounter any information to contradict that assumption.[32] Moreover, the citizen would be told that a

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[30] Barto et al, 2013, Executive Summary, page vi.
[31] Barto et al, 2013, Executive Summary, page vi.
[32] The Study's Executive Summary refers to high-density and low-density scenarios for pool loading. (See: Barto et al, 2013, Executive Summary, page vi.) A person reading only the initial sections of the Study

switch to low-density storage would not reduce the potential for a pool fire. In this context, NRC says:[33]

> "The likelihood of a spent fuel pool release [due to a pool fire] was equally low for both high- and low-density fuel loading. This is because high- and low-density fuel loading contains the same amount of new, hotter spent fuel recently moved from the reactor to the spent fuel pool."

(V-6) The preceding NRC statement is highly misleading. As discussed in paragraph III-4, above, if low-density, open-frame racks were used, then water loss from a pool would lead to fuel ignition only in very rare circumstances. NRC does not dispute that fact. Instead, NRC uses the phrase "low density" to refer to a situation in which a substantial fraction of the cells in a high-density, closed-frame rack do not contain fuel. That situation cannot offer the dramatic reduction in pool-fire risk that would come from reverting to low-density, open-frame racks.

(V-7) This one example demonstrates that the initial sections – Foreword, Abstract, and Executive Summary – of NRC's Draft Consequence Study contain a highly misleading statement. Given that the Study is lengthy and complex, many readers will not penetrate beyond these initial sections, as NRC personnel undoubtedly know. Thus, it is reasonable to conclude that NRC made this misleading statement deliberately, in order to serve some purpose.

(V-8) In Section VI, below, I discuss this one example further. I also discuss other instances in which NRC's Draft Consequence Study is misleading, incomplete in its examination of risk, and/or designed to support pre-determined conclusions.

VI. NRC's Draft Consequence Study: Actual Scope, and Credibility

(VI-1) As discussed in Section V, above, NRC's Draft Consequence Study seeks to create the appearance of being a comprehensive assessment of the risk of a pool fire. That image is conveyed by the structure of the Study, by the way the Study is described in its Foreword, Abstract, and Executive Summary, and by unequivocal statements that high-density spent-fuel pools protect public health and safety.[34] In fact, the Study's scope is narrow. As a result, the Study cannot support the broad findings that it presents.

(VI-2) To its credit, the Study does acknowledge the limitations in its scope, to a reader who penetrates to the interior sections of the Study. For example, Section 2 of the Study articulates many of the questionable assumptions and analytic limitations that permeate

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would be unlikely to realize that the allegedly low-density scenario does not involve the use of open-frame racks.

[33] Barto et al, 2013, Executive Summary, page vii.

[34] For example, the Study's Executive Summary concludes with the statement: "The NRC continues to believe, based on this study and previous studies that spent fuel pools protect public health and safety." (See: Barto et al, 2013, Executive Summary, page xii.)

the Study. Overall, the Study has misleading parts and comparatively honest parts. This internal difference may be attributable to different authorship for different parts.

(VI-3) As discussed in paragraphs V-5 and V-6, above, the Study claims to compare the respective risks posed by high-density and low-density modes of fuel storage in a pool. In fact, the Study makes no such comparison. Instead, the Study adopts misleading terminology, using the phrase "low density" to refer to a reduced inventory of fuel in a high-density, closed-frame rack. NRC explains its failure to assess the risk implications of reverting to low-density, open-frame racks with the following statement:[35]

> "Re-racking the pool would represent a significant expense, along with additional worker dose, and was not felt to be the likely regulatory approach taken based on consultation with the Office of Nuclear Reactor Regulation. Much of the benefit of low-density racking is achieved by the implementation of a favorable fuel pattern (1x4). Additionally, to get the full benefit of low-density racking, BWR fuel would likely need to have the channel boxes removed."

(VI-4) This statement by NRC is revealing. It shows that, when NRC began the Study, some of its conclusions were pre-determined. In this instance, NRC rejected the option of reverting to low-density, open-frame racks on the basis of no analysis whatsoever. This rejection was done before the Study commenced, on the basis of a "feeling".

(VI-5) As discussed in Section III, above, between 1979 and 2000 NRC's work on pool-fire risk employed the erroneous assumption that complete drainage of a pool would be the most severe case of water loss. This error apparently arose from the failure of NRC personnel to fully understand a 1979 Sandia report that NRC had commissioned. NRC indirectly acknowledged this error in 2000.

(VI-6) Curiously, in light of this history, NRC's Draft Consequence Study focuses exclusively on complete drainage of a pool. The Study examines two cases. In the "moderate" leak case, drainage would be complete after about 6 hours, while in the "small" leak case, drainage would be complete after about 40 hours.[36] Such cases are more useful for pool-fire risk analysis than the assumption of instantaneous, total drainage, which NRC employed in some of its previous studies. However, these two cases do not cover a full range of water-loss scenarios. Notably, they do not cover the Severe Reference scenario and its variants, as discussed in paragraph III-6, above. That scenario, although not necessarily the "worst" case of water loss from a pool, does capture the role of residual water in the pool.

(VI-7) The implications of the presence of residual water for fuel ignition are illustrated by some simple calculations set forth in Section VII, below. These calculations assume a pool loading (see Figure VII-1) and operating cycle phase (OCP4) as used in NRC's Draft Consequence Study. The contrast with that study is that drainage of water would

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[35] Barto et al, 2013, Table 3, page 23.
[36] Barto et al, 2013, Figures 52 and 54.

not be complete. Instead, residual water would be present in the pool for an extended period. The calculations yield estimates of the time between fuel exposure and fuel ignition. Here, I refer to that time as "ignition delay time". Results are summarized in paragraph VII-13, below. Assuming an adiabatic situation for exposed fuel yields an ignition delay time of about 5 hours. Extrapolation of NRC's moderate-leakage and small-leakage cases yields ignition delay times of about 7 hours and 20 hours, respectively.

(VI-8) These time estimates provoke two immediate questions. First, how significant for risk is an ignition delay time in the range 5 to 20 hours? Second, how accurate are these time estimates? I address these questions in order, in the following two paragraphs.

(VI-9) During the Fukushima accident in 2011, the Japanese nuclear industry and government struggled unsuccessfully for several days to establish water makeup to spent-fuel pools. Eventually, they established water makeup using the concrete-pumping truck shown in Figure IV-1. Yet, the Fukushima experience was far from a worst case in terms of onsite phenomena, such as radioactive contamination from a reactor core melt accident, that could preclude mitigating actions. Thus, we have ample evidence that water makeup and other mitigating actions could be precluded for a period substantially exceeding 20 hours. Accordingly, if the ignition delay time is 20 hours, or even longer, it is entirely realistic to consider an event sequence involving: (i) an initial rapid exposure of fuel followed by the presence of residual water for an extended time; (ii) no water makeup; (iii) fuel ignition; and (iv) propagation of a pool fire.

(VI-10) As to the accuracy of these time estimates, neither the adiabatic assumption nor the extrapolation from NRC findings is adequate for the purpose of thoroughly investigating pool-fire risk. However, in the absence of better analysis, these estimates are reasonable for illustrative purposes. Appropriate analysis would require sophisticated modeling backed by experiment, done in a scientific manner. NRC has never done such analysis in a pool-fire context.

(VI-11) These illustrative calculations show that a pool fire could occur if water loss occurred during a particular operating cycle phase – OCP4. NRC's Draft Consequence Study finds (see Figures VII-2 and VII-3) that a pool fire would not occur in OCP4 with the same pool loading. That finding reflects NRC's decision to focus its analysis exclusively on water-loss scenarios involving total drainage of water from a pool. By adopting that focus, NRC has ignored a substantial part of the pool-fire risk.

(VI-12) Water could be lost from a pool as a result of an accident or an attack. NRC's Draft Consequence Study dismisses the possibility of an attack by stating:[37] "Note that sabotage events have been excluded from the scope of this study." No further explanation is offered. Thus, NRC arbitrarily excludes a category of events that contributes substantially to pool-fire risk. As discussed in paragraph IV-9, above, an attack causing a reactor core melt and/or pool fire is a credible threat. The probability of

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[37] Barto et al, 2013, page 8.

an attack with a substantial likelihood of success is at least equal to the probability of the earthquake that NRC does consider (i.e., 1 in 60,000 years).[38] Also, knowledgeable attackers could time and shape their attack in a manner that maximizes the potential for radioactive release.

(VI-13) As discussed in paragraphs IV-7 and IV-8, above, risk linkages among pools and reactors at a particular site could be major determinants of pool-fire risk at that site. NRC's Draft Consequence Study actually provides a useful introduction to these linkages – which they term "interplays" – under the rubric of "multi-unit considerations".[39] Having identified this risk-significant issue, the Study goes on to say:[40]

> "To the extent practicable, this study has attempted to qualitatively account for some of these effects. For example, when the reactor and SFP are hydraulically connected (during refueling), the decay heat and water volumes from both sources are considered. The study also explores these effects on mitigation (Section 8), and addresses some aspects of the uncertainty associated with this treatment (Section 9). However, explicitly modeling multiunit effects was not a focus of this study, because of the existing limitations with the available computational tools. An ongoing project described in SECY-11-0089 will attempt to more rigorously address these effects in the framework of a multiunit Level 3 PRA for Vogtle Electric Generating Plant Units 1 and 2."

(VI-14) In other words, NRC recognizes that pool-reactor linkages are significant to risk, says that a future effort will "attempt" to overcome the limitations of relevant analytic tools, but cannot resist the temptation to include a shoddy treatment of these linkages in NRC's Draft Consequence Study. That inclusion adds to the misleading nature of the Study.

(VI-15) Paragraph IV-2, above, discusses the need to consider "collateral conditions" in a thorough investigation of pool-fire phenomena. One such condition would be the presence of debris in a pool. NRC acknowledges the significance of this issue and then proceeds to ignore it, further adding to the misleading nature of the Study. NRC says:[41]

> "The occurrence of a hydrogen combustion event from a concurrent reactor accident has the potential to generate debris which could impair SFP natural circulation air or steam cooling (should the fuel in the SFP become uncovered) for conditions in which the fuel might otherwise be cooled by means of these passive cooling modes. However, this latter situation is inherently tied to the study's lack of a comprehensive treatment of multiunit aspects."

(VI-16) NRC's Draft Consequence Study focuses its attention exclusively on one pool-fire initiating event – an earthquake with a probability of 1 in 60,000 years. At the same

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[38] Barto et al, 2013, Figure ES-2, page x.
[39] Barto et al, 2013, Section 2.2, pp 28-29.
[40] Barto et al, 2013, page 29.
[41] Barto et al, 2013, Table 3, page 25.

time, as discussed above, NRC acknowledges the risk significance of pool-reactor linkages but proceeds to ignore them. Yet, the probability of a reactor core melt is at least equal to the probability of the earthquake that NRC does consider. Generation 2 commercial reactors have accrued about 15,000 reactor-years of operating experience worldwide, and have experienced five core melts.

(VI-17) The feasibility and effectiveness of mitigating actions – such as providing makeup water to a pool – are significant to pool-fire risk. The Study addresses this matter in its Section 8, under the rubric of "human reliability analysis". In the Study, human error probability is equated to mitigation failure probability. The Study acknowledges the limitations of its analysis in this area, saying:[42]

> "Consistent with the limited scope of the SFPS, a limited scope human reliability analysis (HRA) was performed, to develop initial insights into the likelihood of successful operator actions to prevent spent fuel damage for the specific seismic event and consequence scenarios studied. A full scope HRA would primarily be useful as part of a PRA analysis. A PRA would necessarily consider a much broader scope than the SFPS."

(VI-18) Despite this acknowledgment, the Study proceeds to make unequivocal statements about the feasibility of mitigation. For example, in addressing the potential for a boil-off scenario of water loss, the Study says that the probability of mitigation failure extending for 7 days is "negligible".[43] That statement is based on no analysis, and reflects a pre-determined conclusion. NRC ignores, for example, the possibility that radiation fields and other onsite impacts of a reactor core melt could preclude mitigation for an extended period.

(VI-19) NRC's Draft Consequence Study addresses an issue that is significant in terms of public health and safety. This significance is illustrated by one of the Study's findings. In modeling the offsite impacts of a potential pool fire, the Study considers a case in which modeling indicates that 4.1 million people would experience long-term displacement from their homes.[44]

VII. NRC's Use of the MELCOR Code

(VII-1) NRC has adapted the MELCOR code package, version 1.8.6, to examine the physical and chemical phenomena directly associated with a potential pool fire. Section 6 of NRC's Draft Consequence Study describes MELCOR and its use in this instance. Here, I discuss selected points regarding this application of MELCOR. This discussion does not purport to be a comprehensive review, but addresses some important points.

(VII-2) In Section IV, above, I outline a process whereby a code such as MELCOR could be used to address pool-fire issues in a manner consistent with the principles of

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[42] Barto et al, 2013, page 173.
[43] Barto et al, 2013, page 175.
[44] Barto et al, 2013, Table 33, page 162.

science. The process would include NRC funding of independent investigators who would have access to MELCOR, and NRC funding of independently-run workshops where NRC investigators and independent investigators could engage in open, scientific discourse. To my knowledge, NRC's application of MELCOR in the pool-fire context has not employed such a process.

(VII-3) MELCOR was developed to model a reactor core melt. Accordingly, its fuel-behavior module employs a two-dimensional cylindrical geometry. By contrast, a pool, in plan view, is a rectangle within which the racks form a combination of rectangles. In an effort to accommodate this difference, NRC has assumed that spent fuel in a pool would be arranged in "rings" whose boundaries roughly approximate concentric circles, with overlap between some of these boundaries. Figure VII-1 illustrates this assumption. Each ring would be composed of fuel with a particular age and burnup. Also, NRC has added a modeling capability to account for the presence of racks, which are not present in a reactor core.

(VII-4) If NRC's application of MELCOR had employed a scientific process as discussed above, then an independent reviewer could examine the associated documents and form a professional opinion on the validity of NRC's findings. To my knowledge, no such documents exist. Thus, at this time, I do not have a professional opinion on the quality of the MELCOR findings presented by NRC. It is, however, easy to identify issues and questions that should be addressed in a scientific process to examine NRC's findings. Consider, for example, two issues pertaining to the validity of MELCOR in the pool-fire context:

1. MELCOR has no capability to model the deformation of fuel cladding as temperature rises. Yet, NUREG-1738 predicted that cladding would balloon and burst in a temperature range of 700–850°C. That outcome could reduce heat transfer and promote ignition of cladding. NRC says that these effects would not be significant, but rests that claim on secret, unpublished studies.[45]
2. Radiative heat transfer is an important consideration in pool-fire modeling. Yet, MELCOR employs a simplified approach to modeling this mode of heat transfer. In this context, NRC says:[46] "It should be noted that there is a temperature gradient within each ring, and MELCOR attempts to model a multidimensional geometry with a simplified two-surface radiation model."

(VII-5) In addition to questions about the validity of MELCOR, there are questions about NRC's input assumptions. For example, how closely does the pool layout shown in Figure VII-1 correspond with actual practice in the nuclear industry? In that context, there is a puzzling NRC assumption associated with Figure VII-1. That figure shows a total of 284 newly-discharged fuel assemblies. Of these, 88 assemblies are assumed by NRC to produce decay heat at the rate of 10.9 kW per assembly when aged 20 days,

[45] Barto et al, 2013, Table 3, page 26.
[46] Barto et al, 2013, footnote 23, page 110.

while the remaining 196 assemblies produce 6.6 kW per assembly at the same age.[47] If this is typical practice, then licensees are forgoing substantial available burnup of the majority of their fuel assemblies, with a resulting economic penalty.[48] As a related matter, Figure VII-1 shows a rather elaborate layout of fuel, whose achievement would involve substantial shuffling of assemblies. NRC says that this layout is comparatively favorable in terms of the risk of a pool fire. Yet, licensees are allowed a period of time, during and perhaps after a refueling outage, to perform the shuffling needed to achieve a favorable layout. The length of that period of time is a secret because, NRC says, this information could be useful to an adversary.[49] Thus, is it appropriate to assume, as a MELCOR input, that a comparatively favorable layout has been achieved before water is lost?

(VII-6) In the Study, NRC has focused its analysis exclusively on water-loss scenarios involving total drainage of water from a pool. By adopting that focus, NRC has ignored a substantial part of the pool-fire risk. Here, I provide some simple calculations that illustrate the implications of NRC's narrow focus. These calculations show how the presence of residual water could affect fuel ignition. One calculation employs the simplifying assumption that, if residual water is present, the exposed portion of a fuel assembly in a high-density rack is in an adiabatic situation. Using that assumption, anyone with technical training can use pencil and paper to calculate the time required for the temperature of the fuel cladding to rise to its ignition point. The other calculations determine that time by extrapolating from NRC's findings using MELCOR. As indicated above, I do not necessarily accept that MELCOR is valid for its application by NRC to the pool-fire problem, or that NRC's input assumptions are appropriate.

(VII-7) These illustrative calculations consider loss of water from the pool considered in NRC's Draft Consequence Study. This event would occur during operating cycle phase 4 (OCP4). According to NRC, OCP4 and higher-risk phases account for 34 percent of the duration of the total operating cycle.[50] Attention is focused here on Ring 1 fuel, as shown in Figure VII-1. The pool would be loaded at high density.

(VII-8) The assumed scenario for water loss is the Severe Reference scenario as articulated in paragraph III-6, above. Initially, water level would fall rapidly to a point between the top and bottom of the racks. Thereafter, residual water would be lost comparatively slowly by evaporation.[51] The presence of residual water would block air

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[47] These decay heat outputs are calculated from data in Table 25 of: Barto et al, 2013. The same data apply to Figure VII-1 in this declaration.
[48] Other factors being equal, decay heat output increases with burnup.
[49] Barto et al, 2013, Section 9.3, page 208.
[50] Barto et al, 2013, Table 16, page 78.
[51] The rate of loss of residual water by evaporation can be estimated as follows. The floor of the pool is 12.2 m by 10.8 m (Barto et al, 2013, page 103) and the total decay heat output in OCP4 is 1,868 kW (Barto et al, 2013, Table 25). Let the submerged fraction of the active length of the fuel be F_s and assume uniform output of decay heat along the active length. Assume 60% water content by volume in the lower portion of the pool. Set water density at 960 kg/m^3 and latent heat of evaporation at 2,260 kJ/kg. Then, the rate of fall of the water surface due to evaporation = F_s(1,868)/((2,260)(960)(0.6)(12.2x10.8)) = F_s(1.09E-05) m/s = 0.04F_s m/hr. For comparison, active length of the fuel is about 4 m.

flow beneath the racks. The exposed portion of the fuel would gradually increase in temperature.

(VII-9) For the first illustrative calculation, assume that the exposed portion of the fuel is in an adiabatic situation. As shown in Table VII-1, it is easy, with this assumption, to calculate the rate at which fuel temperature would rise. According to NRC, Ring 1 fuel in OCP4 has a decay heat output of 26.6 kW per Mg U.[52] From Table VII-1, one sees that fuel temperature would rise at the rate of 170 K per hour.[53]

(VII-10) Now, consider MELCOR outputs for NRC's examination of a moderate-leakage case in OCP4, as shown in Figure VII-2. During the evolution of this case, there would be a period of time when the upper portion of the fuel is exposed and residual water is present. That period would extend from about t = 3 hours to about t = 6 hours. During that 3-hour period, at the "Lev 5" elevation of the fuel, cladding temperature would rise from about 300 K to about 700 K. Thus, the average rate of temperature rise would be about 130 K per hour. This finding indicates that the exposed portion of the fuel at the Lev 5 elevation would be in an approximately adiabatic situation, at least for temperatures up to 700 K.

(VII-11) Now, apply the same process, as in the preceding paragraph, to NRC's examination of a small-leakage case as shown in Figure VII-3. In that case, the period of time when fuel at the Lev 5 elevation is exposed and residual water is present would extend from about t = 28 hours to about t = 40 hours. During that 12-hour period, the temperature of fuel cladding at the Lev 5 elevation would rise from about 350 K to about 900 K. Thus, the average rate of temperature rise would be about 46 K per hour.

(VII-12) The slower average temperature rise in NRC's small-leakage case, compared to the moderate-leakage case, appears to be attributable to a MELCOR finding that heat transfer from exposed fuel would be more effective at temperatures between 700 K and 900 K than it would be at temperatures below 700 K.[54] Radiative heat transfer would be a substantial contributor to that effect.

(VII-13) NRC assumes that zircaloy ignition would occur at a temperature of about 1,200 K. If the initial fall of water level is rapid, then exposed fuel would have an initial temperature of about 300 K. Thus, ignition would require a temperature rise of about 900 K. Accordingly, the three illustrative calculations, as described above, yield a time to ignition, after exposure of fuel, as follows:

1. <u>Adiabatic assumption</u>: Adiabatic heatup would lead to a temperature rise of 170 K per hour. Thus, time to ignition = 900/170 = 5.3 hours

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[52] NRC says (Barto et al, 2013, Table 25) that 88 Ring 1 fuel assemblies have a combined decay heat output of 422 kW in OCP4. If the mass of one assembly is assumed to be 0.18 Mg U, then decay heat output = (422/88)/(0.18) = 26.6 kW per Mg U.

[53] In Table VII-1, set R = 26.6 kW per Mg U. Then, rate of temperature rise = (26.6)(6.38) = 170 K/hr.

[54] Note the respective shapes of the Lev 5 curves in the temperature-time charts in Figures VII-2 and VII-3.

2. Extrapolation of NRC's moderate-leakage case: If temperature rise continued at 130 K per hour, time to ignition = 900/130 = 6.9 hours
3. Extrapolation of NRC's small-leakage case: If temperature rise continued at 46 K per hour, time to ignition = 900/46 = 19.6 hours

(VII-14) Extrapolation of NRC's findings is reasonable for illustrative purposes, in the absence of better analysis. However, neither the adiabatic assumption nor the extrapolation used here is adequate for the purpose of thoroughly investigating pool-fire risk. As discussed in Section IV, above, a thorough, comprehensive investigation would begin by establishing a solid technical understanding of phenomena directly related to a potential pool fire, including heat transfer, zircaloy ignition, and fire dynamics. The necessary modeling and experimental work would be done according to scientific principles. That work could yield, for example, scientifically-defensible estimates of ignition delay time in a Severe Reference scenario for water loss. It is far from clear that MELCOR can yield good estimates of this time, given MELCOR's simplified treatment of radiative heat transfer.

(VII-15) If ignition of fuel occurred in a Severe Reference scenario for water loss, the fire would begin as a steam-zircaloy reaction. Progress of the fire would be limited by the amount of steam that would be generated from residual water and rise through each fuel assembly. Note, however, that the flow of steam reaching the exposed portion of a particular assembly would be determined primarily by the decay heat output of that assembly. Thus, for a pool layout as shown in Figure VII-1, Ring 1 fuel would not only be the first fuel in the pool to experience steam-zircaloy ignition, but would also experience the highest flow of steam that could feed a steam-zircaloy fire.

VIII. Conclusions and Recommendations

Conclusions

(VIII-1) Prior to publication of the Draft Consequence Study, NRC's technical credibility on the pool-fire issue was low. Over a period exceeding three decades, NRC had published bad analysis and hidden other analysis behind a veil of secrecy. Moreover, NRC failed to conduct sophisticated modeling and supporting experiments that could have resolved technical issues central to pool-fire risk, despite having an appropriate capability prior to 1990.

(VIII-2) NRC's Draft Consequence Study seeks to create the appearance of being a comprehensive assessment of the risk of a pool fire. That image is conveyed by the structure of the Study, by the way the Study is described in its Foreword, Abstract, and Executive Summary, and by unequivocal statements that high-density spent-fuel pools protect public health and safety. In fact, the Study's scope is narrow. As a result, the Study's examination of pool-fire risk is incomplete, and cannot support the broad, unequivocal findings that the Study presents. This disjunction between the apparent and actual scope of the Study is misleading. Moreover, in specific instances, the Study is misleading and is designed to support pre-determined conclusions. Examples of specific deficiencies in the Study are provided in the following paragraph.

(VIII-3) Some specific instances in which NRC's Draft Consequence Study is incomplete, misleading, and/or designed to support pre-determined conclusions are as follows:

1. Pretence of considering low-density storage: The Study does not consider the risk implications of reverting to low-density, open-frame racks. Instead, NRC misuses the phrase "low density" in order to create a false impression of the Study's scope. This pretence reflects pre-determined conclusions based on a "feeling".
2. Limited consideration of water-loss scenarios: The Study focuses its analysis exclusively on water-loss scenarios involving total drainage. By so doing, the Study ignores a substantial part of the pool-fire risk. For example, the Study makes no effort to determine how the presence of residual water could affect fuel ignition. Extrapolation of Study findings indicates that consideration of this issue would substantially increase the estimated risk.
3. Limited consideration of initiating events: The Study considers only one type of initiating event – an earthquake. That narrow focus reflects a pre-determined conclusion that earthquake is the dominant contributor to the risk of a pool fire.
4. No consideration of attack: The Study ignores the potential for an attack on a pool and/or adjacent reactor to initiate a pool fire. Yet, the probability of an attack with a substantial likelihood of success is at least equal to the probability of the severe earthquake that the Study does consider. Thus, the Study significantly under-estimates pool-fire risk.
5. No analysis of risk linkages among pools and reactors: The Study identifies the potential for risk linkages, but does not properly analyze them. For example, the Study does not analyze a situation in which onsite radioactive contamination and other impacts of a reactor core melt would preclude mitigating actions that might prevent a pool fire. Yet, the probability of a core melt at an adjacent reactor is at least equal to the probability of the severe earthquake that the Study does consider. Thus, the Study significantly under-estimates pool-fire risk.
6. Misleading statements regarding mitigating actions: The Study concedes that its analysis of the feasibility of mitigating actions is very limited. Yet, the Study makes unequivocal statements about this feasibility. Some of those statements are misleading, and reflect pre-determined conclusions.

(VIII-4) In the Study, NRC employs the MELCOR code to model phenomena related to a pool fire – including heat transfer, cladding ignition, and fire dynamics. MELCOR findings are significant to NRC's estimation of pool-fire risk. Yet, the validity of MELCOR in this context, and the appropriateness of NRC's input assumptions, have not been tested through a process of open scientific inquiry. There are significant issues that should be addressed through such a process, including MELCOR's simplified treatment of radiative heat transfer.

(VIII-5) In the Study, NRC has erected an elaborate superstructure of analysis on a weak foundation of basic knowledge about pool-fire phenomena. This superstructure culminates in a regulatory analysis. As discussed in paragraph VIII-2, above, the findings emanating from this superstructure lack scientific credibility and are misleading. Thus, the design of the Study is fundamentally and irredeemably flawed.

(VIII-6) The Study addresses an issue that is significant in terms of public health and safety. This significance is illustrated by the Study's finding that a pool fire could lead to long-term displacement from their homes of more than 4 million people. Thus, citizens deserve a much better analysis of pool-fire risk than the incomplete, misleading work presented in NRC's Draft Consequence Study.

Recommendations

(VIII-7) NRC's Draft Consequence Study should be scrapped.

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

****

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 1 August 2013.

G.R. Thompson

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Gordon R. Thompson

APPENDIX A: Tables and Figures

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Table III-1
Potential Sabotage Events at a Spent-Fuel Pool, as Postulated in 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 IV-1
Some Potential Modes and Instruments of Attack on a Nuclear Power Plant

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

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

Table IV-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 IV-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

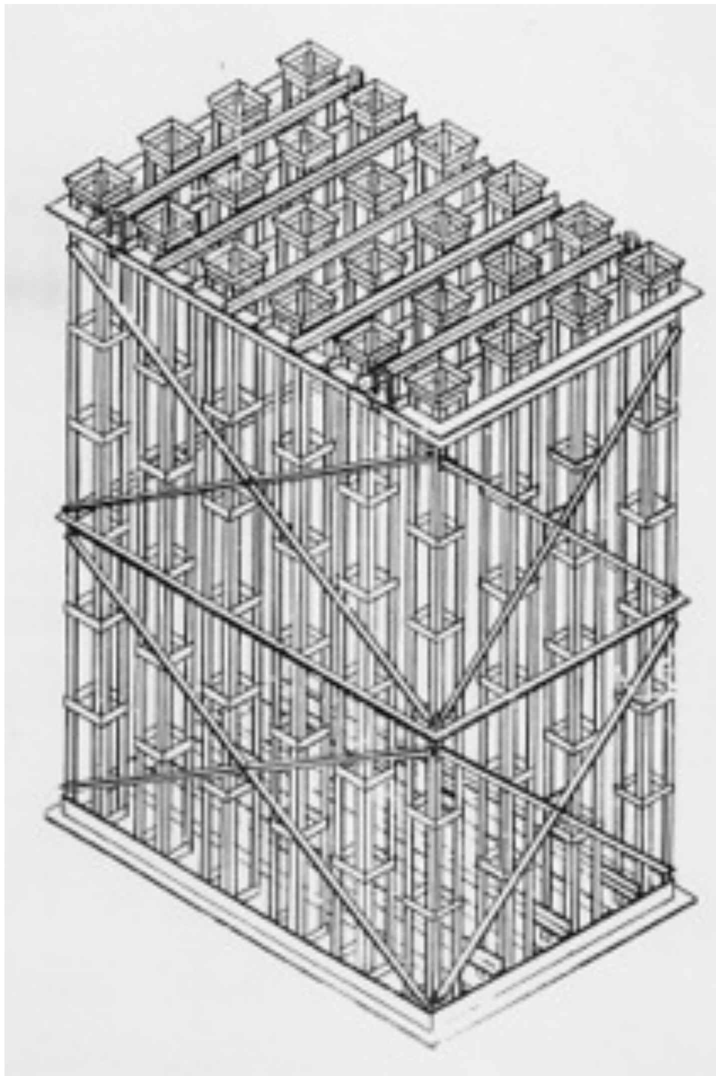
Notes:
(a) Data are from US Army Field Manual FM 5-25: Army, 1967, pp 13-15 and page 100.
(b) The M2A3 charge has a mass of 5 kg, a maximum diameter of 18 cm, and a total length of 38 cm including the standoff ring.
(c) The M3 charge has a mass of 14 kg, a maximum diameter of 23 cm, a charge length of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

Table VII-1
Adiabatic Heatup of a Spent BWR Fuel Assembly

Indicator	Value	
	Zircaloy	**UO_2 Pellets**
Mass per Mg U of fuel	564 kg (includes cladding, channel box, and grid spacers)	1,130 kg
Specific heat (av., approx.)	400 J/kg/K	300 J/kg/K
Radioactive decay heat	R kW per Mg U (or W per kg U) of fuel	
Rate of temperature (T) rise from decay heat, if pellets and zircaloy are a tightly coupled adiabatic system	T' = R/(400x0.564 + 300x1.13) K/s = R(1.77E-03) K/s (or R(6.38) K/hr)	

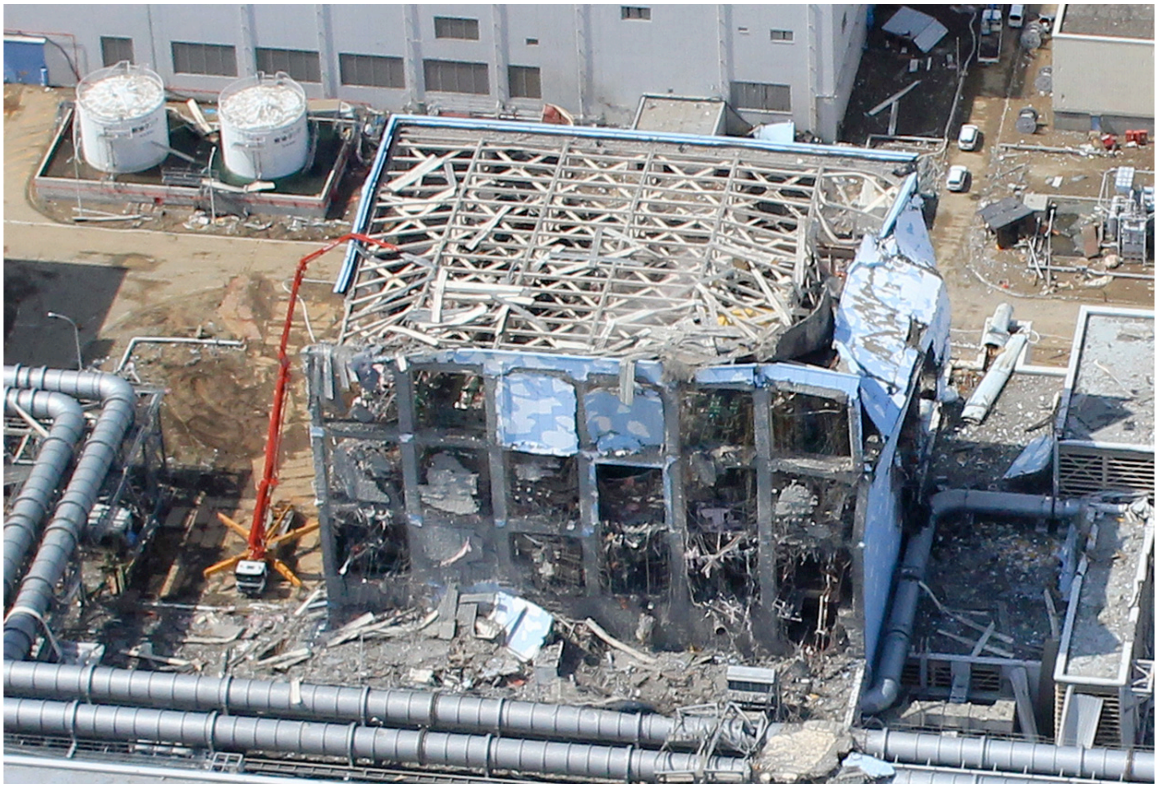
Notes:
(a) Zircaloy mass is from Table 3.2 of: Roddy et al, 1986.
(b) The specific heats shown are averages over the temperature range 100-1,000 °C. For zircaloy, specific heat spikes sharply between about 800 °C and 1,000 °C. (See: IAEA, 1997, Figure 4.2.1.1.) For UO_2, specific heat does not spike until temperature approaches 3,000 K. (See: Popov et al, 2000, Figure 4.2.)
(c) This calculation applies to any portion of the active length of a fuel assembly, provided that decay heat output is uniform along the active length.
(d) The influence of materials other than zircaloy and UO_2 (e.g., fission products) is neglected here. That influence could be examined in a more precise calculation.
(e) No credit is taken here for heat output from exothermic reactions.

Figure III-1
Typical Low-Density, Open-Frame Rack for Pool Storage of PWR Spent Fuel



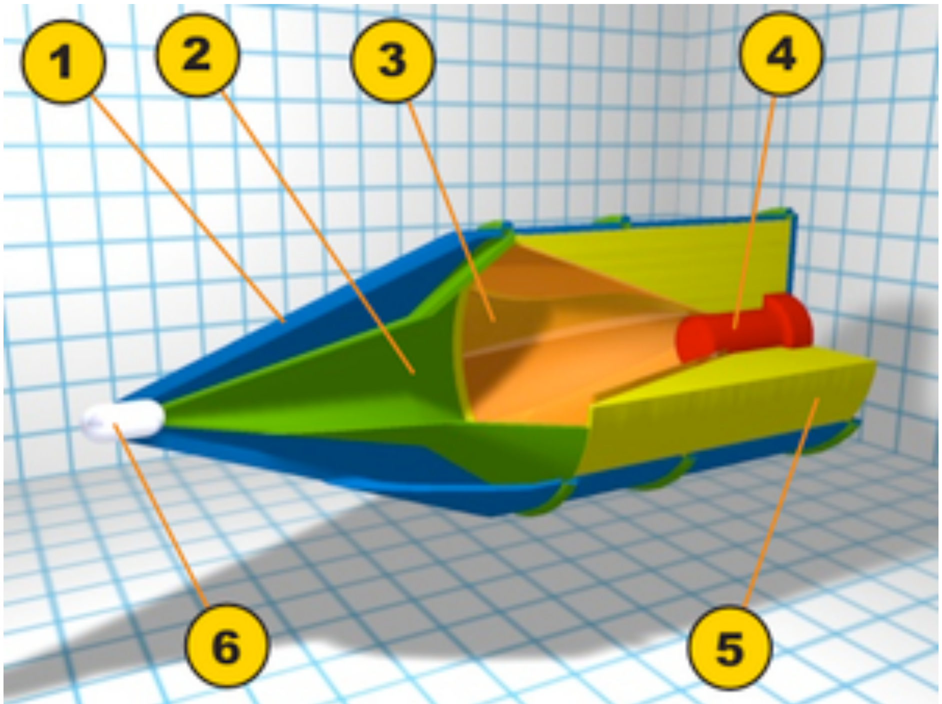
Source:
Adapted from Figure B.2 of: NRC, 1979.

Figure IV-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 IV-2
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 IV-3
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 IV-4
January 2008 Test of a Raytheon Shaped Charge, Intended as the Penetration (Precursor) Stage of a Tandem Warhead System

Before Test

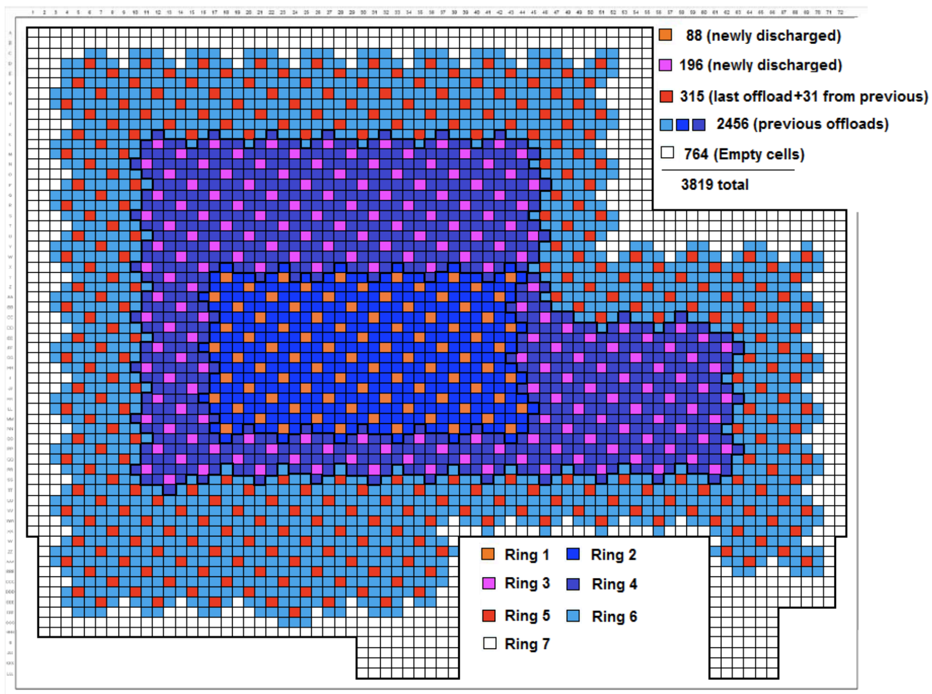
After Test (viewed from the attacked face)

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 IV-5
Aftermath of a Small-Aircraft Suicide Attack on an Office Building in Austin, Texas, February 2010

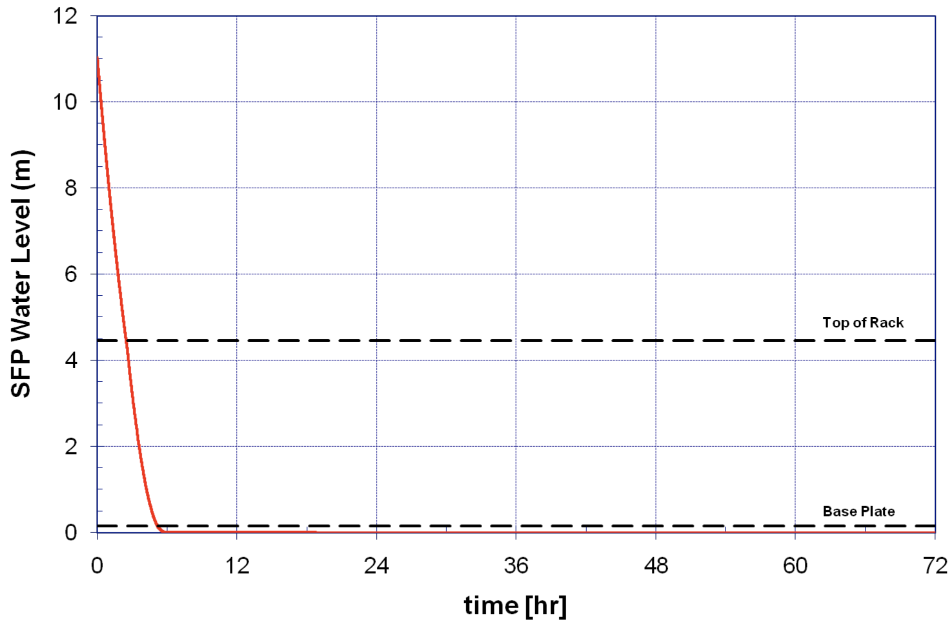
Notes:
(a) Photograph and information in these notes are from: Brick, 2010.
(b) A major tenant of the building was the Internal Revenue Service (IRS).
(c) The aircraft was a single-engine, fixed-wing Piper flown by its owner, Andrew Joseph Stack III, an Austin resident who worked as a computer engineer.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

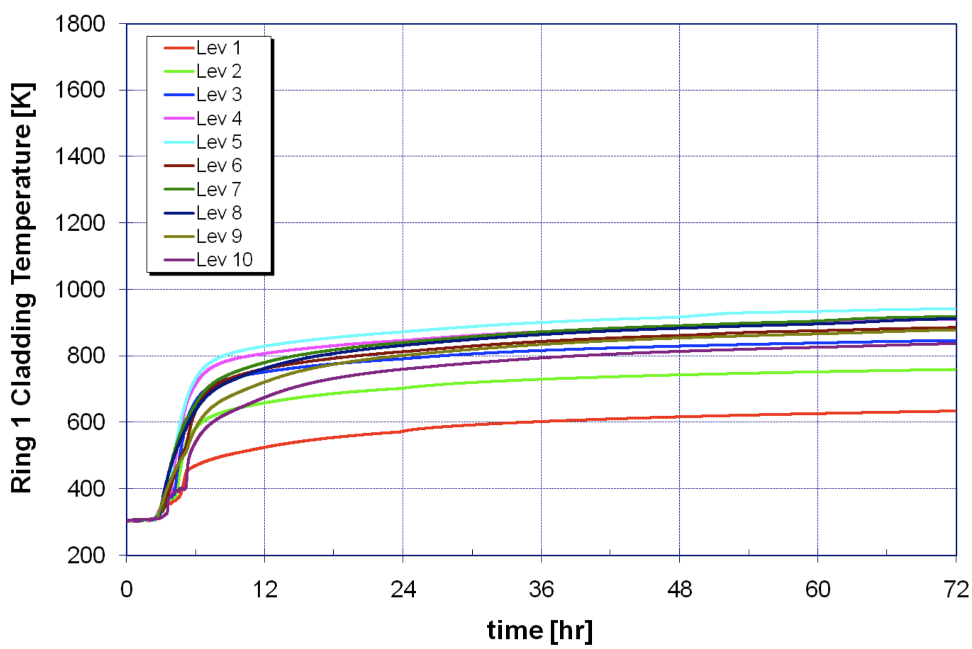
Figure VII-1
One of the Pool Layouts Modeled in NRC's Draft Consequence Study: The OCP2, High-Density, 1x4 Case



Notes:
(a) This figure is a copy of Figure 46 from: Barto et al, 2013.
(b) OCP2 (operating cycle phase 2) is described in Table 25 of: Barto et al, 2013.

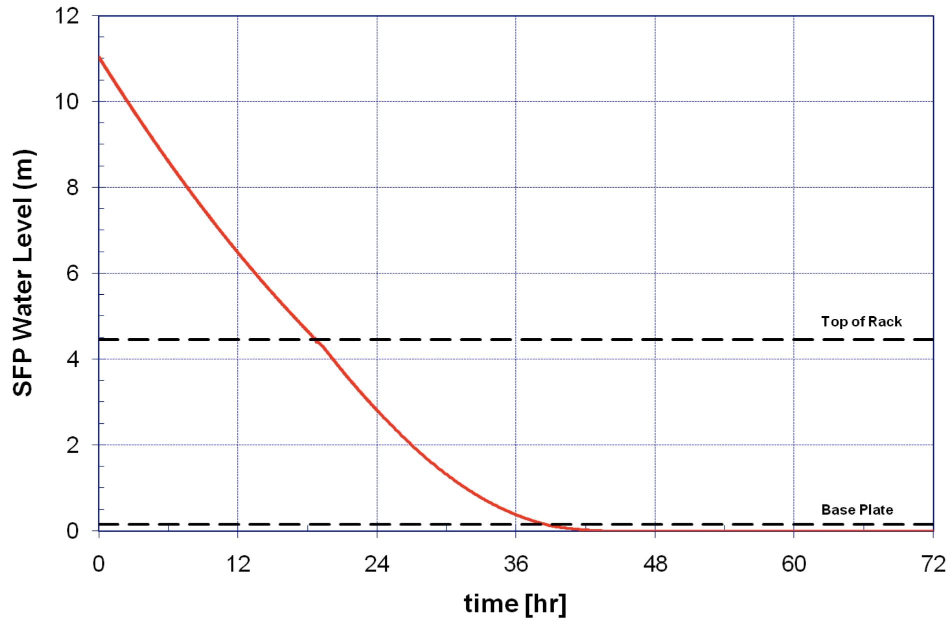
Figure VII-2
Findings from NRC's Draft Consequence Study: Water Level and Ring 1 Cladding Temperature for Unmitigated High-Density Moderate Leak (OCP4)

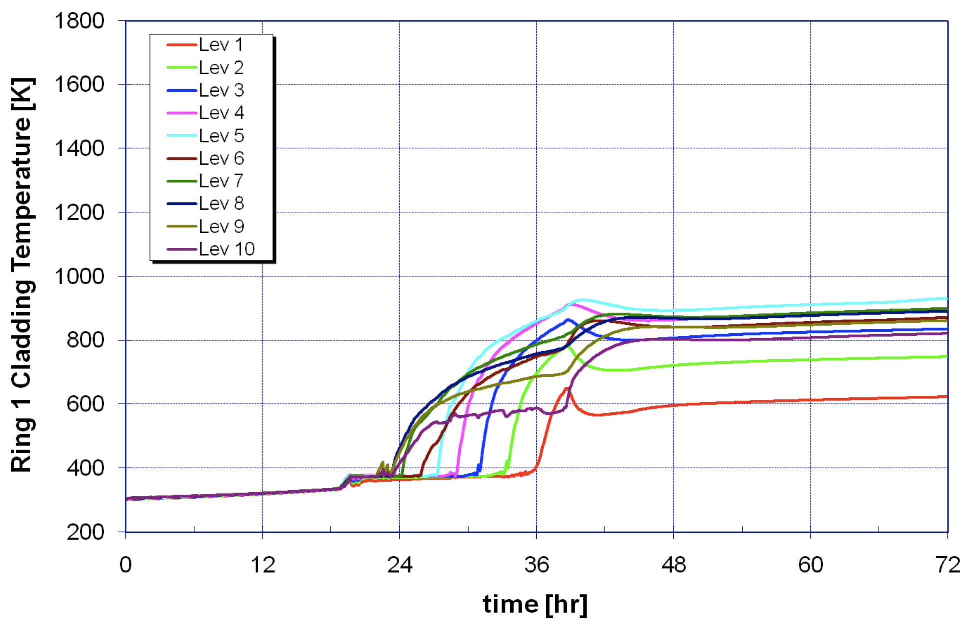




Notes:
a) These figures are copies of Figures 52 and 53 from: Barto et al, 2013.
(b) OCP4 (operating cycle phase 4) is described in Table 25 of: Barto et al, 2013.
(c) Vertical nodalization (Lev 1, etc.) is shown in Figure 41 of: Barto et al, 2013.
(d) Distribution of fuel (Ring 1, etc.) is shown in Figure 46 of: Barto et al, 2013.

Figure VII-3
Findings from NRC's Draft Consequence Study: Water Level and Ring 1 Cladding Temperature for Unmitigated High-Density Small Leak (OCP4)





Notes:
(a) These figures are copies of Figures 54 and 55 from: Barto et al, 2013.
(b) OCP4 (operating cycle phase 4) is described in Table 25 of: Barto et al, 2013.
(c) Vertical nodalization (Lev 1, etc.) is shown in Figure 41 of: Barto et al, 2013.
(d) Distribution of fuel (Ring 1, etc.) is shown in Figure 46 of: Barto et al, 2013.

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