SECURITY AND PROLIFERATION RISKS ASSOCIATED WITH MANAGEMENT OF SPENT NUCLEAR FUEL

Alex Bednarek, Andrew Newman

Nuclear Threat Initiative: 1776 I St NW, Suite 600, Washington, DC, 20006, bednarek@nti.org

Globally, commercial nuclear reactors generate roughly 10,000 metric tons of spent nuclear fuel each year; more than 250,000 tons of spent fuel is currently held in storage worldwide. After removal from a reactor, spent fuel must be cooled in pools for extended periods of time before it can be moved to dry cask storage, reprocessed, etc. In most countries, it will be decades before repositories are available to accept waste in sufficient quantities to begin to significantly reduce the inventory. The lack of functional disposal pathways strains the credibility of the nuclear community and undercuts public and political acceptance for all nuclear activities. While the technical challenges, financial burdens, and political complexities of spent fuel management are well understood, important security and nonproliferation dimensions are often ignored or minimized.

Spent fuel contains plutonium – approximately 1% by weight – that can be separated out through reprocessing. This sensitive technology can be used to make reactor fuel or nuclear explosives. Because fissile material production is the biggest hurdle in a nuclear weapons program, the separation and stockpiling of plutonium poses real security and proliferation risks. In addition, the longer spent fuel is stored, the more the shorter-lived 'self-protecting' isotopes decay and the less radioactive it becomes, the greater security risk it presents. In light of some terrorists' demonstrated willingness to disregard their self-preservation in the pursuit of their objectives, the adequacy of the current self-protection standard has been called into question.

This paper will describe the security and proliferation risks associated with management of spent fuel and offer recommendations to address those risks.

I. INTRODUCTION

This paper reviews the security and proliferation risks posed by spent nuclear fuel and outlines the contentious debate surrounding the assumptions about, and consequences of, spent fuel pool fires. It concludes with a set of recommendations to help mitigate these risks. The authors' main focus is on the United States, but the issues are broadly applicable to all countries operating nuclear reactors.

II. SECURITY/PROLIFERATION

While the financial burdens and political complexities of spent fuel management are well understood, if not always acted upon expeditiously, the important security/proliferation dimension often is ignored or minimized.[1] In a once-through fuel cycle, spent fuel needs to be securely stored for extended periods of time until it has cooled sufficiently for disposal. Because the allowable thermal and radiation limits for transportation often are substantially lower than the limits for storage, increasingly high burn-up fuel and large dry storage canisters require an extended period of aging before the canisters have cooled down enough to be moved.[2] In most countries, it will be decades before repositories are open and able to accept waste in sufficient quantities to begin to significantly draw down the inventory. The longer spent fuel is stored, the less self-protecting it becomes as the highly radiotoxic shorter-lived isotopes that provide the protection continue to decay. Therefore, the security risk increases over time.

In addition, spent fuel contains plutonium – approximately 1% by weight – that can be separated out through reprocessing and used to make mixed oxide (MOX) fuel or build nuclear weapons. This separated plutonium could also be acquired by non-state actors for use in nuclear explosive devices. For a variety of reasons, including the lack of near-term disposal options, some countries chose to recycle this plutonium into MOX fuel. However, to provide any of the economic and waste management benefits, the fuel would need to be continuously recycled and most countries today are recycling only once because of the buildup of undesirable isotopes in the plutonium. Even a mature and efficient recycling

program generates significant waste streams – high level waste with greater heat output (over a shorter period of time) than spent LEU fuel as well as intermediate and low-level waste – that require permanent disposal.[3]

II.A. Spent Fuel Radiation Barrier

The concept of a self-protecting radiation barrier is that sufficiently high external radiation will serve as an effective deterrent to the unauthorized removal/use of spent fuel. But, like all radioactive materials, as spent fuel ages the radiation field diminishes and eventually it is no longer self-protecting. A 2005 Oak Ridge National Laboratory (ORNL) report defined self-protection as "the incapacitation [an inability to function effectively] inflicted upon a recipient from inherent radiation emissions in a time frame that prevents the recipient from completing an intended task."[4] The United States Department of Energy self-protection guidance for radioactive material is 1 gray/hour (100 rem/hour) at one meter unshielded. This is the same threshold the US Nuclear Regulatory Commission (NRC) and the IAEA currently use.[5] However, the adequacy of the threshold has been called into question in light of some terrorists' demonstrated willingness to disregard their self-preservation in the pursuit of their objectives. The 2005 ORNL report also noted that while the current self-protection dose guidance is considered lethal for 50% of recipients, immediate health effects are minimal (onset sometime between 30 minutes and 16 hours) allowing substantial time for exposed persons to function and complete a task. The authors determined that a dose rate of 100 grays/hour at one meter was "the level that significantly affected performance and offered limited self-protection."[6] In 2015, the NRC advised that "the continued use of the existing external radiation dose-rate threshold as a security feature might not be prudent or realistic since, in some cases, the adversary may fulfill their goal prior to succumbing to the effects of radiation that may include death." As a result, the Commission initiated rulemaking to revise the threshold.[7]

The situation for research reactor fuel is very different from power reactors.[8] Because fuel elements are less irradiated, many types of research reactor fuel elements are no longer 'self-protecting' after 5-10 years. In addition, research reactor fuel elements are small relative to power reactor fuel rods/assemblies which makes them easier to manhandle. And because the elements are still quite enriched when 'spent,' irradiated highly enriched uranium (HEU) fuel can present a serious proliferation risk even at relatively high burnup levels.[9] However this is becoming less of a global problem as more HEU-fueled research reactors are converted to LEU fuel or shut down.

Through a combination of natural (geological) and man-made (engineered) barriers deep underground, mined repositories permanently isolate spent fuel from the biosphere, rendering the security need for a protective radiation barrier redundant. However, some analysts have suggested that such structures could eventually serve as 'plutonium mines' – that is, accessible and affordable sources of plutonium for nuclear weapons – for future generations.[10] While theoretically true, there are several reasons why this is not practical. First, drilling back into a repository to retrieve spent fuel is expensive, complex, time-consuming and extremely difficult to conceal. Second, repositories are easier to safeguard than other methods of eliminating plutonium and those alternatives, such as reprocessing, "are associated with greater proliferation risks and would require much more extensive and costly safeguards."[11]

II.A.1 Safeguards

Irradiated fuel in storage is typically safeguarded using a combination of containment & surveillance measures and attribute confirmation measurements associated with irradiation. This approach is neither a direct measurement of fissile material nor independent because it requires operator-declared information about the operating history.[12] Gilinsky, Miller and Hubbard have noted some potentially exploitable vulnerabilities in the safeguards system: "The IAEA uses surveillance cameras primarily to monitor the movement of spent fuel transport casks from the pool area, and the surveillance record is checked by inspectors at three-month intervals during inspection visits. In addition, the inspectors count the assemblies in the pool and also use a Cerenkov light detector to verify that they have been irradiated. However, the resolution of the Cerenkov device is not good enough to detect the replacement of a significant number of the irradiated rods in an assembly with non-radioactive dummies. Moreover, the surveillance cameras have only a limited view of the pool area. This makes the covert diversion of spent fuel possible."[13] Significantly, a 2006 National Academy of Sciences (NAS) report noted that there are "broken fuel rods and other debris, mostly from older assemblies, in storage at many plants. These materials are typically stored along the sides of the spent fuel pools and could be more easily removed from the plant than an entire assembly."[14]

II.B. Spent Fuel Pools

A 2006 NAS report succinctly summarized how spent fuel pools are integrated into reactor designs: "Almost all spent fuel pools are located outside of the containment structure that holds the reactor pressure vessel. In some reactor designs, the spent fuel pools are contained within the reactor building, which is typically constructed of about 2 feet of reinforced concrete. In other designs, however, one or more walls of the spent fuel pool may be located on the exterior wall of an auxiliary building that is located adjacent to the containment building."[15] It should be noted that because they are all located above grade, BWR pools are more vulnerable to catastrophic loss-of-coolant events than PWR pools:

- Mark I & II BWR pools are located above grade and are shielded by at least one exterior building wall. Some pools are shielded by the reactor buildings, some pools are also shielded by "significant" surrounding structures and some have supplemental floor and column supports;
- PWR pools are located in buildings adjoining the reactor containment buildings. Some pools are positioned such that their spent fuel is below grade, some pool walls also serve as the external walls of the spent fuel pool buildings and some plants have structures surrounding the building that would provide some shielding of the pools from low-angle line-of-sight attacks.[16]

Historically, most analysis of spent fuel pools focused on safety. According to the Union of Concerned Scientists, the industry and Nuclear Regulatory Commission (NRC) security studies undertaken prior to September 11, 2001 concluded that a 707-sized aircraft crashing into a spent fuel pool would cause structural failure allowing the water to drain away. Although dire, that result was considered acceptable because the probability that a 707 would accidently land on a pool was very small.[17]

After 9/11, studies started to consider security against terrorist attacks, particularly the possibility of draining a pool to create a zirconium cladding fire – discussed below. According to the NRC, key features of the current spent fuel storage protection program include intrusion detection, assessment of alarms, response to intrusions and offsite assistance when necessary. In addition, while there have been no known or suspected attempts to sabotage spent fuel casks or storage facilities, the Commission also required security enhancements for spent fuel storage, both in pools and dry casks (including work to understand the robustness of dry casks to terrorist attacks).[18]

Not surprisingly, very little official analysis of the terrorism threat exists in the public domain. Risk assessments for the nation's commercial power plants are reflected in Design Basis Threats but these are not publicly available. According to interviews conducted by the Committee staff for a 2006 NAS report, the NRC believed at the time that the consequences of a terrorist attack on a spent fuel pool would unfold slowly enough to mitigate a large release of radioactivity.[19] The Committee was not convinced by the NRC's arguments, asserting that while the "probability of terrorist attacks on spent fuel storage cannot be assessed quantitatively or comparatively," terrorists might choose to attack pools because they are "less well protected structurally than reactor cores and … they typically contain inventories of medium- and long-lived radionuclides that are several times greater than those contained in individual reactor cores."[20] The Committee also judged that the likelihood terrorists could steal enough spent fuel for a 'significant' radiological dispersal device would be small because the assemblies are large, heavy and highly radioactive. While theft and removal during an assault on the plant might be easier, even then the amount that could be removed would be small.[21]

The National Academies of Sciences, Engineering, and Medicine revisited the subject in 2014, issuing a number of spent fuel findings and recommendations:

- The NRC should sponsor a spent fuel storage security assessment and examine the potential benefits of expedited transfer of spent fuel from pools to dry casks.
- The NRC has made good progress upgrading requirements for protecting spent fuel rods not in assemblies, is enhancing inspections, is updating guidance for fuel rods and rod fragments and is revising material control and accounting rulemaking.
- The NRC has not obtained the independent examination of surveillance and security measures for protecting stored spent fuel NAS recommended in 2006.[22]
- The vulnerabilities of spent fuel pools to terrorist attack are "plant-design specific and can be understood only by examining the characteristics of spent fuel storage at each plant."
- Based on four general types of terrorist scenarios, "only attacks that involve the application of large energy impulses or that

allow terrorists to gain interior access have any chance of releasing substantial quantities of radioactive material."[23] The Committee noted, however, that if the intent is simply to instill fear and cause economic disruption, "then an attack need not result in any release of radioactive material from the plant to be judged a success."

- Other threats, particularly insider and cyber, have grown in prominence and must be fully explored.[24]

More recently, security assessments focused on attacks with large aircraft and ground assaults were completed for a range of NRC-licensed facilities including Independent Spent Fuel Storage Installations (ISFSIs) and dry cask storage designs. The NRC concluded that no immediate changes in security requirements for ISFSIs were necessary but increases may be warranted over the longer term.[25] In addition, a *Used Fuel Storage Security Team* – the labs involved were Idaho, Lawrence Livermore, Oak Ridge, Pacific Northwest, Sandia and Savannah River – was assembled some years ago to evaluate security issues related to extended storage and transportation of spent fuel, which includes the self-protection threshold although it is not clear what the group advised or whether it still meets.[26]

Even less clear is why terrorists would select power reactor spent fuel as a bomb material. The entire process is both elaborate and conspicuous. After gaining access to the nuclear plant, the *assault* team would need to commandeer an overhead crane to extract an assembly from a pool or cut open a fuel cask. That assembly (or assemblies) would need to be moved, presumably but not necessarily, in some sort of container, to a waiting truck to be moved off-site. Alternatively, a truck could be hijacked on a public road while transporting spent fuel.[27] Unless the objective is a radiological dispersal device, the *design* team is then left with a large object that must be reprocessed in the presence of a radiation field to separate the uranium and plutonium before a weapon can be fabricated. However, as divining terrorist tactics is a difficult task, such a scenario cannot be dismissed.[28]

II.C. Pool Fires

Given the complexity of the operations outlined above, a number of experts have speculated that a loss-of-pool-coolant event leading to a fire is a more realistic threat. A primary concern in this case is cesium-137, which was the main radioactive contaminant forcing long-term relocations of populations around Chernobyl and Fukushima.[29] In 2001, the NRC released a report documenting a study of spent fuel pool accident risk at decommissioning nuclear power plants. The study was undertaken to support development of a risk-informed technical basis for reviewing exemption requests and a regulatory framework for integrated rulemaking. The study indicates that risks at spent fuel pools were low, and well within the Commission's Quantitative Health Objectives, because of the very low likelihood of a zirconium fire even though the consequences could be serious.[30]

The following year, Robert Alvarez observed that while concerns about attacks on commercial nuclear power plants focused mainly on the vulnerability of reactor containment buildings, spent fuel pools are located in much more vulnerable buildings and contain much more radiation: "On average, spent fuel ponds hold five to 10 times more long-lived radioactivity than a reactor core. Particularly worrisome is the large amount of cesium 137 in fuel ponds, which contain anywhere from 20 to 50 million curies of this dangerous isotope."[31] This risk is compounded by the practice of re-racking so the pools can hold more fuel than they were originally designed to contain. Citing the consequences of a loss-of-coolant event in a "dense-packed" pool, particularly in light of concerns that terrorists might find nuclear facilities attractive targets, a group of prominent experts called for an end to high-density pool storage and the placement of most SNF in dry casks in 2003. They estimated that this could be completed for $3.5-$7 billion within 10 years.[32] The NRC published a scathing response in August 2003 that challenged the pool damage probabilities, radiation release estimates, consequences and costs of dry cask transfer, concluding that "spent fuel, in both wet and dry configurations, is safe and measures are in place to adequately protect the public."[33] According to interviews conducted by the authors for the 2005 book *The Four Faces of Nuclear Terrorism*, industry officials agreed with the NRC's assessment.[34] Alvarez et al then rebutted the NRC factsheet and the issue was addressed in two subsequent National Academies studies:

- A 2006 National Academy of Sciences report concluded that "under some conditions, a terrorist attack that partially or completely drained a spent fuel pool could lead to a propagating zirconium cladding fire and the release of large quantities of radioactive materials to the environment." The report also endorsed reconfiguration in the pools so recently-discharged assemblies

were surrounded by older, lower decay heat assemblies.[35]

- A follow-on National Academies of Sciences, Engineering, and Medicine study dedicated a full chapter in its 2014 report to providing supporting information for spent fuel pool loss-of-coolant events. It advised that reconfiguring fuel in pools to more evenly distribute heat loads and enhance heat transfer can be an effective strategy for reducing the likelihood of fuel damage and zirconium cladding fires following loss-of-pool-coolant events, and recommended that the NRC sponsor an end-to-end validation of the MELCOR code for modeling loss-of-coolant in spent fuel pools.[36]

A post-Fukushima NRC 'lessons learned' taskforce studied *expedited transfer* to dry casks – removal of 80% of the fuel from high density storage while leaving the closed racks in place – but determined that the estimated cost (roughly $50 million/pool) "would provide only a minor or limited safety benefit (i.e., less than safety goal screening criteria), and that its expected implementation costs would not be warranted."[37]

Since then, a number of analyses have called into question the NRC's assumptions about and consequences of a spent fuel fire, including: excluding terrorism as a potential cause; excluding consequences beyond 50 miles; not updating the value assigned to reduced radiation doses to the public; underestimating the economic losses to relocated populations and using shielded rather than unshielded projected dose; not taking into consideration the possibility that all US nuclear plants would be closed indefinitely after such an accident; not including indirect losses (reduced property values, tourism income and agricultural sales) from neighboring regions; and not considering the impacts of psychological distress of even small radiation doses.[38] Dr. Steve Aoki recently wrote that while an attack on a spent fuel pool might not be the most likely form of terrorism, the consequences could be catastrophic so regulators and government officials are obligated to think of ways to reduce the risk. Aoki also noted that the US nuclear industry has "developed a strategy to stockpile necessary portable equipment at or near reactors to ensure that an alternative source of emergency electrical power and cooling water circulation can be provided even after a Fukushima-like event renders unavailable both normal off-site power and hard-wired backup generators. While designed primarily to ensure continued reactor core cooling in the event of a larger-than-expected earthquake, windstorm, or other natural disaster, this approach would also help recovery from a terrorist-initiated incident, including an attack on a spent fuel pool."[39]

III. RECOMMENDATIONS

Managing the security and nonproliferation risks associated with spent fuel should be informed by assessing both the probability of an event occurring and the consequences of such an event; risks that will persist given the lack of near-term disposal options in nearly all countries that operate nuclear reactors. With that in mind, the authors offer the following recommendations:

1. **Revise the spent fuel self-protection standard.** Given terrorists' demonstrated willingness to disregard personal safety in pursuit of their goals, the current self-protection standard is no longer adequate. Raising the threshold and instituting further security measures once the fuel is no longer self-protecting would help to mitigate risks.

2. **Where possible, expedite movement of spent fuel from wet storage to dry cask storage.** The goal is to reduce the density of fuel in the pools and facilitate reconfigurations to redistribute heat loads in order to minimize the consequences should a loss-of-coolant event occur.

3. **Where possible, encourage international spent fuel take-back services.** Consolidating global spent fuel stockpiles offers a number of benefits including promoting economies of scale, lowering environmental impacts and increasing international security. According to a 2007 US-Russian National Academies workshop, "arrangements that would provide assured return of spent nuclear fuel could provide a much more powerful incentive for countries to rely on international nuclear fuel supply than would assured supply of fresh fuel, because assured take-back could mean that countries would not need to incur the cost and uncertainty of trying to establish their own repositories for spent nuclear fuel or nuclear waste."[40] The United States and Russia have been doing this for years with research reactor fuel, and Russia is promising to take back spent fuel as part of several power reactor deals .[41] This take-back could be part of a fuel leasing program where the leaser is responsible for disposing

of the returned spent fuel or it might be sent (for example, through an IAEA-brokered deal) to a third-party state or a regional/multinational fuel cycle center located elsewhere. As long as the host country can ensure state-of-the-art competence and facilities, the international community should support any and all such offers, recognizing that they enhance regional and global safety and security.

4. **Explore other ways to mitigate the security and non-proliferation risks associated with management of spent fuel.** Convene an off-the-record roundtable of government/lab, industry (for example, storage/transportation cask manufacturers, fuel fabricators and reactor operators) and non-government/academic experts to discuss the benefits and financial/operational costs associated with existing and novel mitigation strategies at a level of specificity appropriate with national/international security considerations and protection of commercial proprietary information. Follow-on conversations could include regulators.

IV. ACKNOWLEDGEMENTS

The views expressed in this paper are those of the authors and do not necessarily reflect the views of NTI officers, staff, or the NTI Board of Directors, or the institutions with which they are associated.

V. REFERENCES

1. For a discussion of security issues see T. SUMERLING, *Work Package 4 – Safety and Security of Regional Repositories, Strategic Action Plan for Implementation of European Regional Repositories: Stage 2*, October 2008, http://www.erdo-wg.com/Sapierr_2_Documents/SAPIERR%20II%20WP-4%20web.pdf; C. MCCOMBIE, ET AL. "Security Concerns at the Back End of the Nuclear Fuel Cycle," *IHLRWM Conference*, Las Vegas, September 2008, http://www.arius-world.org/pdf_2008/Back_end_Security_Concerns.pdf; and T. GRAHAM JR. and J. GLASGOW, *Nonproliferation Aspects of Spent Fuel Storage and Disposition*, Nuclear Waste Management Organization, NWMO Background Papers, December 2003, https://www.nwmo.ca/~/media/Site/Files/PDFs/2015/11/04/17/31/610_1-8NonproliferationAspectsofSpentFuelStorageandDisposition.ashx?la=en.
2. In the United States, the Nuclear Regulatory Commission is still assessing the impacts of high burnup fuel on transportation and storage. See NRC, *Backgrounder: High Burnup Spent Fuel*, Office of Public Affairs, September 2015, https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/bg-high-burnup-spent-fuel.pdf, R. TORRES, "Dry Storage and Transportation of High Burnup Fuel," *Nuclear Regulatory Commission Webinar to State Liaison Officers & Indian Tribes*, September 21, 2016, https://www.nrc.gov/docs/ML1626/ML16266A040.pdf and EPRI, "High Burnup Issues Resolution – Cladding Performance," in *Used Fuel and High-Level Waste Management*, August 2016, http://mydocs.epri.com/docs/Portfolio/P2017/Roadmaps/NUC_HLW_03-High-Burnup-Fuel-Transportation.pdf. Advances in dry storage and transport system technologies that can accommodate spent fuel with higher burnup levels plus corresponding NRC license amendments are shortening required cooling times. See, for example, "Dry storage license change supports faster decommissioning," *World Nuclear News*, April 10, 2019, http://world-nuclear-news.org/Articles/Dry-storage-licence-amendment-supports-accelerated.
3. M. BUNN, ET AL., *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel* (Cambridge, Mass.: Project on Managing the Atom, Harvard University, 2003), https://dash.harvard.edu/bitstream/handle/1/30209100/Bunn_The_Economics_of_Reprocessing_vs_Direct_Disposal_of_Spent_Nuclear_Fuel.pdf?sequence=1 and J. CARLSON, *The Case for a Pause in Reprocessing in East Asia: Economic Aspects*, NTI Paper, August 2016, https://media.nti.org/documents/Reprocessing_East_Asia_final.pdf.
4. C.W. COATES, ET AL., *Radiation Effects on Personnel Performance Capability and a Summary of Dose Levels for Spent Research Reactor Fuels*, ORNL/TM-2005/261, December 2005, p.2.
5. 10 CFR § 73.6 (Exemptions for certain quantities and kinds of special nuclear material), https://www.nrc.gov/reading-rm/doc-collections/cfr/part073/part073-0006.html and IAEA, *Nuclear Security Recommendations on Physical Protection of Nuclear Material and Nuclear Facilities (INFCIRC/225/Revision 5)*, 2011, p.20, http://www-pub.iaea.org/MTCD/publications/PDF/Pub1481_web.pdf.

6. COATES, ET AL., *Radiation Effects on Personnel Performance Capability and a Summary of Dose Levels for Spent Research Reactor Fuels*, p.1, 15.
7. NRC, *Rulemaking for Enhanced Security of Special Nuclear Material*, January 2015, https://www.nrc.gov/docs/ML1432/ML14321A007.pdf.
8. For a review of the utility of power reactor SNF and research reactor SNF for possible terrorist purposes see G. BUNN and C. BRAUN, "Terrorism Potential for Research Reactors Compared With Power Reactors: Nuclear Weapons, "Dirty Bombs," and Truck Bombs," *American Behavioral Scientist*, Vol. 46, No. 6, February 2003, p.714-726.
9. See A. GLASER and F. VON HIPPEL, "On the Importance of Ending the Use of HEU in the Nuclear Fuel Cycle: An Updated Assessment," *2002 International Meeting on Reduced Enrichment for Research and Test Reactors (RERTR)*, San Carlos de Bariloche, Argentina, November 3-8, 2002, p.4, http://www.princeton.edu/~aglaser/2002aglaser_bariloche.pdf.
10. See, for example, IAEA, *Fissile Material Management Strategies for Sustainable Nuclear Energy: Proceedings of a Technical Meeting*, Vienna September 12-15, 2005 (IAEA: Vienna, 2007) p.10, 295, https://www-pub.iaea.org/MTCD/Publications/PDF/P1288_web.pdf; N. OI, "Plutonium challenges: Changing dimensions of global cooperation," *IAEA Bulletin*, 40/1/1998, https://www.iaea.org/sites/default/files/publications/magazines/bulletin/bull40-1/40104781216.pdf; and P. PETERSON, "Long-Term Safeguards for Plutonium in Geologic Repositories," *Science & Global Security*, Vol. 6, June 1996, pp.1-29, http://scienceandglobalsecurity.org/archive/sgs06peterson.pdf.
11. E. LYMAN and H. FEIVESON, "The Proliferation Risks of Plutonium Mines," *Science & Global Security*, Vol. 7, January 1998, p.120, 126. See also E. LYMAN, "WIPP and Plutonium Disposition: Feasibility and Security Issues," *International Nuclear Materials Management 54th Annual Meeting*, Palm Desert, CA, July 2013, https://www.ucsusa.org/sites/default/files/legacy/assets/documents/nwgs/wipp-plutonium-security.pdf.
12. W. CHARLTON, "Measurement of Irradiated Nuclear Fuel," Presentation, Advanced Reactor Safeguards Workshop, Texas A&M University, April 2019
13. V. GILINSKY, M. MILLER and H. HUBBARD, A Fresh Examination of the Proliferation Dangers of Light Water Reactors, NPEC Working Paper 1701, Updated March 2017, p.40, http://npolicy.org/article_file/1701_Fresh_Examination_of_LWR_Proliferation_Dangers.pdf.
14. National Research Council, *Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report*, p.34.
15. National Research Council, *Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report*, p.40.
16. *Ibid*, p.43.
17. L. GRONLUND, D. LOCHBAUM and E. LYMAN, *Nuclear Power in a Warming World*, Union of Concerned Scientists, December 2007, p,34, http://www.ucsusa.org/sites/default/files/legacy/assets/documents/nuclear_power/nuclear-power-in-a-warming-world.pdf
18. Nuclear Regulatory Commission, *Spent Fuel Storage in Pools and Dry Casks: Key Points and Questions & Answers*, Updated August 9, 2017, https://www.nrc.gov/waste/spent-fuel-storage/faqs.html#25
19. National Research Council, *Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report* (Washington DC: National Academies Press, 2006), p.34, https://www.nap.edu/catalog/11263/safety-and-security-of-commercial-spent-nuclear-fuel-storage-public. A classified version of the report was produced in 2004. The unclassified report goes on to say that the nuclear industry and NRC have asserted that the robust construction and stringent security requirements at nuclear power plants make them less vulnerable to terrorist attack than softer targets like chemical plants and refineries. See D. CHAPIN, ET AL., "Nuclear Power Plants and Their Fuel as Terrorist Targets," *Science*, Vol. 297, September 20, 2002, p.1997-1999.
20. The report also makes an important observation about refueling: "Although only one-third of the fuel in the reactor core is replaced during each refueling cycle, operators commonly offload the entire core (especially at pressurized water reactors [PWRs]) into the pool during refueling to facilitate loading of fresh fuel or for inspection or repair of the reactor vessel and internals. Heat generation in the pool is at its highest point just after the full core has been offloaded." National Research Council, *Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report*, p.40.

21. National Research Council, *Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report*, p.36.
22. The NAS also stated that, to its knowledge, there were no NRC programs in place to evaluate the effectiveness of measures for mitigating insider threat.
23. The four scenarios: air attack (large civilian aircraft or smaller aircraft with explosives); ground attack (well-armed, well-trained groups); combined air-ground attack; and theft involving knowledgeable insiders for RDD use.
24. All information is taken from National Academies of Sciences, Engineering, and Medicine, *Lessons Learned from the Fukushima Nuclear Accident for Improving Safety and Security of U.S. Nuclear Plants: Phase 2* (Washington, DC: The National Academies Press, 2016), p.88-100, https://www.nap.edu/catalog/21874/lessons-learned-from-the-fukushima-nuclear-accident-for-improving-safety-and-security-of-us-nuclear-plants
25. NRC, *Background on the Proposed Security Rulemaking for Independent Spent Fuel Storage Installations*, updated May 31, 2017, https://www.nrc.gov/about-nrc/radiation/related-info/isfsi-security/background.html
26. F. DURAN, "Security for Long-Term Storage of Used Nuclear Fuel," *MPACT Working Group Meeting*, Gaithersburg, MD, September 14-15, 2011, Slide 5, https://www.osti.gov/scitech/servlets/purl/1289855
27. On transportation security see "Safety and Security of Spent Nuclear Fuel Transportation," *Hearing before the Committee on Commerce, Science, and Transportation*, United States Senate, 110th Congress, 2nd Session, September 24, 2008, https://www.gpo.gov/fdsys/pkg/CHRG-110shrg80371/html/CHRG-110shrg80371.htm and NRC, *Backgrounder on Transportation of Spent Fuel and Radioactive Materials*, March 2016, https://www.nrc.gov/reading-rm/doc-collections/fact-sheets/transport-spenfuel-radiomats-bg.html
28. This section was informed by email communication with Professor Matthew Bunn, Harvard University, August 31, 2017.
29. F. VON HIPPEL and M. SCHOEPPNER, "Reducing the Danger from Fires in Spent Fuel Pools," *Science & Global Security*, Vol. 24, No. 3, 2016, p.141. See also H. ZHANG, "Radiological Terrorism: Sabotage of Spent Fuel Pools," *INESAP*, December 2003, http://www.belfercenter.org/publication/radiological-terrorism-sabotage-spent-fuel-pools.
30. T.E. COLLINS and G. HUBBARD, "Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants," U.S. Nuclear Regulatory Commission, NUREG-1738, January 2001, p. ix, https://www.nrc.gov/docs/ML0104/ML010430066.pdf
31. R. ALVAREZ, "What about the spent fuel?" *Bulletin of the Atomic Scientists*, Vol. 58, No. 1, January/February 2002, p.45, http://www.efmr.org/Xtra/Spent_fuel.pdf.
32. R. ALVAREZ, ET AL., "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States," *Science and Global Security*, 11, 2003, p.2, https://www.princeton.edu/sgs/publications/articles/fvhippel_spentfuel/rAlvarez_reducing_hazards.pdf. According to a 1987 Brookhaven National Lab report: "The one universal prevention measure is to promote air cooling in the event of loss of water cooling of the spent fuel. The new high density fuel storage racks restrict air flow and make even old spent fuel (one to two years) susceptible to heat-up and self-sustaining oxidation. The older style fuel baskets with large inlet holes (3 inch diameter or more per assembly) allow much freer air circulation. If all recently discharged fuel (less than two years) is kept in low density fuel baskets and they are separated from the wall and the older fuel by a one foot gap then the likelihood of self-sustaining oxidation would be reduced by a factor of 5 or more compared to the high density storage configuration." V. L. SAILOR, K. R. PERKINS, J. R. WEEKS, H. R. CONNELL, *Severe Accidents in Spent Fuel Pools in Support of Generic Safety Issue 82*, NUREG/CR-4982, July 1987, p.79, https://www.osti.gov/scitech/servlets/purl/6135335
33. *NRC Factsheet: NRC Review of Paper on Reducing Hazards From Stored Spent Nuclear Fuel*, August 2003, https://www.nrc.gov/docs/ML0523/ML052340737.pdf
34. C. FERGUSON and W. POTTER with A. SANDS, ET AL., *The Four Faces of Nuclear Terrorism* (New York: Routledge, 2005), p.229.
35. National Research Council, *Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report*, p.57, 8.
36. National Academies of Sciences, Engineering, and Medicine, *Lessons Learned from the Fukushima Nuclear Accident for Improving Safety and Security of U.S. Nuclear Plants: Phase 2*, p.97.

37. NRC, *Staff Evaluation and Recommendation for Japan Lessons-Learned Tier 3 Issue on Expedited Transfer of Spent Fuel*, COMSECY-13-0030, November 12, 2013, p.1, https://www.nrc.gov/docs/ML1327/ML13273A601.pdf. In 2015, NEA released a report on loss of coolant accidents: *Status Report on Spent Fuel Pools under Loss-of-Coolant Accident Conditions: Final Report*, NEA/CSNI/R(2015)2, May 2015, https://www.oecd-nea.org/nsd/docs/2015/csni-r2015-2.pdf. Sandia National Lab led a Fukushima accident reconstruction study that included analysis of the spent fuel pools. See R. GAUNTT, ET AL. *Fukushima Daiichi Accident Study (Status as of April 2012)*, SAND2012-6173, July 2012, http://energy.sandia.gov/wp-content/gallery/uploads/Fukushima_SAND2012-6173.pdf. Installation of water level instrumentation in spent fuel pools was one of the post-Fukushima safety enhancements the NRC required of all U.S. plants. NRC, "Order Modifying Licenses With Regard To Reliable Spent Fuel Pool Instrumentation," March 12, 2012, https://www.nrc.gov/docs/ML1205/ML12056A044.pdf
38. See ALVAREZ, "Pushing the storage horse with a nuclear waste cart: the spent fuel pool problem"; E. LYMAN, M. SCHOEPPNER and F. VON HIPPEL, "Nuclear safety regulation in the post-Fukushima era, *Science*, Vol. 356, Issue 6340, May 26, 2017; VON HIPPEL AND SCHOEPPNER, "Reducing the Danger from Fires in Spent Fuel Pools"; and F. VON HIPPEL, M. SCHOEPPNER, "Economic Losses From a Fire in a Dense-Packed U.S. Spent Fuel Pool," *Science & Global Security*, May 2017.
39. S. AOKI, "Nuclear Terrorism and Spent Fuel Storage," *NAPSNet Special Reports*, August 31, 2017, https://nautilus.org/napsnet/napsnet-special-reports/nuclear-terrorism-and-spent-fuel-storage/
40. International Atomic Energy Agency, *Viability of Sharing Facilities for the Disposal of Spent Fuel and Nuclear Waste: An Assessment of Recent Proposals*, IAEA-TECDOC-1658, Vienna, September 2011, p.22, http://www-pub.iaea.org/MTCD/Publications/PDF/TE-1658_web.pdf.
41. Russia was reportedly offering this service to Vietnam until Vietnam's National Assembly voted in November 2016 to cancel its nuclear power program. World Nuclear Association, *Emerging Nuclear Energy Countries*, updated April 2018, http://www.world-nuclear.org/information-library/country-profiles/others/emerging-nuclear-energy-countries.aspx and V.P. NGUYEN, "The fate of nuclear power in Vietnam," *The Bulletin of the Atomic Scientists*, December 5, 2016 https://thebulletin.org/fate-nuclear-power-vietnam10245.