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Rulemaking Comments

From: John Runkle [jrunkle@pricecreek.com]
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DOCKETED
USNRC

May 11, 2011 (9:00 am)

OFFICE OF SECRETARY
RULEMAKINGS AND
ADJUDICATIONS STAFF

Part 1 of 2

May 10, 2010

Attached please find the following

1. Union of Concerned Scientists, "Safer Storage of Spent Nuclear Fuel: The Problems of Spent Fuel Pools," revised March 24, 2011

2. Statement of David Lockbaum, Director, Nuclear Safety Project, before the U.S. Senate Energy and Natural Resources Committee, March 29, 2011

3. Alvarez et al., "Reducing the Hazardous from Stored Spent Power-Reactor Fuel in the United States," January 2003

4. Thompson, "Robust Storage of Spent Nuclear Fuel: A Neglected Issue of Homeland Security," January 2003.

5. National Academies of Science, "Safety and Security of Commerical Spent Nuclear Storage (Public Report)," 2006

Because of you size limitations, I am including document 5 in a separate email.

Together these document provide additional support that the AP1000 Certification rulemaking should be DENIED because of the inadequate spent fuel pools, and/or postponed or significantly extended to allow the NRC to develop and implement lessons learned from the Fukushima accident. As stated in the PETITION TO SUSPEND AP1000 DESIGN CERTIFICATION RULEMAKING PENDING EVALUATION OF FUKUSHIMA ACCIDENT IMPLICATIONS ON DESIGN AND OPERATIONAL PROCEDURES AND REQUEST FOR EXPEDITED CONSIDERATION, there was a significant backsliding from Revision 15 to Revision 18 by increasing the density of the spent fuel pools.

It is also readily apparent that some of the lessons learned from the Fukushima accident are:

a. spent fuel pools should not be densely packed b. there should be a robust containment around the fuel pools c. there should be redundant cooling systems for the fuel pools d. the build up of hydrogen in the fuel pools needs to be addressed e. there should be back up power for pumps, cooling systems and monitoring systems

Other lessons regarding the spent fuel pools may be learned after investigation.

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Union of Concerned Scientists

Safer Storage of Spent Nuclear Fuel

The Problems with Spent Fuel Pools

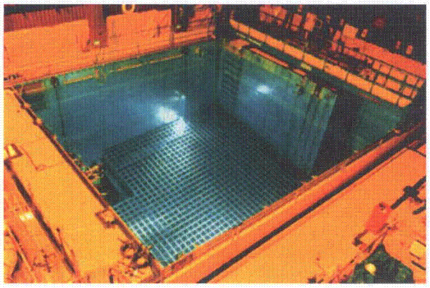
When fuel rods in a nuclear reactor are "spent," or no longer usable, they are removed from the reactor core and replaced with fresh fuel rods. The spent fuel rods are still highly radioactive and thus continue to generate heat for years. The fuel assemblies, which consist of dozens of fuel rods, are moved to pools of water to cool. They are on kept on racks in the pool, and water is continuously circulated to draw heat away from the rods.

Because no permanent repository for spent fuel exists in the United States (or elsewhere), reactor owners have kept spent fuel at the reactor sites. As the amount of spent fuel has increased, the Nuclear Regulatory Commission has authorized many power plant owners to increase the amount in their storage pools to as much as five times what they were designed to hold. As a result, virtually all U.S. spent fuel pools have been "re-racked" to hold spent fuel assemblies at densities that approach those in reactor cores. In order to prevent the spent fuel from going critical, the spent fuel assemblies are placed in metal boxes whose walls contain neutron-absorbing boron.

If a malfunction, a natural disaster, or a terrorist attack causes the water to leak from the pool or the cooling system to stop working, the rods will begin to heat the remaining water in the pool, eventually causing it to boil and evaporate. If the water that leaks or boils away cannot be replaced, the water level will drop, exposing the fuel rods.

Once the fuel is uncovered, it could become hot enough to suffer damage, which in turn could release large amounts of radioactive gases, such as cesium-137, into the environment. A typical spent fuel pool in the United States holds 1,000 or more tons of fuel, so a radioactive release could be very large.

Spent Fuel Pool Vulnerabilities



The spent fuel pools are located only within the secondary containment of the reactor—the reactor building—and not within the more robust primary containment that is designed to keep radiation released from the reactor vessel during an emergency event from escaping into the environment. Thus, any radiation released from a spent fuel pool is more likely to reach the outside environment than is radiation released from the reactor core. Moreover, because it is outside the primary containment, the spent fuel pool is more vulnerable than the reactor core to terrorist attack.

Continuing to add spent fuel to these pools compounds this problem by increasing the amount of radioactive material that could be released into the environment. A large radiation release from a spent fuel pool could result in thousands of cancer deaths and hundreds of billions of dollars in decontamination costs and economic damage. The amount of land contaminated by a release from a spent fuel pool could be significantly greater than that contaminated by the Chernobyl disaster.

Like the cooling system for the reactor core, the cooling system for the spent fuel pools is powered by the electric grid. However, the reactor core cooling system has two back-up power supplies—diesel generators and either a four- or eight-hour DC battery—whereas the spent fuel pool system typically has none. More generally, the industry and the NRC have given little thought to spent fuel pool accidents, and there is virtually no operator training for handling such accidents.

Advantages of Dry Cask Storage

The risks from spent fuel in storage pools can be reduced by placing some of it in dry casks. Dry casks are made of steel and concrete, with the concrete providing shielding from radiation, and are stored outdoors on concrete pads. To become cool enough to be placed in the dry casks currently licensed and used in the United States, the spent fuel must first spend about five years in a spent fuel pool. By then it is cool enough that further cooling can be accomplished by natural convection—air flow driven by the decay heat of the spent fuel itself.

By transferring fuel from spent fuel pools to dry casks, plants can lower the risk from spent fuel in several ways:

First, with less spent fuel remaining in the pools, workers will have more time to cope with a loss of cooling or loss of water from the pool, because the amount of heat released by the spent fuel is lower. With less heat, it takes longer for the water to heat up and boil away.

Second, if there is less fuel in the pool, it can be spread out more, making it easier for water to cool the fuel. When fuel is densely packed, less water flows past each fuel assembly.

Third, because there is less fuel in the pool, if workers are unable to prevent an accident, the amount of radioactive gas emitted from the pool will be much lower than it would be otherwise.

The combination of reducing the likelihood of an event and reducing the consequences of an event significantly reduces the risk from a spent-fuel accident. In contrast to spent fuel pools, dry casks are not vulnerable to loss of coolant because their cooling is passive.

While dry casks are still vulnerable to safety and security hazards, those risks are reduced. In contrast to the large amount of fuel in a single spent fuel pool, each dry cask only holds about 15 tons of spent fuel. Thus, it would require safety failures at many dry casks to produce the scale of radiological release that could result from a safety failure at one spent fuel pool. Likewise, terrorists would have to break open many dry casks to release as much radioactivity as a single spent fuel pool could release. Therefore, an attack on a dry cask storage area would, in most circumstances, result in a much smaller release of radioactivity than an attack on a storage pool.

UCS recommendations

- All spent fuel should be transferred from wet to dry storage within five years of discharge from the reactor core. This can be achieved with existing technologies.
- The NRC should upgrade existing regulations to require that dry cask storage sites be made more secure against a terrorist attack.
- The NRC should significantly upgrade emergency procedures and operator training for spent fuel pool accidents.

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ROBUST STORAGE OF SPENT NUCLEAR FUEL: A Neglected Issue of Homeland Security

by

Gordon Thompson

January 2003

A report commissioned by

Citizens Awareness Network

About IRSS

The Institute for Resource and Security Studies (IRSS) is an independent, non-profit corporation. It was founded in 1984 to conduct technical and policy analysis and public education, with the objective of promoting international security and sustainable use of natural resources. IRSS projects always reflect a concern for practical solutions to resource, environment and security problems. Projects include detailed technical studies, participation in public education and debate, and field programs that promote the constructive management of conflict.

About the author

Dr. Gordon Thompson is the executive director of IRSS and a research professor at Clark University. He received an undergraduate education in science and mechanical engineering in Australia and a doctorate in applied mathematics from Oxford University. Thompson has extensive experience in assessing the safety and security hazards associated with nuclear facilities, and in identifying alternative designs and modes of operation that can reduce a facility's hazard potential.

Acknowledgements

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Abstract

The prevailing practice of storing most US spent nuclear fuel in high-density pools poses a very high risk. Knowledgeable attackers could induce a loss of water from a pool, causing a fire that would release to the atmosphere a huge amount of radioactive material. Nuclear reactors are also vulnerable to attack. Dry-storage modules used in independent spent fuel storage installations (ISFSIs) have safety advantages in comparison to pools and reactors, but are not designed to resist a determined attack. Thus, nuclear power plants and their spent fuel can be regarded as pre-deployed radiological weapons that await activation by an enemy. The US government and the Nuclear Regulatory Commission seem unaware of this threat.

This report sets forth a strategy for robust storage of US spent fuel. Such a strategy will be needed whether or not a repository is opened at Yucca Mountain. This strategy should be implemented as a major element of a defense-in-depth strategy for US civilian nuclear facilities. In turn, that defense-in-depth strategy should be a component of a homeland-security strategy that provides solid protection of our critical infrastructure.

The highest priority in a robust-storage strategy for spent fuel would be to re-equip spent-fuel pools with low-density, open-frame racks. As a further measure of risk reduction, ISFSIs would be re-designed to incorporate hardening and dispersal. Preliminary analysis suggests that a hardened, dispersed ISFSI could be designed to meet a two-tiered design-basis threat. The first tier would require high confidence that no more than a small release of radioactive material would occur in the event of a direct attack on the ISFSI by various non-nuclear instruments. The second tier would require reasonable confidence that no more than a specified release of radioactive material would occur in the event of attack using a 10-kilotonne nuclear weapon.

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1. Introduction

> "One fact dominates all homeland security threat assessments: terrorists are strategic actors. They choose their targets deliberately based on the weaknesses they observe in our defenses and our preparations. They can balance the difficulty in successfully executing a particular attack against the magnitude of loss it might cause."
> National Strategy for Homeland Security[1]

It is well known that nuclear power plants and their spent fuel contain massive quantities of radioactive material. (Note: Irradiated fuel discharged from a nuclear reactor is described as "spent" because it is no longer suitable for generating fission power.) Consequently, thoughout the history of the nuclear power industry, informed citizens have expressed concern that a substantial amount of this material could be released to the environment. One focus of concern has been the possibility of an accidental release caused by human error, equipment failure or natural forces (e.g., an earthquake). In response to citizens' demands and events such as the Three Mile Island reactor accident of 1979, the US Nuclear Regulatory Commission (NRC) has taken some actions that address this threat.

To date, citizens have been much less successful in forcing the NRC to address a related threat -- the possibility that a release of radioactive material will be caused by an act of malice or insanity. The citizens' failure is not for lack of effort. For many years, citizen groups have petitioned the NRC and engaged in licensing interventions, seeking to persuade the NRC to address this threat. Yet, the agency has responded slowly, reluctantly and in limited ways, even after the terrorist attacks of 11 September 2001. This limited response is not unique to the NRC. The US government in general seems unwilling to address the possibility that an enemy, domestic or foreign, will exploit a civilian nuclear facility as a radiological weapon.

The terrorist attacks of September 2001 demonstrated the vulnerability of our industrial society to determined acts of malice, and cruelly validated long-neglected warnings by many analysts and concerned citizens. In response, the United States employed its military capabilities in Afghanistan and has signaled its willingness to use those capabilities in Iraq and elsewhere. Yet, nothing significant has been done to defend US nuclear power plants and their spent fuel against attack. There is much discussion in the media about "dirty bombs" that disperse radioactive material, but decision makers seem

[1] Office of Homeland Security, 2002, page 7.

largely unaware that civilian nuclear facilities contain massive quantities of radioactive material and are vulnerable to attack.

What is Robust Storage?

This report addresses robust storage of spent fuel from nuclear power plants. Here, the term "robust" means that a facility for storing spent fuel is made resistant to attack. The provision of robust storage would substantially reduce the potential for a maliciously-induced release of radioactive material from spent fuel, and would thereby enhance US homeland security. Robust storage of spent fuel should be viewed as a component of a national strategy for reducing the vulnerability of all civilian nuclear facilities, within the context of homeland security. This report takes such a view.

A spent-fuel-storage facility can be made resistant to attack in three ways. First, the facility can be made passively safe, so that spent fuel remains in a safe state without needing electrical power, cooling water or the presence of an operating crew. Second, the facility can be "hardened", so that the spent fuel and its containment structure are protected from damage by an instrument of attack (e.g., an anti-tank missile). For a facility at ground level, hardening involves the provision of layers of concrete, steel, gravel or other materials above and around the spent fuel. Third, the facility can be "dispersed", so that spent fuel is not concentrated at one location, but is spread more uniformly across the site. Dispersal can reduce the magnitude of the radioactive release that would arise from a given attack.

At present, all but a tiny fraction of US spent fuel is stored at the nation's nuclear power plants. Most of this fuel is stored at high density in water-filled pools that are adjacent to, but outside, the containments of the reactors. This mode of storage does not meet any of the above-stated three conditions for robustness. High-density spent-fuel pools are not passively safe. Indeed, if water is lost from such a pool, which could occur in various ways, the fuel will heat up, self-ignite and burn, releasing a large amount of radioactive material to the environment. Spent-fuel pools are not hardened against attack, and a pool concentrates a large amount of spent fuel in a small space, which is the antithesis of dispersal.

A growing fraction of US spent fuel, now about 6 percent of the total inventory, is stored in dry-storage facilities at nuclear power plants. The storage is "dry" in the sense that the spent fuel is surrounded by a gas such as helium, rather than by water. The NRC describes a spent-fuel-storage facility, other than a spent-fuel pool at a nuclear power plant, as an independent spent fuel storage installation (ISFSI).[2] All but two of the existing ISFSIs are at the sites of nuclear power plants, either operational plants or plants undergoing decommissioning.[3] Future ISFSIs could be built at nuclear-power-plant sites or at away-from-reactor sites. An application to build an ISFSI at an away-from-reactor site -- Skull Valley, Utah -- is awaiting decision by the NRC. It should be noted that the nuclear industry is building dry-storage ISFSIs not as an alternative to high-density pools, but to accommodate the growing inventory of spent fuel as pools become full.

Dry-storage ISFSIs meet one of the above-stated three conditions for robust storage of spent fuel. They are passively safe, because their cooling depends on the natural circulation of ambient air. However, none of the existing or proposed ISFSIs is hardened, and none of them is dispersed across its site.

A Broader Context

This report describes the need for robust storage of all US spent fuel, whether in pools or dry-storage ISFSIs, and sets forth a strategy for meeting this need. As discussed above, a productive discussion of these issues must occur within a broader context, which is is addressed in this report. The provision of robust storage of spent fuel must be viewed as a component of a national strategy for defending the nation's civilian nuclear industry, including all of the nuclear power plants and all of their spent fuel. That strategy must in turn be viewed as a component of homeland security in general. Finally, homeland security must be viewed as a key component of US strategy for national defense and international security.

The various levels of security, ranging from the security of nuclear facilities to the security of the nation and the international community, are linked in surprising ways. If our nuclear facilities and other parts of our infrastructure -- such as the airlines -- are poorly defended, we may feel compelled to use military force aggressively around the world, to punish or pre-empt attackers. Such action poses the risk of arousing hostility and promoting anarchy, leading to new attacks on our homeland. The potential exists for an escalating spiral of violence. If, however, our nuclear facilities and other critical items of infrastructure are strongly defended, we can gain a double benefit. First, the communities around each facility will receive direct protection. Second, we can take a more measured approach to national defense, with a greater prospect of detecting, deterring and apprehending potential attackers without undermining civil liberties or international

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[2] One wet-storage ISFSI exists in the USA, at Morris, Illinois. All other existing ISFSIs, and all planned ISFSIs, employ dry storage.

[3] The existing ISFSIs that are not at nuclear-power-plant sites are the small wet-storage facility at Morris and a facility in Idaho that stores fuel debris from Three Mile Island Unit 2.

security. Thus, a decision about the level of protection to be provided at a nuclear facility has wide-ranging implications.

The Need for Further Investigation

The investigation leading to this report has identified a number of technical issues that could not be resolved within the scope of the investigation. Issues of this kind are flagged in relevant parts of the report. Also, this report has a broad focus. It sets forth a strategy for providing robust storage of US spent fuel, and outlines a design approach for hardened, dispersed, dry storage. Additional analysis, supported by experiments, would be needed to test and refine this design approach and to determine the feasibility of implementing hardened, dispersed, dry storage at particular sites. That work would, in turn, set the stage for detailed, engineering-design studies that could lead to site-specific implementation. Moreover, a variety of governmental actions would be needed to support nationwide implementation of robust storage. For example, the NRC would need to develop new regulations and guidance. Also, the implementation program would require new financing arrangements, which would probably require new legislation.

Sensitive Information

An attack on a nuclear facility could be assisted by detailed information about the facility's vulnerability and the measures taken to defend the facility. Thus, certain categories of information related to a facility are not appropriate for general distribution. However, experience shows that secrecy breeds incompetence, complacency and conflicts of interest within the organizations that are shielded from public view.[4] Thus, in the context of defending nuclear facilities, protection of the public interest requires that secrecy be limited in two respects. Firstly, the only information that should be withheld from the public is detailed technical information that would directly assist an attacker. Second, stakeholder groups should be fully engaged in the development and implementation of measures for defending nuclear facilities, through processes that allow debate but protect sensitive information.[5] It should be noted that this report does not contain sensitive information and is suitable for general distribution.

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[4] Thompson, 2002a, Section X.
[5] Thompson, 2002a, Sections IX and X.

Robust Storage and Related Concepts

Issues addressed in this report have been the subject of public debate around the United States, and this debate has been framed in a number of ways. One approach has been to speak of "risk reduction", whereby robust storage of spent fuel and related measures are used to reduce the risk of a maliciously-induced release of radioactive material from nuclear facilities. This approach explicitly recognizes that the risk can be reduced but, given the continued existence of radioactive material, cannot be eliminated. Another approach has been to speak of "hardened on-site storage" as a strategy for managing US spent fuel. This approach advocates the robust storage of all spent fuel, but only at the sites of nuclear power plants. A related but distinct approach is "nuclear guardianship", whose supporters argue that radioactive materials should be contained in accessible, monitored storage facilities for the foreseeable future. The robust-storage strategy that is outlined in this report is compatible with all three approaches, and with a prudent assessment of the likelihood and timeframe for development of a radioactive-waste repository at Yucca Mountain.

Structure of this Report

The remainder of this report begins, in Section 2, with the provision of some basic information about US nuclear power plants and their spent fuel. Then, Section 3 discusses the potential for attacks on nuclear facilities, describes the US government's response to this threat, and outlines a balanced response. Section 4 addresses the vulnerability of nuclear facilities to attack, describes the potential consequences of an attack, outlines a defense-in-depth strategy for a nuclear facility, and sets forth a national strategy for robust storage of spent fuel. Elaborating upon this proposed strategy for robust storage, Section 5 discusses the various factors that must be considered in planning hardened, dispersed, dry storage of spent fuel. Section 6 offers a design approach that accounts for these factors. A set of requirements for nationwide implementation of robust storage is described in Section 7. Conclusions are set forth in Section 8, and a bibliography is provided in Section 9. Documents cited in this report are, unless indicated otherwise, drawn from this bibliography.

2. Nuclear Power Plants and Spent Fuel in the USA

2.1 Status and Trends of Nuclear Power Plants and Spent Fuel

There are 103 commercial nuclear reactors operating in the USA at 65 sites in 31 states.[6] Of these 103 reactors, 69 are pressurized-water reactors (PWRs), 9 with ice-condenser containments and 60 with dry containments. The remaining 34 reactors are boiling-water reactors (BWRs), 22 with Mark I containments, 8 with Mark II containments and 4 with Mark III containments. In addition there are 27 previously-operating commercial reactors in various stages of storage or decommissioning. As of December 2000, all but 2 of the 103 operating reactors had been in service for at least 9 years, and 55 reactors had been in service for at least 19 years.[7] Thus, the reactor fleet is aging. The nominal duration of a reactor operating license is 40 years.

Four of the 103 operating reactors have design features intended to resist aircraft impact. The Limerick Unit 1, Limerick Unit 2 and Seabrook reactors were designed to withstand the impact of an aircraft weighing 6 tonnes, while the Three Mile Island Unit 1 reactor was designed to withstand the impact of an aircraft weighing 90 tonnes. No other US reactor was designed to withstand aircraft impact.[8]

Wet and Dry Storage of Spent Fuel

The core of a commercial nuclear reactor consists of several hundred fuel assemblies.[9] Each fuel assembly contains thousands of cylindrical, uranium-oxide pellets stacked inside long, thin-walled tubes made of zirconium alloy. These tubes are often described as the "cladding" of the fuel. After several years of use inside an operating reactor, a fuel assembly becomes "spent" in the sense that it is no longer suitable for generating fission power. Then, the fuel is discharged from the reactor and placed in a water-filled pool adjacent to the reactor but outside the reactor containment. This fuel, although spent, contains numerous radioactive isotopes whose decay generates ionizing radiation and heat.

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[6] In addition, Browns Ferry Unit 1, a BWR with a Mark I containment, is nominally operational. However, it is defueled and not in service.

[7] Data from the NRC website (www.nrc.gov), 24 April 2002.

[8] Markey, 2002, page 73.

[9] The number of fuel assemblies in a reactor core ranges from 121 (in some PWRs) to 764 (in some BWRs).

After a period of storage in a pool, the thermal power produced by a fuel assembly declines to a level such that the assembly can be transferred to a dry-storage ISFSI. Current practice is to allow a minimum cooling period of 5 years before transfer to dry storage. However, this cooling period reflects an economic and safety tradeoff rather than a fundamental physical limit. Fuel cooled for a shorter period than 5 years could be transferred to dry storage, but in that case fewer assemblies could be placed in each dry-storage container. Alternatively, older and younger spent fuel (counting age from the date of discharge from the reactor) could be co-located in a dry-storage container. The major physical limit to placement of spent fuel in dry storage is the maximum temperature of the cladding, which the NRC now sets at 400 degrees C. This temperature limit constrains the allowable heat output of the fuel, which in turn constrains the cooling period.

Development of ISFSIs

At present, there are 20 ISFSIs in the USA, of which 15 are at sites where commercial reactors are in operation.[10] More ISFSIs will be needed, because the spent-fuel pools at operating reactors are filling up. Analysis by Allison Macfarlane of MIT shows that, by 2005, almost two-thirds of reactor licensees will face the need to acquire onsite dry-storage capacity, even if shipment of spent fuel away from the reactor sites begins in 2005.[11] NAC International, a consulting firm and vendor of dry-storage technology, reaches similar conclusions. NAC estimates that, at the end of 2000, about 6 percent of the US inventory of commercial spent fuel was stored in ISFSIs at reactor sites, whereas about 30 percent of the inventory will be stored in ISFSIs by 2010.[12] New ISFSIs entering operation by 2010 will generally be at reactor sites, although some might be at new sites. At present, only one proposed ISFSI at a new site -- Skull Valley, Utah -- seems to be a plausible candidate for operation by 2010.

Shipment of Spent Fuel from Reactor Sites

If spent fuel is shipped away from a reactor site, the fuel could have three possible destinations. First, fuel could be shipped to another reactor site, which Carolina Power and Light Co. is now doing, shipping fuel from its

[10] Data from the NRC website (www.nrc.gov), 24 April 2002.
[11] Macfarlane, 2001a.
[12] NAC, 2001. NAC estimates that the end-2000 US inventory of spent fuel was 42,900 tonnes, of which 2,430 tonnes was in ISFSIs. Also, NAC estimates that the 2010 US inventory will be 64,300 tonnes, of which 19,450 tonnes will be in ISFSIs.

Brunswick and Robinson reactors to its Harris site.[13] Second, fuel could be shipped to an ISFSI at an away-from-reactor site, such as Skull Valley. Third, fuel could be shipped to a repository at Yucca Mountain, Nevada. At Yucca Mountain, the fuel would be emplaced in underground tunnels. Under some scenarios for the operation of Yucca Mountain, emplacement would be preceded by a period of interim storage at the surface.

There seems to be no current planning for shipment of spent fuel to any reactor site other than Harris. Also, there are factors that argue against shipping fuel to an away-from-reactor ISFSI. First, such shipment would increase the overall transport risk, because fuel would be shipped twice, first from the reactor site to the ISFSI, and then from the ISFSI to the ultimate repository. Second, an away-from-reactor ISFSI would hold a comparatively large inventory of spent fuel, creating a potentially attractive target for an enemy.[14] Third, shipment to an away-from-reactor ISFSI would not free most reactor licensees from the obligation to build some ISFSI capacity at each reactor site.[15] Fourth, there is a risk that a large, away-from-reactor ISFSI would become, by default, a permanent repository, despite having no long-term containment capability. Finally, storage of spent fuel in reactor-site ISFSIs could be cheaper than shipping fuel to away-from-reactor ISFSIs.[16] Time will reveal the extent to which these factors affect the development of away-from-reactor ISFSIs at Skull Valley or elsewhere.

Yucca Mountain

The Yucca Mountain repository project will not free reactor licensees from the obligation to develop ISFSI capacity, for three reasons. First, the Yucca Mountain repository may never open. This project is politically driven, does not have a sound scientific basis, and is going forward only because previously-specified technical criteria for a repository have been abandoned.[17] These deficiencies add weight to the determined opposition to this project by the state of Nevada and other entities. That opposition will also be fueled by concern about the risk of transporting fuel to Yucca Mountain. Second, decades will pass before fuel can be emplaced in a repository at Yucca Mountain. The US Department of Energy (DOE) claims that it can open the repository in 2010, but the US General Accounting Office has determined that

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[13] The Harris site features one reactor and four spent-fuel pools, and thus has more pool-storage capacity than other reactor sites. Spent fuel that is shipped to Harris is placed in a pool, and there is no current plan to build an ISFSI at Harris.

[14] The proposed Skull Valley ISFSI could hold 40,000 tonnes of spent fuel, according to the Private Fuel Storage website (www.privatefuelstorage.com), 4 October 2002.

[15] Macfarlane, 2001a.

[16] Macfarlane, 2001b.

[17] Ewing and Macfarlane, 2002.

several factors, including budget limitations, could extend this date to 2015 or later.[18] DOE envisions that, after the repository is opened, emplacement of fuel will occur over a period of at least 24 years and potentially 50 years.[19] This vision may prove to be optimistic. Third, under present federal law the Yucca Mountain repository will hold no more than 63,000 tonnes of commercial spent fuel.[20] Yet, the cumulative amount of commercial spent fuel to be generated during the lifetimes of the 103 currently-licensed reactors is likely to exceed 80,000 tonnes.[21] Reactor licensees have shown strong interest in obtaining license extensions which, if granted, would lead to the production of a substantial additional amount of spent fuel.

Summary

To summarize the preceding paragraphs, it is clear that thousands of tonnes of spent fuel will be stored at reactor sites for several decades to come, in pools and/or ISFSIs. Similar amounts of fuel might be stored at away-from-reactor ISFSIs. Moreover, it is entirely possible that the Yucca Mountain repository will not open, with the result that the entire national inventory of spent fuel will be stored for decades, perhaps for 100 years or more, at reactor sites (in pools and/or ISFSIs) and/or at away-from-reactor ISFSIs. It is therefore imperative that each ISFSI is planned to allow for its possible extended use. The NRC has begun to recognize this need, by performing research to determine if dry storage of spent fuel can safely continue for a period of up to 100 years.[22]

2.2 Present Practice for Storing Spent Fuel

The technology that is currently used for storing spent fuel was developed without consideration of the possibility of an attack. Nor was there any consideration of the possibility that spent fuel would be stored for many decades. Instead, the technology has developed incrementally, in response to

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18 Jones, 2002b.

19 DOE, 2002. DOE contemplates the construction of a surface facility for interim storage of spent fuel at Yucca Mountain, especially if emplacement of fuel occurs over a period of 50 years. However, given the cost of this surface facility, a more likely alternative is that fuel would remain in ISFSIs until it could be emplaced in the repository.

20 DOE, 2002. The Nuclear Waste Policy Act limits the total amount of waste that can be placed in a first repository to 70,000 tonnes until a second repository is in operation. DOE plans to use 63,000 tonnes of this capacity for commercial spent fuel. DOE has studied the possible expansion of Yucca Mountain's capacity to include 105,000 tonnes of commercial spent fuel together with other wastes.

21 Macfarlane, 2001a.

22 "Radioactive Waste Safety Research", from NRC website (www.nrc.gov), 23 September 2002.

changing circumstances. Throughout this process, cost minimization has been a top priority.

When the present generation of nuclear power plants was designed, the nuclear industry and the US government both assumed that spent nuclear fuel would be reprocessed. Thus, spent-fuel pools were designed to hold only the amount of spent fuel that a reactor would discharge over a period of a few years. This was accomplished by equipping the pools with low-density, open-frame racks. However, in the mid-1970s the US government banned reprocessing, and the industry faced the prospect of an accumulating inventory of spent fuel.

High-Density Spent-Fuel Pools

Industry's response to growing spent-fuel inventories has been to re-rack spent-fuel pools at progressively higher densities, so that more fuel can be stored in a given pool. Now, pools across the nation are equipped with high-density, closed-frame racks that, in many instances, fill the floor area of the pool from wall to wall. The NRC has allowed this transition to occur despite the fact that a loss of water from a pool equipped with high-density racks can cause the zirconium cladding of the spent fuel to heat up, spontaneously ignite and burn, releasing a large amount of radioactive material to the atmosphere. This hazard is discussed further in Section 4.2.

Dry Storage as a Supplement to High-Density Pools

Consistent with the focus on cost minimization, the nuclear industry has turned to alternative methods of fuel storage only when pools have begun to fill up. Preventing a pool fire has not been a consideration. Thus, dry-storage ISFSIs have not been introduced as an alternative to high-density pool storage. Instead, standard industry practice is to fill a pool to nearly its maximum capacity, then to transfer older spent fuel from the pool to an ISFSI at a rate just sufficient to open up space in the pool for fuel that is discharged from the reactor.[23]

As a part of this strategy, each ISFSI has a modular design. One or more concrete pads are laid in the open air. Each pad supports an array of identical fuel-storage modules that are purchased and installed as needed, so that the ISFSI grows incrementally. Additional pads can be laid as needed.

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[23] In standard practice, the maximum storage capacity of a spent-fuel pool is less than the number of fuel-assembly slots in the pool, to allow for the possibility of offloading a full reactor core. However, preserving the capacity for a full-core offload is not a licensing requirement.

This modular approach to the development of ISFSIs has functional and cost advantages. However, the present implementation of the approach is not driven by security considerations, and is therefore proceeding slowly. Pools remain packed with fuel at high density, and can therefore be readily exploited as radiological weapons. Moreover, the ISFSIs themselves are not designed to resist attack.

Types of Dry-Storage Module

The NRC has approved 14 different designs of dry-storage module for general use in ISFSIs.[24] In each of these designs, the central component of the module is a cylindrical, metal container whose interior is equipped with a metal basket structure into which spent fuel assemblies can be inserted. This container is filled with spent fuel while immersed in a spent-fuel pool. Then, the container's lid is attached, the container is removed from the pool and sealed, its interior is dried and filled with an inert gas (typically helium), and it is transferred to the ISFSI.

Available designs of dry-storage modules for ISFSIs fall into two basic categories. In the first category, the metal container has a thick wall, and no enclosing structure is provided. This type of module is commonly described as a "<u>monolithic cask</u>". In the second category, the metal container has a thin wall and is surrounded by an overpack. Different overpacks are used during the three phases of spent-fuel management. First, during the initial transfer of fuel from a spent-fuel pool to an onsite ISFSI, the metal container is surrounded by a transfer overpack. Second, during storage in an ISFSI, the metal container is surrounded by a storage overpack. Third, if fuel is eventually shipped away from the site, the metal container would be placed inside a transport overpack. The second category of module is described here as an "<u>overpack system</u>".

A Typical Monolithic Cask

One example of a monolithic cask is the CASTOR V/21, which was approved by the NRC in 1990 for general use and is employed at the Surry ISFSI. This cask is about 4.9 meters long and 2.4 meters in diameter, and can hold 21 PWR fuel assemblies. In the storage position the cask axis is vertical. The cask body is made of ductile cast iron with a wall thickness of about 38 cm. Circumferential fins on the outside of the cask body facilitate cooling by natural circulation of ambient air. Fully loaded, this cask weighs about 98 tonnes.[25] The NRC has approved this cask for storage but not for transport,

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[24] "Dry Spent Fuel Storage Designs: NRC Approved for General Use", from NRC website (www.nrc.gov), 20 September 2002.
[25] Raddatz and Waters, 1996.

although CASTOR casks are widely used in Europe for both purposes. CASTOR casks have not been popular in the US market.

Examples of Overpack Systems

One example of an overpack system is the NUHOMS design, which the NRC approved for general use in 1995. In this design, the metal container that holds the spent fuel is about 4.7 meters long and 1.7 meters in diameter, and has a wall thickness of 1.6 cm. This container, which is placed horizontally inside its storage overpack, is made of stainless steel and can hold 24 PWR fuel assemblies or 52 BWR fuel assemblies. The storage overpack is a reinforced-concrete box about 6.1 meters long, 4.6 meters high and 2.7 meters wide, with walls and roof 91 cm thick.[26] Ambient air passes into and out of this structure through vents, and cools the metal container by natural convection. NUHOMS modules are in use at the Davis-Besse site and some other reactor sites.

A second example of an overpack system is the NAC-UMS, which the NRC approved for general use in 2000. In this instance, the metal container is about 4.7 meters long and 1.7 meters in diameter, and has a wall thickness of 1.6 cm. This container, which is made of stainless steel, can hold 24 PWR fuel assemblies or 56 BWR fuel assemblies. The storage overpack is a vertical-axis reinforced-concrete cylinder about 5.5 meters high and 3.5 meters in diameter. The wall of this overpack consists of a steel liner 6.4 cm thick and a layer of concrete 72 cm thick. Ambient air passes into and out of the overpack through vents, and cools the metal container by natural convection. At the Maine Yankee nuclear power plant, which is being decommissioned, sixty NAC-UMS modules are being installed. Most of the modules will be used to store spent fuel discharged from the plant. Some modules will store pieces of the reactor core shroud, which is classified as greater-than-Class C (GTCC) waste.[27]

Monolithic Casks versus Overpack Systems

The two categories of dry-storage module employ distinct design approaches. In a monolithic cask such as the CASTOR, spent fuel is contained within a thick-walled metal cylinder that is comparatively robust.[28] In an overpack system the fuel is contained within a thin-walled metal container that has a

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[26] Ibid.

[27] Stone and Webster, 1999.

[28] The vendor of the CASTOR cask has developed a cheaper type of monolithic cask that is made as a steel-concrete-steel sandwich. This cask, known as CONSTOR, was developed for storage and transport of spent fuel from Russian reactors. The vendor states that the CONSTOR cask could be used in the USA. See: Peters et al, 1999.

limited capability to withstand impact, fire or corrosion. The storage overpack employs concrete -- a cheap material -- as its primary constituent. The transfer and transport overpacks can be used multiple times. Thus, an overpack system can be substantially cheaper -- about half as expensive per fuel assembly, according to some reports -- than a monolithic cask.

ISFSI Configuration

At ISFSIs in the USA, dry-storage modules are placed on concrete pads in the open air. This approach contrasts with German practice, where dry-storage modules -- usually CASTOR casks -- are placed inside buildings. These buildings are designed to have some resistance to attack from outside using anti-tank weapons. This aspect of their design has been informed by tests conducted in the period 1979-1980. At one German reactor site -- Neckarwestheim -- the ISFSI is inside a tunnel built into the side of a hill.[29]

Another feature of the US approach to ISFSI design, consistent with the high priority assigned to cost minimization, is that dry-storage modules are packed closely together in large numbers. In illustration, consider the ISFSI that is proposed for the Diablo Canyon site in California. This facility would hold up to 140 of Holtec's HI-STORM 100 dry-storage modules, whose design is similar to the NAC-UMS system described above. These modules would sit on concrete pads, 20 casks per pad in a 4 by 5 array. Initially, two pads would be built. Ultimately, as the ISFSI expanded, seven pads would be positioned side by side, covering an area about 150 meters by 32 meters. Each module would be a vertical-axis cylinder about 3.7 meters in diameter and 5.9 meters high. The center-to-center spacing of modules would be about 5.5 meters, leaving a gap of 1.8 meters between modules. A security fence would surround the area needed for this array, at a distance of about 15 meters from the outermost modules. That fence would in turn be surrounded by a second fence, at a distance of about 30 meters from the outermost modules.[30]

2.3 Present Security Arrangements

One could reasonably expect that the defense strategy for a nuclear-facility site would be a component of a strategy for homeland security, which would itself be a component of an overall strategy for national security. Moreover, one could expect that the site-level strategy would provide a defense in depth. (See Section 4.4 of this report for an explanation of defense in depth.) Logical planning of this kind may eventually occur. However, at present, the security

29 Janberg, 2002.
30 PG&E, 2001a.

arrangements for US nuclear facilities are not informed by any strategic vision.

Differing Positions on the Threat of Attack

For several decades it has been clear to many people that nuclear power plants and other commercial nuclear facilities are potential targets of acts of malice or insanity, including highly destructive acts. The NRC has repeatedly rebuffed citizens' requests that this threat be given the depth of analysis that would be expected, for example, in an environmental impact statement (EIS).[31] This history is illustrated by a September 1982 ruling by the Atomic Safety and Licensing Board (ASLB) in the operating-license proceeding for the Harris plant. The intervenor, Wells Eddleman, had proffered a contention alleging, in part, that the plant's safety analysis was deficient because it did not consider the "consequences of terrorists commandeering a very large airplane.....and diving it into the containment." In rejecting this contention the ASLB stated:[32]

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

In this statement, the ASLB correctly described the design basis for US nuclear power plants. However, other design bases are possible. In the early 1980s the

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31 In illustration of this continuing policy, on 18 December 2002 the NRC Commissioners dismissed four licensing interventions calling for EISs that consider the potential for malicious acts at nuclear facilities. One intervention, by the state of Utah, addressed the proposed ISFSI at Skull Valley. The other three interventions, by citizen groups, addressed: a proposed spent-fuel-pool expansion at Millstone Unit 3; a proposed MOX-fuel-fabrication facility; and proposed license renewals for the McGuire and Catawba nuclear power plants.
32 ASLB, 1982.

reactor vendor ASEA-Atom developed a preliminary design for a commercial reactor known as the PIUS reactor. The design basis for the PIUS reactor included events such as equipment failures, operator errors and earthquakes, but also included: (i) takeover of the plant for one operating shift by knowledgeable saboteurs equipped with large amounts of explosives; (ii) aerial bombardment with 1,000-pound bombs; and (iii) abandonment of the plant by the operators for one week.[33] It seems likely that this design basis would also provide protection against a range of other assaults, including the impact of a large, fuel-laden aircraft. Clearly, ASEA-Atom foresaw a world in which acts of malice could pose a significant threat to nuclear facilities. The NRC has never exercised an equivalent degree of foresight.

A Brief History

Some US nuclear facilities have been specifically designed to resist attack. For example, in the early 1950s five heavy-water reactors were built at the Savannah River site in South Carolina, to produce plutonium and tritium for use in US nuclear weapons. In order to resist an attack by the USSR using nuclear weapons, the reactors were dispersed across a large site and hardened against blast. The reactor buildings were designed to withstand an external blast of 7 psi, the overpressure that could be experienced at about 2 miles from a 1-megatonne surface burst. However, the purpose was to preserve the reactors' ability to produce weapons material after an attack, rather than to protect the public from a release of radioactive material. Indeed, these reactors had minimal safety systems when they first entered service. Safety systems were added over the years, but the reactors' safety standards never approached the level that is expected for commercial reactors.[34]

In 1950, the Reactor Safeguards Committee of the US Atomic Energy Commission (AEC) produced a report -- designated WASH-3 -- that considered the potential for reactor accidents and estimated the offsite effects of an accident. This report gave special attention to sabotage as a potentially important cause of reactor accidents. About 16 years later, during the construction license proceedings for Turkey Point Units 3 and 4 in Florida, an intervenor raised the question of an attack on these nuclear power plants from a hostile country (i.e., Cuba). The AEC held that it was not responsible for providing protection against such an attack.[35] This position remains enshrined in the NRC's regulation 10 CFR 50.13, which states:[36]

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[33] Hannerz, 1983.
[34] Thompson and Sholly, 1991.
[35] Okrent, 1981, pp 18-19.
[36] NRC Staff, 2002.

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

Pursuant to this regulation, the NRC's licensees are not required to design or operate nuclear facilities to resist enemy attack. However, events have forced the NRC to progressively modify this position, so as to require greater protection against acts of malice or insanity. A series of incidents, including the 1993 bombing of the World Trade Center in New York, eventually forced the NRC to introduce, in 1994, regulations requiring licensees to defend nuclear power plants against vehicle bombs. The terrorist events of 11 September 2001 forced the NRC to require additional, interim measures by licensees to protect nuclear facilities, and are also forcing the NRC to consider strengthening its regulations in this area. Nevertheless, present NRC regulations require only a light defense of nuclear facilities.

NRC Regulations for Defending Nuclear Facilities

Present NRC regulations for the defense of nuclear facilities are focused on site security. As described in Section 4.4, below, site security is one of four types of measure that, taken together, could provide a defense in depth against acts of malice or insanity. The other three types of measure are, with some limited exceptions, ignored in present NRC regulations and requirements.[37]

At a nuclear power plant or an ISFSI, the NRC requires the licensee to implement a set of physical protection measures. According to the NRC, these measures provide defense in depth by taking effect within defined areas with increasing levels of security. In fact, these measures provide only a fraction of the protection that could be provided by a comprehensive defense-in-depth strategy. Within the outermost physical protection area, known as the Exclusion Area, the licensee is expected to control the area but is not required to employ fences and guard posts for this purpose. Within the Exclusion area is a Protected Area encompassed by physical barriers including one or more fences, together with gates and barriers at points of entry. Authorization for unescorted access within the Protected Area is based on background and behavioral checks. Within the Protected Area are Vital

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[37] For information about the NRC's present regulations and requirements for nuclear-facility defense, see: the NRC website (www.nrc.gov) under the heading "Nuclear Security and Safeguards", 2 September 2002; Markey, 2002; Meserve, 2002; and NRC, 2002.

Areas and Material Access Areas that are protected by additional barriers and alarms; unescorted access to these locations requires additional authorization.

Associated with the physical protection areas are measures for detection and assessment of an intrusion, and for armed response to an intrusion. Measures for intrusion detection include guards and instruments whose role is to detect a potential intrusion and notify the site security force. Then, security personnel seek additional information through means such as direct observation and closed-circuit TV cameras, to assess the nature of the intrusion. If judged appropriate, an armed response to the intrusion is then mounted by the site security force, potentially backed up by local law enforcement agencies and the FBI.

The Design Basis Threat

The design of physical protection areas and their associated barriers, together with the design of measures for intrusion detection, intrusion assessment and armed response, is required to accommodate a "design basis threat" (DBT) that is specified by the NRC in 10 CFR 73.1. The DBT for an ISFSI is less demanding than that for a nuclear power plant. At a nuclear power plant, the dominant sources of hazard are the reactor and the spent-fuel pool(s). In theory, both of these items receive the same level of protection, but in practice the reactor has been the main focus of attention. At present, the DBT for a nuclear power plant has the following features:[38]

> "(i) A determined violent external assault, attack by stealth, or deceptive actions, of several persons with the following attributes, assistance and equipment: (A) Well-trained (including military training and skills) and dedicated individuals, (B) inside assistance which may include a knowledgeable individual who attempts to participate in a passive role (e.g., provide information), an active role (e.g., facilitate entrance and exit, disable alarms and communications, participate in violent attack), or both, (C) suitable weapons, up to and including hand-held automatic weapons, equipped with silencers and having effective long range accuracy, (D) hand-carried equipment, including incapacitating agents and explosives for use as tools of entry or for otherwise destroying reactor, facility, transporter, or container integrity or features of the safeguards system, and (E) a four-wheel drive land vehicle used for transporting personnel and their hand-carried equipment to the proximity of vital areas, and

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[38] 10 CFR 73.1, Purpose and Scope, from the NRC web site (www.nrc.gov), 2 September 2002.

(ii) An internal threat of an insider, including an employee (in any position), and

(iii) A four-wheel drive land vehicle bomb."

For an ISFSI, the DBT is the same as for a nuclear power plant except that it does not include the use of a four-wheel-drive land vehicle, either for transport of personnel and equipment or for use as a vehicle bomb. This is true whether the ISFSI is at a new site or a reactor site. Thus, an ISFSI at a reactor site will be less protected than the reactor(s) and spent-fuel pool(s) at that site. At a reactor site or a new site, an ISFSI will be vulnerable to attack by a vehicle bomb. (Note: An NRC order of October 2002 to reactor-site ISFSI licensees, as discussed below, might require vehicle-bomb protection at reactor-site ISFSIs. Measures required by this order have not been disclosed.)

Interim, Additional Requirements by the NRC

After the events of 11 September 2001, the NRC concluded that its requirements for nuclear power plant security were inadequate. Accordingly, the NRC issued an order to licensees of operating plants in February 2002, and similar orders to licensees of decommissioning plants in May 2002 and reactor-site ISFSI licensees in October 2002, requiring "certain compensatory measures", also described as "prudent, interim measures", whose purpose is to "provide the Commission with reasonable assurance that the public health and safety and common defense and security continue to be adequately protected in the current generalized high-level threat environment".[39] The additional measures required by these orders have not been publicly disclosed, but the NRC Chairman has stated that they include:[40]

(i) increased patrols;
(ii) augmented security forces and capabilities;
(iii) additional security posts;
(iv) vehicle checks at greater stand-off distances;
(v) enhanced coordination with law enforcement and military authorities;
(vi) additional restrictions on unescorted access authorizations;
(vii) plans to respond to plant damage from explosions or fires; and
(viii) assured presence of Emergency Plan staff and resources.

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[39] The quoted language is from page 2 of the NRC's order of 25 February 2002 to all operating power reactor licensees. Almost-identical language appears in the NRC's orders of 23 May 2002 to all decommissioning power reactor licensees and 16 October 2002 to all ISFSI licensees who also hold 10 CFR 50 licenses.
[40] Meserve, 2002.

In addition to requiring these additional security measures, the NRC has established a Threat Advisory System that warns of a possible attack on a nuclear facility. This system uses five color-coded threat conditions ranging from green (low risk of attack) to red (severe risk of attack). These threat conditions conform with those used by the Office of Homeland Security. Also, the NRC is undertaking what it describes as a "top-to-bottom review" of its security requirements. The NRC has stated that it expects that this review will lead to revision of the present DBT. The review is not proceeding on any specific schedule.

Limitations of the Design Basis Threat

A cursory examination of the present DBT reveals significant limitations. For example, this threat does not include aircraft bombs (e.g., fuel-laden commercial aircraft, light aircraft packed with high explosive) or boat bombs.[41] This threat does not include lethal chemical weapons as instruments for disabling security personnel. This threat allows for one vehicle bomb, but not for a subsequent vehicle bomb that gains access to a vital area after the first bomb has breached a security barrier. Also, this threat envisions a small attacking force equipped with light weapons, rather than a larger force (e.g., 20 persons) equipped with heavier weapons such as anti-tank missiles. In sum, the present DBT is inadequate in light of the present threat environment. The compensatory measures required by the NRC's recent orders do not correct this deficiency.[42]

3. The Potential for Attacks on Nuclear Facilities

3.1 A Brief History

There is a rich history of events which show that acts of malice or insanity pose a significant threat to nuclear facilities around the world.[43] Consider some examples. Nuclear power plants under construction in Iran were repeatedly bombed from the air by Iraq in the period 1984-1987. Yugoslav Air Force fighters made a threatening overpass of the Krsko nuclear plant in Slovenia -- which was operating at the time -- a few days after Slovenia declared independence in 1991. So-called research reactors in Iraq were destroyed by aerial bombing by Israel in 1981 and by the United States in 1991. In 1987, Iranian radio threatened an attack by unspecified means on US nuclear plants if the United States attacked launch sites for Iran's Silkworm anti-ship missiles. Bombs damaged reactors under construction in Spain in

[41] An NRC Fact Sheet (NRC, 2002) mentions new measures "against water-borne attacks", but it does not appear that these measures provide significant protection against boat bombs.
[42] POGO, 2002.
[43] Thompson, 1996.

1977 and in South Africa in 1982. Anti-tank missiles struck a nuclear plant under construction in France in 1982. North Korean commandos were killed while attempting to come ashore near a South Korean plant in 1985. These and other events illustrate the "external" threat to nuclear plants. Numerous crimes and acts of sabotage by plant personnel illustrate the "internal" threat.

Vehicle Bombs

The threat posed to nuclear facilities by vehicle bombs became clearly apparent from an October 1983 attack on a US Marine barracks in Beirut. In a suicide mission, a truck was driven at high speed past a guard post and into the barracks. A gas-boosted bomb on the truck was detonated with a yield equivalent to about 5 tonnes of TNT, destroying the building and killing 241 Marines. In April 1984 a study by Sandia National Laboratories titled "Analysis of Truck Bomb Threats at Nuclear Facilities" was presented to the NRC. According to an NRC summary:[44] "The results show that unacceptable damage to vital reactor systems could occur from a relatively small charge at close distances and also from larger but still reasonable size charges at large setback distances (greater than the protected area for most plants)." Eventually, in 1994, the NRC introduced regulations that require reactor licensees to install defenses (gates, barriers, etc.) against vehicle bombs. The NRC was spurred into taking this action by two incidents in February 1993. In one incident, a vehicle bomb was detonated in a parking garage under the World Trade Center in New York. In the other incident, a man recently released from a mental hospital crashed his station wagon through the security gate of the Three Mile Island nuclear plant and rammed the vehicle under a partly-opened door in the turbine building.

Suicidal Aircraft Attack

The threat of suicidal aircraft attack on symbolic or high-value targets became clearly apparent from three incidents in 1994.[45] In April 1994 a Federal Express flight engineer who was facing a disciplinary hearing was travelling as a passenger on a company DC-10. He stormed the cockpit, severely wounded all three members of the crew with a hammer, and tried to gain control of the aircraft. The crew regained control with great difficulty. Federal Express employees said that the flight engineer was planning to crash into a company building. In September 1994 a lone pilot crashed a stolen single-engine Cessna into the grounds of the White House, just short of the President's living quarters. In December 1994 four Algerians hijacked an Air France Airbus 300, carrying 20 sticks of dynamite. The aircraft landed in

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[44] Rehm, 1984.
[45] Wald, 2001.

Marseille, where the hijackers demanded that it be given a large fuel load -- three times more than necessary for the journey -- before flying to Paris. Troops killed the hijackers before this plan could be implemented. French authorities determined that the hijackers planned to explode the aircraft over Paris or crash it into the Eiffel Tower.

The Insider Threat

The incident involving the Federal Express flight engineer illustrates the vulnerability of industrial systems, including nuclear plants, to "internal" threats. That vulnerability is further illustrated by a number of incidents. In December 2000, Michael McDermott killed seven co-workers in a shooting rampage at an office building in Massachusetts. He had worked at the Maine Yankee nuclear plant from 1982 to 1988 as an auxiliary operator and operator before being terminated for exhibiting unstable behavior.[46] In 1997, Carl Drega of New Hampshire stockpiled weapons and killed four people -- including two state troopers and a judge -- on a suicide mission. He had passed security clearances at three nuclear plants in the 1990s.[47] In October 2000 a former US Army sergeant pleaded guilty to assisting Osama bin Laden in planning the bombing of the US embassy in Nairobi, which occurred in 1998.[48] In June 1999, a security guard at the Bradwell nuclear plant in Britain hacked into the plant's computer system and wiped out records. It emerged that he had never been vetted and had two undisclosed criminal convictions.[49] These and other incidents demonstrate clearly that it is foolish to ignore or downplay the "internal" threat of acts of malice or insanity at nuclear plants.

The General Threat of Terrorism

The events mentioned in the preceding paragraphs occurred against a background of numerous acts of terrorism around the world. Many of these acts have been highly destructive. US facilities have been targets on many occasions, as illustrated by the bombing of the US embassy in Beirut in 1983, the embassies in Nairobi and Dar es Salaam in 1998, and the USS Cole in 2000. There have been repeated warnings that the threat of terrorism is growing and could involve the US homeland. For example, in 1998 three authors with high-level government experience wrote:[50]

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46 Barnard and Kerber, 2001.
47 Ibid.
48 Goldman, 2000.
49 Maguire, 2001.
50 Carter et al, 1998.

> "Long part of the Hollywood and Tom Clancy repertory of nightmarish scenarios, catastrophic terrorism has moved from far-fetched horror to a contingency that could happen next month. Although the United States still takes conventional terrorism seriously, as demonstrated by the response to the attacks on its embassies in Kenya and Tanzania in August, it is not yet prepared for the new threat of catastrophic terrorism."

Some years ago the US Department of Defense established an advisory commission on national security in the 21st century. This commission -- often known as the Hart-Rudman commission because it was co-chaired by former Senators Gary Hart and Warren Rudman -- issued reports in September 1999, April 2000 and March 2001. The findings in the September 1999 report included the following:[51]

> "America will become increasingly vulnerable to hostile attack on our homeland, and our military superiority will not entirely protect us..............States, terrorists and other disaffected groups will acquire weapons of mass destruction and mass disruption, and some will use them. Americans will likely die on American soil, possibly in large numbers."

It is clear that the potential for acts of malice or insanity at nuclear facilities -- including highly destructive acts -- has been foreseeable for many years, and has been foreseen. However, the terrorist attacks on the World Trade Center and the Pentagon on 11 September 2001 provided significant new information. These attacks conclusively demonstrated that the threat of highly-destructive acts of malice or insanity is a clear and present danger, and that no reasonable person can regard this threat as remote or speculative. According to press reports, US authorities have obtained information suggesting that the hijackers of United Airlines flight 93, which crashed in Pennsylvania on 11 September 2001, were planning to hit a nuclear plant.[52] This may be true or false, or the truth may never be known. Whatever the truth is, it would be foolish to regard nuclear plants as immune from attack.

Estimating the Probability of an Attack on a Nuclear Facility

The NRC has a longstanding policy of dismissing citizens' concerns about nuclear-facility accidents if the probability of such accidents is, in the agency's judgement, low. A body of analytic techniques known as probabilistic risk

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[51] Commission on National Security, 1999.

[52] Rufford et al, 2001.

assessment (PRA) has been developed to support such judgements.[53] However, the NRC Staff has conceded that it cannot provide a quantitative assessment of the probability of an act of malice at a nuclear facility. In a memo to the NRC Commissioners, the Staff has stated:[54]

> "The staff, as a result of its ongoing work with the Federal national security agencies, has determined that the ability to quantify the likelihood of sabotage events at nuclear power plants is not currently supported by the state-of-the-art in PRA methods and data. The staff also believes that both the NRC and the other government stakeholders would need to conduct additional research and expend significant time and resources before it could even attempt to quantify the likelihood of sabotage events. In addition, the national security agencies, Intelligence Community, and Law Enforcement Agencies do not currently quantitatively assess the likelihood of terrorist, criminal, or other malevolent acts."

To date, there has been no determined attack on a US civilian nuclear facility. At present, we cannot quantitatively estimate the probability of such an attack in the future. However, from a qualitative perspective, it is clear that the probability is significant.

3.2 The Strategic Context

In considering the need to defend civilian nuclear facilities, one is obliged to take a broad view of the security environment. An ISFSI, for example, may remain in service for 100 years or more. During that period the level of risk will vary but the cumulative risk will continue to grow. Thus, the ISFSI's designer should take a conservative position in specifying a DBT. That position should be informed by a sober assessment of the range of threats that may be manifested over coming decades.

A Turbulent World?

A number of strategic analysts have warned that world affairs may become more turbulent over the coming decades. Analysts have pointed to destabilizing factors that include economic inequality, poverty, political grievances, nationalism, environmental degradation and the weakening of international institutions. For example, a 1995 RAND study for the US Department of Defense contains the statement:[55]

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[53] The state of the art of PRA can be illustrated by: NRC, 1990. For a critique of PRA, see: Hirsch et al, 1989.

[54] Travers, 2001.

[55] Kugler, 1995, page xv.

> "If the worst does transpire, the world could combine the negative features of nineteenth-century geopolitics, twentieth-century political passions, and twenty-first century technology: a chronically turbulent world of unstable multi-polarity, atavistic nationalism, and modern armaments."

As another example, the Stockholm Environment Institute (SEI) has identified a range of scenarios for the future of the world over the coming decades, and has studied the policies and actions that will tend to make each scenario come true. In summarizing this work, SEI states:[56]

> "In the critical years ahead, if destabilizing social, political and environmental stresses are addressed, the dream of a culturally rich, inclusive and sustainable world civilization becomes plausible. If they are not, the nightmare of an impoverished, mean and destructive future looms. The rapidity of the planetary transition increases the urgency for vision and action lest we cross thresholds that irreversibly reduce options -- a climate discontinuity, locking-in to unsustainable technological choices, and the loss of cultural and biological diversity."

SEI has specifically considered the implications of the September 2001 terrorist attacks, concluding:[57]

> "Certainly the world will not be the same after 9/11, but the ultimate implications are indeterminate. One possibility is hopeful: new strategic alliances could be a platform for new multinational engagement on a wide range of political, social and environmental problems. Heightened awareness of global inequities and dangers could support a push for a more equitable form of global development as both a moral and a security imperative. Popular values could eventually shift toward a strong desire for participation, cooperation and global understanding. Another possibility is ominous: an escalating spiral of violence and reaction could amplify cultural and political schisms; the new military and security priorities could weaken democratic institutions, civil liberties and economic opportunity; and people could grow more fearful, intolerant and xenophobic as elites withdraw to their fortresses."

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[56] Raskin et al, 2002, page 11.
[57] Ibid.

Nuclear Facilities as Symbolic Targets

In view of the range of possibilities for world order or turbulence over the coming decades, it would be prudent to assume that any US civilian nuclear facility could be the subject of a determined attack. Moreover, civilian nuclear facilities may be especially prime targets because of their symbolic connection with nuclear weapons. The US government flaunts its superiority in nuclear weapons and rejects any constraint on these weapons through international law.[58] At the same time, the government has signaled its willingness to attack Iraq because that country might acquire a nuclear weapon. It would be prudent to assume that this situation will motivate terrorist groups to search for ways to attack US nuclear facilities. For example, a terrorist group possessing a crude nuclear weapon might choose to use that weapon on a US civilian nuclear facility for two reasons. First, because the target would be highly symbolic. Second, because the radioactive fallout from the weapon would be greatly amplified.

The Domestic Threat

There is a natural tendency to look outside the country for sources of threat. However, an attack on a nuclear facility could also originate within the United States. The national strategy for homeland security contains the statement:[59]

> "Terrorist groups also include domestic organizations. The 1995 bombing of the Murrah Federal Building in Oklahoma City highlights the threat of domestic terrorist acts designed to achieve mass casualties. The US government averted seven planned terrorist acts in 1999 -- two were potentially large-scale, high-casualty attacks being organized by domestic extremist groups."

3.3 The US Government's Response to this Threat

The preceding discussion shows that there is a significant potential for a determined attack on a US civilian nuclear facility. Such an attack could employ a level of sophistication and violence that is characteristic of military operations. However, in most attack scenarios the attacking group would have a negligible capability for direct confrontation with US military forces. Thus, it is appropriate to think of an attack of this kind as a form of asymmetric warfare. The attacking group, be it domestic or foreign, will have

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58 Deller, 2002; Scarry, 2002.

59 Office of Homeland Security, 2002, page 10.

a set of political objectives. For symbolic and practical reasons, the attackers will prefer to obtain their weapons and logistical resources inside the USA.

US Strategy for National Security and Homeland Security

The White House has recently articulated a national security strategy for the United States.[60] This strategy rests primarily on the use of military force outside the country, to deter, disrupt or punish potential attackers. In support of this concept, the strategy asserts the right to conduct unilateral, pre-emptive attacks around the world, and repudiates the International Criminal Court. Homeland security is regarded as a secondary form of defense, as illustrated by the statement:[61]

> "While we recognize that our best defense is a good offense, we are also strengthening America's homeland security to protect against and deter attack."

A strategy for homeland security has been articulated by the White House.[62] This document contains a section titled "Defending against Catastrophic Threats", and that section begins with an aerial photograph of a nuclear power plant. Yet, the section does not mention civilian nuclear facilities or the NRC. Thus, at the highest levels of strategic planning, the US government has nothing to say about the potential for an attack on a nuclear facility, or about the measures that could be taken to defend against such attacks. In fact, the US government seems largely unaware of this threat, and has delegated its responsibility to the NRC. As described in Section 2.3 of this report, the NRC's response to the threat has been limited and ineffectual.

Imbalance in National Security and Defense Planning

Inattention to the vulnerability of nuclear facilities is symptomatic of a larger imbalance in national security and defense planning. As another example of imbalance, consider the threat of attack on the United States by inter-continental ballistic missiles (ICBMs). Large expenditures are devoted to the development of technologies that might, ultimately, allow missile warheads to be intercepted. Yet, in considering the respective risks of attack by missiles or other means, the US National Intelligence Council has stated:[63]

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[60] White House, 2002.
[61] Ibid, page 6.
[62] Office of Homeland Security, 2002.
[63] National Intelligence Council, 2001, page 18.

> "Nonmissile means of delivering weapons of mass destruction [WMD] do not provide the same prestige or degree of deterrence and coercive diplomacy associated with ICBMs. Nevertheless, concern remains about options for delivering WMD to the United States without missiles by state and nonstate actors. Ships, trucks, airplanes, and other means may be used. In fact, the Intelligence Community judges that US territory is more likely to be attacked with WMD using nonmissile means, primarily because such means:
>
> - Are less expensive than developing and producing ICBMs.
> - Can be covertly developed and employed; the source of the weapon could be masked in an attempt to evade retaliation.
> - Probably would be more reliable than ICBMs that have not completed rigorous testing and validation programs.
> - Probably would be much more accurate than emerging ICBMs over the next 15 years.
> - Probably would be more effective for disseminating biological warfare agent than a ballistic missile.
> - Would avoid missile defenses."

The defense analyst John Newhouse has contrasted the high level of attention given to the ICBM threat with the lack of effort in other areas of defense. He notes that the State Department advised US embassies in early 2001 that the principal threat to US security is the use of long-range missiles by rogue states, and comments:[64]

> "This dubious proposition -- an article of faith within parts of the defense establishment -- obscured existing and far more credible threats from truly frightful weapons, some of which are within the reach of terrorists. They include Russia's shaky control of its nuclear weapons and weapons-usable material; the vulnerability of US coastal cities and military forces stationed abroad to medium-range missile systems, ballistic and cruise; the vulnerabilities of all cities to chemical and biological weapons, along with so-called suitcase weapons and other low-tech delivery expedients. Vehicles that contain potentially destructive amounts of stored energy are a major source of concern, as is one of their most attractive potential targets, a nuclear spent-fuel storage facility."

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[64] Newhouse, 2002, page 43.

Nuclear Facilities as Targets

It is clear that US civilian nuclear facilities are candidates for attack under conditions of asymmetric warfare. They are large, fixed targets that are, at present, lightly defended. In the eyes of an enemy, they can be regarded as pre-deployed radiological weapons. They can be attacked using comparatively low levels of technology. Given the United States' overt reliance on nuclear weapons as offensive instruments, civilian nuclear facilities offer highly symbolic targets. In light of these considerations, it is remarkable that the US government has largely ignored this threat.

The Danger of an Offense-Dominated Strategy

At present, US policy for national security assigns a higher priority to offensive actions worldwide than to defensive actions within the homeland. This is a tradition of many years' standing. However, in the contemporary era of asymmetric warfare, this policy can be dangerous.[65] If our vulnerable infrastructure -- including nuclear facilities, the airlines, etc. -- is poorly defended, we may feel compelled to use military force aggressively around the world, in order to pre-empt or punish attackers. Such action poses the risk of arousing hostility and promoting anarchy, leading to new attacks on our homeland. The potential exists for an escalating spiral of violence. Strategic analysts have warned of this danger, both before and after the terrorist events of September 2001.[66]

3.4 A Balanced Response to the Threat

The United States needs a balanced, mature strategy for national defense and international security. Within that strategy, it needs a balanced strategy for homeland security. Finally, as a part of homeland security, the nation needs a defense-in-depth strategy to protect its civilian nuclear facilities. At present, all three levels of strategy are deficient.

The Role of Protection in a Balanced Response

Articulation of a balanced strategy at all three levels is a task beyond the scope of this report. However, this report does articulate, in Sections 4.4 and 4.5

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[65] A recent essay (Betts, 2003) argues that US decision makers have neglected the risk that Iraq's leaders will strike back at the US homeland if we attack Iraq. Betts' essay focusses on the potential for Iraq to use chemical or biological weapons on US territory, but the same general arguments apply to the potential for an attack on a US civilian nuclear facility.
[66] See, for example: Sloan, 1995; Martin, 2002 (see especially the chapter by Conrad Crane in this volume); Mathews, 2002; Conetta, 2002; Crawford, 2003; and Newhouse, 2002.

respectively, a defense-in-depth strategy for nuclear facilities and a national strategy for robust storage of spent fuel. As an illustration of how these protective measures could fit within a higher-level strategy, consider Carl Conetta's suggestion of a four-pronged campaign against the terrorist group al-Qaeda. The four prongs would be:[67]

> "(i) squeeze the blood flow of the organization -- its financial support system;
> (ii) throw more light on the organization's members and components through intelligence gathering activities;
> (iii) impede the movement of the organization by increasing the sensitivity of screening procedures at critical gateways -- borders, financial exchanges, arms markets, and transportation portals; and
> (iv) improve the protection of high-value targets."

The importance of protecting high-value targets is emphasized in the recent report of a high-level task force convened by the Council on Foreign Relations and chaired by former Senators Gary Hart and Warren Rudman. One of the report's major findings is:[68]

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

The Need for Proactive Planning

Other findings by the Council on Foreign Relations' task force also deserve attention. For example, their report points out that proactive planning will yield better protection at lower cost than reacting after each new attack.[69] This point is especially important in an era of asymmetric warfare, when opponents will employ unfamiliar tactics. Planning techniques such as "competitive strategies" and "net assessment" have been developed to accommodate such situations. In discussing net assessment, one author has stated:[70]

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67 Conetta, 2002, page 3.
68 Hart et al, 2002, pp 14-15.
69 Ibid, page 16.
70 Hoffman, 2002, pp 3-4.

"One of the advantages of such an approach is that it credits the opponent with having a brain and a will, which Clausewitz suggested is also fundamental to war. Rarely do US strategists credit adversaries with being as cunning or adaptive as they usually turn out to be. It is well to be reminded on occasion that any opponent has strategies and options at his disposal too. The essence of the homeland security challenge is based on this consideration."

4. Defending Nuclear Power Plants and Spent Fuel

4.1 Potential Modes and Instruments of Attack

It is not appropriate to publish a detailed discussion of scenarios whereby a nuclear power plant or a spent-fuel-storage facility might be successfully attacked. However, it must be assumed that attackers are technically sophisticated and possess considerable knowledge about individual nuclear facilities. For decades, engineering drawings, photographs and technical analyses have been openly available for every civilian nuclear facility in the USA. This material is archived at many locations around the world. Thus, a public discussion, in general terms, of potential modes and instruments of attack will not assist attackers. Indeed, such a discussion is needed to ensure that appropriate defensive actions are taken.

Safety Systems and their Vulnerability

The safe operation of a US commercial reactor or a spent-fuel pool depends upon the fuel in the reactor or the pool being immersed in water. Moreover, that water must be continually cooled to remove fission heat or radioactive decay heat generated in the fuel. A variety of systems are used to ensure that water is available and is cooled, and that other safety-related functions -- such as shutdown of the fission reaction when needed -- are performed. Some of the relevant systems -- such as the switchyard -- are highly vulnerable to attack. Other systems are located inside reinforced-concrete structures -- such as the reactor auxiliary building -- that provide some degree of protection against attack. The reactor itself is inside a containment structure. At some plants, but not all, the reactor containment is a concrete structure that is highly reinforced and comparatively robust. Spent-fuel pools have thick concrete walls but are typically covered by lightweight structures.

Attack through Brute Force or Indirectly?

A group of attackers equipped with highly-destructive instruments could take a brute-force approach to attacking a reactor or a spent-fuel pool. Such an approach would aim to directly breach the reactor containment and primary cooling circuit, or to breach the wall or floor of a spent-fuel pool. Alternatively, the attacking group could take an indirect approach, and many such approaches will readily suggest themselves to technically-informed attackers. Insiders, or outsiders who have taken over the plant, could obtain a release of radioactive material without necessarily employing destructive instruments. Some attack scenarios will involve the disabling of plant personnel, which could be accomplished by armed attack, use of lethal chemical weapons, or radioactive contamination of the site by an initial release of radioactive material.

Vulnerability of ISFSIs

Dry-storage ISFSIs differ from reactors and spent-fuel pools in that their operation is entirely passive. Thus, each dry-storage module in an ISFSI must be attacked directly. To obtain a release of radioactive material, the wall of the fuel container must be penetrated from the outside, or the container must be heated by an external fire to such an extent that the containment envelope fails. The attack could also exploit stored chemical energy in the zirconium cladding of spent fuel inside the module. Combustion of this cladding in air, if initiated, would generate heat that could liberate radioactive material from the fuel to the outside environment. A knowledgeable attacker could combine penetration of the fuel container with the initiation of combustion.

Relevance of Site-Security Barriers

In some attack scenarios that involve the use of destructive instruments, the attackers may need to carry these instruments, by hand or in a vehicle, to the point of application. Such an action would require the overcoming of site-security barriers. In other scenarios, the instruments could be launched from a position outside some or all of these barriers.

Commercial Aircraft as Instruments of Attack

One instrument that an attacking group will consider is a fuel-laden commercial aircraft. As indicators of the forces that could accompany the impact of such an aircraft, consider the weights and fuel capacities of some typical jetliners.[71] The Boeing 737-300 has a maximum takeoff weight of 56-63 tonnes and a fuel capacity of 20-24 thousand liters. The Boeing 747-400 has a maximum takeoff weight of 363-395 tonnes and a fuel capacity of 204-217 thousand liters. The Boeing 757 has a maximum takeoff weight of 104-116 tonnes and a fuel capacity of 43 thousand liters. The Boeing 767 has a

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[71] Jackson, 1996.

maximum takeoff weight of 136-181 tonnes and a fuel capacity of 63-91 thousand liters.

Commercial jet fuel typically has a heat of combustion of about 38 MJ per liter. For comparison, 1 kilogram of TNT will yield 4.2 MJ of energy. Thus, complete combustion of 1 liter of jet fuel will yield energy equivalent to that from 9 kilograms of TNT. Complete combustion of 100 thousand liters of jet fuel -- about half the fuel capacity of a Boeing 747-400 -- will yield energy equivalent to that from 900 tonnes of TNT. Thus, the impact of a fuel-laden aircraft could lead to a violent fuel-air explosion. Fuel-air munitions have been developed that yield more than 5 times the energy of their equivalent weight in TNT, and create a blast overpressure exceeding 1,000 pounds per square inch.[72] A fuel-air explosion arising from an aircraft impact will be less efficient than a munition in converting combustion energy into blast, but could generate a highly-destructive blast if fuel vapor accumulates in a confined space before igniting.

Explosive-Laden, General-Aviation Aircraft

The attacking group might choose to use an explosive-laden, general-aviation aircraft as an instrument of attack. Such an aircraft could be much easier to obtain than a large commercial aircraft. In 1999, about 219,000 general-aviation aircraft were in use in the USA.[73] Of these, about 172,000 had piston engines, 5,700 were turboprops, 7,100 were turbojets and 7,400 were helicopters.[74] In the piston-engine category, about 21,000 aircraft had two engines, the remainder having one engine. The general-aviation fleet in 2002 must be similar to that in 1999.

It is clear that terrorist groups can readily obtain and use explosive materials. Such use is a tragic accompaniment to political disputes around the world. Moreover, explosives are easily obtainable within the USA. In 2001, about 2.4 million tonnes of explosives were sold in the USA. Most of this material consisted of blasting agents and oxidizers used for mining, quarrying and construction. Much of the blasting material consisted of mixtures of ammonium nitrate and fuel oil, which are readily-available materials. It is also noteworthy that current law in many US states allows high explosives to be purchased without a permit or a background check.[75]

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[72] Gervasi, 1977.

[73] Data from the website of the General Aviation Manufacturers Association (www.generalaviation.org), 30 September 2002.

[74] The remainder of the fleet consisted of gliders, balloons/blimps and experimental aircraft.

[75] Information from the website of the Institute of Makers of Explosives (www.ime.org), 30 September 2002.

Anti-Tank Missiles

Another instrument of attack that could be used is an anti-tank missile. Large numbers of these missiles exist around the world, and they can be obtained by many terrorist groups. As an example, consider the tube-launched, optically-tracked, wire-guided (TOW) anti-tank missile system, which is now marketed by Raytheon.[76] This system is said to be the most successful anti-tank missile system in the world. It first entered service with the US Army in 1970 and is currently in use by more than 40 military forces. As of 1991, more than 460,000 TOW missiles had been produced, and the cumulative production up to 2002 must be substantially higher. The TOW missile has a maintenance-free storage life of 20 years, and all versions of the missile can be fired from any TOW launcher. TOW systems have been sold to countries such as Colombia, Iran, Lebanon, Pakistan, Somalia, Yugoslavia and South Yemen, so it must be presumed that they can be obtained by terrorist groups. There is no indication from available literature that the TOW missile or launcher is self-disabling if it passes into inappropriate hands. In connection with the availability of systems of this kind, it is interesting to note that, in August 2002, federal agents seized more than 2,300 unregistered armor-piercing missiles from a private, counter-terrorism training school in New Mexico.[77]

Modern anti-tank missiles are reliable, accurate and easy to use. They are capable of penetrating considerable thicknesses of armor plate using a shaped-charge warhead that is designed for this purpose. Some types of missile can also be equipped with a general-purpose warhead that would be used for attacking targets such as fortified bunkers and gun emplacements. All types can be set up and reloaded comparatively quickly. Consider the TOW missile system as an example. The launcher can be mounted on a light vehicle or carried a short distance and mounted on the ground on a tripod. A late-model TOW launcher weighs about 93 kilograms, the guidance set about 24 kilograms and each missile about 22 kilograms. A rate of fire of about two rounds per minute can be sustained, and the missile has a range in excess of 3,000 meters. It is reported that an early-model TOW missile can blow a hole as much as two feet in diameter in the armor of a Soviet T-62 tank, or cut through three feet of concrete. Later-model TOW missiles are more capable.[78]

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[76] Information from: Hogg, 1991; Gervasi, 1977; Raytheon website (www.raytheon.com), 26 September 2002; US Marine Corps website (www.hqmc.usmc.mil), 26 September 2002; and Canadian Army website (www.army.forces.gc.ca), 27 September 2002.
[77] Reuters, 2002.
[78] Information from: Hogg, 1991; Gervasi, 1977; Raytheon website (www.raytheon.com), 26 September 2002; US Marine Corps website (www.hqmc.usmc.mil), 26 September 2002; and Canadian Army website (www.army.forces.gc.ca), 27 September 2002.

Nuclear Weapons

A nuclear weapon could be used to attack a civilian nuclear facility. This possibility was a source of concern during the Cold War, and there is a body of technical and policy literature on this subject.[79]. Russia retains the capability to attack US nuclear facilities using ICBMs with thermonuclear warheads, and might be motivated at some future date to threaten or implement such an attack. A greater concern in the current period is that a sub-national group, with or without the assistance of a government, might use a comparatively low-yield fission weapon -- perhaps one with an explosive yield in the vicinity of 10 kilotonnes of TNT equivalent -- to attack a US nuclear facility. The means of delivery might be a land vehicle or a general-aviation aircraft. Such a weapon would be difficult to obtain, but many knowledgeable experts have warned that the fissionable material for a simple nuclear weapon could be diverted from poorly-secured stocks in Russia and elsewhere.[80] There is even the possibility that a complete nuclear weapon will be diverted. A high-level group advising the US government has examined the security of nuclear weapons and fissile material in Russia, concluding:[81]

> "The most urgent unmet national security threat to the United States today is the danger that weapons of mass destruction or weapons-usable material in Russia could be stolen and sold to terrorists or hostile nation states and used against American troops abroad or citizens at home. This threat is a clear and present danger to the international community as well as to American lives and liberties."

Summary

Table 1, on the following page, briefly summarizes the characteristics of some potential modes of attack on civilian nuclear facilities, and the present defense against each mode. Other modes of attack can be identified, and an attacking group might use several modes simultaneously or in sequence. The characteristics of each mode are, of course, more complex and varied than is shown in Table 1. Nevertheless, this table shows that determined, knowledgeable attackers have a range of options available to them.

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[79] See, for example: Fetter, 1982; Fetter and Tsipis, 1980; Ramberg, 1984; and SIPRI, 1981.
[80] See, for example: Baker, Cutler et al, 2001; Bunn et al, 2002; and Sokolski and Riisager, 2002.
[81] Baker, Cutler et al, 2001, first page of Executive Summary.

MODE OF ATTACK	CHARACTERISTICS	PRESENT DEFENSE
Commando-style attack	• Could involve heavy weapons and sophisticated tactics • Successful attack would require substantial planning and resources	Alarms, fences and lightly-armed guards, with offsite backup
Land-vehicle bomb	• Readily obtainable • Highly destructive if detonated at target	Vehicle barriers at entry points to Protected Area
Anti-tank missile	• Readily obtainable • Highly destructive at point of impact	None if missile launched from offsite
Commercial aircraft	• More difficult to obtain than pre-9/11 • Can destroy larger, softer targets	None
Explosive-laden smaller aircraft	• Readily obtainable • Can destroy smaller, harder targets	None
10-kilotonne nuclear weapon	• Difficult to obtain • Assured destruction if detonated at target	None

TABLE 1

SOME POTENTIAL MODES OF ATTACK ON CIVILIAN NUCLEAR FACILITIES

4.2 Vulnerability to Attack

The preceding section of this report describes, in deliberately general terms, the potential modes and instruments of attack on a nuclear power plant or an ISFSI. No sensitive information is disclosed. In discussing the vulnerability of nuclear facilities to such attacks, one must be similarly careful to avoid disclosing sensitive information. In this context, the word "vulnerability" refers to the potential for an act of malice or insanity to cause a release of radioactive material to the environment. At the site of a nuclear power plant or an ISFSI, most of the radioactive material at the site is in the reactor(s), the spent-fuel pool(s) and the ISFSI modules.

Requirements for a Vulnerability Study

Every US commercial reactor has been subjected to a PRA-type study by the licensee. This study addressed the reactor's potential to experience accidents, but did not consider acts of malice or insanity. No spent-fuel pool or ISFSI has been subjected to a PRA-type study or a study of its vulnerability to acts of malice or insanity. Indeed, there has never been a comprehensive, published study of the vulnerability of any US nuclear facility to acts of malice or insanity. Spurred by the terrorist events of September 2001, the NRC has sponsored secret, ongoing studies on the vulnerability of nuclear facilities to impact by a large commercial aircraft. Available information suggests that these studies are narrow in scope and will provide limited guidance regarding the overall vulnerability of nuclear facilities.

A comprehensive study of a facility's vulnerability would begin by identifying a range of potential attacks on the facility. The probability of each potential attack would be qualitatively estimated, with consideration of the factors (e.g., international events, changing availability of instruments of attack) that could alter the probability over time. Site-specific factors affecting the feasibility and probability of attack scenarios include local terrain and the proximity of coastlines, airports, population centers and national symbols. A variety of modes and instruments of attack would be considered, of the kind discussed in Section 4.1.

After identifying a range of potential attacks, a comprehensive study would examine the vulnerability of the subject facility to those attacks. This could be done by adapting and extending known techniques of PRA, with an emphasis on the logical structure of PRA rather than the numerical probabilities of events. The analysis would consider the potential for interactions among facilities at a site. For example, a potentially important interaction could be the prevention of personnel access at one facility (e.g., a spent-fuel pool) due to a release of radioactive material at another facility (e.g., a reactor). Attention would be given to the potential for "cascading" scenarios in which attacks at some parts of a nuclear-power-plant site (e.g., control room, switchyard, diesel generators) lead to releases from reactors and/or spent fuel pools that were not directly attacked.

Working with Partial or Misleading Information

In the absence of any comprehensive study of vulnerability, one is obliged to rely upon partial information. Also, one must contend with misleading information disseminated by the nuclear industry. An egregious example is a recent paper in Science, a journal that is usually sound.[82] Two points illustrate the low scientific quality of this paper. First, the paper cites an experiment performed at Sandia National Laboratories as proof that an aircraft cannot penetrate the concrete wall of a reactor containment. In response, Sandia officials have stated that the test has no relevance to the structural behavior of a containment wall, a fact that is readily evident from the nature of the test.[83] Second, the paper states, in connection with the vulnerability of spent-fuel shipping casks, that "there is virtually nothing one could do to these shipping casks that would cause a significant public hazard".[84] A report prepared by Sandia for the NRC is cited in support of this statement.[85] Yet, examination of the Sandia report reveals that it considers only the effects on a shipping cask of impact and fire pursuant to a truck or train accident. The Sandia report does not address the effects of, for example, attack by a TOW missile, a vehicle bomb, or a manually-placed charge.

Aircraft Impact

A rough, preliminary indication of the vulnerability of a nuclear power plant to aircraft impact can be obtained from the PRA for the Seabrook reactor. This reactor is a 4-loop Westinghouse PWR with a large, dry containment, and is one of only four US reactors that were specifically designed to resist impact by an aircraft, a 6-tonne aircraft in the case of Seabrook.[86] The Seabrook PRA finds that any direct impact on the containment by an aircraft weighing more than 37 tonnes will lead to penetration of the containment and a breach in the reactor coolant circuit. Also, the Seabrook PRA finds that a similar impact on the control building or auxiliary building will inevitably lead to a core melt.[87] All of the typical, commercial aircraft mentioned in Section 4.1 of this

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82 Chapin et al, 2002.
83 Jones, 2002a.
84 Chapin et al, 2002, page 1997.
85 Sprung et al, 2000.
86 Markey, 2002, page 73.
87 PLG, 1983, pp 9.3-10 to 9.3-11.

report weigh considerably more than 37 tonnes. Moreover, the Seabrook PRA does not consider the effects of a fuel-air explosion and/or fire as an accompaniment to an aircraft impact. Finally, this PRA, like other PRAs, does not consider malicious acts. Thus, it does not consider, for example, an attack on the Seabrook reactor by an explosive-laden, general-aviation aircraft.

Analytic techniques are available for estimating the effects that aircraft impact will have on the structures and equipment of a nuclear facility. Two recent studies illustrate the use of such techniques. First, the Nuclear Energy Institute (NEI), an industry lobbying organization, has released some preliminary findings from an analysis of aircraft impact on reactor containments and spent-fuel facilities.[88] The analysis itself will not be published, so the findings cannot be verified. Second, a group at Purdue University has released the results of its simulation of the aircraft impact on the Pentagon that occurred on 11 September 2001.[89] A simulation of this kind could be performed for aircraft impact on a nuclear facility. The Purdue group employs commercially-available software and, in contrast to NEI, seems willing to publish its analysis.

The analytic techniques discussed in the preceding paragraph focus on the kinetic energy of the impacting aircraft and its contents. Effects of an accompanying fuel-air explosion and/or fire are given, at best, a crude analysis. A 1982 review by Argonne National Laboratory of the state of the art for aircraft-impact analysis stated:[90]

> "Based on the review of past licensing experience, it appears that fire and explosion hazards have been treated with much less care than the direct aircraft impact and the resulting structural response. Therefore, the claim that these fire/explosion effects do not represent a threat to nuclear power plants has not been clearly demonstrated."

Examination of PRAs and related studies for nuclear facilities shows that the Argonne statement remains valid today. Indeed, in view of the large amount of energy that can be liberated in a fuel-air fire or explosion, previous analyses of aircraft impacts may have substantially underestimated the vulnerability of nuclear facilities to such impacts.

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88 NEI, 2002.

89 Purdue, 2002; Sozen et al, 2002.

90 Kot et al, 1982, page 78.

Vulnerability of Spent-Fuel Pools

The vulnerability of spent-fuel pools deserves special attention because these pools contain large amounts of long-lived radioactive material that could be liberally released to the atmosphere during a fire.[91] The potential for such a fire exists because the pools have been equipped with high-density racks. In the 1970s, the spent-fuel pools of US nuclear power plants were typically equipped with low-density, open-frame racks. If water were partially or totally lost from such a pool, air or steam could circulate freely throughout the racks, providing convective cooling to the spent fuel. By contrast, the high-density racks that are used today have a closed structure. To suppress criticality, each fuel assembly is surrounded by solid, neutron-absorbing panels, and there is little or no gap between the panels of adjacent cells. In the absence of water, this configuration allows only one mode of circulation of air and steam around a fuel assembly -- vertically upward within the confines of the neutron-absorbing panels.

If water is totally lost from a high-density pool, air will pass downward through available gaps such as the gap between the pool wall and the outer faces of the racks, will travel horizontally across the base of the pool, will enter each rack cell through a hole in its base, and will rise upward within the cell, providing cooling to the spent fuel assembly in that cell. If the fuel has been discharged from the reactor comparatively recently, the flow of air may be insufficient to remove all of the fuel's decay heat. In that case, the temperature of the fuel cladding may rise to the point where a self-sustaining, exothermic oxidation reaction with air will begin. In simple terms, the fuel cladding -- which is made of zirconium alloy -- will begin to burn. The zirconium-alloy cladding can also enter into a self-sustaining, exothermic oxidation reaction with steam. Other exothermic oxidation reactions can also occur. For simplicity, the occurrence of one or more of the possible reactions can be referred to as a pool fire.

In many scenarios for loss of water from a pool, the flow of air that is described in the preceding paragraph will be blocked. For example, a falling object (e.g., a fuel-transfer cask) might distort rack structures, thereby blocking air flow. As another example, an attack might cause debris (e.g., from the roof of the fuel handling building) to fall into the pool and block air flow. The presence of residual water in the bottom of the pool would also block air flow. In most scenarios for loss of water, residual water will be present for significant periods of time. Blockage of air flow, for whatever reason, will lead to ignition of fuel that has been discharged from a reactor for long

[91] The NRC has published a variety of technical documents that address spent-fuel-pool fires. The most recent of these documents is: Collins et al, 2000.

periods -- potentially 10 years or longer.[92] The NRC Staff failed to understand this point for more than two decades.[93]

Loss of Water from a Pool

Partial or total loss of water from a spent-fuel pool could occur through leakage, evaporation, siphoning, pumping, displacement by objects falling into the pool, or overturning of the pool. These modes of loss of water could arise, directly or indirectly, through a variety of attack scenarios. As a simple example, consider leakage as a direct result of aircraft impact on the wall of a pool. This example represents a brute-force attack on the model of 11 September 2001. Other attack options will suggest themselves to knowledgeable attackers.

An NRC Staff study includes a crude, generic analysis of the conditional probability that aircraft impact will cause a loss of water from a spent fuel pool.[94] The pool is assumed to have a 5-ft-thick reinforced-concrete wall. Impacting aircraft are divided into the categories "large" (weight more than 5.4 tonnes) and "small" (weight less than 5.4 tonnes). The Staff estimates that the conditional probability of penetration of the pool wall by a large aircraft is 0.45, and that 50 percent of penetration incidents involve a loss of water which exposes fuel to air. Thus, the Staff estimates that, for impact of a large aircraft, the conditional probability of a loss of water sufficient to initiate a pool fire is 0.23 (23 percent).

Facility Interactions and Cascading Scenarios

An earlier paragraph in Section 4.2 of this report mentions the potential for interactions among facilities on a site, and points out that a potentially important interaction could be the prevention of personnel access at one facility (e.g., a spent-fuel pool) due to a release of radioactive material at another facility (e.g., a reactor). This type of interaction was partially addressed during a licensing proceeding for the Harris nuclear power plant. In that proceeding, the NRC Staff conceded that a fire in one spent-fuel pool would preclude the provision of cooling and makeup to nearby pools, thereby leading to evaporation of water from the nearby pools followed by fires in those pools.[95] This situation would arise mostly because the initial fire would contaminate the site with radioactive material, generating high radiation fields that preclude personnel access. An analogous situation could

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[92] The role of residual water in promoting ignition of old fuel is discussed in: Thompson, 1999, Appendix D.

[93] Thompson, 2002a, Section II.

[94] Collins et al, 2000, page 3-23 and Appendix 2D.

[95] Parry et al, 2000, paragraph 29.

arise in which the release of radioactive material from a damaged reactor precludes the provision of cooling and makeup to nearby pools. For example, an attack on a reactor could lead to a rapid-onset core melt with an open containment, accompanied by a raging fire. That event would create high radiation fields across the site, potentially precluding any access to the site by personnel. One can envision a variety of "cascading" scenarios, in which there might eventually be fires in all of the pools at a site, accompanied by core-melt events at all of the reactors.

Progression of a Pool Fire

A pool fire could begin comparatively soon after water is lost from a pool. For example, suppose that most of the length of the fuel assemblies is exposed to air, but the flow of air to the base of the racks is precluded by residual water or a collapsed structure. In that event, fuel heatup would be approximately adiabatic. Fuel discharged for 1 month would ignite in less than 2 hours, and fuel discharged for 3 months would ignite in about 3 hours. The fire would then spread to older fuel. Once a fire has begun, it could be impossible to extinguish. Spraying water on the fire could feed an exothermic zirconium-steam reaction that would generate flammable hydrogen. High radiation fields could preclude the approach of firefighters.

Vulnerability of Dry-Storage Modules

The dry-storage modules used at ISFSIs are passively safe, as discussed in Section 4.1 of this report. Thus, an attacking group that seeks to obtain a radioactive release from an ISFSI must attack each module directly. To obtain a release of radioactive material, the wall of the fuel container must be penetrated from the outside, or the container must be heated by an external fire to such an extent that the containment envelope fails. In addition, a technically-informed and appropriately-equipped attacker could exploit stored chemical energy in the zirconium cladding of the stored spent fuel. Such an attacker would arrange for penetration of the container to be accompanied by the initiation of combustion of the cladding in air. Combustion would generate heat that could liberate radioactive material from the fuel to the outside environment. Initiation of combustion could be facilitated by the presence of zirconium hydride in the fuel cladding, which is a characteristic of high-burnup fuel. The NRC Staff has noted that zirconium hydride can experience auto-ignition in air.[96] This point had been brought to the Staff's attention by the NRC's Advisory Committee on Reactor Safeguards.[97]

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[96] Collins et al, 2000, page A1B-3.
[97] Powers, 2000, page 3.

There is a body of literature that addresses aspects of the vulnerability of dry-storage modules for ISFSIs. Consider some examples. First, NAC International has analyzed the impact of a Boeing 747-400 aircraft on a NAC-UMS storage module of the type discussed in Section 2.2 of this report.[98] According to NAC, this analysis shows that failure of the fuel container would not occur, either from impact or fire. Second, analyses of aircraft impact have been done in Germany in connection with the licensing of ISFSIs that employ CASTOR casks. In Germany, ISFSIs are typically located inside buildings to provide some protection against anti-tank missiles, a practice which creates the potential for pooling of jet fuel following an aircraft impact. As a result, the intensity and duration of fire has become a key issue in technical debates about the release of radioactive material following an aircraft impact.[99] Third, in a test done in Germany in 1992, a shortened CASTOR cask containing simulated fuel assemblies made from depleted uranium was penetrated by a static, shaped charge, in order to simulate attack by an anti-tank missile.[100] The metal jet created by the shaped charge caused a small amount of finely-divided uranium to be released from the cask, but this test did not account for several important factors that are discussed in the following paragraph. Fourth, analyses of aircraft, cruise-missile and dummy-bomb impact on a dry-storage module have been done in connection with the licensing of the proposed Skull Valley ISFSI. The accompanying technical debate suggests that the magnitude of the radioactive release following penetration of a fuel container would be sensitive to the fraction of a fuel assembly's inventory of radionuclides, such as cesium-137, that would be present in the pellet-cladding gap region.[101]

Requirements for a Comprehensive Study of Dry-Storage Vulnerability

The literature that is exemplified in the preceding paragraph addresses only some of the attack scenarios and physical-chemical phenomena that would be addressed in a comprehensive assessment of the vulnerability of dry-storage modules. Such an assessment would consider a range of instruments of attack, including anti-tank missiles, manually-placed charges, a vehicle bomb or an aircraft bomb. Modes of attack that promote zirconium ignition would be considered. Factors that would be accounted for include: (i) the presence of zirconium hydride in fuel cladding; (ii) radioactive-decay heat in fuel pellets; (iii) a pre-attack temperature characteristic of an actual, operating module; and (iv) source-term phenomena (such as the gap inventory of radionuclides) that are characteristic of high-burnup fuel. There is no evidence from

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98 McCough and Pennington, 2002.

99 Hirsch, 2002.

100 Lange et al, 2002.

101 Resnikoff, 2001.

published literature that a comprehensive vulnerability assessment of this kind has been made. Some components of a comprehensive assessment may have been performed secretly. For example, there are rumors of NRC-sponsored tests that have combined penetration of a fuel container with incendiary effects. Given the information that is available, it is prudent to assume that a variety of modes and non-nuclear instruments of attack could release to the atmosphere a substantial fraction of the radioactive inventory of a dry-storage module.

Attack Using a Nuclear Weapon

As indicated in Section 4.1 of this report, it is prudent to assume that a low-yield nuclear weapon (with a yield of perhaps 10 kilotonnes of TNT equivalent) might be used as an instrument of attack at a nuclear power plant or an ISFSI. A thorough assessment of the vulnerability to such an attack of the reactor(s), spent-fuel pool(s) and ISFSI modules at a site would require detailed analysis. Absent such an analysis, rough judgements can be made.

Consider, for example, a 10-kilotonne ground burst at an unhardened, surface-level ISFSI of the usual US type. It seems reasonable to assume that any module within the crater area would, as a result of blast effects and heating by the fireball, become divided into fragments, many of them small enough to travel downwind for many kilometers before falling to earth. A 10-kilotonne ground burst over sandstone, which is perhaps representative of an ISFSI, would yield a crater about 68 meters in diameter and 16 meters deep.[102]

As an indication of the potential release of radioactive material following a nuclear detonation at an ISFSI, consider a 10-kilotonne groundburst at an ISFSI that employs vertical-axis fuel-storage modules with a center-to-center distance of 5.5 meters, as would be the case for the proposed Diablo Canyon facility. Given a large, square array of such modules, about 120 modules would fall within the 68-meter diameter of the anticipated crater. Thus, it is plausible to assume that 100 percent of the volatile radionuclides (such as cesium-137) in 120 modules, together with a lesser fraction of the non-volatile radionuclides, would be carried downwind in a radioactive plume. This quantity could be an over-estimate, because the ISFSI has finite dimensions and is not an infinite array, or it could be an under-estimate, because damage to modules outside the crater is not considered. Note that a NAC-UMS module, as used at Maine Yankee, can hold 24 PWR fuel assemblies or 56

[102] Glasstone, 1962, Chapter VI.

BWR fuel assemblies.[103] The HI-STORM 100 modules that would be used at the proposed Diablo Canyon ISFSI can each hold 32 PWR fuel assemblies.[104]

Comparative Risks of Attack Options

Section 4.1 of this report shows that a determined, knowledgeable group has available to it a range of options for attacking reactors, spent-fuel pools and ISFSIs. The preceding paragraphs of Section 4.2 provide a brief discussion of the vulnerability of reactors, pools and ISFSI modules to such options. These topics could be discussed more comprehensively, but that task was beyond the scope of this report. A comprehensive assessment -- whose underlying technical analysis should not, for obvious reasons, be openly published -- would identify a wide range of attack scenarios and would estimate their outcomes. Such an assessment could provide a perspective on the comparative risks of attack options.

As an illustration of comparative risk, consider three potential options for obtaining a release of radioactive material. Option I would be an attack on an ISFSI using a 10-kilotonne nuclear weapon delivered by a general-aviation aircraft. Delivery of the weapon could be straightforward, given the lack of air defense at ISFSIs, but the weapon would be difficult to obtain. Thus, this attack option seems to have a comparatively low probability. However, it would yield a large release of radioactive material. Option II would be a commando-style attack in which the attackers seize control of a nuclear power plant, initiate a reactor-core melt, breach the reactor containment, and initiate the removal of water from the spent-fuel pool(s) by siphoning and/or breaching the pool(s). Such an attack is feasible but would require substantial planning and resources and might be repulsed. Thus, this attack option may have a comparatively low probability. It would, however, yield a large release of radioactive material. Option III would be an attack on one or more ISFSI modules using anti-tank missiles fired from one or more offsite locations. In a plausible time window the attackers might, for example, be able to obtain 10 hits. The probability of this option is presumably substantially greater than the probability of Options I and II, but the release of radioactive material would be considerably smaller.

4.3 Consequences of Attack

The offsite radiological consequences of a potential attack on a nuclear facility can be estimated with widely-used, computer-based models. In order to apply such a model, one must have an estimate of the accident "source term". The

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[103] Stone and Webster, 1999.
[104] PG&E, 2001a.

source term is a set of characteristics -- magnitude, timing, etc. -- that describe a potential release of radioactive material to the atmosphere. Using this source term, together with weather data for the release site, the model can estimate the magnitude of each of a range of radiological impacts at specified locations downwind.

Cesium-137 as an Indicator

A full analysis of this type is beyond the scope of this report. Instead, some scoping calculations are presented here, focussing on one radioactive isotope -- cesium-137. This isotope is a useful indicator of the potential, long-term consequences of a release of radioactive material. Cesium-137 has a half-life of 30 years, and accounts for most of the offsite radiation exposure that is attributable to the 1986 Chernobyl reactor accident, and for about half of the radiation exposure that is attributable to fallout from nuclear weapons tests in the atmosphere.[105] Cesium is a volatile element that would be liberally released during nuclear-facility accidents or attacks. For example, an NRC study has concluded that a generic estimate of the release fraction of cesium isotopes during a spent-fuel-pool fire -- that is, the fraction of the pool's inventory of cesium isotopes that would reach the atmosphere -- is 100 percent.[106] It is reasonable to assume such a high release fraction because cesium is volatile, because a fire in a high-density pool, once initiated, would eventually involve all of the fuel in the pool, and because pool buildings are not designed as containment structures.

Inventories of Cesium-137 at Indian Point

The Indian Point site provides an illustration of the inventories of cesium-137 at nuclear facilities. Three nuclear power plants have been built at this site. Unit 1 had a rated power of 590 MW (thermal) and operated from 1962 to 1974.[107] Unit 2 has a rated power of 2,760 MW (thermal), commenced operating in 1974, and remains operational. Unit 3 has a rated power of 2,760 MW (thermal), commenced operating in 1976, and remains operational. Unit 2 and Unit 3 each employ a four-loop Westinghouse PWR with a large, dry containment. The reactor cores of Unit 2 and Unit 3 each contain 193 fuel assemblies.[108]

Unit 2 and Unit 3 are each equipped with one spent-fuel pool. The capacity of the Unit 2 pool is 1,374 fuel assemblies, while the capacity of the Unit 3 pool is

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105 DOE, 1987.

106 Sailor et al, 1987.

107 Thompson and Beckerley, 1973, Table 4-1.

108 Larson, 1985, Table A-2.

1,345 fuel assemblies.[109] Both pools employ high-density racks. As of November 1998, the Unit 2 pool contained 917 fuel assemblies, while the Unit 3 pool contained 672 fuel assemblies.[110] It can be assumed that the number of fuel assemblies in each pool has increased since November 1998.

The inventory of cesium-137 in the Indian Point pools can be readily estimated. Three parameters govern this estimate -- the number of spent fuel assemblies, their respective burnups, and their respective ages after discharge. Assuming a representative, uniform burnup of 46 GW-days per tonne, one finds that the 917 fuel assemblies that were in the Unit 2 pool in November 1998 now contain about 42 million Curies (460 kilograms) of cesium-137. The 672 fuel assemblies that were in the Unit 3 pool in November 1998 now contain about 31 million Curies (350 kilograms) of cesium-137. Additional amounts of cesium-137 would be present in any fuel assemblies that have been added to these pools since November 1998.

For comparison, the cores of the Indian Point Unit 2 and Unit 3 reactors each contain about 6 million Curies (67 kilograms) of cesium-137. Also, it should be noted that the Chernobyl reactor accident of 1986 released about 2.4 million Curies (27 kilograms) of cesium-137 to the atmosphere. That release represented 40 percent of the Chernobyl reactor core's inventory of 6 million Curies (67 kg) of cesium-137.[111] Also, atmospheric testing of nuclear weapons led to the deposition of about 20 million Curies (220 kilograms) of cesium-137 across the land and water surfaces of the Northern Hemisphere.[112]

As another comparison, consider a HI-STORM 100 dry-storage module that contains 32 PWR fuel assemblies. Assuming that these fuel assemblies have an average post-discharge age of 20 years, this module would contain about 1.3 million Curies (14 kilograms) of cesium-137.

Inventories of Cesium-137 at Vermont Yankee

The Vermont Yankee site provides a second illustration of the inventories of cesium-137 at nuclear facilities. At this site there is a single BWR with a rated power of 1,590 MW (thermal) and a Mark I containment. This plant commenced operating in 1972 and remains operational. The reactor core contains 368 fuel assemblies.[113] One spent-fuel pool is provided at this plant.

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109 "Reactor Spent Fuel Storage", from NRC website (www.nrc.gov), 30 May 2001.
110 Ibid.
111 Krass, 1991.
112 DOE, 1987.
113 Larson, 1985, Table A-1.

The pool is equipped with high-density racks and has a capacity of 2,870 fuel assemblies, with a possible recent increase in this capacity.[114]

In 2000, the Vermont Yankee pool contained 2,439 fuel assemblies.[115] Licensee projections done in 1999 showed the pool inventory increasing to a maximum of 2,687 assemblies in 2004, after which the inventory would decrease until the pool would be empty in 2017. These projections assumed continuing operation of the plant until 2012, transfer of spent fuel from the pool to an on-site ISFSI beginning in 2004, and shipment of fuel to Yucca Mountain beginning in 2010.[116] To date, there has been no license application for an ISFSI at Vermont Yankee. Thus, transfer of fuel to an on-site ISFSI in 2004 is unlikely. As discussed in Section 2.1 of this report, shipment of fuel to Yucca Mountain in 2010 is unlikely.

The inventories of cesium-137 in the Vermont Yankee pool and reactor can be estimated as described above for Indian Point. One can assume that the Vermont Yankee pool now (in January 2003) contains 2,639 fuel assemblies, which have been discharged from the reactor during refuelling outages since 1972.[117] Thus, the pool now contains about 35 million Curies (390 kilograms) of cesium-137. The Vermont Yankee reactor contains about 2.3 million Curies (26 kilograms) of cesium-137.

Land Contamination by Cesium-137 After a Pool Fire

Now consider the potential for a spent-fuel-pool fire at Indian Point or Vermont Yankee. As explained above, it is reasonable to assume that 100 percent of the cesium-137 in a pool would be released to the atmosphere in the event of a fire. The cesium-137 would be released to the atmosphere in small particles that would travel downwind and be deposited on the ground and other surfaces. The deposited particles would emit intense gamma radiation, leading to external, whole-body radiation doses to exposed persons. Cesium-137 would also contaminate water and foodstuffs, leading to internal radiation doses.

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[114] According to information compiled by licensee staff in February 1999 (Weyman, 1999), the licensed storage limit for the Vermont Yankee pool was 2,870 fuel assemblies in 1999, and was projected to increase to 3,355 fuel assemblies in 2001. According to information compiled by the NRC, the capacity of the Vermont Yankee pool in November 1998 was 2,863 assemblies; see "Reactor Spent Fuel Storage", from NRC website (www.nrc.gov), 30 May 2001.

[115] Vermont Yankee, 2000.

[116] Weyman, 1999.

[117] Ibid.

One measure of the scope of radiation exposure attributable to deposition of cesium-137 is the area of land that would become uninhabitable. For illustration, one can assume that the threshold of uninhabitability is an external, whole-body dose of 10 rem over 30 years. This level of radiation exposure, which would represent about a three-fold increase above the typical level of background (natural) radiation, was used in the NRC's 1975 Reactor Safety Study as a criterion for relocating populations from rural areas.

A radiation dose of 10 rem over 30 years corresponds to an average dose rate of 0.33 rem per year.[118] The health effects of radiation exposure at this dose level have been estimated by the National Research Council's Committee on the Biological Effects of Ionizing Radiations.[119] This committee has estimated that a continuous lifetime exposure of 0.1 rem per year would increase the incidence of fatal cancers in an exposed population by 2.5 percent for males and 3.4 percent for females.[120] Incidence would scale linearly with dose, in this low-dose region.[121] Thus, an average lifetime exposure of 0.33 rem per year would increase the incidence of fatal cancers by about 8 percent for males and 11 percent for females. About 21 percent of males and 18 percent of females normally die of cancer.[122] In other words, in populations residing continuously at the threshold of uninhabitability (an external dose rate of 0.33 rem per year), about 2 percent of people would suffer a fatal cancer that would not otherwise occur.[123] Internal doses from contaminated food and water could cause additional cancer fatalities.

The increased cancer incidence described in the preceding paragraph would apply at the boundary of the uninhabitable area. Within that area, the external dose rate from cesium-137 would exceed the threshold of 10 rem over 30 years. At some locations, the dose rate would exceed this threshold by orders of magnitude. Therefore, persons choosing to live within the uninhabitable area would experience an incidence of fatal cancers at a level higher than is set forth above.

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118 At a given location contaminated by cesium-137, the resulting external, whole-body dose received by a person at that location would decline over time, due to radioactive decay and weathering of the cesium-137. Thus, a person receiving 10 rem over an initial 30-year period would receive a lower dose over the subsequent 30 -year period.

119 National Research Council, 1990.

120 Ibid, Table 4-2.

121 The BEIR V committee assumed a linear dose-response model for cancers other than leukemia, and a model for leukemia that is effectively linear in the low-dose range. See National Research Council, 1990, pp 171-176.

122 National Research Council, 1990, Table 4-2.

123 For males, 0.08 x 0.21 = 0.017. For females, 0.11 x 0.18 = 0.020.

Area of Uninhabitable Land After a Pool Fire at Indian Point or Vermont Yankee

For a postulated release of cesium-137 to the atmosphere, the area of uninhabitable land can be estimated from calculations done by Dr Jan Beyea.[124] Four releases of cesium-137 are postulated here. The first postulated release is 42 million Curies, representing the fuel that was present in the Indian Point Unit 2 pool in November 1998. The second postulated release is 31 million Curies, representing the fuel that was present in the Indian Point Unit 3 pool in November 1998. (Actual, present inventories of cesium-137 in the Unit 2 and Unit 3 pools are higher than these numbers, assuming that fuel has been added since November 1998.) The third postulated release is 35 million Curies, representing the present (January 2003) inventory of fuel in the Vermont Yankee pool. The fourth postulated release is 1 million Curies, representing the cesium-137 inventory in a dry-storage ISFSI module that contains 32 PWR fuel assemblies. This fourth release does not represent a pool fire or a predicted release from an ISFSI. Instead, it is a notional release that provides a scale comparison.

For typical weather conditions, assuming that the radioactive plume travels over land rather than out to sea, a release of 42 million Curies of cesium-137 would render about 95,000 square kilometers of land uninhabitable. Under the same conditions, a release of 31 million Curies would render about 75,000 square kilometers uninhabitable, and a release of 35 million Curies would render about 80,000 square kilometers uninhabitable. A release of 1 million Curies would render uninhabitable about 2,000 square kilometers. For comparison, note that the area of New York state is 127,000 square kilometers, while the combined area of Vermont, New Hampshire and Massachusetts is 70,000 square kilometers. The use of a little imagination shows that a spent-fuel-pool fire at Indian Point or Vermont Yankee would be a regional and national disaster of historic proportions, with health, environmental, economic, social and political dimensions.

Cesium-137 Fallout From a Nuclear Detonation

For attack scenarios involving the use of a nuclear weapon on a spent-fuel-storage facility, it is instructive to compare the long-term radiological significance of the nuclear detonation itself with the significance of the release that the detonation could induce. For example, detonation of a 10-kilotonne fission weapon would directly generate about 2 thousand Curies (21

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[124] Beyea et al, 1979.

grams) of cesium-137.[125] Yet, this weapon could release to the atmosphere tens of millions of Curies of cesium-137 from a spent-fuel pool or an unhardened, undispersed ISFSI.

4.4 Defense in Depth

Four types of measure, taken together, could provide a comprehensive, defense-in-depth strategy against acts of malice or insanity at a nuclear facility. The four types of measure, which are described in the following paragraphs, are in the categories: (i) site security; (ii) facility robustness; (iii) damage control; and (iv) emergency response planning. The degree of protection provided by these measures would be greatest if they were integrated into the design of a facility before its construction. However, a comprehensive set of measures could provide significant protection at existing facilities.

Site Security

Site-security measures are those that reduce the potential for implementation of destructive acts of malice or insanity at a nuclear site. Two types of measure fall into this category. Measures of the first type would be implemented at offsite locations, and the implementing agencies might have no direct connection with the site. Airline or airport security measures are examples of measures in this category. Measures of the second type would be implemented at or near the site. Implementing agencies would include the licensee, the NRC and, potentially, other entities (e.g., National Guard, Coast Guard). The physical protection measures now required by the NRC, as discussed in Section 2.3 of this report, are examples of site-security measures of the second type. More stringent measures could be introduced, such as:

(i) establishment of a mandatory aircraft exclusion boundary around the site;
(ii) deployment of an approaching-aircraft detection system that triggers a high-alert status at facilities on the site;
(iii) expansion of the DBT, beyond that now applicable to a nuclear power plant, to include additional intruders, heavy weapons, lethal chemical weapons and more than one vehicle bomb; and
(iv) any ISFSI on the site to receive protection equivalent to that provided for a nuclear power plant.

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[125] SIPRI, 1981, page 76.

Facility Robustness

Facility-robustness measures are those that improve the ability of a nuclear facility to experience destructive acts of malice or insanity without a significant release of radioactive material to the environment. In illustration, the PIUS reactor design, as discussed in Section 2.3, was intended to withstand aerial bombardment by 1,000-pound bombs without suffering core damage or releasing a significant amount of radioactive material to the environment. An ISFSI could be constructed with a similar degree of robustness. At existing facilities, a variety of opportunities are available for enhancing robustness. As a high-priority example, the spent fuel pool(s) at a nuclear power plant could be re-equipped with low-density racks, so that spent fuel would not ignite if water were lost from a pool. As a second example, the reactor of a nuclear power plant could be permanently shut down, or the reactor could operate at reduced power, either permanently or at times of alert. Other robustness-enhancing opportunities could be identified. For a nuclear power plant whose reactor is not permanently shut down, robustness could be enhanced by an integrated set of measures such as:

(i) automated shutdown of the reactor upon initiation of a high-alert status at the plant, with provision for completion of the automated shutdown sequence if the control room is disabled;
(ii) permanent deployment of diesel-driven pumps and pre-engineered piping to be available to provide emergency water supply to the reactor, the steam generators (at a PWR) and the spent fuel pool(s);
(iii) re-equipment of the spent fuel pool(s) with low-density racks, excess fuel being stored in an onsite ISFSI; and
(iv) construction of the ISFSI to employ hardened, dispersed, dry storage.

Damage Control

Damage-control measures are those that reduce the potential for a release of radioactive material from a facility following damage to that facility due to destructive acts of malice or insanity. Measures of this kind could be ad hoc or pre-engineered. One illustration of a damage control measure would be a set of arrangements for patching and restoring water to a spent fuel pool that has been breached. Many other illustrations can be provided. It appears, from the list of additional measures set forth in Section 2.3 of this report, that the NRC's recent orders have required licensees to undertake some planning for damage control following explosions or fires. Additional measures would be appropriate. For example, at a site housing one or more nuclear power plants and an ISFSI, the following damage-control measures could be implemented:

(i) establishment of a damage control capability at the site, using onsite personnel and equipment for first response and offsite resources for backup;
(ii) periodic exercises of damage-control capability;
(iii) establishment of a set of damage-control objectives -- to include patching and restoring water to a breached spent fuel pool, fire suppression in the ISFSI, and provision of cooling to a reactor whose support systems and control room are disabled -- with accompanying plans; and
(iv) provision of equipment and training to allow damage control to proceed on a radioactively-contaminated site.

Offsite Emergency Response

Emergency-response measures are those that reduce the potential for exposure of offsite populations to radiation, following a malice- or insanity-induced release of radioactive material from a nuclear facility. Measures in this category would in many respects be similar to emergency planning measures that are designed to accommodate "accidental" releases of radioactive material arising from human error, equipment failure or natural forces (e.g., earthquake). However, there are two major ways in which malice- or insanity-induced releases might differ from accidental releases. First, a malice- or insanity-induced release might be larger and begin earlier than an accidental release.[126] Second, a malice- or insanity-induced release might be accompanied by deliberate degradation of emergency response capabilities (e.g., the attacking group might block an evacuation route). Accommodating these differences could require additional measures of emergency response. Overall, an appropriate way to improve emergency-response capability at a nuclear-power-plant site could be to implement a model emergency response plan that was developed by a team based at Clark University in Massachusetts.[127] This model plan was specifically designed to accommodate radioactive releases from spent-fuel-storage facilities, as well as from reactors. That provision, and other features of the plan, would provide a capability to accommodate both accidental releases and malice- or insanity-induced releases. Major features of the model plan include:[128]

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[126] Present plans for emergency response do not account for the potential for a large release of radioactive material from spent fuel, as would occur during a pool fire. The underlying assumption is that a release of this kind is very unlikely. That assumption cannot be sustained in the present threat environment.
[127] Golding et al, 1992.
[128] Ibid, pp 8-13.

(i) structured objectives;
(ii) improved flexibility and resilience, with a richer flow of information;
(iii) precautionary initiation of response, with State authorities having an independent capability to identify conditions calling for a precautionary response[129];
(iv) criteria for long-term protective actions;
(v) three planning zones, with the outer zone extending to any distance necessary[130];
(vi) improved structure for accident classification;
(vii) increased State capabilities and power;
(viii) enhanced role for local governments;
(ix) improved capabilities for radiation monitoring, plume tracking and dose projection;
(x) improved medical response;
(xi) enhanced capability for information exchange;
(xii) more emphasis on drills, exercises and training;
(xiii) improved public education and involvement; and
(xiv) requirement that emergency preparedness be regarded as a safety system equivalent to in-plant systems.

4.5 A Strategy for Robust Storage of Spent Fuel

The preceding section of this report sets forth a defense-in-depth strategy for nuclear facilities. This strategy could be implemented at every civilian nuclear facility in the United States. Within the context of that strategy, it would be necessary to establish a nationwide strategy for the robust storage of spent fuel. The strategy must protect all spent fuel that has been discharged from a reactor but has not been emplaced in a repository. Available options for storing this fuel are wet storage in pools and dry storage in ISFSIs.

Timeframe for a Robust-Storage Strategy

As pointed out in Section 2.1 of this report, thousands of tonnes of US spent fuel will remain in interim storage for decades, even if a repository opens at Yucca Mountain. If a repository does not open, the entire national inventory of spent fuel will remain in interim storage for many decades. Thus, the robust-storage strategy for spent fuel must minimize the overall risk of interim storage throughout a period that may extend for 100 years or longer.

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129 A security alert could be a condition calling for a precautionary response.
130 The inner and intermediate zones would have radii of 5 and 25 miles, respectively. As an example of the planning measures in each zone, potassium iodide would be predistributed within the 25-mile zone and made generally accessible nationwide.

Moreover, this interim storage strategy must be compatible with the eventual emplacement of the spent fuel in a repository in a manner that minimizes long-term risk.

Reactor Risk and Spent-Fuel Risk

This report focusses on the risk of a radioactive release from spent fuel. It also, by necessity, discusses the risk of a similar release from a reactor. These risks are closely intertwined in two practical ways. First, many scenarios for a spent-fuel-pool fire involve interactions between the affected pool(s) and the reactor(s) on the site. Second, the security of an at-reactor ISFSI is an adjunct to the security of a nuclear-power-plant site.

A robust-storage strategy for spent fuel could substantially reduce the risk of a radioactive release from spent fuel, at a comparatively low cost. Given the design of US nuclear power plants, there is no obvious strategy for achieving a comparable reduction in reactor risk. Thus, even if a defense-in-depth strategy is implemented for every reactor, a substantial fraction of the present reactor risk will continue to exist as long as the reactors continue to operate.

What should be the risk target for a robust-storage strategy? There are three major considerations that argue for seeking a spent-fuel risk that is substantially lower than the reactor risk. First, measures are available for substantially reducing the spent-fuel risk at a comparatively low cost. Second, storing spent fuel creates no benefit to offset its risk, whereas reactors generate electricity. Third, spent fuel may be in interim storage for 100 years or longer, whereas the present reactors will operate for at most a few more decades.

Elements of a Robust-Storage Strategy

From Sections 4.2 and 4.3 of this report, it is evident that storing spent fuel in high-density pools poses a very high risk. Dry storage of spent fuel, even employing the present practice that is described in Section 2.3, poses a lower risk. Thus, a robust-storage strategy must assign its highest priority to re-equipping each spent fuel pool with low-density racks, in order to reduce the pool's inventory of fuel and to prevent self-ignition and burning of fuel if water is lost from the pool.[131] The excess fuel, for which space would no longer be available in pools, would be transferred to ISFSIs. When a nuclear power plant is shut down, the fuel remaining in its pool(s) would be transferred to an ISFSI after an appropriate period of cooling. These steps would dramatically reduce the overall risk of spent-fuel storage. A further,

[131] Further protection of the spent fuel that remains in pools could be provided by a variety of site-security, facility-robustness and damage-control measures of the kind that are described in Section 4.4 of this report.

substantial reduction of the overall risk would be obtained by employing hardened, dispersed, dry storage at every ISFSI.

Figure 1, on the following page, shows how a robust-storage strategy for spent fuel would operate in a larger context. The robust-storage strategy would have the three elements represented by the three boxes at the base of the figure: low-density pools; hardened dry-storage modules; and dispersed dry-storage modules. In turn, the robust-storage strategy would be one of the elements of facility robustness, which itself would be one of four components of a defense in depth for US civilian nuclear facilities. This defense would contribute to homeland security and national security.

Away-from-Reactor ISFSIs

In a robust-storage strategy, any ISFSI would employ hardened, dispersed dry storage. The essential principles would be the same whether the ISFSI is at a nuclear-power-plant site or at another site such as Skull Valley.

Section 2.1 of this report discusses factors that argue against shipping spent fuel to an away-from-reactor ISFSI. Some of these factors are economic in nature. However, three factors affect the overall risk of interim storage. First, shipment to an away-from-reactor ISFSI would increase the overall transport risk, because fuel would be shipped twice, first from the reactor site to the ISFSI, and then from the ISFSI to the ultimate repository. Second, an away-from-reactor ISFSI would hold a comparatively large inventory of spent fuel, creating a potentially attractive target for an enemy. Third, there is a risk that a large, away-from-reactor ISFSI would become, by default, a permanent repository, despite having no long-term containment capability. These three factors must be considered in minimizing the overall risk of interim storage.

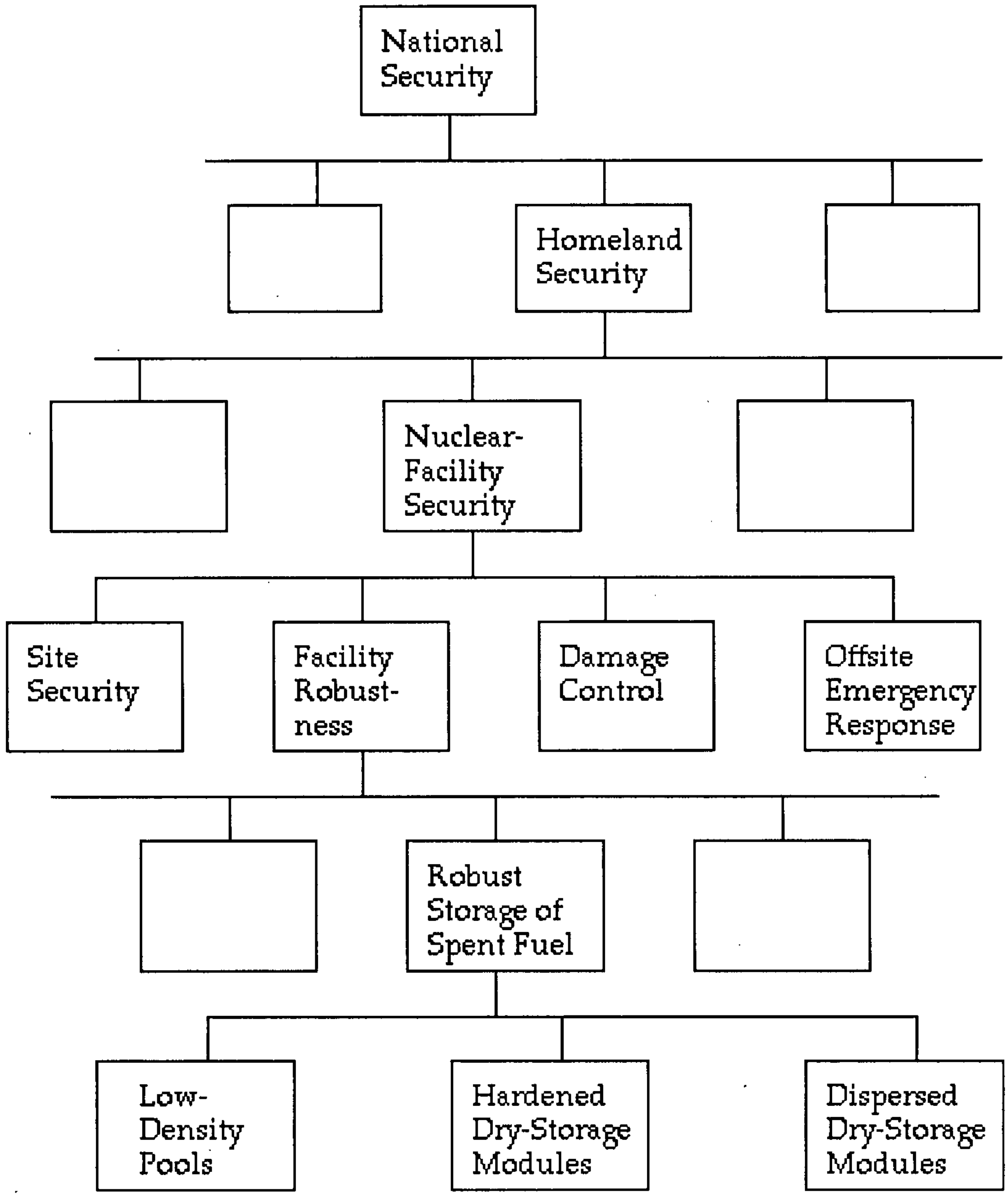

FIGURE 1

ROBUST STORAGE OF SPENT FUEL IN THE CONTEXT OF NATIONAL SECURITY

5. Considerations in Planning Hardened, Dispersed, Dry Storage

5.1 Balancing Short- and Long-Term Risks

Interim storage of spent fuel could lead to eventual emplacement of the fuel in a repository at Yucca Mountain. In this case, fuel would remain in interim storage for several decades. That period is long enough to require action to reduce the very high risk that is posed by pool storage, and the smaller but still significant risk that is posed by unhardened, undispersed ISFSIs. However, in this case the long-term risk posed by spent-fuel management would not be relevant to interim storage. The long-term risk, which will be significant for many thousands of years, would be associated with the Yucca Mountain repository.

Avoiding a Repository by Default

If a repository does not open, a different problem will arise. That problem is the possibility that society will extend the life of interim-storage facilities until they become, by default, repositories for spent fuel. These facilities would function poorly as repositories, and the environment around each facility would become contaminated by radioactive material leaking from the facility. This outcome would pose a substantial long-term risk. The prospect of society acting in this improvident manner may seem far-fetched, but becomes more credible when one examines the history of the Yucca Mountain project. That project is politically driven, and is going forward only because previously-specified technical criteria for a repository have been abandoned.[132]

Any current planning for the implementation of interim storage must account for the possibility that a repository will not open at Yucca Mountain. Thus, the design approach that is adopted for a hardened, dispersed, dry-storage ISFSI must balance two objectives. <u>The first objective</u> is that the facility should be comparatively robust against attack. <u>The second objective</u> is that the facility should not have features that encourage society to allow the facility to become, by default, a repository.

Consideration of the second objective dictates that the ISFSI should not, unless absolutely necessary, be located underground. Therefore, the first objective should be pursued through a design in which the ISFSI modules are stored at grade level (i.e., at the general level of the site). Hardening would then be achieved by placing steel, concrete, gravel or other materials above

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[132] Ewing and Macfarlane, 2002.

and around each module. The remaining protection would be provided by dispersal of the storage modules.

5.2 Cost and Timeframe for Implementation

As discussed in Section 2.1 of this report, forecasts show a rapid expansion in dry-storage capacity across the USA over the coming years. NAC International predicts that about 30 percent of US commercial spent fuel will be in dry-storage ISFSIs by 2010, as compared with 6 percent at the end of 2000. Vendors have developed a comparatively cheap technology for these ISFSIs, in response to to industry preferences. This technology -- the overpack system -- involves the placement of spent fuel into thin-walled metal containers that are stored inside overpacks made primarily from concrete. The resulting modules are placed close together in large numbers on concrete pads in the open air. A preference for vertical-axis modules seems to be emerging.

Required Properties of Dry-Storage Modules

Re-equipping US spent fuel pools with low-density racks would create a large additional demand for dry-storage modules. This demand should be met as quickly as possible, in view of the very high risk that is posed by high-density pool storage. Also, the cost of the additional storage capacity should be minimized, consistent with the achievement of performance objectives. Thus, it is desirable that module designs already approved by the NRC be used. However, any module that is used for a hardened, dispersed ISFSI must be capable, when hardened, of resisting a specified attack. This requirement did not exist when module designs were approved by the NRC. Also, it is desirable that modules be capable of retaining their integrity for 100 years or more, which was not a requirement when module designs were approved by the NRC. A module that does not have a long-life capability may need to be replaced at some point if it is used in an ISFSI that serves for an extended period. Finally, the design of a module should allow for the eventual transport of spent fuel from an ISFSI to a repository.

Meeting the Requirements:
Monolithic Casks versus Overpack Systems

Of the module designs already approved by the NRC, monolithic casks such as the CASTOR are probably more capable of meeting attack-resistance and long-life requirements than are modules that employ a thin-walled metal container inside a concrete overpack. However, monolithic casks are more expensive. Thus, it would be convenient if some of the cheaper and more widely-used module designs proved to be capable of meeting attack-resistance and long-life requirements. This outcome would minimize the cost of offloading fuel from pools to hardened, dispersed dry storage, and would expedite this transition.

The development of detailed requirements for attack resistance and long life is a task beyond the scope of this report. Section 7 of the report sets forth a process for developing attack-resistance requirements, drawing upon experiments. When that process is completed, it will be possible to determine which of the already-approved module designs can be used for hardened, dispersed, dry storage.

5.3 Design-Basis Threat

The specification of a DBT for a nuclear facility inevitably reflects a set of tradeoffs. In the case of a hardened, dispersed, dry-storage ISFSI, five major considerations must be balanced. First, the ISFSI must protect spent fuel against a range of possible attacks. Second, the cost of the ISFSI should not be dramatically higher than the cost of an ISFSI built according to present practice. Third, the timeframe for building of the ISFSI should be similar to the timeframe for building an ISFSI according to present practice. Fourth, the ISFSI should not, unless absolutely necessary, be built underground. Fifth, it should be possible to construct an ISFSI of this kind at every US nuclear-power-plant site.

These considerations suggest a two-tier DBT for a hardened, dispersed, dry-storage ISFSI. This DBT might have the following structure:

<u>Tier I</u>

There should be high confidence that the release of radioactive material from the ISFSI to the environment would not exceed a small, specified amount in the event of a direct attack on any part of the ISFSI by:

(i) a TOW missile;
(ii) a specified manually-placed charge;
(iii) a specified vehicle bomb;
(iv) a specified explosive-laden general-aviation aircraft; or
(v) a fuel-laden commercial aircraft.

<u>Tier II</u>

There should be reasonable confidence that the release of radioactive material from the ISFSI to the environment would not exceed a specified amount in the event of a ground burst, at any part of the ISFSI, of a 10-kilotonne nuclear weapon. .

5.4 Site Constraints

At each ISFSI site there will be a site-specific set of constraints on the development of a hardened, dispersed ISFSI. Some constraints will be political, financial or in some other non-physical category. Other constraints will be physical, reflecting the geography of the site. Of the physical constraints, the most significant will be the land area required for dispersal of dry-storage modules.

At many nuclear-power-plant sites, ample land area will be available for dispersal. At some, smaller sites, it may not be possible to achieve the desired degree of dispersal, but this deficiency might be compensated by increased hardening. At the smallest sites, it might be necessary to relax the requirement that the ISFSI should not be built underground. This step would allow a substantial increase in hardening, to offset the limited degree of dispersal that could be achieved. At especially-constricted sites, it might be necessary to ship some spent fuel from the site to an ISFSI elsewhere.

6. A Proposed Design Approach for Hardened, Dispersed, Dry Storage

An ISFSI design approach that offers a prospect of meeting the above-specified DBT involves an array of vertical-axis dry-storage modules at a center-to-center spacing of perhaps 25 meters. Each module would be on a concrete pad slightly above ground level, and would be surrounded by a concentric tube surmounted by a cap, both being made of steel and concrete. This tube would be backed up by a conical mound made of earth, gravel and rocks. Further structural support would be provided by triangular panels within the mound, buttressing the tube. The various structural components would be tied together with steel rods. Air channels would be provided, to allow cooling of the dry-storage module. These channels would be inclined, to prevent pooling of jet fuel, and would be configured to preclude line-of-sight access to the dry-storage module. Figure 2, on the following page, provides a schematic view of the proposed design.

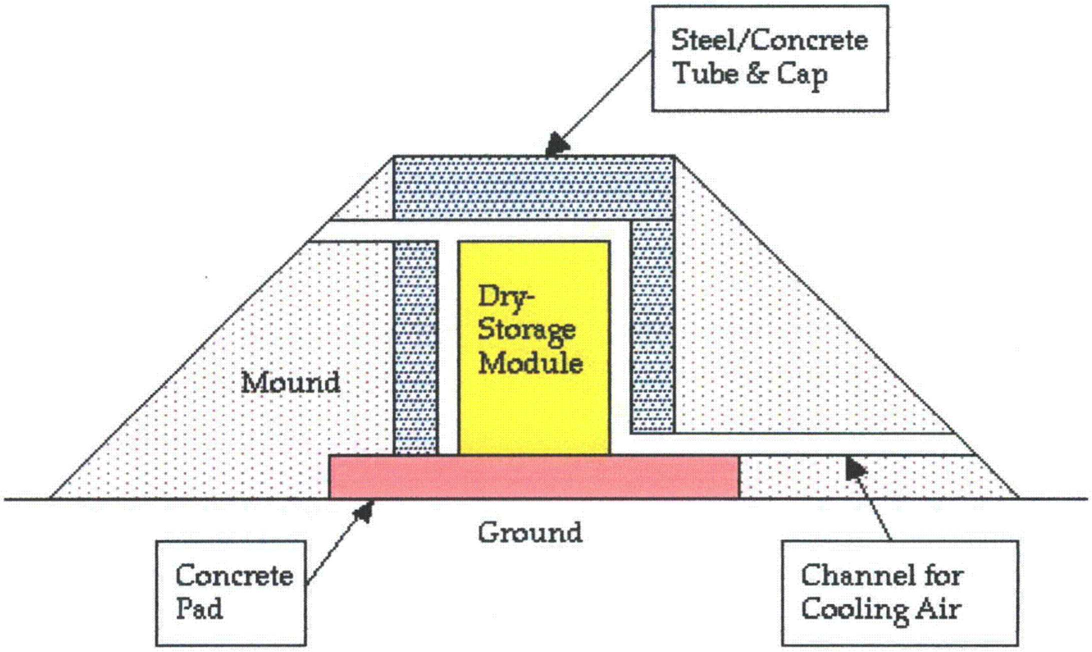

FIGURE 2

SCHEMATIC VIEW OF PROPOSED DESIGN FOR HARDENED, DRY STORAGE

Notes

1. Cooling channels would be inclined, to prevent pooling of jet fuel, and would be configured to preclude line-of-sight access to the dry-storage module.
2. The tube, cap and pad surrounding the dry-storage module would be tied together with steel rods, and spacer blocks would prevent the module from moving inside the tube.
3. The steel/concrete tube could be buttressed by several triangular panels connecting the tube and the base pad.

Further analysis and full-scale experiments would be needed to determine whether this design approach, or something like it, could meet the DBT and other requirements that are set forth in Section 5, above. Ideally, these requirements could be met while using dry-storage modules that are approved by the NRC and are in common use. Another objective would be that the hardening elements (concentric tube, cap, tie rods, mound, etc.) could be built and assembled comparatively quickly and cheaply. These elements would not be high-technology items.

The Benefits of Dispersal

As an illustration of the benefits of dispersal, consider an attack on an ISFSI involving a ground burst of a 10-kilotonne nuclear weapon. In Section 4.2 of this report, it was noted that this attack could excavate a crater about 68 meters in diameter and 16 meters deep. If dry-storage modules had a center-to-center spacing of 5.5 meters, as is typical of present practice, about 120 modules could fall within the crater area and suffer destruction. However, if the center-to-center spacing were 25 meters, as is proposed here, only 6 modules could fall within the crater area and suffer destruction.

Site-Specific Tradeoffs

Within this design approach it would be possible to trade off, to some extent, hardening and dispersal. As suggested in Section 5.4, above, dispersal could be reduced and hardening could be increased at smaller sites. Detailed, site-specific analysis is needed to determine how such tradeoffs might work.

An alternative design approach might be used at a few sites where space is insufficient to allow wide dispersal. In this approach, a number of dry-storage modules would be co-located in an underground, reinforced-concrete bunker. Similar bunkers would be dispersed across the site to the extent allowed by the site's geography. At an especially-constricted site, it might be necessary to reduce the overall inventory of spent fuel in order to meet design objectives. Thus, some spent fuel from the site would be shipped to an ISFSI elsewhere.

7. Requirements for Nationwide Implementation of Robust Storage

7.1 Experiments on Vulnerability of Dry-Storage Options

Section 5.3 of this report outlines a DBT for hardened, dispersed, dry storage of spent fuel. Section 6 describes a design approach that offers a prospect of meeting a DBT of this kind, together with other requirements that are set forth in Section 5. Further investigation is needed to determine the extent to which the various requirements can be met. This determination would be made at two levels. First, the investigation would determine if the DBT and other requirements set forth in Section 5 are broadly compatible with the proposed design approach or something like it. Second, assuming an affirmative determination at the first level, the investigation would go into more detail, exploring the various tradeoffs that could be made.

An essential part of this investigation would be a series of full-scale, open-air experiments. These experiments would be sponsored by the US government, and would be conducted at US government laboratories and testing centers. The experiments would involve a range of non-nuclear instruments of attack, including anti-tank missiles, manually-placed charges, vehicle bombs and aircraft bombs. Each instrument of attack would be tested against several test specimens that would simulate alternative design approaches for a hardened, dispersed ISFSI.

A separate set of experiments would be conducted in contained situations. These experiments would study the potential for release of radioactive material following penetration or prolonged heating of a fuel container.[133] Factors discussed in Section 4.2 of this report, such as the presence of zirconium hydride in fuel cladding, would be accounted for. The potential for auto-ignition of hydrided cladding when exposed to air deserves special attention in the experimental program, because this potential is relevant not only to the vulnerability of dry-storage modules, but also to the initiation of a fire in a spent-fuel pool.[134]

7.2 Performance-Based Specifications for Robust Storage

The investigation called for in Section 7.1 would establish the technical basis for a set of performance-based specifications for hardened, dispersed, dry storage of spent fuel. These specifications would include a detailed, precise formulation of the DBT. Also included would be design guidelines for meeting the DBT, and an allowable range of design parameters within which tradeoffs could be made. The specifications would apply not only to the design of external, hardening elements, but also to dry-storage modules. Thus, some modification of the licensing basis for currently-licensed dry-storage modules may be required.

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[133] The proposed experiments would simulate, among other events, an attack in which penetration of a fuel container is accompanied by incendiary effects.

[134] At the higher fuel burnups now commonly achieved, zirconium hydride forms in the fuel cladding. A potential for auto-ignition of zirconium hydride in air has been identified. See: Powers, 2000, page 3; Collins et al, 2000, page A1B-3.

Specifications for Low-Density Pool Storage

Performance specifications would also be required for the nationwide reversion to low-density pool storage. A primary objective would be to prevent the initiation of a pool fire in the event of a loss of water from a pool. This would be accomplished by reverting to low-density, open-frame racks that allow convective cooling of fuel by air or steam in the event of water loss, as discussed in Section 4.2. (Note: Low-density, open-frame racks would not necessarily preclude a pool fire after water loss if auto-ignition of zirconium hydride, as discussed in Section 7.1, could occur. Thus, it is important to empirically resolve the auto-ignition issue.)

At nuclear power plants with larger pools, reverting to low-density, open-frame racks will not conflict with other objectives. At plants with smaller pools, the pursuit of low density may conflict with other objectives, including: (i) preserving open spaces in the racks to allow offloading of the reactor core; (ii) allowing fuel to age for at least 5 years before transferring it to an ISFSI; and (iii) suppressing criticality of fresh or low-burnup fuel without relying on soluble boron in the pool water. Tradeoffs and technical fixes could resolve many of these conflicts.[135] New analysis, perhaps supplemented by some experiments, would establish the technical basis for performance specifications that include the necessary tradeoffs.

Establishing the Specifications

Establishing a comprehensive set of specifications for robust storage would call for the exercise of judgement. There is no purely objective basis for deciding upon one level of required performance as opposed to another. However, judgement must be exercised with full awareness of the wide-ranging implications of a particular choice. As discussed in Section 3 of this report, the defense of US nuclear facilities should be seen as a key component of homeland security and international security.

In view of the national importance of the needed set of specifications, these should be developed with the full engagement of stakeholders. Relevant stakeholders include citizen groups, local governments and state

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[135] Examples of possible tradeoffs and technical fixes include: (i) relaxing the requirement to offload a full core; (ii) providing some high-density rack spaces for fresh fuel and core offload; (iii) relying on soluble boron in normal operation, with limited addition of unborated water if borated water is lost; (iv) adding some solid boron to rack structures while preserving an open-frame configuration; (v) relaxing the 5-year cooling period by partially filling some dry-storage modules or mixing younger fuel with older fuel in dry-storage modules; and (vi) shipping some fuel to plants with larger pools.

governments. Processes are available that could allow full engagement of stakeholders while protecting sensitive information.[136]

7.3 A Homeland-Security Strategy for Robust Storage

A robust-storage strategy for US spent fuel would involve two major initiatives. The first initiative would be to re-equip the nation's spent-fuel pools with low-density racks and to provide other defense-in-depth measures to protect the pools. The second initiative would be to place all spent fuel, other than the residual amount that would then be stored in low-density pools, into hardened, dispersed, dry-storage ISFSIs.

Fast, effective implementation of this strategy would require decisive action by the US government. It would require expenditures that are comparatively small by national-security standards but are nonetheless significant. At present, there is no sign that the needed action will be taken. The US government in general seems largely unaware of the threat posed by the present practice of storing spent fuel. The NRC appears to be paralyzed, perhaps through fear of being criticized for its previous inattention to the threat of attack on nuclear facilities.

A new paradigm is needed, in which spent-fuel-storage facilities are seen as pre-deployed radiological weapons that await activation by an enemy. Correcting this situation is an imperative of national defense. If the NRC continues to undermine national defense, it should be bypassed. Citizens should insist that Congress and the executive branch promptly initiate a strategy for robust storage of spent fuel, as a key element of homeland security.

8. Conclusions

The prevailing practice of storing most US spent fuel in high-density pools poses a very high risk because knowledgeable attackers could induce a loss of water from a pool, causing a spent-fuel fire that would release a huge amount of radioactive material to the atmosphere. Nuclear reactors are also vulnerable to attack. Dry-storage modules used in ISFSIs have safety advantages in comparison to pools and reactors, but are not designed to resist a determined attack.

Thus, nuclear power plants and their spent fuel can be regarded as pre-deployed radiological weapons that await activation by an enemy. The US government in general and the NRC in particular seem unaware of this

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[136] Thompson, 2002a, Sections IX and X.

threat. US nuclear facilities are lightly defended and are not designed to resist attack. This situation is symptomatic of an unbalanced US strategy for national security, which is a potentially destabilizing factor internationally.

A strategy for robust storage of US spent fuel is needed, whether or not a repository is opened at Yucca Mountain. This strategy should be implemented as a major element of a defense-in-depth strategy for US civilian nuclear facilities. In turn, that defense-in-depth strategy should be a component of a homeland-security strategy that provides solid protection of our critical infrastructure.

The highest priority in a robust-storage strategy for spent fuel would be to re-equip spent-fuel pools with low-density, open-frame racks. As a further measure of risk reduction, ISFSIs should be re-designed to incorporate hardening and dispersal. These measures should not be implemented in a manner such that an ISFSI may become, by default, a repository. Therefore, a hardened ISFSI should not, unless absolutely necessary, be built underground. Also, the cost and timeframe for implementing hardening and dispersal should be minimized. These considerations argue for the use, if possible, of dry-storage modules that are already approved by the NRC and are in common use.

Preliminary analysis suggests that a hardened, dispersed ISFSI meeting these criteria could be designed to meet a two-tiered DBT. The first tier would require high confidence that no more than a small release of radioactive material would occur in the event of a direct attack on the ISFSI by various non-nuclear instruments. The second tier would require reasonable confidence that no more than a specified release of radioactive material would occur in the event of attack using a 10-kilotonne nuclear weapon.

Three major requirements must be met if a robust-storage strategy for spent fuel is to be implemented nationwide. First, appropriate experiments are needed. Second, performance-based specifications for robust storage must be developed with stakeholder involvement. Third, robust storage for spent fuel must be seen as a vital component of homeland security.

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Union of Concerned Scientists

Citizens and Scientists for Environmental Solutions

Statement by David Lochbaum, Director – Nuclear Safety Project

Before the U.S. Senate Energy and Natural Resources Committee

March 29, 2011

The Fukushima Dai-Ichi nuclear plant in Japan experienced a station blackout. A station blackout occurs when a nuclear power plant loses electrical power from all sources except that provided by onsite banks of batteries. The normal power supply comes from the plant's own main generator or from the electrical grid when the reactor is shut down. All the equipment needed to operate the plant on a daily basis as well as the emergency equipment needed during an accident can be energized by the normal power supply. When the normal power supply is lost, backup power is supplied from onsite emergency diesel generators. These generators provide electricity only to the smaller set of equipment needed to cool the reactor cores and maintain the containments' integrity during an accident.

At Fukushima, the earthquake caused the normal power supply to be lost. Within an hour, the tsunami caused the backup power supply to be lost. This placed the plant into a station blackout where the only source of power came from batteries. These batteries provided sufficient power for the valves and controls of the steam-driven system—called the reactor core isolation cooling system—that provided cooling water for the reactor cores on Units 1, 2, and 3. When those batteries were exhausted, there were no cooling systems for the reactor cores or the spent fuel pools. There are clear indications that the fuel in the reactor cores of units 1, 2, and 3 and some spent fuel pools has been damaged due to overheating.

Had either normal or backup power been restored before the batteries were depleted, we would not be here today discussing this matter. The prolonged station blackout resulted in the inability to cool the reactor cores in Units 1, 2, and 3, the spent fuel pools for all six units, and the consolidated spent fuel pool. There are lessons, learned at high cost in Japan, that can and should be applied to lessen the vulnerabilities at U.S. reactors. And I cannot emphasize enough that the lessons from Japan apply to all U.S. reactors, not just the boiling water reactors like those affected at Fukushima. None are immune to station blackout problems. All must be made less vulnerable to those problems.

As at Fukushima, U.S. reactors are designed to cool the reactor core during a station blackout of only a fairly short duration. It is assumed that either the connection to an energized electrical grid or the repair of an emergency diesel generator will occur before the batteries are depleted. Eleven U.S. reactors are designed to cope with a station blackout lasting eight hours, as were the reactors in Japan. Ninety-three of our reactors are designed to cope for only four hours. But unless the life of the on-site batteries is long enough to eliminate virtually any chance that the batteries would be depleted before power from another source is restored, one lesson from Fukushima is the need to provide workers with options for dealing with a station blackout lasting longer than the life of the on-site batteries. In other words, the moment that any U.S. reactor enters a station blackout, response efforts should proceed along three parallel paths: (1) restoration of the electrical grid as soon as possible, (2) recovery of one or more emergency diesel generators as soon as possible, and (3) acquisition of additional batteries and/or temporary generators as soon as possible. If either of the first two paths leads to success, the station blackout ends and the reenergized safety systems can cool the reactor core and spent fuel pool. If the first two paths lead to failure, success on the third path will hopefully provide enough time for the first two paths to achieve belated success.

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The timeline associated with the third path should determine whether the life of the on-site batteries is adequate or whether additional batteries should be required. For example, the existing battery life may be sufficient when a reactor is located near a facility where temporary generators are readily available, such as the San Onofre nuclear plant in California, which is next to the U.S. Marine base at Camp Pendleton. When a reactor is more remotely located, it may be necessary to add on-site batteries to increase the chance that the third path leads to success if the first two paths do not.

The second lesson from Fukushima is the need to address the vulnerability of spent fuel pools. At many U.S. reactors, there is far more irradiated fuel in the spent fuel pool than in the reactor core. At all U.S. reactors, the spent fuel pool is cooled by fewer and less reliable systems than are provided for the reactor core. At all U.S. reactors, the spent fuel pool is housed in far less robust structures than surround the reactor core. This means that any release of radiation from the pool will not be as well contained as radiation released from the reactor core. It also means that spent fuel pools are more vulnerable to terrorist attack than is the reactor itself. More irradiated fuel that is less well protected and less well defended is an undue hazard. There are two measures to better manage this risk: (1) accelerate the transfer of spent fuel from spent fuel pools to dry cask storage, and (2) upgrade the guidelines for how to address an emergency and the operator training for spent fuel pool problems.

Currently, the U.S. spent fuel storage strategy is to nearly fill the spent fuel pools to capacity and then to transfer fuel into dry cask storage to provide space for the new fuel discharged from the reactor core. This keeps the spent fuel pools nearly filled with irradiated fuel, thus maintaining the risk level about as high as possible. Added to that risk is the risk from dry casks stored onsite, which is less than that from the spent fuel pools but not zero.

A better strategy would be to reduce the inventory of irradiated fuel in the pools to the minimum amount, which would be only the fuel discharged from the reactor core within the past five years. Reducing the spent fuel stored in the pools would lower the risk in two ways. First, less irradiated fuel in the pools would generate a lower heat load. If cooling of the spent fuel pool was interrupted or water inventory was lost from the pool, the lower heat load would give workers more time to recover cooling and/or water inventory before overheating caused fuel damage. And second, if irradiated fuel in a spent fuel pool did become damaged, the amount of radioactivity released from the smaller amount of spent fuel would be significantly less than that released from a nearly full pool. Reducing the amount of irradiated fuel in spent fuel pools would significantly reduce the safety and security risks from a nuclear power plant.

Following the 1979 accident at Three Mile Island, reactor owners significantly upgraded emergency procedures and operator training. Prior to that accident, procedures and training relied on the operators quickly and correctly diagnosing what had happened and taking steps to mitigate the consequences. If the operators mis-diagnosed the accident they faced, the guidelines could lead them to take the wrong steps for the actual accident in progress. The revamped emergency procedures and training would guide the operators' response to an abnormally high pressure or an unusually low water level without undue regard for what caused the abnormalities. The revamped emergency procedures and training represent significant improvements over the pre-TMI days. But they apply only to reactor core accidents. No comparable procedures and training would help the operators respond to a spent fuel pool accident. It is imperative that comparable emergency procedures and training be provided for spent fuel pool accidents to supplement the significant gains in addressing reactor core accidents that were made following the TMI accident.

The Nuclear Regulatory Commission has announced a two-phase response plan to Fukushima: a 90-day quick look followed by a more in-depth review. If the past three decades have demonstrated anything, it's that the NRC will likely come up with a solid action plan to address problems revealed at Fukushima, but will be glacially slow in implementing those identified safety upgrades. A comprehensive action plan does little to protect Americans until its goals are achieved. We urge the U.S. Congress to force the NRC to not merely chart a course to a safer place, but actually reach that destination as soon as possible.

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Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States

Robert Alvarez, Jan Beyea, Klaus Janberg, Jungmin Kang, Ed Lyman, Allison Macfarlane, Gordon Thompson, Frank N. von Hippel

Because of the unavailability of off-site storage for spent power-reactor fuel, the NRC has allowed high-density storage of spent fuel in pools originally designed to hold much smaller inventories. As a result, virtually all U.S. spent-fuel pools have been re-racked to hold spent-fuel assemblies at densities that approach those in reactor cores. In order to prevent the spent fuel from going critical, the fuel assemblies are partitioned off from each other in metal boxes whose walls contain neutron-absorbing boron. It has been known for more than two decades that, in case of a loss of water in the pool, convective air cooling would be relatively ineffective in such a "dense-packed" pool. Spent fuel recently discharged from a reactor could heat up relatively rapidly to temperatures at which the zircaloy fuel cladding could catch fire and the fuel's volatile fission products,

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including 30-year half-life ^{137}Cs, would be released. The fire could well spread to older spent fuel. The long-term land-contamination consequences of such an event could be significantly worse than those from Chernobyl.

No such event has occurred thus far. However, the consequences would affect such a large area that alternatives to dense-pack storage must be examined—especially in the context of concerns that terrorists might find nuclear facilities attractive targets. To reduce both the consequences and probability of a spent-fuel-pool fire, it is proposed that all spent fuel be transferred from wet to dry storage within five years of discharge. The cost of on-site dry-cask storage for an additional 35,000 tons of older spent fuel is estimated at \$3.5–7 billion dollars or 0.03–0.06 cents per kilowatt-hour generated from that fuel. Later cost savings could offset some of this cost when the fuel is shipped off site. The transfer to dry storage could be accomplished within a decade. The removal of the older fuel would reduce the average inventory of ^{137}Cs in the pools by about a factor of four, bringing it down to about twice that in a reactor core. It would also make possible a return to open-rack storage for the remaining more recently discharged fuel. If accompanied by the installation of large emergency doors or blowers to provide large-scale airflow through the buildings housing the pools, natural convection air cooling of this spent fuel should be possible if airflow has not been blocked by collapse of the building or other cause. Other possible risk-reduction measures are also discussed.

Our purpose in writing this article is to make this problem accessible to a broader audience than has been considering it, with the goal of encouraging further public discussion and analysis. More detailed technical discussions of scenarios that could result in loss-of-coolant from spent-fuel pools and of the likelihood of spent-fuel fires resulting are available in published reports prepared for the NRC over the past two decades. Although it may be necessary to keep some specific vulnerabilities confidential, we believe that a generic discussion of the type presented here can and must be made available so that interested experts and the concerned public can hold the NRC, nuclear-power-plant operators, and independent policy analysts such as ourselves accountable.

INTRODUCTION

The U.S. Nuclear Regulatory Commission (NRC) has estimated the probability of a loss of coolant from a spent-fuel storage pool to be so small (about 10^{-6} per pool-year) that design requirements to mitigate the consequences have not been required.[1] As a result, the NRC continues to permit pools to move from open-rack configurations, for which natural-convection air cooling would have been effective, to "dense-pack" configurations that eventually fill pools almost wall to wall. A 1979 study done for the NRC by the Sandia National Laboratory showed that, in case of a sudden loss of all the water in a pool, dense-packed spent fuel, even a year after discharge, would likely heat up to the point where its zircaloy cladding would burst and then catch fire.[2] This would result in the airborne release of massive quantities of fission products.

No such event has occurred thus far. However, the consequences would be so severe that alternatives to dense-pack storage must be examined—especially in the context of heightened concerns that terrorists could find nuclear facilities attractive targets.

The NRC's standard approach to estimating the probabilities of nuclear accidents has been to rely on fault-tree analysis. This involves quantitative estimates of the probability of release scenarios due to sequences of equipment failure, human error, and acts of nature. However, as the NRC staff stated in a June 2001 briefing on risks from stored spent nuclear fuel:[3] "No established method exists for quantitatively estimating the likelihood of a sabotage event at a nuclear facility."

Recently, the NRC has denied petitions by citizen groups seeking enhanced protections from terrorist acts against reactor spent-fuel pools.[4] In its decision, the NRC has asserted that "the possibility of a terrorist attack . . . is speculative and simply too far removed from the natural or expected consequences of agency action . . ."[5]

In support of its decision, the NRC stated: "Congress has recognized the need for and encouraged high-density spent fuel storage at reactor sites,"[6] referencing the 1982 Nuclear Waste Policy Act (NWPA). In fact, although the NWPA cites the need for "the effective use of existing storage facilities, and necessary additional storage, at the site of each civilian nuclear power reactor consistent with public health and safety," it does *not* explicitly endorse dense-pack storage.[7]

If probabilistic analysis is of little help for evaluating the risks of terrorism, the NRC and the U.S. Congress will have to make a judgment of the probability estimates that will be used in cost-benefit analyses. Here, we propose physical changes to spent-fuel storage arrangements that would correct the most obvious vulnerabilities of pools to loss of coolant and fire. The most costly of these proposals, shifting fuel to dry cask storage about 5 years after discharge from a reactor, would cost $3.5–7 billion for dry storage of the approximately 35,000 tons of older spent fuel that would otherwise be stored in U.S. pools in 2010. This corresponds to about 0.03–0.06 cents per kilowatt-hour of electricity generated from the fuel. Some of this cost could be recovered later if it reduced costs for the shipment of the spent fuel off-site to a long-term or permanent storage site.

For comparison, the property losses from the deposition downwind of the cesium-137 released by a spent-fuel-pool fire would likely be hundreds of billions of dollars. The removal of the older spent fuel to dry storage would therefore be justified by a traditional cost-benefit analysis if the likelihood of a spent-fuel-pool fire in the U.S. during the next 30 years were judged to be greater than about a percent. Other actions recommended below could be justified by much lower probabilities.

It appears unlikely that the NRC will decide its own to require such actions. According to its Inspector General, the "NRC appears to have informally established an unreasonably high burden of requiring absolute proof of a safety problem, versus lack of a reasonable assurance of maintaining public health and safety . . . "[8]

This situation calls for more explicit guidance from Congress. Indeed, 27 state Attorneys General have recently signed a letter to Congressional leaders asking for legislation to "protect our states and communities from terrorist attacks against civilian nuclear power plants and other sensitive nuclear facilities," specifically mentioning spent-fuel pools.[9]

Congress could do this by updating the Nuclear Waste Policy Act to require "defense in depth" for pool storage; and the minimization of pool inventories of spent fuel. The second requirement would involve the transfer, over a transition period of not more than a decade, of all spent fuel more than five years post discharge to dry, hardened storage modes.

To establish the basis for an informed, democratic decision on risk-reduction measures, it would be desirable to have the relevant analysis available to a full range of concerned parties, including state and local governments and concerned citizens. Despite the need to keep sensitive details confidential, we believe that we have demonstrated in this article that analysts can describe and debate a range of measures in an open process. The same can be done in the regulatory area. Evidentiary hearings held under NRC rules already have specific provisions to exclude security details—along with proprietary and confidential personnel information—from the public record.

In outline, we describe:

- The huge inventories of the long-lived, volatile fission product cesium-137 (^{137}Cs) that are accumulating in U.S. spent fuel pools and the consequences if the inventory of one of these pools were released to the atmosphere as a result of a spent-fuel fire;
- The various types of events that have been discussed in the public record that could cause a loss of coolant and the high radiation levels that would result in the building above the pool as a result of the loss of the radiation shielding provided by the water;
- The limitations of the various cooling mechanisms for dry spent fuel: conduction, infra-red radiation, steam cooling and convective air cooling;
- Possible measures to reduce the vulnerability of pools to a loss of coolant event and to provide emergency cooling if such an event should occur; and

- The feasibility of moving spent fuel from pools into dry-cask storage within 5 years after discharge from the reactor. This would allow open-rack storage of the more-recently discharged fuel, which would make convective air-cooling more effective in case of a loss of water, and would reduce the average inventory of ^{137}Cs in U.S. spent-fuel pools by about a factor of four.

There are 103 commercial nuclear reactors operating in the U.S. at 65 sites in 31 states (Figure 1).[11] Of these, 69 are pressurized-water reactors (PWRs) and 34 are boiling-water reactors (BWRs). In addition there are 14 previously-operating light-water-cooled power reactors in various stages of decommissioning. Some of these reactors share spent-fuel pools, so that there is a total of 65 PWR and 34 BWR pools.[12] Figure 2 shows diagrams of "generic" pressurized-water reactor (PWR) and boiling-water-reactor (BWR) spent-fuel pools.[13] For simplicity, when we do illustrative calculations in this article, we use PWR fuel and pool designs. However, the results of detailed studies done for the NRC show that our qualitative conclusions are applicable to BWRs as well.[14]

Figure 1: Locations of nuclear power plants in the United States. Circles represent sites with one reactor, squares represent plants with two; and stars represent plants with three. Open symbols represent sites with at least one shutdown reactor. Only the plant in Zion, Illinois has more than one shutdown reactor. It has two (*Source:* authors[10]).

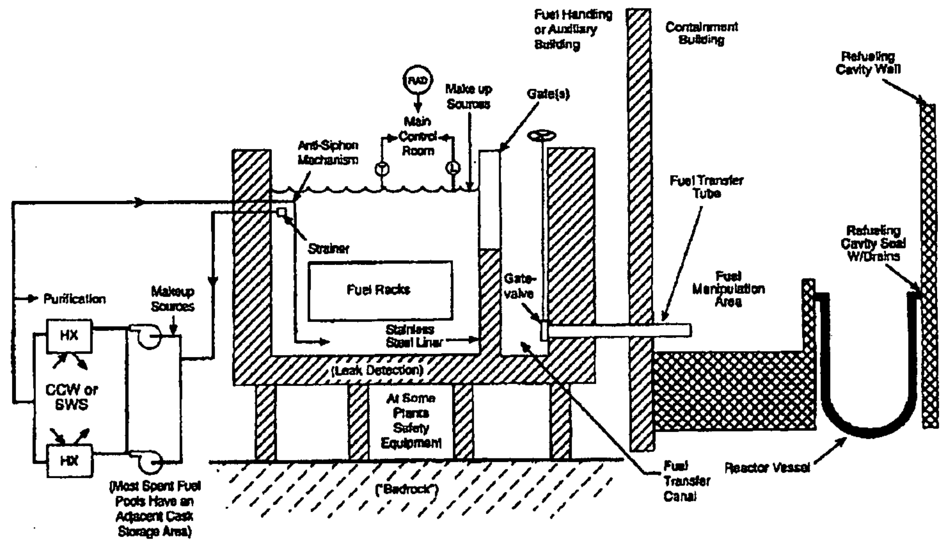


Figure 2a: Layout of spent fuel pool and transfer system for pressurized water reactors (*Source:* NUREG-1275, 1997).

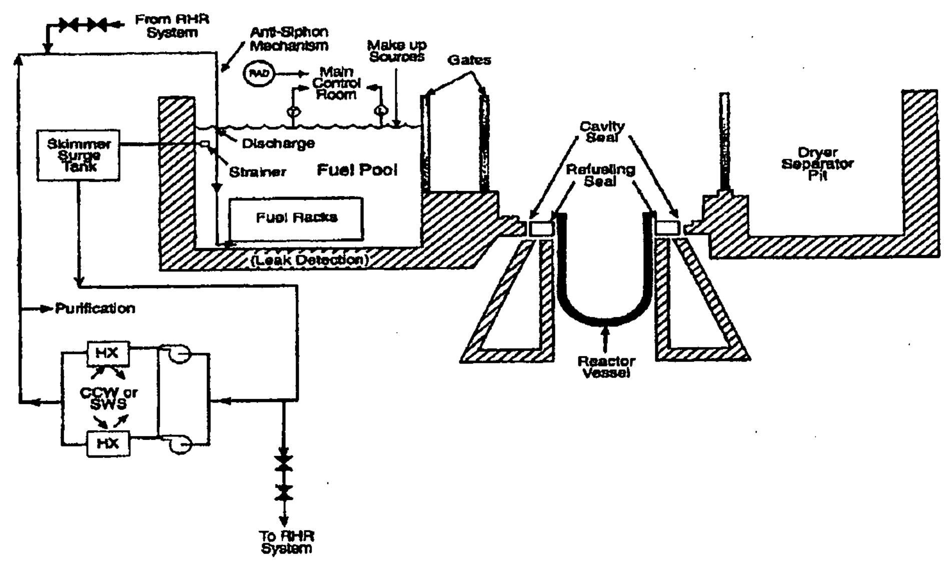


Figure 2b: Layout of spent fuel pool and transfer system for boiling water reactors (*Source:* NUREG-1275, 1997).

THE HAZARD FROM CESIUM-137 RELEASES

Although a number of isotopes are of concern, we focus here on the fission product ^{137}Cs. It has a 30-year half-life, is relatively volatile and, along with its short-lived decay product, barium-137 (2.55 minute half-life), accounts for about half of the fission-product activity in 10-year-old spent fuel.[15] It is a potent land contaminant because 95% of its decays are to an excited state of ^{137}Ba, which de-excites by emitting a penetrating (0.66-MeV) gamma ray.[16]

The damage that can be done by a large release of fission products was demonstrated by the April 1986 Chernobyl accident. More than 100,000 residents from 187 settlements were permanently evacuated because of contamination by ^{137}Cs. Strict radiation-dose control measures were imposed in areas contaminated to levels greater than 15 Ci/km^2 (555 kBq/m^2) of ^{137}Cs. The total area of this radiation-control zone is huge: 10,000 km^2, equal to half the area of the State of New Jersey. During the following decade, the population of this area declined by almost half because of migration to areas of lower contamination.[17]

Inventories of Cs-137 in Spent-Fuel Storage Pools

The spent-fuel pools adjacent to most power reactors contain much larger inventories of ^{137}Cs than the 2 MegaCuries (MCi) that were released from the core of Chernobyl 1000-Megawatt electric (MWe) unit #4[18] or the approximately 5 MCi in the core of a 1000-MWe light-water reactor. A typical 1000-MWe pressurized water reactor (PWR) core contains about 80 metric tons of uranium in its fuel, while a typical U.S. spent fuel pool today contains about 400 tons of spent fuel (see Figure 3). (In this article, wherever tons are referred to, metric tons are meant.) Furthermore, since the concentration of ^{137}Cs builds up almost linearly with burnup, there is on average about twice as much in a ton of spent fuel as in a ton of fuel in the reactor core.

For an average cumulative fission energy release of 40 Megawatt-days thermal per kg of uranium originally in the fuel (MWt-days/kgU) and an average subsequent decay time of 15 years, 400 tons of spent power-reactor fuel would contain 35 megaCuries (MCi) of ^{137}Cs.[19] If 10–100% of the ^{137}Cs in a spent-fuel pool,[20] i.e., 3.5–35 MCi, were released by a spent-fuel fire to the atmosphere in a plume distributed vertically uniformly through the atmosphere's lower "mixing layer" and dispersed downwind in a "wedge model" approximation under median conditions (mixing layer thickness of 1 km, wedge opening angle of 6 degrees, wind speed of 5 m/sec, and deposition velocity of 1 cm/sec) then 37,000–150,000 km^2 would be contaminated above 15 Ci/km^2, 6,000–50,000 km^2 would

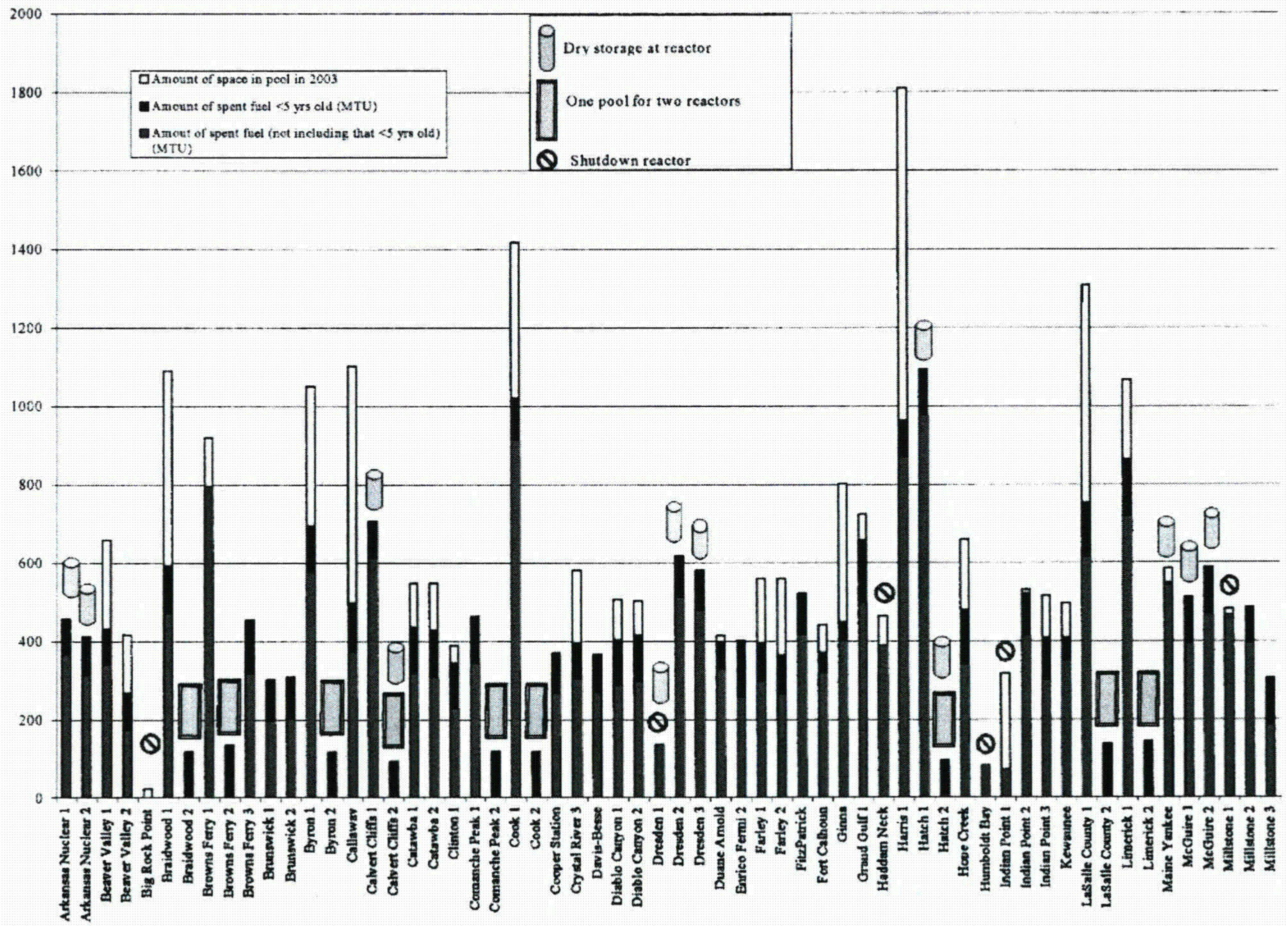


Figure 3: Estimated 2003 spent fuel inventory at each U.S. spent-fuel pool, measured in metric tons of contained uranium. Height of bar indicates total licensed capacity (1998, with some updates). Shading indicates estimated tonnage of spent fuel in pool as of 2003. Dark shading indicates the estimated amount of fuel discharged from the reactors within the past 5 years. Canister indicates the presence of on-site dry storage. Pool indicates that reactor shares a pool with the reactor to the left (*Source:* authors[25]). *(Continued)*

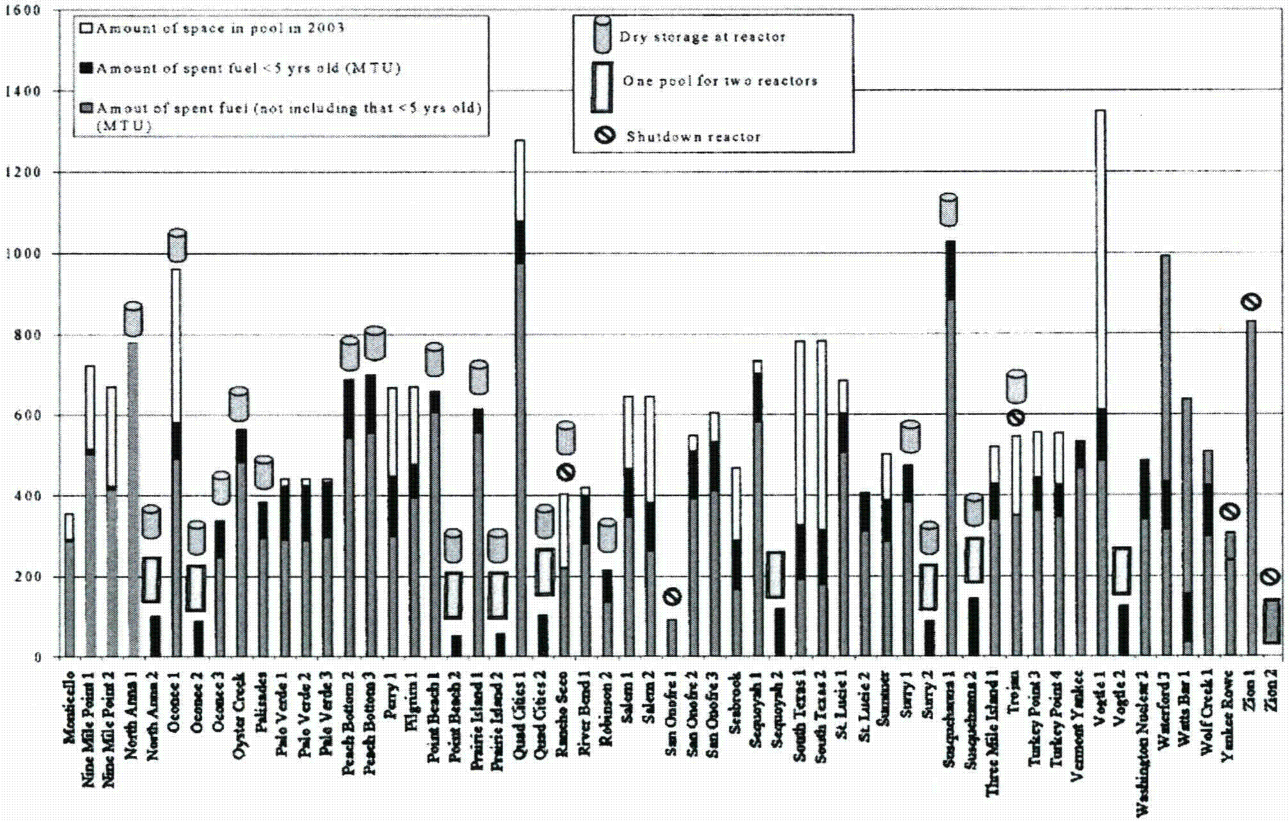


Figure 3: (Continued)

Table 1: Typical plume areas (km^2).

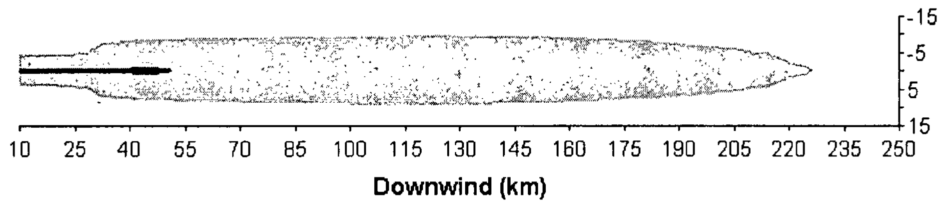
Release	>100 Ci/km^2	>1000 Ci/km^2
Chernobyl (2 MCi, hot, multi-directional)	≈700	
3.5 MCi (MACCS2)	3,500	200
3.5 MCi (wedge model)	6,000	180
35 MCi (MACCS2)	45,000	2,500
35 MCi (wedge model)	50,000	6,000

be contaminated to greater than 100 Ci/km^2 and 180–6000 km^2 to a level of greater than 1000 Ci/km^2.[21] Table 1 and Figure 4 show typical contaminated areas, calculated using the MACCS2 Gaussian plume dispersion code used by the NRC[22] for fires with 40 MWt thermal power.[23] This corresponds to fire durations of half an hour and 5 hours, respectively for fires that burn 10 or 100 percent of 400 tons of spent fuel.[24] Similar results were obtained for slower-burning fires with powers of 5 MWt.

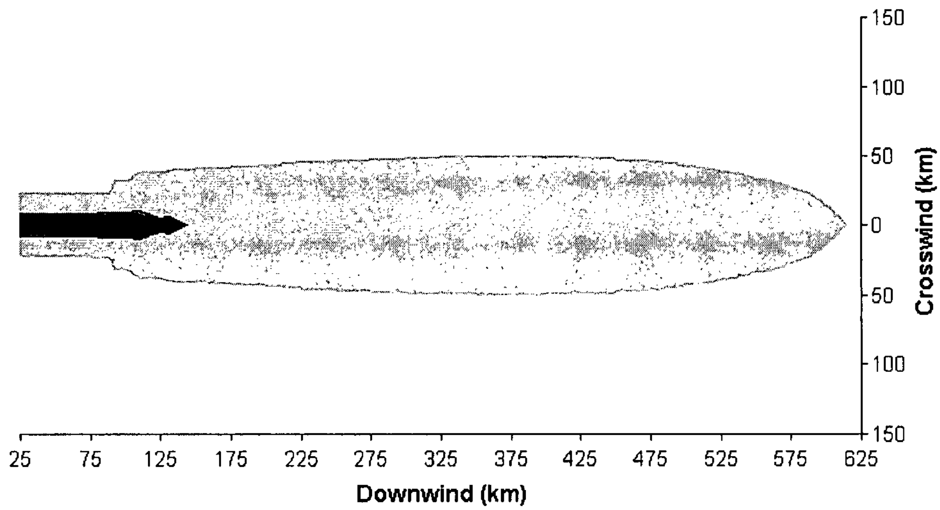
It will be seen in Table 1 that, for the 3.5 MCi release, the area calculated as contaminated above 100 Ci/km^2 are 5–9 times larger than the area contaminated to this level by the 2 MCi release from the Chernobyl accident. The reasons are that, at Chernobyl: 1) much of the Cs-137 was lifted to heights of up to 2.5 km by the initial explosion and the subsequent hot fire and therefore carried far downwind;[26] and 2) the release extended over 10 days during which the wind blew in virtually all directions. As a result, more than 90 percent of the ^{137}Cs from Chernobyl was dispersed into areas that were contaminated to less than 40 Ci/km^2.[27] In contrast, in the wedge-model calculations for the 3.5 MCi release, about 50 percent of the ^{137}Cs is deposited in areas contaminated to greater than this level.

The projected whole-body dose from external radiation from ^{137}Cs to someone living for 10 years in an area contaminated to 100 or 1000 Ci/km^2 would be 10–20 or 100–200 rem, with an associated additional risk of cancer death of about 1 or 10 percent respectively.[28] A 1 or 10 percent added risk would increase an average person's lifetime cancer death risk from about 20 percent to 21 or 30 percent.

A 1997 study done for the NRC estimated the median consequences of a spent-fuel fire at a pressurized water reactor (PWR) that released 8–80 MCi of ^{137}Cs. The consequences included: 54,000–143,000 extra cancer deaths, 2000–7000 km^2 of agricultural land condemned, and economic costs due to evacuation of $117–566 billion.[29] This is consistent with our own calculations using the MACCS2 code. It is obvious that all practical measures must be taken to prevent the occurrence of such an event.



(a)



(b)

Figure 4: Typical areas contaminated above 100 (shaded) and 1000 (black) Ci/km^2 for release of (a) 3.5 MCi and (b) 35 MCi of ^{137}Cs. The added chance of cancer death for a person living within the shaded area for 10 years is estimated very roughly as between 1 and 10 percent. For someone living within the black area, the added risk would be greater than 10 percent (i.e. the "normal" 20% lifetime cancer death risk would be increased to over 30 percent.) (*Source:* authors).

SCENARIOS FOR A LOSS OF SPENT-FUEL-POOL WATER

The cooling water in a spent-fuel pool could be lost in a number of ways, through accidents or malicious acts. Detailed discussions of sensitive information are not necessary for our purposes. Below, we provide some perspective for the following generic cases: boil-off; drainage into other volumes through the opening of some combination of the valves, gates and pipes that hold the water in the pool; a fire resulting from the crash of a large aircraft; and puncture by an aircraft turbine shaft or a shaped charge.

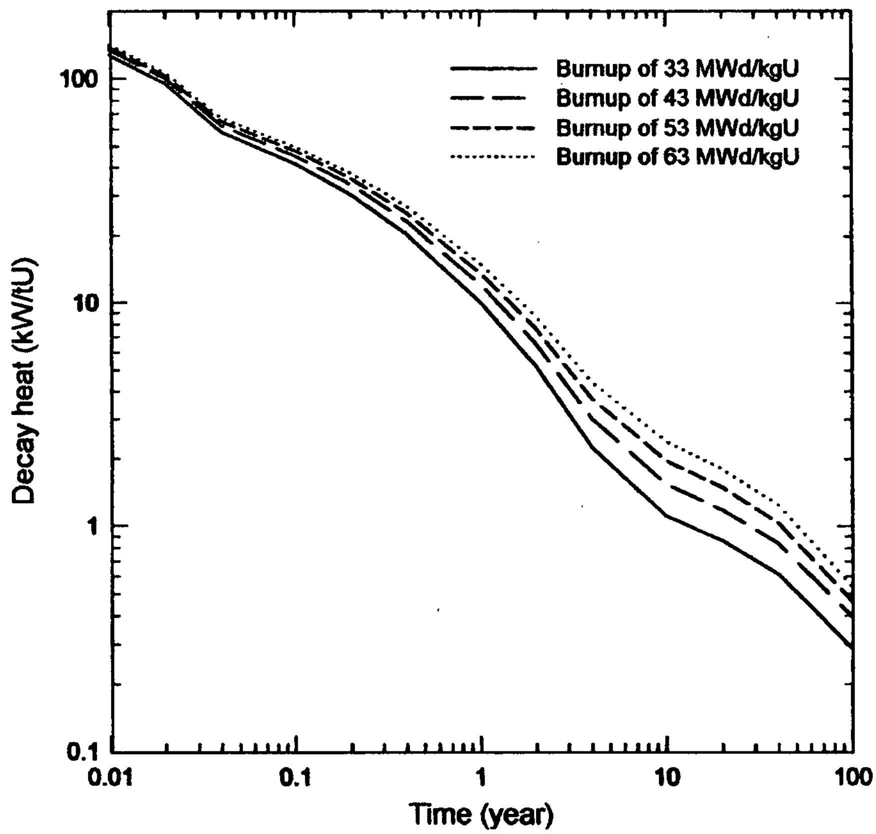


Figure 5: Decay heat as a function of time from 0.01 years (about 4 days) to 100 years for spent-fuel burnups of 33, 43, 53 and 63 MWd/kgU. The lowest burnup was typical for the 1970s. Current burnups are around 50 MWd/kgU (*Source:* authors[38]).

Boil Off

Keeping spent fuel cool is less demanding than keeping the core in an operating reactor cool. Five minutes after shutdown, nuclear fuel is still releasing 800 kilowatts of radioactive heat per metric ton of uranium (kWt/tU)[30]. However, after several days, the decay heat is down to 100 kWt/tU and after 5 years the level is down to 2–3 kWt/tU (see Figure 5).

In case of a loss of cooling, the time it would take for a spent-fuel pool to boil down to near the top of the spent fuel would be more than 10 days if the most recent spent-fuel discharge had been a year before. If the entire core of a reactor had been unloaded into the spent fuel pool only a few days after shutdown, the time could be as short as a day.[31] Early transfer of spent fuel into storage pools has become common as reactor operators have reduced shutdown periods. Operators often transfer the entire core to the pool in order to expedite refueling or to facilitate inspection of the internals of the reactor pressure vessel and identification and replacement of fuel rods leaking fission products.[32]

Even a day would allow considerable time to provide emergency cooling if operators were not prevented from doing so by a major accident or terrorist act such as an attack on the associated reactor that released a large quantity of radioactivity. In this article, we do not discuss scenarios in which spent-fuel fires compound the consequences of radioactive releases from reactors. We therefore focus on the possibility of an accident or terrorist act that could rapidly drain a pool to a level below the top of the fuel.

Drainage

All spent-fuel pools are connected via fuel-transfer canals or tubes to the cavity holding the reactor pressure vessel. All can be partially drained through failure of interconnected piping systems, moveable gates, or seals designed to close the space between the pressure vessel and its surrounding reactor cavity.[33] A 1997 NRC report described two incidents of accidental partial drainage as follows:[34]

> Two loss of SFP [spent fuel pool] coolant inventory events occurred in which SFP level decrease exceeded 5 feet [1.5 m]. These events were terminated by operator action when approximately 20 feet [6 m] of coolant remained above the stored fuel. Without operator actions, the inventory loss could have continued until the SFP level had dropped to near the top of the stored fuel resulting in radiation fields that would have prevented access to the SFP area.

Once the pool water level is below the top of the fuel, the gamma radiation level would climb to 10,000 rems/hr at the edge of the pool and 100's of rems/hr in regions of the spent-fuel building out of direct sight of the fuel because of scattering of the gamma rays by air and the building structure (see Figure 6).[35] At the lower radiation level, lethal doses would be incurred within about an hour.[36] Given such dose rates, the NRC staff assumed that further *ad hoc* interventions would not be possible.[37]

Fire

A crash into the spent fuel pool by a large aircraft raises concerns of both puncture (see below) and fire. With regard to fire, researchers at the Sandia National Laboratory, using water to simulate kerosene, crashed loaded airplane

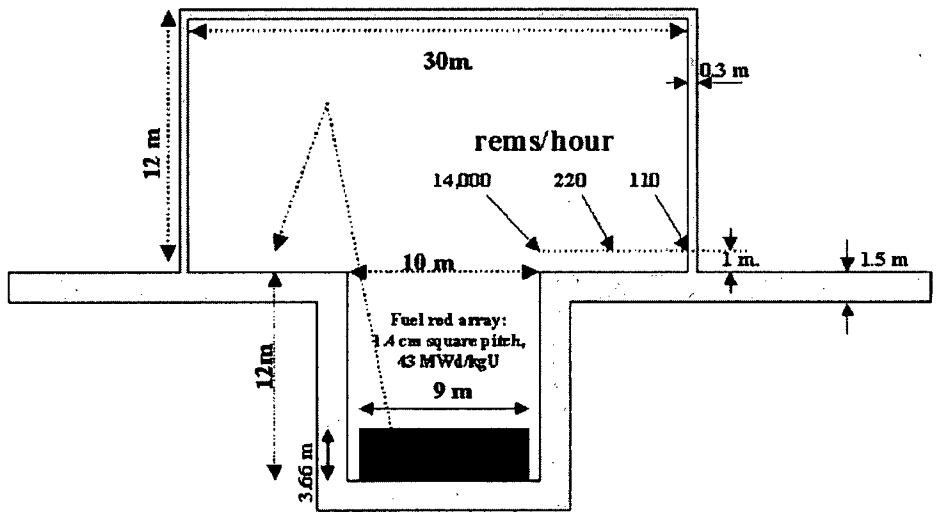


Figure 6: Calculated radiation levels from a drained spent-fuel pool one meter above the level of the floor of a simplified cylindrically-symmetric spent-fuel-pool building. Even out of direct sight of the spent fuel, the radiation dose rates from gamma rays scattered by the air, roof and walls are over a hundred rems/hr.

wings into runways. They concluded that at speeds above 60 m/s (135 mph), approximately

> 50% of the liquid is so finely atomized that it evaporates before reaching the ground. If this were fuel, a fireball would certainly have been the result, and in the high-temperature environment of the fireball a substantially larger fraction of the mass would have evaporated.[39]

The blast that would result from such a fuel-air explosion might not destroy the pool but could easily collapse the building above, making access difficult and dropping debris into the pool. A potentially destructive fuel-air deflagration could also occur in spaces below some pools. Any remaining kerosene would be expected to pool and burn at a rate of about 0.6 cm/minute if there is a good air supply.[40]

The burning of 30 cubic meters of kerosene—about one third as much as can be carried by the type of aircraft which struck the World Trade Center on September 11, 2001[41]—would release about 10^{12} joules of heat—enough to evaporate 500 tons of water. However, under most circumstances, only a relatively small fraction of the heat would go into the pool.

Puncture by an Airplane Engine Turbine Shaft, Dropped Cask or Shaped Charge

As Figure 2 suggests, many spent-fuel pools are located above ground level or above empty cavities. Such pools could drain completely if their bottoms were punctured or partially if their sides were punctured.

Concerns that the turbine shaft of a crashing high-speed fighter jet or an act of war might penetrate the wall of a spent-fuel storage pool and cause a loss of coolant led Germany in the 1970s to require that such pools be sited with their associated reactors inside thick-walled containment buildings. When Germany decided to establish large away-from-reactor spent-fuel storage facilities, it rejected large spent-fuel storage pools and decided instead on dry storage in thick-walled cast-iron casks cooled on the outside by convectively circulating air. The casks are stored inside reinforced-concrete buildings that provide some protection from missiles.[42]

Today, the turbine shafts of larger, slower-moving passenger and freight aircraft are also of concern. After the September 11, 2001 attacks against the World Trade Center, the Swiss nuclear regulatory authority stated that

> From the construction engineering aspect, nuclear power plants (worldwide) are *not* protected against the effects of warlike acts or terrorist attacks from the air.... one cannot rule out the possibility that fuel elements in the fuel pool or the primary cooling system would be damaged and this would result in a release of radioactive substances [emphasis in original][43]

The NRC staff has decided that it is prudent to assume that a turbine shaft of a large aircraft engine could penetrate and drain a spent-fuel-storage pool.[44] Based on calculations using phenomenological formulae derived from experiments with projectiles incident on reinforced concrete, penetration cannot be ruled out for a high-speed crash but seems unlikely for a low-speed crash.[45]

This is consistent with the results of a highly-constrained analysis recently publicized by the Nuclear Energy Institute (NEI).[46] The analysis itself has not been made available for independent peer review "because of security considerations." According to the NEI press release, however, it concluded that the engine of an aircraft traveling at the low speed of the aircraft that struck the Pentagon on Sept. 11, 2001 (approximately 350 miles/hr or 156 m/s) would not penetrate the wall of a spent-fuel-storage pool. Crashes at higher speed such as that against the World Trade Center South Tower (590 miles/hr or 260 m/s), which had about three times greater kinetic energy, were ruled out because the "probability of the aircraft striking a specific point on a structure—particularly one of the small size of a nuclear plant—is significantly less as speed increases."

The NEI press release included an illustration showing a huge World Trade Center tower (63 meters wide and 400 meters tall) in the foreground and a tiny spent-fuel pool (24 meters wide and 12 meters high) in the distance. Apparently no analysis was undertaken as to the possibility of a crash destroying the supports under or overturning a spent-fuel pool. A less constrained analysis should be carried out under U.S. Government auspices.

A terrorist attack with a shaped-charge anti-tank missile could also puncture a pool—as could a dropped spent-fuel cask.[47]

COOLING PROCESSES IN A PARTIALLY OR FULLY-DRAINED SPENT-FUEL POOL

"Dense packing"

U.S. storage pools—like those in Europe and Japan—were originally sized on the assumption that the spent fuel would be stored on site for only a few years until it was cool enough to transport to a reprocessing plant where the fuel would be dissolved and plutonium and uranium recovered for recycle. In 1974, however, India tested a nuclear explosive made with plutonium recovered for "peaceful" purposes. The Carter Administration responded in 1977 by halting the licensing of an almost completed U.S. reprocessing plant. The rationale was that U.S. reprocessing might legitimize the acquisition of separated plutonium by additional countries interested in developing a nuclear-weapons option. In the 1982 Nuclear Waste Policy Act, therefore, the U.S. Government committed to provide an alternative destination for the spent fuel accumulating in reactor pools by building a deep-underground repository. According to the Act, acceptance of spent fuel at such a repository was supposed to begin by 1998. As of this writing, the US Department of Energy (DoE) projects that it can open the Yucca Mountain repository in 2010[48] but the US General Accounting Office has identified several factors, including budget limitations, that could delay the opening to 2015 or later.[49]

U.S. nuclear-power plant operators have dealt with the lack of an off-site destination for their accumulating spent fuel by packing as many fuel assemblies as possible into their storage pools and then, when the pools are full, acquiring dry storage casks for the excess. The original design density of spent fuel in the pools associated with PWRs had the fuel assemblies spaced out in a loose square array. The standard spacing for new dense-pack racks today is 23 cm—barely above the 21.4 cm spacing in reactor cores.[50] This "dense-packed" fuel is kept sub-critical by enclosing each fuel assembly in a metal box whose walls contain neutron-absorbing boron[51] (see Figure 7[52]).

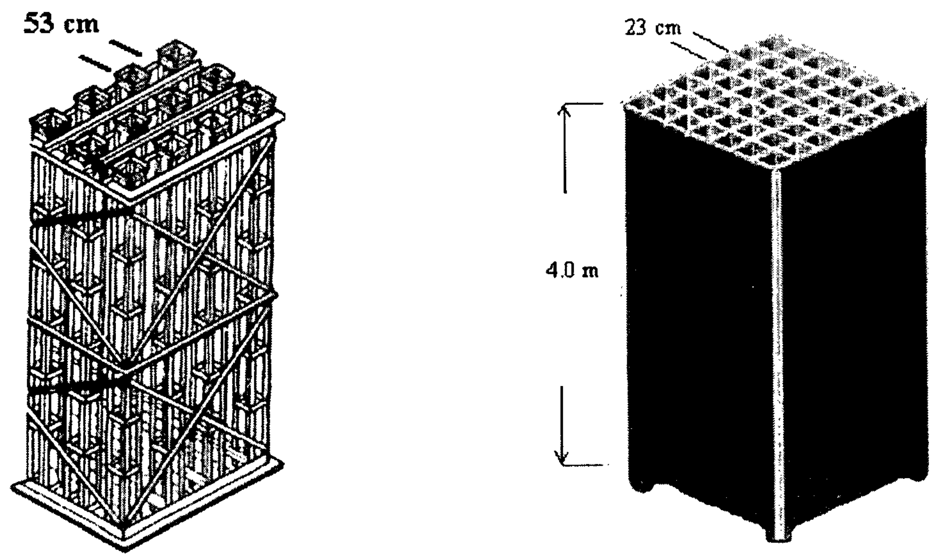


Figure 7: Open and dense-pack PWR spent-fuel racks (*Sources:* Left: NUREG/CR-0649, SAND77-1371, 1979; right: authors).

These boron-containing partitions would block the horizontal circulation of cooling air if the pool water were lost, greatly reducing the benefits of mixing recently-discharged with older, cooler fuel. During a partial uncovering of the fuel, the openings at the bottoms of the spent-fuel racks would be covered in water, completely blocking air from circulating up through the fuel assemblies. The portions above the water would be cooled primarily by steam produced by the decay heat in the below-surface portions of the fuel rods in the assemblies and by blackbody radiation.[53]

In the absence of *any* cooling, a freshly-discharged core generating decay heat at a rate of 100 kWt/tU would heat up adiabatically within an hour to about 600°C, where the zircaloy cladding would be expected to rupture under the internal pressure from helium and fission product gases,[54] and then to about 900°C where the cladding would begin to burn in air.[55] It will be seen that the cooling mechanisms in a drained dense-packed spent-fuel pool would be so feeble that they would only slightly reduce the heatup rate of such hot fuel.

In 2001, the NRC staff summarized the conclusions of its most recent analysis of the potential consequences of a loss-of-coolant accident in a spent fuel pool as follows:

> [I]t was not feasible, without numerous constraints, to establish a generic decay heat level (and therefore a decay time) beyond which a zirconium fire is

> physically impossible. Heat removal is very sensitive to... factors such as fuel assembly geometry and SFP [spent fuel pool] rack configuration... [which] are plant specific and ... subject to unpredictable changes after an earthquake or cask drop that drains the pool. Therefore, since a non-negligible decay heat source lasts many years and since configurations ensuring sufficient air flow for cooling cannot be assured, the possibility of reaching the zirconium ignition temperature cannot be precluded on a generic basis.[56]

We have done a series of "back-of-the-envelope" calculations to try to understand the computer-model calculations on which this conclusion is based. We have considered thermal conduction, infrared radiation, steam cooling, and convective air cooling.

Thermal Conduction

Conduction through the length of uncovered fuel could not keep it below failure temperature until the fuel had cooled for decades.[57]

Infrared Radiation

Infrared radiation would bring the exposed tops of the fuel assemblies into thermal equilibrium at a temperature of $T_0 = [PM/(A\sigma)]^{1/4}$ °K, where P is the power (Watts) of decay heat generated per metric ton of uranium, M is the weight of the uranium in the fuel assembly (0.47 tons), A = 500 cm^2 is the cross-sectional area of the dense-pack box containing the fuel assembly, and σ (= 5.67×10^{-12} T_K^4 Watts/cm^2) is the Stefan-Boltzman constant. (We assume that the top of the fuel assembly radiates as a black body, i.e., maximally.) For P = 1 kW or 10 kW, T_0 is respectively 370 or 860°C.

With radiative cooling only, however, the temperatures in the depths of the fuel assemblies would be much hotter, because most of the radiation from the interior of the fuel would be reabsorbed and reradiated by other fuel rods many times before it reached the top end of the fuel assembly. Even for P = 1 kW/tU (roughly 30-year-old fuel) the temperature at the bottom of the fuel assembly would be about 2000°C.[58] Therefore, while radiation would be effective in cooling the exposed surfaces of older fuel assemblies, it would not be effective in cooling their interiors.

Steam Cooling

Steam cooling could be effective as long as the water level covers more than about the bottom quarter of the spent fuel. Below that level, the rate of steam generation by the fuel will depend increasingly on the rate of heat transfer from the spent fuel to the water via blackbody radiation. The rate at which heat is transferred directly to the water will decline as the water level sinks and the temperature of the fuel above will climb. When the water is at the bottom of the fuel assembly, it appears doubtful that this mechanism could keep the peak temperature below 1200°C for fuel less than a hundred years post discharge.[59] Since even steels designed for high-temperature strength lose virtually all their strength by 1000°C and zircaloy loses its strength by 1200°C, the tops of the racks could be expected to begin to slump by the time this water level is reached.[60]

Convective Air Cooling

After a complete loss of coolant, when air could gain access to the bottom of the fuel assemblies, convective air cooling would depend upon the velocity of the air through the fuel assemblies. The heat capacity of air is about 1000 joules/kg-°C, its sea-level density at a 100°C (373°K) entrance temperature into the bottom of a fuel assembly is about 0.9 kg/m^3, the cross-section of the portion of a dense-pack box that is not obstructed by fuel rods would be about 0.032 m^2,[61] and each fuel assembly contains about 0.47 tons of uranium. The vertical flow velocity of air at the bottom of the assembly for an air temperature rise to 900°C (1173°K) then would be 0.023 m/sec per kW/tU. Because the density of the air varies inversely with its absolute temperature, this velocity would increase by a factor of (1173/373) $\approx$ 3 at the top of the fuel assembly.

The pressure accelerating the air to this velocity would come from the imbalance in density—and therefore weight—of the cool air in the space between the fuel racks and the pool wall (the "down-comer") and the warming air in the fuel assemblies. If we assume that the density of the air in the down-comer is 1 kg/m^3 and that it has an average density of 0.5 kg/m^3 in the fuel assemblies, then the weight difference creates a driving pressure difference. Neglecting friction losses, this pressure difference would produce a velocity for the air entering the bottom of the fuel assembly of about 2.7 m/s, sufficient to remove heat at a rate of 120 kW/tU. Adding friction losses limits the air velocity to about 0.34 m/s, however, which could not keep PWR fuel below a temperature of 900°C for a decay heat level greater than about 15 kW/tU—corresponding to about a year's cooling.[62] Adding in conductive and radiative cooling would not change this result significantly.

This is consistent with results obtained by more exact numerical calculations that take into account friction losses in the down-comer and the heating of the air in the building above the spent-fuel pool.[63] The 1979 Sandia study obtained similar results. It also found that, in contrast to the situation with dense-pack storage, with open-frame storage and a spacing between fuel assemblies of 53 cm (i.e., a density approximately one fifth that of dense-packed fuels), convective air cooling in a well-ventilated spent-fuel storage building (see below) could maintain spent fuel placed into the spent-fuel pool safely below its cladding failure temperature as soon as 5 days after reactor shutdown.[64] These important conclusions should be confirmed experimentally with, for example, electrically heated fuel rods.[65]

Spread of Fires from Hot to Colder Fuel

The above discussion has focused on the likelihood that recently-discharged dense-packed fuel could heat up to ignition temperature in either a partially or fully drained pool. It is more difficult to discuss quantitatively the spread of such a fire to adjacent cells holding cooler fuel that would not ignite on its own. A 1987 Brookhaven report attempted to model the phenomena involved and concluded that "under some conditions, propagation is predicted to occur for spent fuel that has been stored as long as 2 years."[66] The conditions giving this result were dense-packing with 5 inch [13 cm] diameter orifices at the bottom of the cells—i.e., typical current U.S. storage arrangements.

The report notes, however, that its model

> does not address the question of Zircaloy oxidation propagation after clad melting and relocation [when] a large fraction of the fuel rods would be expected to fall to the bottom of the pool, the debris bed will remain hot and will tend to heat adjacent assemblies from below [which] appears to be an additional mechanism for oxidation propagation.

The report therefore concludes that the consequences of two limiting cases should be considered in estimating the consequences of spent-fuel pool fires: 1) only recently discharged fuel burns, and 2) all the fuel in the pool burns.[67] This is what we have done above. We would add, however, that any blockage of air flow in the cooler channels of a dense-packed pool by debris, residual water, or sagging of the box structure would facilitate the propagation of a spent-fuel fire.[68]

MAKING SPENT-FUEL POOLS, THEIR OPERATION, AND THEIR REGULATION SAFER

A variety of possibilities can be identified for reducing the risk posed by spent-fuel pools. Some were considered in reports prepared for the NRC prior to the

Sept. 11, 2001 destruction of the World Trade Center and rejected because the estimated probability of an accidental loss of coolant was so low (about 2 chances in a million per reactor year) that protecting against it was not seen to be cost effective.[69]

Now it is necessary to take into account the potentially higher probability that a terrorist attack could cause a loss of coolant. Since the probabilities of specific acts of malevolence cannot be estimated in advance, the NRC and Congress will have to make a judgment of the probability that should be used in cost-benefit analyses. The most costly measures we propose would be justified using the NRC's cost-benefit approach if the probability of an accident or attack on a U.S. spent-fuel pool resulting in a complete release of its ^{137}Cs inventory to the atmosphere were judged to be 0.7 percent in a 30-year period. *This is at the upper end of the range of probabilities estimated by the NRC staff for spent-fuel fires caused by accidents alone.* For a release of one tenth of the ^{137}Cs inventory, the break-even probability would rise to about 5 percent in 30 years.[70]

Below, we discuss more specifically initiatives to:

- Reduce the probability of an accidental loss of coolant from a spent-fuel pool,
- Make the pools more resistant to attack,
- Provide emergency cooling,
- Reduce the likelihood of fire should a loss of coolant occur, and
- Reduce the inventory of spent fuel in the pools.

Included are three recommendations made in the 1979 Sandia study on the consequences of possible loss-of-coolant accidents at spent-fuel storage pools.[71] Unfortunately, all of these approaches offer only partial solutions to the problem of spent-fuel-pool safety. That problem will remain as long as nuclear power plants operate. However, the probability of a spent-fuel fire can be significantly reduced, as can its worst-case consequences. Some options will involve risk tradeoffs, and will therefore require further analysis before decisions are made on their implementation.

We discuss the specific changes below under three headings: regulatory, operational, and design.

Regulatory

NRC regulations do not currently require either qualified or redundant safety systems at spent-fuel pools or emergency water makeup capabilities.[72] The

NRC should require reactor owners to remedy this situation and demonstrate the capability to operate and repair spent-fuel pools and their supporting equipment under accident conditions or after an attack. This capability would contribute to defense in depth for nuclear power plants and spent fuel.[73]

Operational

Minimize the Movement of Spent-Fuel Casks Over Spent-Fuel Pools

The NRC staff study, *Spent Fuel Accident Risk*, concludes that "spent fuel casks are heavy enough to catastrophically damage the pool if dropped." The study cites industry estimates that casks are typically moved "near or over the SFP (spent fuel pool) for between 5 and 25 percent of the total path." It was concluded that this was not a serious concern, however, because industry compliance with NRC guidance would result in the probability of a drop being reduced to less than 10^{-5} per reactor-year.[74] Nevertheless, we recommend consideration of whether the movements of spent-fuel casks over pools can be reduced. We also acknowledge that reducing a pool's inventory of fuel, as recommended below, will increase the number of cask movements in the near term—although all the fuel will eventually have to be removed from the pools in any case. The resulting risk increase should be minimized as part of the implementation plan.

Minimize Occasions When the Entire Core is Moved to the Pool During Refueling Outages

Refueling outages occur every 12 to 18 months and typically last a month or so. Pool dry-out times decrease dramatically when full cores are placed into spent-fuel-storage pools only a few days after reactor shutdown. Only a third to a quarter of the fuel in the core is actually "spent." The remainder is moved back into the core at new positions appropriate for its reduced fissile content. It is not necessary to remove the entire core to the spent fuel pool to replace the fuel assemblies in their new locations.[75] Even when it is necessary to inspect the interior of the pressure vessel or to test the fuel for leakage, removal of part of the fuel should be adequate in most cases. The only regulatory *requirement* for removal of the entire core is on those infrequent occasions when work is being done that has the potential for draining the reactor pressure vessel. This would be the case, for example, when work is being done on a pipe between the pressure vessel and the first isolation valve on that pipe—or on the isolation valve itself.[76]

Design

Go to Open-Frame Storage

As already noted, the Sandia study found that, for pools with open-frame storage in well-ventilated storage buildings (see below), spent fuel in a drained storage pool will not overheat if it is cooled at least 5 days before being transferred to the pool. Furthermore, for partial drainage, which blocks air flow from below, open-frame storage allows convective cooling of the fuel assemblies from the sides above the water surface.

The simplest way to make room for open-frame storage at existing reactors is to transfer all spent fuel from wet to dry storage within five years of discharge from the reactor. Consequently, our proposal for open-frame storage is tied to proposals for dry storage, as discussed below.

The open-frame storage considered in the Sandia study could store, however, only 20 percent as much fuel as a modern dense-pack configuration. Thus, a pool that could hold 500 tons of dense-packed spent fuel from a 1000-MWe unit could accommodate in open racks the approximately 100 tons of spent fuel that would be discharged in five years from that reactor.[77] However, about twice as large a pool would be required to provide enough space in addition to accommodate the full reactor core in open-frame storage. If this much space were not available, occasions in which a full-core discharge is required would remain dangerous—although less frequent, if the recommendation to minimize full-core offloads is adopted.

Alternative approaches to a lack of sufficient space for open-rack storage would be to move spent fuel out of the pool earlier than five years after discharge or to adopt racking densities intermediate between dense-pack and the Sandia open rack arrangement. Two interesting intermediate densities that should be analyzed are: 1) an arrangement where one fifth of the fuel assemblies are removed in a pattern in which each of the remaining fuel assemblies has one side next to an empty space; 2) an arrangement where alternate rows of fuel assemblies are removed from the rack. These geometries would have to include perforations in the walls to allow air circulation in situations where enough water remained in the pool to block the openings at the bottoms of the boxes, or removal of some partitions entirely.

One problem with open-rack storage is that it creates a potential for a criticality accident for fresh or partially burned fuel if the fuel racks are crushed.

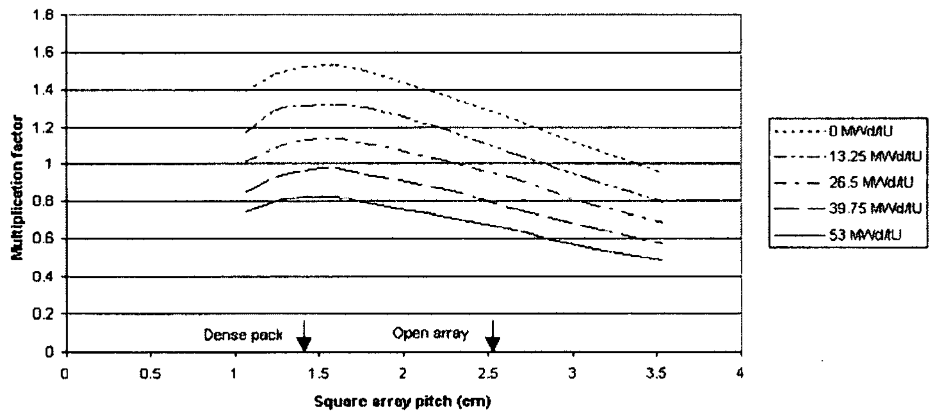


Figure 8: Neutron multiplication as a function of array pitch in an infinite square array of 4.4% enriched fuel rods with a design burnup of 53 MWd/kgU for 0, 25, 50, 75 and 100% irradiation (*Source:* authors).

Figure 8 shows the value of the neutron multiplication factor k_{eff} in an infinite square array of 4.4% enriched fuel at various burnups as a function of the spacing between the rod centers (the array "pitch") in a pool of unborated water.[78] It will be seen that, for burnups of less than 50 percent, the open array is critical at a pitch of 2.6 cm and that the neutron multiplication factor increases as the pitch decreases to about 1.6 cm.

This situation is most problematical for low-burnup fuel. One way to remedy the situation for low-burnup fuel would be to put in neutron-absorbing plates between rows of fuel assemblies.[79] This would still allow free convection of air through the rows. Other configurations of neutron-absorbing material could also be consistent with allowing free convection. Suppression of criticality could also be achieved by adding a soluble compound of neutron-absorbing boron to the pool water.[80] Finally, some high-density rack spaces could be provided for low-burnup fuel. If fresh fuel is stored in pools, it could certainly be put in dense-rack storage since fresh fuel does not generate significant heat.

Provide for Emergency Ventilation of Spent-Fuel Buildings

The standard forced air exchange rate for a spent-fuel-storage building is two air changes per hour.[81] Consider a building with an air volume *V* and an air exchange rate of *n* volumes of external air per hour. If the spent fuel generates heat at a rate P, the air temperature rise will be $\Delta T = 3600P/(nV\rho c_p)$ where ρ is the density of the air entering the building (about 1 kg/m^3) and c_p is the heat capacity of the air per kg at constant pressure [(about 1000 joules/(kg-°C)]. Therefore, $\Delta T \sim 3.6P/(nV)$. Consider a case where the spent-fuel pool contains 80 tons of freshly-discharged fuel generating 100 kWt/tU of decay heat (i.e., P = 8 MWt) and where V = 10,000 cubic meters (e.g., a building roughly 30 meters square and 10 meters tall). For this case, $\Delta T \sim 2900/n$°C. To bring ΔT down to 100°C would require about 30 air exchanges per hour.

The Sandia report proposed that, in case of a loss-of-coolant accident, large vents in the sides and roof of the building be opened to allow a high rate of convective air exchange. The required area of the openings was calculated by equating the outside-inside air pressure difference at the floor of a building H meters high due to the difference in air densities outside and inside: $\Delta p = gH(\rho_o - \rho_i)$ with the sum of the throttling pressure losses at the openings: $\Delta p_{th} = 0.5\rho_o(v_i/C_D)^2 + 0.5\rho_i(v_o/C_D)^2$. Here v_i and v_o are respectively the average velocities of the incoming and exiting air and the "discharge coefficient," $C_D \sim 0.6$, reflects the reduction of the air velocity due to turbulence caused by the edges of the openings. Taking into account the fact that air density varies inversely with absolute temperature, the minimum area of the openings can be calculated as[82]

$$A = \{P/[C_D c_p \rho_o (2gH)^{1/2}]\}\{T_i(T_o + T_i)/[T_o(\Delta T)^3]\}^{1/2}$$

For H = 10 m, T_i = 300°K and ΔT = 100°K, this equation becomes A = 3.6P m^2 if P is measured in megawatts. Thus, if P = 8 MWt, A would have to be 30 m^2, e.g. an opening 10 meters long and 3 meters high.

Of course, such a system would not prevent a fire in a dense-packed pool because of the poor air circulation in the spent-fuel racks. It is a complement to open-rack storage, not a substitute.

The venting system design proposed in the Sandia report is attractive because it is passive. However, it might be difficult to retrofit into existing buildings, the door-opening system might be incapacitated, and it would not work if the building collapsed as a result of an accident or terrorist act. Furthermore, if a fire did start, the availability of ventilation air could feed the fire. Therefore, high-capacity diesel-powered blowers should be considered as an alternative or complement to a passive ventilation system.

Install Emergency Water Sprays

The Sandia report also proposed that a sprinkler system be installed.[83] For 80 tons of spent fuel generating 100 kWt/MTU, the amount of water required if it were all evaporated would be about 3 liters per second. Such a flow could easily be managed in a sprinkler system with modest-sized pipes.[84] The sprinkler system should be designed with an assured supply of water and to be robust and protected from falling debris. It should also be remotely operated, since the radiation level from uncovered fuel would make access to and work in a spent-fuel building difficult to impossible—especially if the building were damaged. The hottest fuel should be stored in areas where spray would be the heaviest, even if the building collapses on top of the pool (e.g., along the sides of the pool). The spray would need to reach all of the spent fuel in the pool, however—especially in scenarios where the spray water accumulated at the bottom of the pool and blocked air flow into the dense-pack racks.

Another circumstance in which the spray could aggravate the situation would be if the spent-fuel racks were crushed or covered with debris, blocking the flow of air. In such a case, steam generated from water dripping into the superheated fuel could react with the zirconium instead. The circumstances under which sprays should be used would require detailed scenario analysis.

Make Preparations for Emergency Repairs of Holes

A small hole, such as might be caused by the penetration of a turbine shaft or an armor-piercing warhead, might be patched. For a hole in the side, a flexible sheet might be dropped down the inside of the pool.[85] However, in the turbine-shaft case, the space might be blocked if the projectile was protruding from the wall into the spent-fuel rack. Or the racks might be damaged enough to close the gap between them and the side of the pool. Also, if the top of the fuel were already exposed, the radiation levels in the pool area would be too high for anything other than pre-emplaced, remotely controlled operations.

Patching from the outside would be working against the pressure of the water remaining in the pool (0.1 atmosphere or 1 kg/cm^2 per meter of depth above the hole). However, there could be better access and the pool wall would provide shielding—especially if the hole were small. Techniques that have been developed to seal holes in underground tunnels might be useful.[86]

Armor Exposed Outside Walls and Bottoms Against Projectiles

The water and fuel in the pool provide an effective shield against penetration of the pool wall and floor from the inside. It should be possible to prevent penetration by shaped charges from the outside with a stand-off wall about 3 meters away that would cause the jet of liquid metal formed by the shaped charge to expand and become much less penetrating before it struck the pool wall. In the case of the turbine shaft, Pennington's analysis for dry casks suggests that it also might be possible to absorb the shaft's energy with a thick sheet of steel that is supported in a way that allows it to stretch elastically and absorb the projectile's kinetic energy (see below).

REDUCING THE INVENTORY OF SPENT-FUEL POOLS

Our central proposal is to move spent fuel into dry storage casks after it has cooled for 5 years.[87] In addition to allowing for a return to open-frame storage, such a transfer would reduce the typical ^{137}Cs inventory in a pool by approximately a factor of four,[88] thereby reducing the worst-case release from a pool by a comparable factor. Casks are already a growing part of at-reactor storage capacity. Out of the 103 operating power reactors in the U.S., 33 already have dry cask storage and 21 are in the process of obtaining dry storage.[89] On average about 35 casks would be needed to hold the 5-year or more aged spent fuel in a spent fuel pool filled to capacity.[90]

As already noted, to a certain extent this proposal runs counter to the earlier proposal to mimimize the movement of spent fuel casks over pools. The risk of dropped casks should be considered in deciding on which types of dry storage transfer casks are utilized.

SAFETY OF DRY-CASK STORAGE

Shifting pools back toward open-rack storage would require moving much of the spent fuel currently in pools into dry storage casks. With currently licensed casks, this could be done by the time the fuel has cooled 5 years.

In principle, the transfer of the spent fuel to dry storage could take place earlier. Spent fuel cooled for 2.5 years has about twice the decay heat per ton as spent fuel 5 years after discharge (see figure 5). Such spent fuel might be stored next to the walls of storage casks with older, cooler spent fuel stored in the interior.

Casks are not vulnerable to loss of coolant because they are cooled by natural convection that is driven by the decay heat of the spent fuel itself. Thus dry-storage casks differ from reactors and existing spent-fuel pools in that their cooling is completely passive. To obtain a release of radioactive material, the wall of the fuel container must be penetrated from the outside, or the container must be heated by an external fire to such an extent that the containment envelope fails. However, many dry-storage modules must fail or be attacked simultaneously to produce the very large releases that are possible today at spent-fuel pools. Nevertheless, since the total ^{137}Cs inventory on-site does not change under our proposal, it is important to examine the safety of dry-cask storage as we envisage it being used.

There are two basic types of dry storage cask currently licensed in the U.S. (see Figure 9):[91]

1. Casks whose walls are thick enough to provide radiation protection; and
2. Thin-walled canisters designed to be slid into a concrete storage overpack that provides the radiation shielding with space between the cask and overpack for convective circulation of air. (Transfer overpacks and transport overpacks are used for onsite movement and offsite shipping, respectively.)

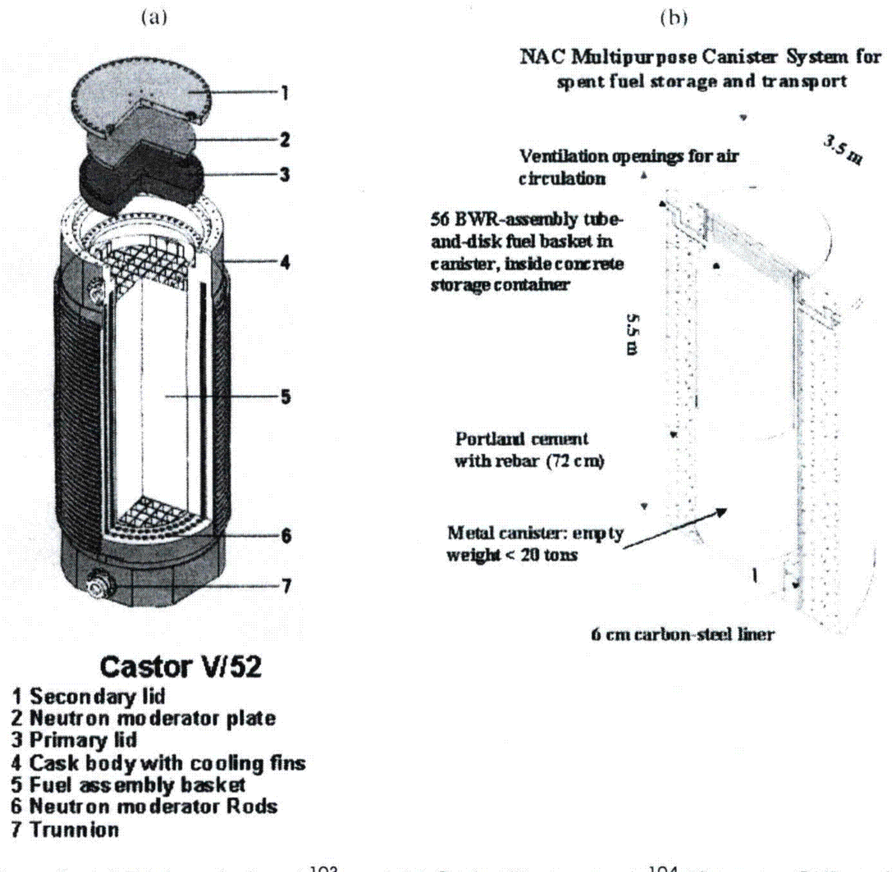


Figure 9: (a) Thick-walled cask[103] and (b) Cask with overpack.[104] (*Sources:* GNB and NAC).

Among the possible threats to such casks are: shaped-charge missiles, aircraft turbine spindles, and fire.

Shaped-Charge Missile

Dry storage casks in the U.S. are stored on concrete pads in the open. Missiles tipped with shaped charges designed to penetrate tank armor could penetrate such an unprotected storage cask and cause some damage to the fuel within. Experiments on CASTOR-type spent fuel casks of 1/3 length and containing a 3 × 3 array of assemblies were carried out in 1992 at a French army test site for Germany's Ministry of the Environment and Nuclear Safety (BMU). The simulated fuel was made of unirradiated depleted uranium pressurized to 40 atmospheres to simulate the pressure buildup from fission product gases in spent fuel.

The particulate matter released through the hole was collected and analyzed for size distribution. When the initial pressure within the cask was atmospheric, about 3.6 grams of particles with diameters less than 100 microns were released in a puff from the hole. In the analysis of radiological consequences, it was assumed that, because of its volatility, ^{137}Cs equivalent to that in 50 grams of spent fuel with a burnup of 48.5 MWd/tU would be released.[92] Another analysis assumed a ^{137}Cs release 1000 times larger.[93] A still larger release could occur if a cask were attacked in such a way as to initiate and sustain combustion of the zirconium cladding of the fuel.

It has been found possible to plug the relatively small hole made by a shaped charge in a thick-walled iron cask with a piece of lead before much radioactivity could be released.[94] Plugging the hole would be considerably more difficult in the case of a thin-walled cask surrounded by a concrete overpack.

In each case, unless the fuel-in a significant fraction of the casks were ignited, the release would be small in comparison to the potential release resulting from a spent-fuel-pool fire. Nevertheless, German authorities require casks to be stored inside a shielding building. The building walls could be penetrated by a shaped charge but the liquid metal would spread in the space between the wall and the nearest cask and therefore be relatively harmless. U.S. dry-cask storage areas are not currently so protected but the casks could be protected with an overpack[95] and/or a berm.

Turbine Spindle

The Castor cask has survived, without penetration impacts, from various angles by a simulated turbine spindle weighing about half a ton surrounded by additional steel weighing about as much and traveling at almost sonic speed

(312 m/sec).[96] Recently, NAC International carried out a computer simulation of the impact of a Boeing 747 turbine on its canister-in-overpack Universal Multipurpose System at a speed of 220 m/sec and concluded it too would not be penetrated. This conclusion should be verified experimentally.[97]

Fire

Theoretical studies of the resistance to fire of Castor V/19 (PWR) and V/52 (BWR) storage/transport casks were done for Austria's Environmental Agency for a number of German reactor sites because of concerns that the contamination from cask failure might extend into Austria. The scenario was a crash of a large commercial airliner into a storage facility. It was assumed that 60 tons of kerosene pooled around the storage casks and burned for 3 to 5 hours at a temperature of 1000°C. It was estimated that, because of the massive heat capacity of the thick cask walls, the seals of their bolted-down lids would begin to fail only after 3 hours. It was also assumed that, by that time, the fuel cladding would have failed. Finally, it was assumed that the contained ^{137}Cs would be in its most volatile possible (elemental) form. On this basis, it was estimated that about 0.04 MCi of ^{137}Cs would be released after a 5-hour, 1000°C fire in a storage facility with 135 casks containing a total of 170 MCi.[98]

Obviously, the release from even such a worst-case incident would be tiny compared with the 100 to 1000 times higher releases from a spent-fuel pool fire considered above. However, a spent-fuel storage facility should be designed, among other requirements, to prevent the pooling of kerosene around the casks.

IMPLEMENTATION ISSUES RELATING TO THE TRANSFER OF OLDER SPENT FUEL TO DRY-CASK STORAGE

As will be explained, given existing cask-production capacity, it would take about a decade to move most of the spent fuel currently in pools into dry-cask storage. Virtually all of the storage would have to be at the reactor sites for some decades until off-site disposal becomes available. The Yucca Mountain underground repository will not open for at least a decade and current plans have spent fuel being shipped to the repository at a rate of 3000 tons per year—only about 1000 tons/yr more than the current rate of spent-fuel discharge from U.S. reactors.[99] If the opening of Yucca Mountain is delayed for many years, approximately 2000 tons of spent fuel per year might be shipped to a proposed large centralized facility on the Goshute reservation west of Salt Lake City, Utah—if it is licensed.[100]

For comparison, the inventory of spent fuel at U.S. reactor sites will be more than 60,000 tons in 2010, of which about 45,000 tons will be in mostly dense-packed pools.[101] If all but the last 5 years of discharges are dry stored, approximately 35,000 tons will have to be unloaded from the pools.[102] Since it would be imprudent to assume that off-site shipments to Yucca Mountain or a centralized interim spent-fuel storage facility could be relied on to solve the problem of dense-packed spent-fuel pools anytime soon, we focus here on the logistical and cost issues associated with increasing the amount of on-site dry storage.

Cask Availability

Cask availability could be a rate-limiting step in moving older spent fuel from pools into dry storage at the reactor sites. Currently, US cask fabrication capacity is approximately 200 casks per year—although the production rate is about half that. Two hundred casks would have a capacity about equal to the spent-fuel output of U.S. nuclear power plants of about 2000 tons per year. However, according to two major U.S. manufacturers, they could increase their combined production capacity within a few years to about 500 casks per year.[105] To use the extra 300 casks per year to unload 35,000 tons of spent fuel out of the storage pools would require about 10 years. This period could be reduced somewhat if the unloading of high-density pools was perceived to be an important issue of homeland security. The United States has substantial industrial capacity that could be allocated to cask production using existing, licensed designs. Casks made in Europe and Japan could be imported as well. However, other potentially rate-limiting factors would also have to be considered in any estimate of how much the transfer period could be shortened.

Dry-Storage Costs

Storage cask capacity costs U.S. utilities from $90 to $210/kgU.[106] Additional capital investments for new on-site dry storage facilities would include NRC licensing, storage pads, security systems, cask welding systems, transfer casks, slings, tractor-trailers, and startup testing. These costs are estimated to range from $9 to $18 million per site.[107] However, at most sites, they will be incurred in any case, since even dense-packed pools are filling up. The capital cost of moving 35,000 tons of spent fuel into dry casks would therefore be dominated by the cost of the casks and would range from about $3.5 to $7 billion ($100–200/kgU). Per GWe of nuclear capacity, the cost would be $35–70 million. The additional cost per kWh would be about 0.03–0.06 cents/kWh.[108] This is 0.4–0.8 percent of the average retail price of electricity in 2001.[109] It is also equivalent to 30 to 60 percent of the federal charge for the ultimate disposition of the spent fuel (see below).

The extra cost would be reduced significantly if the casks could be used for transport and ultimate disposal as well. For multi-purpose canisters with stationary concrete overpacks, the extra cost would then be associated primarily with the overpack (about 20% of the total cost) and with the need to buy the canisters earlier than would have been the case had the spent fuel stayed in dense-packed pools until it was transported to the geological repository. Unfortunately, the Department of Energy has abandoned the idea of multi-purpose containers and currently plans to have spent fuel unpacked from transport canisters and then repacked in special canisters for disposal.[110]

Costs would be increased by the construction of buildings, berms or other structures to surround the casks and provide additional buffering against possible attack by anti-tank missiles or crashing aircraft. The building at Gorleben, which is licensed to hold 420 casks containing about 4200 tons of uranium in spent fuel, would cost an estimated \$20–25 million to build in the United States or about \$6/kgU.[111] Assuming conservatively that the building cost scales with the square root of the capacity (i.e. according to the length of its walls), it would cost about \$12/kgU for a facility designed to store 100 casks containing 1000 tons uranium in spent fuel—about the inventory of a typical 2-reactor site if our proposal was carried through by 2010.[112] Berms for a middle-sized storage area might cost about \$1.5–3/kgU.[113]

Licensing Issues

The NRC currently licenses storage casks for 20 years. Some U.S. dry-cask storage facilities will reach the 20-year mark in a few years. The NRC is therefore currently deciding what analysis will be required to provide a basis for license extensions.

With reactor operators increasing fuel burnup, casks will also eventually have to be licensed for the storage of high-burnup fuel. Current licenses allow burnups of up to 45,000 MWd/MT. However, the CASTOR V/19 cask is already licensed in Germany to store 19 high-burnup Biblis-type fuel assemblies, which are slightly bigger and heavier than U.S. PWR fuel assemblies. The license allows 15 five-year cooled fuel assemblies with burnups of 55 MWd/kgU plus four with burnups of up to 65 MWd/kgU.[114] U.S. storage casks have been tested with fuels with burnups of 60 MWd/kgU.[115]

Finally, some reactor operators have expressed concern that the NRC does not currently have sufficient manpower to accelerate the process of licensing on-site dry storage. However, almost all sites will have to license dry storage in the timeframe considered here in any case.

Who Will Pay?

Nuclear power operators can be expected to balk at the extra cost of moving spent fuel out of pools to on-site dry storage. As a result of deregulation, many operators are no longer able to pass such costs through to customers without fear of being undersold by competing fossil-fueled power plants. Also, many plants have been sold at a few percent of their original construction costs to owners who have established corporations to limit their liability to the value of the plants themselves.[116] Therefore, to prevent extended delays in implementing dry storage, the federal government should consider offering to pay for extra storage casks and any security upgrades that it might require for existing dry storage facilities.

Under the Nuclear Waste Policy Act (NWPA) of 1982, the Department of Energy (DoE) was to enter into contracts with nuclear utilities to begin moving spent fuel from nuclear power plants to a national deep underground repository by 1998. In exchange, the utilities made payments to a national Nuclear Waste Fund at the rate of 0.1 cents per net electrical kilowatt-hour generated by their nuclear plants plus a one-time payment (which some utilities have not yet fully paid) based on their nuclear generation prior to the law's enactment. As of May 31, 2002, this fund had a balance of $11.9 billion. Since 1995, $600–700 million have been deposited annually.[117] The DoE spends about $600 million annually on Yucca Mountain but, for the past several years, about two thirds of this amount has been drawn from the National Defense Account of the U.S. Treasury because the DoE had previously underpaid for the share of the facility that will be occupied by high-level radioactive waste from its defense nuclear programs.

There is therefore, in principle, a considerable amount of money that could be made available in the Nuclear Waste Fund for dry storage. However, under some circumstances, all these funds may eventually be required for the Yucca Mountain facility, whose total cost is projected to be $57.5 billion.[118] Furthermore, the use of the fund for interim storage has been blocked by utility lawsuits.[119] Most likely, therefore, the NWPA would have to be amended to allow the federal government to assume title to dry-stored spent fuel and responsibility for on-site storage.

An alternative approach would be to create an additional user fee similar to that which flows into the NWPA fund. A fee of 0.1 cents per nuclear kWh would generate an additional $750 million per year that could in 5 to 10 years pay the $3.7 to 7 billion cost estimated above to transfer 35,000 tons of spent fuel into dry, hardened, on-site storage. Such a fee would, however, be opposed by the nuclear-plant operators.

SUMMARY

As summarized in Table 2, we have proposed a number of possible actions to correct for the obvious vulnerabilities of spent fuel pools and to reduce the worst-case release that can occur from such pools. These recommendations would result in significant improvements over the current situation but they would also have significant limitations.

Improvements

- The obvious vulnerabilities of spent fuel pools would be addressed.
- The worst-case release from a typical spent fuel pool of ^{137}Cs—the isotope that governs the extent of long-term land contamination—would be reduced by a factor of about four. The residual inventory of ^{137}Cs in the spent fuel pool would be about twice that in a reactor core.
- Our recommendations are achievable with existing technologies at a cost less than a percent of the price of nuclear-generated electricity.

Limitations

- Considerable ^{137}Cs would remain in hot spent fuel in pool storage.
- Terrorists could still cause releases from the dry-cask modules to which the aged spent fuel would be transferred, although it is difficult to imagine how they could release a large fraction of the total stored inventory, short of detonation of a nuclear weapon.
- Our analysis has been largely limited to accidents or terrorist acts that would partially or completely drain the pool while leaving the geometry of the spent fuel racks and the building above intact. Spent fuel fires might still arise in open-racked pools with air circulation blocked by a collapsed building. Such situations require more analysis.
- We have considered generic PWR pools. Additional issues may well arise when specific PWR and BWR pools designs are analyzed.

Table 2: Summary of proposals.

Type	Action	Comment
Regulation	Congress should decide the probability of a terrorist-caused spent-fuel pool fire to be used by the NRC as a basis for regulatory cost-benefit analysis.	The NRC currently has no basis for deciding a limit on how much should be spent on strengthening protections against terrorist actions.
	The NRC should require that nuclear-power plant operators have the capability to operate and repair spent-fuel pools under accident conditions or after an attack.	This would apply the NRC's defense in depth approach for nuclear power plants to spent-fuel pools.
Operation	Minimize the movement of spent fuel casks over spent-fuel pools.	This has to be balanced with the proposal to remove older fuel from the pools.
	Minimize occasions when the entire core is moved to the pool during refueling outages.	Technically possible with some potential inconvenience to licensees.
	Transfer spent fuel to dry-cask storage 5 years after discharge from the power reactor.	Transfer probably could be accomplished somewhat earlier. Implementation will probably require Congress to permit use of the Nuclear Waste Fund or to enact a retrospective fee on electricity consumers—estimated at about 0.03–0.06 cents per kilowatt hour generated from the spent fuel.
Design	Return to open-frame storage—perhaps with additional measures of criticality control.	
	Provide for emergency ventilation of spent-fuel buildings.	Analysis is required on how to control this air supply if a fire did start.
	Install emergency water sprays.	Water from the sprays could block air circulation in a dense-packed pool or feed a fire under some circumstances.
	Make preparation for emergency repair of holes in pool walls and bottom.	
	Armor exposed outside walls and bottoms against projectiles.	Feasibility may vary greatly for different pool designs.

Finally, all of our proposals require further detailed analysis and some would involve risk tradeoffs that also would have to be further analyzed. Ideally, these analyses could be embedded in an open process in which both analysts and policy makers can be held accountable. This process would have to be designed to balance the need for democratic debate with the need to keep from general distribution information that might facilitate nuclear terrorism. We believe that our study shows that such a balance can be achieved.

ACKNOWLEDGEMENTS

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NOTES AND REFERENCES

1. "The results of the study indicate that the risk at SFPs [spent fuel pools] is low and well within the Commission's Quantitative Health Objectives.... The risk is low because of the very low likelihood of a zirconium fire even though the consequences of a zirconium fire could be serious." [*Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants* (NRC, NUREG-1738, 2001) Executive Summary].

2. *Spent Fuel Heatup Following Loss of Water During Storage* by Allan S. Benjamin et al. (Sandia National Laboratory, NUREG/CR-0649, SAND77-1371, 1979), fig. 14.

3. "Policy issues related to safeguards, insurance, and emergency preparedness regulations at decommissioning nuclear power plants storing fuel in spent fuel pools," (NRC, Secy-01-0100, June 4, 2001) pp. 3,5.

4. U.S. NRC, "In the matter of Dominion Nuclear Connecticut, Inc, (Millstone Nuclear Power Station, Unit No. 3)" Docket No. 50-423-LA-3, CLI-02-27, memorandum and order, Dec. 18, 2002.

5. *Ibid.*

6. *Ibid.*

7. Nuclear Waste Policy Act, 42 U.S.C. 10,131 et seq, Subtitle B.

8. *NRC's regulation of Davis-Besse regarding damage to the reactor vessel head* (Inspector General Report on Case No. 02-03S, Dec. 30, 2002, http://www.nrc.gov/reading-rm/doc-collections/insp-gen/2003/02-03s.pdf, accessed, Jan 4, 2003), p. 23.

9. Letter to the Senate majority and minority leaders, and Speaker and minority leader of the House of Representatives from the Attorneys General of Arizona, Arkansas, California, Colorado, Connecticut, Georgia, Hawaii, Iowa, Maryland, Massachusetts, Michigan, Minnesota, Mississippi, Montana, Nevada, New Jersey, New Mexico, New York, North Carolina, Ohio, Oregon, Pennsylvania, Rhode Island, Vermont, West Virginia, Washington and Wisconsin, Oct. 8, 2002.

10. List of spent-fuel pools from *Energy Resources International*, 2002, "2002 Summary of U.S. Generating Company In-Pool Spent Fuel Storage Capability Projected Year That Full Core Discharge Capability Is Lost," June, 2002, (http://www.nei.org/documents/Spent_Fuel_Storage_Status.pdf, Dec. 9, 2002). Latitudes and longitudes of the sites from http://geonames.usgs.gov/fips55.html.

11. In addition, Browns Ferry Unit 1 is nominally operational. However, it is defueled and not in service.

12. *Spent Nuclear Fuel Discharges from US Reactors 1994* (U.S. Department of Energy, Energy Information Agency, report # SR/CNEAF/96-0, 1996.

13. J. G. Ibarra, W. R. Jones, G. F. Lanik, H. L. Ornstein and S. V. Pullani, *Operating Experience Feedback Report: Assessment of Spent Fuel Cooling* (NRC, NUREG-1275, 1997), Vol. 12, figs. 2.1, 2.2.

14. See e.g. *Analysis of Spent Fuel Heatup Following Loss of Water in a Spent Fuel Pool: A Users' Manual for the Computer Code SHARP* by Energy and Environmental Science, Inc. (NUREG/CR-6441/ BNL-NUREG-52494, 2002).

15. Strontium-90 (28-year half-life) and its decay product, yittrium-90 (64 hours) account for another 40 percent of fission-product activity at 10 years [M. Benedict, T. H. Pigford, and H. W. Levi, *Nuclear Chemical Engineering, 2nd ed.* (McGraw-Hill, 1981), Table 8.1]. However ^{90}Sr is less volatile than ^{137}Cs, especially under the oxidizing conditions typical of a spent fuel pool fire. It and ^{90}Y are not gamma emitters and are therefore a hazard primarily if ingested.

16. *Table of Isotopes, 7th ed.*, C. M. Lederer and V. S. Shirley, eds. (John Wiley, 1978).

17. Exposures and effects of the Chernobyl accident," Annex J in *Sources and Effects of Ionizing Radiation* (UN, 2000) http://www.unscear.org/pdffiles/annexj.pdf, "Within these areas, radiation monitoring and preventive measures were taken that have been generally successful in maintaining annual effective doses within 5 mSv [0.5 rems]" ("Exposures and effects of the Chernobyl accident," pp. 472–5).

18. "Exposures and effects of the Chernobyl accident," p. 457.

19. Fission in LEU fuel yields 3.15 Curies of ^{137}Cs per MWt-day of heat released. One Curie is the radioactivity of one gram of radium (3.7×10^{10} disintegrations/sec). 1 Bequerel (Bq) is one disintegration/sec.

20. Range estimated in *A Safety and Regulatory Assessment of Generic BWR and PWR Permanently Shutdown Nuclear Power Plants* by R. J. Travis, R. E. Davis, E. J. Grove, and M.A. Azarm (Brookhaven National Laboratory, NUREG/CR-6451; BNL-NUREG-52498, 1997), Table 3.2. More detailed analysis is provided in *Severe Accidents in Spent Fuel Pools in Support of Generic Safety Issue 82* by V. L. Sailor, K. R. Perkins, J. R. Weeks and H.R. Connell (Brookhaven National Laboratory, NUREG/CR-4982 or BNL-NUREG-52083, 1987), Sections 3 and 4. Virtually all the ^{137}Cs would be released from the spent fuel before the melting temperature of zirconium (1850°C) is reached. See "Report to the American Physical Society by the study group on radionuclide release from severe accidents at nuclear power plants," *Reviews of Modern Physics 57* (1985), p. S64. However, it is possible that some of the older fuel might not catch fire and some fraction of the ^{137}Cs might plate out onto cool surfaces in the building.

21. For the "wedge model" the contamination level $\sigma = [Q/(\theta r R_d)]\exp(-r/R_d)$ Ci/m^2 where Q is the size of the release in Curies, θ is the angular width of a down-wind wedge within which the air concentration is assumed to be uniform across the wedge and vertically through the mixing layer, r is the downwind distance in meters, and R_d is the "deposition length" $R_d = Hv_w/v_d$. H is the thickness of the mixing layer; v_w is the wind velocity averaged over the mixing layer; and v_d, the aerosol deposition velocity, measures the ratio between the air concentration and ground deposition density. This "back-of-the-envelope" approximation was first used in the "Report to the American Physical Society by the study group on light-water reactor safety," *Reviews of Modern Physics*, 47, Supplement 1 (1975), p. S97. For a uniform population density, the population radiation dose is independent of θ. An extensive discussion of aerosol formation and deposition

may be found in "Report to the American Physical Society by the study group on radionuclide release from severe accidents at nuclear power plants," p. S69–S89. Data on the frequency of different dispersion conditions in the U.S. and data on aerosol deposition rates may be found in *Reactor Safety Study*, (U.S. NRC, NUREG-75/014, 1975), Appendix VI-A. See also: *Probabilistic Accident Consequence Uncertainty Analysis: Dispersion & Deposition Uncertainty Assessment*, (U.S. Nuclear Regulatory Commission & Commission of European Communities, NUREG-6244 and EUR 15855EN, 1995), Vols. 1–3.

22. D. I. Chanin and M. L. Young, *Code Manual for MACCS2: Volume 1, User's Guide*, Sandia National Laboratories, Albuquerque, NM, SAND97-0594, March 1997. In the Gaussian plume model with a mixing layer thickness H and a constant wind velocity v_w, the time-integrated plume concentration at a point on the ground a horizontal distance y from the centerline of the plume and a distance h below it is $\chi = [Q/(\pi \sigma_y \sigma_z v_w)] \exp[-y^2/(2\sigma_y^2)] \{\exp[-h^2/(2\sigma_z^2)] + \sum_{n=1-\infty}[\exp[-(2nH-h)^2/(2\sigma_z^2)] + \exp[-(2nH+h)^2/(2\sigma_z^2)]]\}$. The term $\sum_{n=1-\infty}[\exp[-(2nH-h)^2/(2\sigma_z^2)] + \exp[-(2nH+h)^2/(2\sigma_z^2)]]$ takes into account multiple reflections of the plume off the top of the mixing layer and the ground. Q, σ_y, and σ_z are all functions of downwind distance. Q, the number of Curies in the plume, is reduced by deposition. The area deposition concentration is $v_d \chi$, where v_d is the deposition velocity.

23. The calculations used the same median values of mixing layer height (1000 m), wind velocity (5 m/sec), and deposition velocity (0.01 m/sec) used in the wedge-model calculation above. On the basis of a match with the wedge-model value $\theta r = 2.4\ \sigma_y = 11$ km at r = 100 km downwind, dispersion conditions have been chosen to be Pasquill D-type which the MACCS2 code parameterizes as $\sigma_y = 0.1474x^{0.9031}$ and $\sigma_z = 0.3x^{0.6532}$ m where x is the downwind distance in meters.

24. The heat of combustion of zirconium is 8.7 and 4.1 million j/kg in air and steam respectively. We assume that the pool contains 80 tons of zirconium, i.e., 0.2 tons per ton of U.

25. Most of the data in the charts are from 1998 data provided by utility companies to the NRC and previously displayed on its web site at http://www.nrc.gov/OPA/drycask/sfdata.htm. Post September 11, 2001, such data are no longer available on the web. The storage capacity in the storage pools of a few plants has increased since 1998 due to reracking with higher density racks. Such increases are included for the following reactors: Crystal River 3 ["Florida Power Corporation, Crystal River Unit 3, Environmental Assessment and Finding of No Significance" (NRC, *Federal Register* (FR), v. 65, n. 177, pp. 55059–55061, Sept. 12, 2000)]; Callaway [*FR*, v. 64, n. 10, pp. 2687–2688, Jan. 15, 1999]; Nine Mile Point 1 [*FR*, v. 64, n. 70, pp. 18059–18062, April 13, 1999]; and Kewaunee [*FR*, v. 65, n. 236, pp. 76672–76675, Dec. 7, 2000]. Three other plants (Enrico Fermi 1, Comanche Peak, and Vermont Yankee) have re-racked, but no capacity data are available (no environmental assessments were done for them). Brunswick 1 and 2 and Robinson are shipping spent fuel to the Harris plant, also in North Carolina and owned by Carolina Light and Power Company. Nine Mile Point 2, Pilgrim 1, Summer, and Three Mile Island 1 plants intend to re-rack their spent fuel in the next few years ("2002 Summary of U.S. Generating Company In-Pool Spent Fuel Storage Capability Projected Year That Full Core Discharge Capability Is Lost"). Big Rock Point, Browns Ferry 3, Diablo Canyon 1&2, Duane Arnold, Farley 1&2, Grand Gulf 1, Haddam Neck, Humboldt Bay, Palo Verde 1–3, River Bend 1, San Onofre 1–3, Sequoyah 1&2, Washington Nuclear, and Yankee Rowe plants, some of which are being decommissioned, all intend to add dry storage in the next few years (*ibid*). An

earlier version of this figure appeared in Allison Macfarlane, "Interim storage of spent fuel in the United States," *Annual Review of Energy and the Environment* 26 (2001), pp. 201–235.

26. "Simulation of the Chernobyl dispersion with a 3-D hemispheric tracer model" by Janusz Pudykiewicz, *Tellus 41B* (1989), pp. 391–412.

27. "Exposures and effects of the Chernobyl accident," Table 8.

28. One rem = 0.01 Sievert. For estimated exposure-dose coefficients, see *Ionizing Radiation: Sources and Biological Effects* (UN, 1982), Annex E, Table 27 (external) and Table 33 (ratio of internal to external). For the external dose, the ^{137}Cs is assumed to have weathered into the soil with an exponential profile with a mean depth of 3 cm. Shielding by buildings is estimated to reduce the dose by a factor of 0.4 for wooden homes and 0.2 for masonary homes. The resulting total dose-reduction is by a factor of about 1/6. Self shielding by the body is assumed to reduce the dose by an additional average factor of 0.7. See also *Federal Guidance Report No. 12: External Exposure To Radionuclides In Air, Water, And Soil* by K. F. Eckerman and J. C. Ryman (Oak Ridge National Laboratory, EPA-402-R-93-081, 1993) Table II-6. The additional cancer death risk was assumed to be 1/1700 per rem, including a recommended reduction factor of 2 for the risk of chronic radiation per rem relative to that from an "acute" (instantaneous) dose such as that at Hiroshima and Nagasaki ["Epidemiological Evaluation of Radiation-Induced Cancer," Annex I in *Sources and Effects of Ionizing Radiation* (UN, 2000), p. 361.] Note that arguments about the validity of a linear extrapolation to low doses from the high doses at which epidemiological evidence is available are irrelevant in this dose range. The mean dose among the cohort of Hiroshima-Nagasaki survivors who have been followed in Life-Span Study is 21 rem (*op. cit.*, Table 6). A statistically significant response has been found down to 5 rem for solid cancers with a cancer dose-effect response for solid cancers linear up to about 300 rem ["Studies of the mortality of atomic bomb survivors, Report 12, Part I. Cancer: 1950–1990" by D. A. Pierce, Y. Shimizu et al. *Radiation Research 146* (1), p. 10, 1996.]

29. *A Safety and Regulatory Assessment of Generic BWR and PWR Permanently Shutdown Nuclear Power Plants.* The value of the agricultural land was assumed to be \$0.2 million/km^2. The value of the condemned land would therefore be \$0.4–1.4 billion. The remainder of the cost was assumed to be \$0.074 million per permanent evacuee. Therefore, 1.6–7.6 million people would be permanently evacuated in this scenario. \$17–279 billion of these consequences were assumed to occur beyond 50 miles where the population density was assumed to be 80/km^2. This would correspond to an evacuated area beyond 50 miles of 1100–19,000 km^2. We have done a calculation using the MACCS2 code to obtain, for 3.5–35 MCi ^{137}Cs releases with 40 MWt plume heat, damage estimates of \$50–700 billion plus 50,000–250,000 cancer deaths among people remaining on contaminated land [2000 person-rem per cancer death, valued in NRC cost-benefit analyses at \$4 million per cancer death, (Nuclear Regulatory Commission, *Regulatory Analysis Technical Evaluation Handbook* NUREG/BR-0184, 1997)]. An average population density of 250/km^2 was assumed (population density of the U.S. Northeast). Evacuation was assumed if the projected radiation dose was greater than 0.5 rems per year (EPA Protective Action Guide recommendation). The losses due to evacuation were assumed to be \$140,000/person for fixed assets, \$7,500/person relocation costs, and \$2,500/hectare for farmland abandoned because of the projected contamination level of its produce. Two possible decontamination factors (DF) were assumed: DF = 3 and 8 at costs of \$9,000 and \$20,000 per hectare of farmland (assumed to be 20% of the total area) and \$19,000 and \$42,000 per resident (value for a "mixed-use" urban area), excluding

the cost of disposal of the radioactive waste [based on D.I. Chanin and W.B. Murfin, *Estimation of Attributable Costs from Plutonium Dispersal Accidents* (Sandia National Laboratory, SAND96-0957, 1996)]. Based on these cost assumptions, no farmland would be decontaminated but decontamination would be performed in residential areas up to contamination levels that prior to decontamination would result in doses of 4 rems per year up to the end of temporary relocation periods that are assumed to last up to 30 years. The range of ^{137}Cs contamination levels in areas where decontamination would be carried out is from about 2.5 up to 80 Ci/km^2.

30. Calculated using the Origin 2.1 computer code [*ORIGEN 2.1: Isotope Generation and Depletion Code Matrix Exponential Method*, CCC-371 ORIGEN 2.1, (Oak Ridge National Laboratory, Radiation Safety Information Computational Center, August 1996)].

31. In 1996, the NRC staff reported an example in which boiling would occur in 8 hours instead of 4.5 days because the core had been loaded into the spent fuel pool 5 days after shutdown instead of 23 in a previous refueling at the same reactor (NRC, "Briefing On Spent Fuel Pool Study," Public Meeting, November 14, 1996, http://www.nrc.gov/reading-rm/doc-collections/commission/tr/1996/19961114a.html, accessed Dec. 10, 2002, p. 27). This is consistent with the following calculation: Assume a generic PWR pool with an area of 61.3 m^2 and depth of 11.5 m containing about 600 metric tons of water, as described in *Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants*, p. A1A-2. [A more detailed calculation would take into account the amount of water displaced by the fuel assemblies. In subsequent calculations, we will assume 471 kg U per fuel assembly with cross-section of 21.4 × 21.4 cm and a height of 4 meters. Such an assembly has 59% water content by volume (*Nuclear Engineering International*, September 2001, p. 24).] For a pool inventory of 340 tons of 1–20 year-old fuel generating an average decay heat of 3 kWt/tU with or without a freshly discharged core containing 85 metric tons of uranium generating 120 kWt/tU decay heat 4 days after shutdown, the total decay heat would be 1 or 11 MWt. Given the heat capacity of water of 4200 joules/kg-°C, the decay heat would raise the temperature of the pool from 30 to 100°C in 4.4 or 50 hours and thereafter boil off 0.026 or 0.29 meters of water per hour (the latent heat of vaporization of water is 2.3 Mj/kg). Assuming that there are 7 meters of water above the fuel, it would take 1 or 11 days before the radiation shield provided by the water covering was reduced to 1 meter.

32. In principle, removing the spent fuel assemblies and reshuffling the rest before inserting fresh fuel should be faster. However, any departure from a choreographed reshuffle (due, for example, to discovery of damaged fuel) requires time-consuming recalculation of the subcriticality margin (David Lochbaum, Union of Concerned Scientists, private communication, Jan. 7, 2003).

33. "NRR [Nuclear Reactor Regulation staff] determined through a recent survey of all power reactors . . . that some sites do not have anti-siphon devices in potential siphon paths. During refueling operations . . . a flow path exists to the reactor vessel, inventory loss [could occur] through the RHR (residual heat removal), chemical and volume control system, or reactor cavity drains [or the] shipping cask pool drains. For these situations in many designs, the extent of the inventory loss is limited by internal weirs or internal drain path elevations, which maintain the water level above the top of the stored fuel . . . During the NRR survey assessment, the staff found that five SFPs (spent fuel pools) have fuel transfer tubes that are lower than the top of the stored fuel without interposing structures." (*Operating Experience Feedback Report: Assessment of Spent Fuel Cooling*, NUREG-1275, pp. 5–6). In 1994, about 55,000 gallons [200 m^3] of water leaked from piping, which had frozen in an unheated containment fuel pool transfer system

at the closed Dresden I station. The NRC noted the potential for a "failure of 42"[inch, 1 m] fuel transfer tube [which] could rapidly drain fuel pool to a level several feet [>1 m] below top of [660] stored fuel bundles." [*Dresden, Unit 1 Cold Weather Impact on Decommissioned Reactor (Update)*, U.S. NRC, January 24, 1994, pp. 94–109].

34. *Operating Experience Feedback Report: Assessment of Spent Fuel Cooling*, NUREG-1275, p. 32 and Fig. 3.2.

35. Doses calculated from a dry pool containing 650 tons of 43 MWd/kgU spent fuel in a square array with 1.4 cm pitch. The fuel is a composite with a mix of the following cooling times: 20 tons each at 30 days, 1 year, and 2 years; 100 tons at 5 years; 240 tons at 10 years; and 250 tons at 25 years. The gamma-ray source intensities within the fuel were calculated using ORIGEN2, grouped in 18 energy intervals. These radiation-source data were then used as input to the MCNP4B2 code [*Los Alamos National Laboratory, Monte Carlo N-Particle Transport Code System* (Radiation Safety Information Computational Center, CCC-660 MCNP4B2 1998)] which was used to perform radiation transport calculations to obtain the flux and energy spectra of the gamma-rays 1 m above the floor of the building at radii of 5, 10 and 15 meters from its center. The radiation doses were then calculated using the "American National Standard for Neutron and Gamma-Ray Fluence-to-Dose Factors" (American Nuclear Society, ANSI/ANS-6.1.1, 1991) and an average self-shielding factor of 0.7. The concrete has a density of 2.25 gms/cc and a composition in weight percent of 77.5% SiO_2, 6.5% Al_2O_3, 6.1% CaO, 4.0% H_2O, 2.0% Fe_2O_3, 1.7% Na_2O, 1.5% K_2O 0.7% MgO ("Los Alamos concrete, MCNP4B2 manual, pp. 5–12). In the absence of a roof, the dose rates at 10 and 15 meters would be reduced by factors of 0.37 and 0.24 respectively. Similar calculations for 400 tons of 33MWd/kgU spent fuel (25% each 30-day, 1-yr, 2-yr and 3-yr cooling) reported in *Spent Fuel Heatup Following Loss of Water During Storage*, Appendix C: "Radiation dose from a drained spent-fuel pool" give a dose rate of about 300 rads/hr at ground level 15 m from the center of a rectangular 10.6 × 8.3 m pool.

36. Among the emergency workers at Chernobyl, deaths began for doses above 220 rems. The death rate was one third for workers who had received doses in the 420–620 rem range and 95% (1 survivor) for workers who received higher doses ("Exposures and effects of the Chernobyl accident," Table 11).

37. *Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants*, p. A1A-1.

38. Figure 5 was calculated with ORIGEN 2.1 assuming that the initial enrichments for burnups of 33, 43, 53 and 63 MWd/kgU were 3.2, 3.7, 4.4 and 5.2% respectively. The .PWRU.LIB and PERU50.LIB cross-section files were used to calculate the production rates of actinides and fission products in PWR fuel.

39. S. R. Tieszen, *Fuel Dispersal Modeling for Aircraft-Runway Impact Scenarios* (Sandia National Laboratory, SAND95-2529, 1995), p. 73.

40. *Fuel Dispersal Modeling for Aircraft-Runway Impact Scenarios*, p. 70.

41. *World Trade Center Building Performance Study*, (FEMA, 2002) Appendix E, http://www.fema.gov/library/wtcstudy.shtm accessed Dec. 10, 2002.

42. On May 16, 1979, the government of the German state of Lower Saxony issued a ruling about a proposed nuclear fuel center at Gorleben. One aspect of the ruling was a refusal to license high-density pool storage, in part from concern about war impacts. The ruling followed a public hearing in which more than 60 scientists, including two of the present authors (J. B. and G. T.) presented their analyses. A third author (K. J.) had been

responsible for the design of the pool and subsequently oversaw the design of the dry casks currently used in Germany [Klaus Janberg, "History and actual status of aircraft impact and anti-tank weaponry consequences on spent fuel storage installations," paper presented at the International Conference on Irradiated Nuclear Fuel, Moscow IFEM, September 11, 2002]. A brief description (in German) and photographs and diagrams of the German dry-cask central storage facility that was built at Gorleben instead of a spent-fuel pool may be found in *Brennelementlager Gorleben, BLG*, http://www.math.uni-hamburg.de/math/ign/hh/1fi/blg.htm, accessed Dec. 10, 2002. A similar dry-cask storage facility was built instead of a storage pool at Ahaus, Germany.

43. Swiss Federal Nuclear Safety Inspectorate (HSK), Memorandum, "Protecting Swiss Nuclear Power Plants Against Airplane Crash" (undated), p. 7. This memo also describes Swiss protection requirements (the same as those in Germany) http://www.hsk.psi.ch/pub_eng/publications/other%20publications/2001/AN-4111_E-Uebersetz_Flz-absturz.pdf accessed, Jan. 9, 2003.

44. "In estimating . . . catastrophic PWR spent fuel pool damage from an aircraft crash (i.e., the pool is so damaged that it rapidly drains and cannot be refilled from either onsite or offsite resources), the staff uses the point target area model and assumes a direct hit on a 100 × 50 foot spent fuel pool. Based on studies in NUREG/CR-5042, *Evaluation of External Hazards to Nuclear Power Plants in the United States*, it is estimated that 1 of 2 aircrafts are large enough to penetrate a 5-foot-thick reinforced concrete wall . . . It is further estimated that 1 of 2 crashes damage the spent fuel pool enough to uncover the stored fuel (for example, 50 percent of the time the location is above the height of the stored fuel)" (*Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants*, p. 3–23).

45. See e.g. *Accident Analysis for Aircraft Crash into Hazardous Facilities* (U.S. Department of Energy, DOE-STD-3014-96, 1996), Appendix C. We have used these formulae for an aircraft turbine shaft weighing 400 kg with a diameter of 15 cm and traveling at 156 m/sec (350 miles per hour, speed of the aircraft that crashed into the Pentagon according to NEI, see following footnote) and 260 m/sec [590 miles/hr, estimated speed of the aircraft that crashed into the World Trade Center South Tower, (*World Trade Center Building Performance Study*)]. They predict that such an object could perforate a reinforced concrete wall 0.8 to 1.8 meters thick, depending primarily on the impact speed.

It is possible that a spent-fuel pool, with its content of water mixed with dense fuel assemblies, might resist penetration more like an infinitely thick slab. In this case, the range of penetration depths for the large aircraft turbine shaft becomes 0.4–1.3 m. For a useful review, which shows the great uncertainty of empirical penetration formulae and the very limited ranges over which they have been tested empirically, see *Review of empirical equations for missile impact effects on concrete* by Jan A. Teland (Norwegian Defense Research Establishment, FFI/RAPPORT-97/05856, 1998).

An additional reference point is provided by the NRC staff's conclusion that "if the cask were dropped on the SFP [spent-fuel-pool] floor, the likelihood of loss-of-inventory given the drop is 1.0" (*Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants*, p. A2C-3). For a drop height of 12 m (the depth of a pool) the kinetic energy of a 100-ton cask (neglecting the absorption of energy by displacing water and crushing spent-fuel racks) is about 10^7 joules—about the same as the energy of the large jet turbine shaft at a velocity of about 240 m/sec. Because of the larger hole that the cask would have to punch, the energy absorbed by the structure would be expected to be larger. It should also be noted that the weight of the entire jet engine is about 4,000 kg, its diameter, including the fan blades, is about the same as a spent-fuel cask and its kinetic energy at 240 m/sec is about 10 times greater.

46. *Aircraft crash impact analyses demonstrate nuclear power plant's structural strength* (Nuclear Energy Institute Press release, Dec. 2002, http://www.nei.org/documents/EPRINuclearPlantStructuralStudy200212.pdf, accessed Jan. 5, 2003).

47. *Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants*, p. A2C-3.

48. *Analysis of the Total System Lifecycle Cost of the Civilian Radioactive Waste Management Program*, (U.S. DoE, Office of Civilian Waste management, Report # DOE/RW-0533, 2001), pp. 1–7.

49. "Nuclear Waste: Uncertainties about the Yucca Mountain Repository Project," testimony by Gary Jones, Director, Natural Resources and Environment, U.S. General Accounting Office, before the Subcommittee on Energy and Air Quality, House Committee on Energy and Commerce, 21 March 2002.

50. Charles Pennington, NAC International, private communication, Dec. 2, 2002.

51. In recently installed racks, the boron is contained in Boral sheets composed of boron carbide (B_4C) in an aluminum matrix, permanently bonded in a sandwich between aluminum plates. This design has proven more durable than a previous design in which boron carbide was mixed 50 percent by volume with carbon, formed into a 1/4-inch thick sheet and clad in 1/8-inch stainless steel (*Spent Fuel Heatup Following Loss of Water During Storage*, p. 19).

52. A vendor's representation of dense-pack fuel racks is available at http://www.holtecinternational.com

53. This problem could be mitigated to some degree by putting holes in the walls of the dense-pack racks—subject to limitation that considerable neutron absorption in the walls is required keep the spent fuel subcritical. The holes would allow air to circulate through the racks above the water surface. The 1979 Sandia report concluded that such an approach could be effective for fuel a year or more old (*Spent Fuel Heatup Following Loss of Water During Storage*, pp. 78).

54. Based on heat capacities of UO_2 and Zr of 0.3 joules/gmU-°C [S. Glasstone and A. Sesonske, *Nuclear Reactor Engineering* (Van Nostrand Reinhold, 1967) Table A7] and assuming 0.2 grams of Zr per gram U, the heat capacity of reactor fuel is about 0.4 joules/gmU-°C. In a 1997 study done by Brookhaven National Laboratory for the NRC, the "critical cladding temperature" was chosen as 565°C. This was the temperature for "incipient clad failure" chosen in the previous Workshop on Transport Accident Scenarios where "expected failure" was fixed at 671°C. The Brookhaven group chose the lower temperature for fuel failure in a spent-fuel-pool drainage accident because "it would take a prolonged period of time to retrieve the fuel, repair the spent fuel pool or establish an alternate means of long-term storage" [*A Safety and Regulatory Assessment of Generic BWR and PWR Permanently Shutdown Nuclear Power Plants*, pp. 3–4.]

55. The gas-diffusion-limited zirconium oxidization rate has been parameterized as $dw^2/dt = K_o exp(-E_a/RT)$ in the range 920–1155°C, where w is the weight gain of the cladding (g/cm^2) due to oxidation, K_0 is the rate constant [5.76×10^4 $(gm/cm^2)^2$/sec], E_a is the activation energy (52990 calories), R is the gas constant (1.987 cal/°K), and T is the absolute temperature (°K) (*Spent Fuel Heatup Following Loss of Water During Storage*, p. 31–34). At 920°C, therefore, $K_o exp(-E_a/RT) = 1.1 \times 10^{-5}$ $(gm/cm^2)^2$/sec. The

fuel cladding contains 0.34 gmZr/cm^2. w^2 for full oxidation to ZrO_2 will therefore be about 0.014 (gm/cm^2)^2. Thus, the characteristic time for complete oxidation would be about 15 minutes at 920°C and would decrease rapidly as the temperature increased further.

The Advisory Committee on Reactor Safeguards (ACRS) has raised the possibility that, for high-burnup fuel, the ignition temperature might be considerably lower: "there were issues associated with the formation of zirconium-hydride precipitates in the cladding of fuel especially when the fuel has been taken to high burnups. Many metal hydrides are spontaneously combustible in air. Spontaneous combustion of zirconium-hydrides would render moot the issue of 'ignition' temperature ..." In addition, the ACRS points out that nitrogen reacts exothermically with zirconium, "[this] may well explain the well-known tendency of zirconium to undergo breakaway oxidation in air whereas no such tendency is encountered in either steam or in pure oxygen" ["Draft Final Technical Study of Spent Fuel Accident Risk at Decommissioning Nuclear Power Plants," letter from Dana Powers, ACRS chairman, to NRC Chairman Meserve, April 13, 2000, p. 3].

56. *Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants*, "Executive Summary," p. x.

57. Between 300 and 1200 °K, the longitudinal conductivity of a 0.4-cm radius rod of UO_2 clad in zircalloy with an inside radius of 0.41 cm and a cladding thickness of 0.057 cm is about $k = 0.06$ Watts/(°C/cm) [based on temperature-dependent conductivities for UO_2 falling from 0.076 to 0.03 and for zircalloy rising from 0.13 to 0.25 Watts/[cm^2-(°C/cm)] (International Nuclear Safety Center, http://www.insc.anl.gov/matprop/uo2/cond/solid/thcsuo2.pdf, Table 1; http://www.insc.anl.gov/matprop/zircaloy/zirck.pdf, Table 1, accessed Dec. 19, 2002)]. The density of uranium in the UO_2 is about 10 gm/cc. A rod 400 cm long would therefore contain about 2 kg of uranium. For a fuel rod L cm long containing M kg U and cooled at both ends to a temperature T_0, with a heat generation rate of P Watts/kgU uniformly distributed along its length, the temperature difference between the center and ends would be $PML/(8k) \approx 1700$ P °C. Taking into account the thermal conductivity of the steel boxes and boral surrounding the fuel assemblies in the dense-pack configuration lowers this estimated temperature increase to approximately 1000 P °C.

58. Within the fuel assembly, the net radiation flux in the z direction is approximately $F = -4f\sigma T^3(dT/dz)\langle\lambda_z\rangle$ where f is the fraction of the area of the fuel assembly between the fuel rods (about 0.6) and $\langle\lambda_z\rangle = \int d\Omega(\mathrm{Cos}\theta)[\lambda(\theta,\phi)]$ is the average distance that radiation travels up the fuel assembly before being reabsorbed—on the order of centimeters. We have made the approximation that the difference in temperature between the radiating and absorbing points can be calculated using the first derivative of T. We also assume that the rate of heat generation is constant at a rate of PM/(AL) Watts/cm^3 along the length ($L = 400$ cm) of the fuel assembly. In this approximation, the temperature profile can be calculated as $T = [1000PM/(A\sigma)]\{[-(z/L) - z^2/(2L^2)]L/(f\langle\lambda_z\rangle) + 1\}^{1/4}$°K, where z is negative and measured in centimeters downward from the top of the fuel assembly. When $z = -L$, $T(-L) = 600\{P[1 + (0.8L/\langle\lambda_z\rangle)]\}^{1/4}$°K. For P = 1 kW/tU, T(−L) = 2300 or 1700°C if $\langle\lambda_z\rangle = 1$ or 3 cm respectively.

59. Assume that a fuel rod has a length L, contains M = 2 kg of uranium, generates decay heat at a rate of P watts/kgU, has a temperature T_{max} at its top and that the water level is at z_w m (where z = 0 is the bottom of the fuel). In the approximation where the heat rate along the length of the fuel is constant, the combined rate of input of heat into the water from the submerged part of the fuel and from black body radiation impinging on the water's surface will be $P_- = PMz_w/L + P_{bb-}$. The heat generation rate of the

fuel above the water will be $P_+ = PM(L - z_w)/L$. The cooling of the above-water fuel is limited, however, by the availability of steam generated by the below-water fuel. The rate of steam generation will be $P_-/2300$ grams/sec. When z falls below the bottom of the fuel assembly, $P_- = P_{bb-}$. We approximate $P_{bb-} = (A/264)\sigma(T_0 + 273)^4$ where $(A/264) = 2\ cm^2$ is the area in a fuel-assembly box for each of the 264 fuel rods and T_0 is the temperature at the bottom of the fuel assembly. In *Spent Fuel Heatup Following Loss of Water During Storage*, Fig. B-1, it is estimated that $T_0 = 200°C$ at the point when $T_{max} = 900°C$, i.e., when the fuel is about to fail. This gives $P_{bb-} \approx 0.6$ Watts. Assuming perfect heat transfer, the steam will heat to a temperature T_{max}°C as it passes through the fuel assembly and absorb approximately $2.1(T_{max} - 100)$ joules per gram. Therefore, in order to remove the power P_+ and maintain the above water fuel in equilibrium, it is necessary that $P_+ < 2.1(T_{max} - 100)P_{bb-}/2300\ M \approx 0.3$ Watts/kgU when $T_{max} = 1200°C$. This means that the fuel has to be about 100 years old after discharge before steam cooling will remain effective when the water level drops to the bottom of the fuel assembly.

60. For information on the strength of steel at high temperatures, see http://www.avestapolarit.com/template/Page2171.asp, accessed Jan. 10, 2003. The zircaloy tubes of a Canadian CANDU reactor slumped at 1200°C (see *CANDU Safety # 17—Severe Core Damage Accidents*, V. G. Snell, Director Safety & Licensing, http://engphys.mcmaster.ca/canteach/techdoclib/CTTD-0014/CTTD-0014-17/17of25.pdf, accessed Jan 10, 2003).

61. For a square box with inside dimensions of 0.225 m containing a fuel assembly with 264 rods with diameters of 0.95 cm, [*Analysis of Spent Fuel Heatup Following Loss of Water in a Spent Fuel Pool: A Users' Manual for the Computer Code SHARP*, Tables 2.1 and 2.2].

62. This can be derived from the gas momentum conservation equation, $\partial(\rho v)/\partial t + \partial(\rho v^2)/\partial z + P_L = -\partial P/\partial z - \rho g$ where ρ is the air density, v is its velocity, P is the pressure, P_L represents the pressure loss due to friction in the channel and $g = 10\ m/sec^2$ is the gravitational constant. For an equilibrium situation, the first term disappears. Integrating from the bottom of the spent fuel (z = 0) to its top (z = L = 4 m) gives $\rho_L(v_L)^2 - \rho_0(v_0)^2 + \int_0^L P_L dz = P(0) - P(L) - g\int_0^L \rho dz$. Assuming that: the pressure is constant across the top and bottom of the spent fuel, the gas velocity is constant below the spent fuel, the air velocity is zero at the top of the down-comer, and neglecting friction losses in the down-comer and beneath the spent fuel, we may subtract the momentum conservation equation for the down-comer (dc) from that for the fuel assembly (fa) and obtain $\rho_L(v_L)^2 + \int_0^L P_L dz = g\int_0^L[\rho_{dc} - \rho_{fa}]dz$. As indicated in the text, we approximate $\rho_0 = 1\ kg/m^3$, $\int_0^L \rho_{dc} dz \approx L\rho_0$, and $\int_0^L \rho_{fa} dz \approx 0.5\ L\rho_0$. This gives $\rho_L(v_L)^2 + \int_0^L P_L dz \approx 0.5\ g\rho_0 L = 20\ joules/m^3$. Noting that $\partial(\rho v)/\partial z$ is a constant and that, at constant pressure, $\rho \sim T^{-1}$, where T is the absolute temperature, $\rho_L(v_L)^2 = \rho_0(v_0)^2(T_L/T_0)$, where $T_L = 1173$ °K at the ignition point. We assume that $T_0 = 100$ °C = 373 °K. We then obtain $3.1(v_0)^2 + \int_0^L P_L dz = 20\ joules/m^3$ and $v_0 \approx 2.5$ m/s, if the P_L term is neglected.

P_L may be approximated as the sum of a loss term due to the constriction of the air passing through the base-plate hole and surface friction within the fuel assembly, $\int_0^L P_L dz = K_0\rho_0(v_0)^2 + \int_0^L f\rho v^2 dz/(2D_H)$. Here $K_0 = 2(1-x)/x$, $x = (A_h/A_f)^2$, A_h is the area of the hole in the base-plate and $A_f = S^2 - 264\ \pi(D/2)^2$ is the cross-sectional area of the air flow inside the box around the fuel assembly. (S = 0.225 m is the inside width of the box and D = 0.0095 m is the outside fuel-rod diameter). For a dense-pack arrangement with a 5 inch [13 cm] hole in the base-plate, $x \approx 0.15$ and $K_0 \approx 11.3$. In the second pressure-loss term, L = 4m is the height of the fuel assembly, f is the friction factor, $D_H = 4\ A_f/P_w$ is the "hydraulic diameter" of the channel, and $P_w = 4S + 264\ \pi D$ is the total perimeter of all the surfaces in the cross-section (*Users' Manual for the Computer Code SHARP*, pp. 4–7, 4–16). For the fuel assembly in our example, $D_H \approx 0.015$ m. The friction factor may be written as $f = C/(Re)^n$, where $Re = \rho v D_H/\mu$ is the Reynolds number, and μ is the viscosity of air (31×10^{-6} pascal-seconds at 600°K). The exponent $n = 1$ for laminar flow ($Re < 2100$), which will be seen to be the case in the fuel assembly. The coefficient $C \sim 100$ within the fuel assembly in the approximation where all rods are treated as interior rods (*ibid.*, p. 4–7, 4–16/17). Thus, $\int_0^L P_L dz = K_0\rho_0(v_0)^2 + \{C\mu/[2(D_H)^2]\} \int_0^L v dz \approx K_0\rho_0(v_0)^2 + 55v_0$ joules/m^3, where we have approximated $\int_0^L v dz \approx 2Lv_0$, where v_0 is the entrance velocity to the air at the base of the fuel assembly. If we add this friction pressure term to the equation at the end of the paragraph above, we get $14.4(v_0)^2 + 55\ v_0 = 20$ joules/m^3 or $v_0 \approx 0.33$ m/sec.

An approximation of open-rack storage could be obtained by dropping the base-plate constriction term (i.e., setting $x = 1$) and dropping the S in the perimeter term above. Then, if the center-to-center spacing of the fuel assemblies is increased by a factor of $5^{1/2}$ in going from dense-pack to an open-array spacing with a fuel-assembly density lower by a factor of five, $D_H \approx 0.1$ m and the equation above becomes $3.1(v_0)^2 + 1.24\ v_0 = 20$ joules/m^3, or $v_0 = 2.3$ m/sec, which would make it possible to cool a pool filled with fuel generating about 100 KWt/tU. If the hot fuel were surrounded by cooler fuel assemblies, cross flow from the cooler to the hot assemblies would provide still more cooling.

63. *Users' Manual for the Computer Code SHARP*, Figs. 6.3 and 6.5. Our result obtained in the previous footnote corresponds to the case for a wide (e.g., 8-inch or 20 cm) downcomer and constant room temperature.

64. *Spent Fuel Heatup Following Loss of Water During Storage*, fig. 3, p. 85.

65. The 2001 *Users' Manual for the Computer Code SHARP* notes the availability of only "limited data [from] one experiment . . . in a three parallel channel setup" (p. 5-1).

66. *Severe Accidents in Spent Fuel Pools in Support of Generic Safety Issue 82* by V. L. Sailor, K. R. Perkins, J. R. Weeks, and H. R. Connell (Brookhaven National Laboratory, NUREG/CR-4982; BNL-NUREG-52093, 1987), p. 52.

67. *Op cit,* pp. 52, 53, 63.

68. Complete blockage would, however, tend to quench the fire.

69. See, for example: J. H. Jo, P. F. Rose, S. D. Unwin, V. L. Sailor, K. R. Perkins and A. G. Tingle, *Value / Impact Analyses of Accident Preventive and Mitigative Options for Spent Fuel Pools* (Brookhaven National Laboratory, NUREG/CR-5281, 1989). Measures discussed and rejected because of perceived lack of cost-benefit included low density storage and water sprays. Management recommendations to reduce risk have been considered in, *Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants.*

70. To compute the 0.7 and 5 percent probabilities, we compared an investment of $5 billion in dry storage casks (midpoint of our estimated $3.5–7 billion cost range) with a range of estimated costs for spent fuel fires. In footnote 29 the median damages (including cancer deaths at $4 million each) from a 10–100 percent release of ^{137}Cs from 400 tons of spent fuel are estimated at $250–1700 billion. We discount these damages to $100–750 billion because the risk would not be completely eliminated by the measures that we propose and their mitigating effect could occur decades after the investment. The $0.6 - 2.4 \times 10^{-6}$ probability of a spent-fuel fire per pool-year estimated in *Technical Study of Spent Fuel Accident Risk at Decommissioning Nuclear Power Plants* (Table 3.1)

is equivalent to about 0.6 percent in 30 years for the 103 operating power reactors in the U.S.

71. *Spent Fuel Heatup Following Loss of Water During Storage*, "Conclusions," p. 85.

72. *Operating Experience Feedback Report, Assessment of Spent Fuel Cooling*, NUREG-1275, Vol. 12, p. 27.

73. Further discussion of defense in depth is provided in *Robust Storage of Spent Nuclear Fuel* by Gordon Thompson (Institute for Resource and Security Studies, Cambridge, MA, January 2003).

74. *Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants*, pp. 3–16 and Appendix 2C p. A2C-3 and –4.

75. Above, it was noted that an important motivation for moving the entire core into the spent-fuel pool was the need to recalculate the subcriticality of the core in the reactor pressure vessel if there are unplanned fuel movements. This problem deserves a separate study of its own.

76. David Lochbaum, Union of Concerned Scientists, private communication, Jan. 9, 2003.

77. Assuming a thermal to electric power conversion efficiency of one third, an 85 percent capacity factor, and a fuel burnup of 47 MWd/kg. The Sandia study considered fuel with a burnup of only 33 MWd/kgU. However, as can be seen from Figure 5, the decay heat at short decay times (less than a year or so) is insensitive to the fuel burnup because it is dominated by short-lived isotopes.

78. Fuel rod characteristics were for a Westinghouse 17 × 17–25 fuel assembly: uranium density, 9.25 g/cc; pellet radius, 0.41 cm; gap between fuel pellet and cladding, 0.008 cm; clad thickness, 0.057 cm; and outside radius of cladding, 0.475 cm (*Nuclear Fuel International*, Sept. 2001, pp. 24–25). Fuel composition as a function of burnup was calculated with ORIGEN 2.1. Criticality calculations were carried out with the MCNP4B2 code.

79. For 4.4 percent enriched fuel with a burnup of 13.25 MWd/kgHM, introduction of 1 one-cm of borated stainless steel (one percent boron by weight) between rows of fuel assemblies reduces the peak neutron multiplication factor k_{eff} from 1.33 to 0.91. Fresh fuel would be barely critical ($k_{eff} = 1.05$) for a spacing of about 2 cm.

80. Criticality control with soluble boron creates the danger, however, of a criticality if a leaking pool is refilled with unborated water. Also, the water of BWRs must be free of boron. The pressure vessel and connected plumbing of a BWR would therefore have to be flushed after contact with boron-containing spent-fuel water.

81. *Spent Fuel Heatup Following Loss of Water During Storage*, p. 63.

82. *Ibid.*

83. *Op cit.*, p. 79.

84. A flow of 1 liter/sec can be maintained in a steel pipe with 2.5 cm inside diameter and a pressure drop of 0.015 atmosphere/m [*ASHRAE Handbook: Fundamentals* (American Society of Heating, Refrigeration and Air-conditioning Engineers, 2001), p. 35.6].

85. This may have been what a National Academy of Sciences committee had in mind when it stated "emergency cooling of the fuel in the case of attack could probably be accomplished using 'low tech' measures that could be implemented without significant

exposure of workers to radiation" [*Making the Nation Safer: The Role of Science and Technology in Countering Terrorism* (National Academy Press, 2002), p. 43]. One of our reviewers pointed out that a puncture hole in the stainless steel liner of the bottom of the Hatch nuclear power plant spent fuel pool caused by a dropped 350-pound core-shroud bolt in the mid 1990s was temporarily plugged with a rubber mat.

86. An interesting suggestion made by one of our reviewers also deserves further research: add to the escaping water a material such as is used to seal water-cooled automobile engines. Such sealant works by solidifying when it comes into contact with air.

87. The choice of age at transfer represents a tradeoff between cost and risk. We have picked five years based on the capabilities of existing dry storage systems.

88. The U.S. has approximately 100 GWe of nuclear capacity or about 1 GWe of capacity per spent-fuel pool. NAC projects that, in 2010, there will be 45,000 tons of spent fuel in pools (*US Spent Fuel Update: Year 2000 in Review* (Atlanta, Georgia: NAC Worldwide Consulting, 2001), i.e. an average of 450 tons per pool. In five years, a GWe of capacity discharges about 100 tons of fuel.

89. *2002 Summary of U.S. Generating Company In-pool Spent Fuel Storage Capability Projected Year that Full Core Discharge Capability Lost*," (Energy Resources International, 2002, www.nei.org/documents/Spent_Fuel_Storage_Status.pdf, accessed Dec. 14, 2002).

90. On average 350 tons of spent fuel would have to be removed from each of 100 pools (see note above). Spent fuel casks typically have a capacity of about 10 tons.

91. The dry storage casks currently licensed in the U.S. ⟨http://www.nrc.gov/reading-rm/doc-collections/cfr/part072/part072-0214.html⟩ are: **thick-walled:** General Nuclear Systems Castor V/21; **overpack:** Nuclear Assurance Corp. http://www.nacintl.com: NAC Storage/Transport (NAC S/T; NAC C-28 S/T); NAC Multipurpose Cannister System (NAC-MPS); NAC Universal Storage System (NAC-UMS); Transnuclear ⟨http://www.cogema-inc.com/subsidiaries/transnuclear.html⟩: NUHOMS horizontal modular storage system; Transnuclear TN-24, TN-32, and TN-68 Dry Storage Casks; Holtec http://www.holtecinternational.com: HI-STAR 100 and HI-STORM 100; British Nuclear Fuel Limited Spent Fuel Management System W-150 storage cask; and Pacific Sierra (now BNFL Fuel Solutions) Ventilated Storage Cask System VSC-24 ⟨http://www.bnfl.com⟩. See also *Information Handbook on Independent Spent Fuel Storage Installations* by M. G. Raddatz and M. D. Waters (Washington, DC: U.S. NRC, NUREG-1571, 1996).

92. F. Lange and G. Pretzsch, Gesellschaft für Anlagen- und Reaktorsicherheit (GRS) mbH; E. Hoermann, Dornier GmbH; and W. Koch, Fraunhofer Institute for Toxicology and Aerosol Research, "Experiments to quantify potential releases and consequences from sabotage attack on spent fuel casks," 13th International Symposium on the Packaging and Transportation of Radioactive Material, Chicago Sept. 2001. Helium is often used to fill dry casks because of its superior heat-transfer characteristics and for leak detection. GNS-GNB did experiments in the 1980s to determine the temperature rise if helium leaked out of a Castor cask and was replaced by air. It was found that the maximum fuel rod temperature increased from about 400 to 460°C.

93. Helmut Hirsch and Wolfgang Neumann, "Verwundbarkeit von CASTOR-Behältern bei Transport und Lagerung," www.bund.net/lab/reddot2/pdf/studie_castorterror.rtf. (We are grateful to Hirsch for providing a summary in English.)

94. If the hole were not plugged, the UO_2 in the ruptured pins would begin to oxidize to U_3O_8, resulting in the pellets crumbling and releasing additional volatile fission products that could diffuse out of the hole ("History and actual status of aircraft impact and anti-tank weaponry consequences on spent fuel storage installations").

95. A ceramic "Ballistic Protection System" was tested successfully on a CASTOR cask by International Fuel Containers at the U.S. Army's Aberdeen Proving Grounds in June 1998 (Klaus Janberg, "History and actual status of aircraft impact and anti-tank weaponry consequences on spent fuel storage installations"). For a 100-ton cask, the shield would weigh at least 50 tons.

96. "History and actual status of aircraft impact and anti-tank weaponry consequences on spent fuel storage installations."

97. " the [6 cm] carbon steel liner 'balloons' and contracts the canister" ("Plane tough storage" by Michael McGough and Charles Pennington, *Nuclear Engineering International*, May 2002). The simulation assumes that the steel will stretch up to 37% at a stress of 30,000–70,000 psi (average of 3.4×10^8 pascals) without rupturing. The kinetic energy of a 400-kg shaft traveling at a speed of 220 m/sec is about 10^7 joules. We have checked the plausibility of this result using a simplified geometry in which a flat circular sheet of steel 3.1 inches (8 cm) thick (taking into account the canister wall as well as the liner) and 1 meter in radius is stretched into a cone by keeping its edges fixed and pressing its center point in a direction perpendicular to the original plane of the sheet. In order for the sheet to absorb 10^7 joules by stretching in this way, the center point would have to be pushed about 0.3 meters.

98. *Grenzüberschreitende UVP gemäß Art. 7 UVP-RL zum Standortzwischenlager Biblis; Bericht an das Österreichische Bundesministerium für Land- und Forstwirtschaft sowie an die Landesregierungen von Oberösterreich und Vorarlberg*, Federal Environment Agency, Vienna, Austria, February 2002; as well as corresponding reports by the Federal Environment Agency concerning the sites of Grafenrheinfeld, Gundremmingen, Isar, Neckar and Philippsburg. (We are grateful to H. Hirsch for providing us with an English summary of these reports.)

99. 3000 tons per year is the design capacity of the surface spent-fuel receiving facility at Yucca Mountain (Daniel Metlay, U.S. Nuclear Waste Technical Review Board, private communication, Nov 12, 2002). The rate of discharge of spent fuel from U.S. reactors is likely to decline only slowly during the next decades. Eight plants have already received 20-year license extensions from the NRC, 14 more have applications for extension under review, and, according the Nuclear Energy Institute, 26 more plan to apply for extensions by 2005, http://www.nei.org/doc.asp?catnum=3&catid=286.

100. The design capacity would be for 40,000 tons of spent fuel. The fuel handling capability would be about 200 casks or 2000 tonsU per year (Max De Long, Excel Energy, personal communication, November, 2002).

101. NAC estimates that the end-2000 US inventory of spent fuel was 42,900 tons, of which 2,430 tons was in dry storage. It estimates that the 2010 US inventory will be 64,300 tons, of which 19,450 tons will be in dry storage [*U.S. Spent Fuel Update: Year 2000 in Review* (Atlanta, Georgia: NAC Worldwide Consulting, 2001)]. The small increase in projected in-pool storage (4,400 tons) suggests that most U.S. spent-fuel pools are already approaching their dense-packed capacity.

102. We have assumed an average fuel burnup during 2005-10 of 43 MWd/kgU (the approximate average burnup in recent years), an average capacity factor of 0.85, and an

average heat to electrical power conversion efficiency of one third. With these assumptions, the amount of spent fuel discharged in 5 years is simply 100P metric tons, where P is the rated electrical generating capacity of the associated nuclear-power plant in GWe.

103. The cask is made out of ductile cast iron and has the following dimensions and weights: length, 5.45 m; outer diameter 2.44 m; cavity length, 4.55 m; cavity diameter, 1.48 m; wall thickness, 35 cm; empty weight, 104 tons; loaded weight 123 tons [*Transport and Storage Cask V/52* [GNS (Gesellschaft für Nuklear-Behälter mbH, 1997), p. 2, 4]. The CASTOR V/52 is similar to the CASTOR V/19 and V/21 except for being designed to accommodate internally 52 BWR fuel assemblies.

104. The metal canister in the NAC-UMS is made of stainless steel and can hold 24 PWR fuel assemblies or 56 BWR fuel assemblies. It is about 4.7 meters high, 1.7 meters in diameter, and has a wall thickness of 1.6 cm. The overpack is a reinforced-concrete cylinder about 5.5 meters high and 3.5 meters outside diameter. The wall of this overpack consists of a steel liner 6.4 cm thick and a layer of concrete 72 cm thick. Ambient air passes through vents in the overpack, and cools the outside of the metal container by natural convection.

105. NAC International could produce 180 casks per year within two-to-three years (Charles Pennington, NAC International, personal communication, November, 2002). Holtec could currently produce 200 casks per year and could increase this rate to about 300 casks per year (Chris Blessing, Holtec, private communication, November, 2002). We assume 10 tons average storage capacity per cask.

106. Based on discussions with cask manufacturers. The lower end of the range is for thin-walled casks with reinforced-concrete overpack. The upper end is for monolithic thick-walled casks equipped with missile shields.

107. Allison Macfarlane, "The problem of used nuclear fuel: Lessons for interim solutions from a comparative cost analysis," *Energy Policy, 29* (2001) pp. 1379–1389.

108. Assuming a burnup of 43 MWd/kgHM and a heat-to-electric-energy conversion ratio of one third.

109. *Monthly Energy Review, September 2002* [U.S. Department of Energy, Energy Information Administration, DOE/EIA-0035 (2002/09)], Table 9.9.

110. We thank one of our reviewers for pointing this out to us.

111. The walls and roof of the Gorleben building are about 50 and 15 cm thick reinforced concrete respectively (from Klaus Janberg).

112. NAC estimates that, by 2010, the U.S. will have 19,450 tons of spent fuel in dry storage (see note above). If we add 35,000 tons of older spent fuel from the storage pools, the total will be about 55,000 tons or about 550 tons per GWe of U.S. nuclear generating capacity.

113. The berms for the 300-cask site at the Palo Verde, Arizona nuclear power plant cost \$5–10 million (Charles Pennington, NAC, private communication, November 2002).

114. With new NRC guidelines (ISG11, rev.2), which allow dry storage with peak cladding temperature up to 400°C, it is expected that a variant can be fielded with a capacity of 21 fuel assemblies with an average burnup of 60 MWd/tU (from Klaus Janberg).

115. In 2000, cask tests were being conducted with fuel burnups of up to 60 MWd/kgHM (Susan Shankman and Randy Hall, "Regulating Dry Cask Storage," *Radwaste Solutions*, July/August 2000, p. 10).

116. More than 25 nuclear power plants are today owned by such "limited-liability corporations" and additional corporate reorganizations are expected [*Financial Insecurity: The Increasing Use of Limited Liability Companies and Multi-Tiered Holding Companies to Own Nuclear Power Plants*, by David Schlissel, Paul Peterson and Bruce Biewald (Synapse Energy Economics, 2002), p. 1].

117. *Monthly Summary of Program Financial and Budget Information* (Office of Civilian Radioactive Waste Management, May 31, 2002). In 2001, U.S. nuclear power plants generated 769 million megawatt-hours net (*Monthly Energy Review, September 2002*, Table 8.1). With the enactment of the Gramm/Hollings/Rudman Budget Act in 1987, and the Budget Adjustment Act in 1990, the Nuclear Waste Fund ceased to be a stand-alone revolving fund. However, fees are placed in the General Fund Account of the U.S. Treasury and interest is accrued as if it were still a separate revolving account.

118. *Nuclear Waste Fund Fee Adequacy: An Assessment* (Department of Energy, DOE/RW- 0534, 2001). The report concludes that the revenues in the nuclear waste fund should be adequate but that there could be problems if interest rates fall significantly, or DOE incurs high settlement costs from lawsuits, or costs increase significantly.

119. The DOE negotiated with one utility company (PECO/Exelon) to take title to their spent fuel while it remained at the reactor and to pay for dry cask storage with money from the Nuclear Waste Fund. The US Court of Appeals for the 11th Circuit ruled, however, that DOE could not pay from the Fund to cover its own breach of its previous commitment under the Nuclear Waste Policy Act of 1982 to begin moving spent fuel from nuclear power plants to a deep underground repository by 1998 (Melita Marie Garza, 2002, "Exelon rivals win waste-suit round," *Chicago Tribune*, September 26, 2002 and Matthew Wald, 2002, "Taxpayers to owe billions for nuclear waste storage," *New York Times*, September 26, 2002.)

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Comments on: "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States"

Allan S. Benjamin

I am one of the reviewers of the paper entitled: "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States," and am also the principal author of the Sandia report that is cited several times by the authors of the paper. The subject of spent-fuel pool vulnerabilities is a very important one in the present day environment, and I am pleased to be able to provide input. I think the paper correctly points out a problem that needs to be addressed, i.e., the fact that a loss of water from a high-density spent-fuel pool could have serious consequences. However, I also believe the paper falls short of addressing all the considerations that accompany the problem. Some of these considerations could affect the results of the cost-benefit analysis that is used to justify the authors' proposed solution: the re-racking of the pool to a low-density, open-lattice arrangement and the removal of the older fuel to dry storage casks. In a nutshell, the authors correctly identify a problem that needs to be addressed, but they do not adequately demonstrate that the proposed solution is cost-effective or that it is optimal.

On the plus side of the assessment, I agree with the authors' analysis of what would happen if there were a total loss of water from a high-density

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spent-fuel pool that is packed wall-to-wall with zirconium-clad fuel. If some of that fuel had been recently discharged from a reactor core, there is not much doubt that the release of fission products to the environment would be significant. Our analyses in the referenced 1979 Sandia report did indeed show that the hottest part of the pool would heat up to the point where the cladding would first rupture and then ignite. Subsequent experiments we performed with electrically heated zirconium tubes (not formally reported) showed that there was a potential for a fire to propagate from hotter to colder fuel assemblies. It is not clear whether the fire would envelop the whole pool or just a part of it, but either way, the result would be undesirable.

I agree in principle with the calculations in the paper regarding the potential consequences of such an accident, except that it is unlikely that the whole inventory of fission products captured in the spent fuel would escape to the environment or that the wind would blow in one direction only (as assumed in the paper). Although there is clear evidence that some of the fuel would melt in such a situation, we don't know how much. Since we don't, it is conservative and appropriate to assume that a large fraction of the fission product inventory could become released to the environment. Whether that fraction is 0.20 or 1.00 doesn't change the fact that the release would be unacceptable.

It is also correct to say, as the authors have pointed out, that the situation could be even worse if enough water remained in the pool to cover the bottom of the storage racks so that air could not circulate, but not enough water to act as a significant heat sink for all of the decay heat produced by the fuel. This point was also made in the Sandia report.[1]

The authors' assessment of probabilities of occurrence is also reasonable in a bounding sense. They correctly point out that the likelihood of an accident leading to a critical loss of water is very low (estimated by the NRC to be less than one in 100,000 per pool per year). The probability of the same scenario resulting from a terrorist attack is unknown, and so the authors postulate a range of values. They point out, reasonably enough, that the upper end of the range could be significantly higher than the value for a loss of water initiated by an accident. I personally believe that the probability of a successful terrorist attack is very low, and I will give my reasons in a moment. Notwithstanding, the authors are correct in pointing out that the possibility of a terrorist attack is an issue that requires serious attention.

The problem occurs when the authors assert that these figures prove the cost effectiveness of their proposed solution. Before a judgment on cost effectiveness can be made, a variety of additional considerations have to be taken into account. These pervade all areas of the discussion: the calculation of the probabilities of occurrence, the resulting consequences, the effectiveness of the proposed solution, the competing risks introduced by that solution, and the cost of implementation.

Let's talk first about the probability of a successful terrorist attack. The assumed situation is that the adversaries create a large hole in the spent-fuel pool, near the bottom of the pool, without dispersing the fuel or significantly deforming the racking structure. That situation is very unlikely. Using explosives or missiles, including the intentional crash of an aircraft, it would be difficult to accomplish a loss of almost all the water in the pool without disrupting the spent-fuel geometry. Significant damage to the racking structure or outright dispersal of the fuel would create a geometry that is more coolable by air flow and less susceptible to propagation of a zirconium fire than is the actual storage geometry.

Moreover, it would be very difficult for adversaries to achieve enough water loss by draining the pool even if they somehow gained direct access to the pool. The drain valves and gates are all located high enough to prevent the water from draining down to a dangerous level. As originally stated in the Sandia report and acknowledged in the paper, something like 75% of the height of the fuel rods would have to be uncovered for an overheating condition to result.

Gaining access to the pool in itself would be a very difficult proposition. The adversaries would have to figure out a way to avoid being detected by the on-site monitoring equipment and overcome by the on-site security forces. The probability of success in this venture can be analyzed using existing tools, but this has apparently not been done. Such tools exist at the company where I now work, ARES, and at the laboratory where I used to work, Sandia. Both have methods for identifying the pathways an adversary could take to a target and evaluating the probability of success associated with each pathway.

The upshot is that more work needs to be done in accounting for how an adversary's method of attack would change the initial conditions of the analysis, and in evaluating the adversary's likelihood of success.

Now let's discuss the consequences of a loss-of-water incident, which according to the paper could include "hundreds of billions of dollars" in property loss. An accurate accounting of costs versus benefits requires a best-estimate assessment of consequences, not a worst-case assessment. Normally, the evaluation is accomplished by formulating probability distributions to reflect the full range of radioactive releases that could emanate from the spent fuel pool and the full range of meteorological conditions that could affect the dispersion of that material. The most commonly-used result from this analysis is the mean consequence, which is obtained by sampling the probability distributions in a random fashion. It can reasonably be expected that the mean value of the expected property loss would be considerably lower than the worst-case value.

Let's now progress to the subject of evaluating the effectiveness of the proposed solutions. The main one given in the paper is to remove all the fuel that is more than five years old to dry storage casks and to re-rack the pool so that the remaining, younger spent fuel can be contained in a widely-spaced, open-lattice arrangement. The arguments in favor of that approach appear attractive. First, it assures that air cooling would be effective even if all the water were drained from the pool. Second, it reduces the inventory of the long-lived fission products remaining in the pool, so that even if all of them were dispersed to the environment, the long-term effects would be sharply reduced.

Several important factors are not considered here. First, as mentioned above, an adversary's attack involving an explosive, a missile, or an airplane crash that is serious enough to create a big hole in the spent-fuel pool would also probably disperse the fuel or at least rearrange the geometry. Therefore, the final configuration would not necessarily be more coolable than that for a high density pool subjected to the same insult. That leaves only the reduced fission product inventory as a definitive point of difference that could reduce the losses incurred from the event.

However, the results in the paper concerning radioactive contamination are flawed by the fact that the shorter-lived radioisotopes are not considered. Most notable among these are ^{131}I, which has a half-life of 8 days, and ^{134}Cs, which has a half-life of just over two years. Most of these radionuclides are contained within the younger fuel that still remains in the spent-fuel pool. While they do not contribute as highly to long-term property loss as the longer-lived isotope, ^{137}Cs, they contribute more highly to early fatalities and latent cancer fatalities. Thus, a true cost-benefit accounting of the proposed solution must include consideration of these short-lived but very nasty radioisotopes.

Then there is the question of how effective the dry storage casks would be over a long period of time. The paper correctly acknowledges that an airplane crash into an array of dry storage casks could cause a release of radionuclides to the environment. It also presumes that only a few of the many casks in the array would be affected by the crash. Given the robust design of these casks, these observations are probably correct. However, the paper has failed to consider that many materials degrade or become brittle after a long exposure to radioactivity. Degradation or embrittlement can lead to leakage. Cask leakage has been a problem for some dry storage casks in the past, and the paper should acknowledge this. In performing a cost-benefit analysis, the risk from high probability, low consequence incidents, such as cask leakage, has to be considered along with the risk from low probability, high consequence incidents.

Finally, one must consider the competing risks. The process of removing such a large amount of fuel from the spent-fuel pool and transferring it to the dry storage casks carries its own set of hazards. During the transfer process, both the probability of an accident and the degree of exposure in the event of a potential terrorist attack are greater than before or after the transfer. The paper suggests that the transfer would take place over a ten-year period. Someone needs to look at the question of vulnerability during that period.

Another competing risk can be identified for the authors' proposed design change, based on an earlier recommendation made in the Sandia report, to install emergency water sprays. The authors suggest that the hottest fuel should be stored along the sides of the pool, where the spray would be heaviest even if the building collapses on top of the pool. This argument ignores the fact that heat removal by air cooling is most effective when the hottest fuel is stored in the middle of the pool and the coolest fuel is stored along the sides. That arrangement promotes natural convective air flow currents, whereas the one being proposed in the paper inhibits them.

The question of implementation costs is one that I am not prepared to address at the present time. I would note, however, that special consideration needs to be given to the question of whether, on the basis of available space and security requirements, on-site dry storage of so much fuel is feasible at all reactor sites.

As a final but pivotal point, the evaluation of costs versus benefits should consider all plausible alternative risk reduction options. Certainly one such option is to accelerate the transfer of the spent fuel from spent-fuel pools directly to a permanent underground storage site. The paper claims that this process could take decades, given the controversial status of the Yucca Mountain project and the current budgetary limitations. However, if there is a national security issue at stake, Government projects can be accelerated. The Manhattan Project is a good example. It may turn out that when all risks and costs are taken into account, a direct transfer to underground storage is more cost-effective than a temporary transfer to on-site storage casks and a re-racking of the spent-fuel pools.

In summary, the authors are to be commended for identifying a problem that needs to be addressed, and for scoping the boundaries of that problem. However, they fall short of demonstrating that their proposed solution is cost-effective or that it is optimal.

NOTE AND REFERENCE

1. Although most of the references made in the paper to the Sandia report are accurate, in the version reviewed by me, the first paragraph in the Introduction made two incorrect attributions. First, the accident evaluated in the Sandia study was a sudden loss of all the water, not a "sudden loss of water cooling." Loss of the water cooling system would

not result in the consequences cited by the authors since the water would remain as a large heat sink. Second, the Sandia report did not state that the loss-of-water scenario would lead to "the airborne release of massive quantities of fission products." Although zircaloy burning and some fuel melting would certainly occur, the Sandia study stopped short of evaluating, either qualitatively or quantitatively, the amount of fission products that would be released. Both of these points have now been corrected in the final version of the article.

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THE AUTHORS RESPOND TO ALLAN BENJAMIN'S COMMENTS

Robert Alvarez, Jan Beyea, Klaus Janberg, Jungmin Kang, Ed Lyman, Allison Macfarlane, Gordon Thompson, Frank N. von Hippel

As the multiple references to it in our article attest, we have learned a great deal from the pioneering work of Allan Benjamin *et al, Spent Fuel Heatup Following Loss of Water During Storage* (NUREG/CR-0649; SAND77-1371 R-3, 1979). Indeed, many of our conclusions and recommendations essentially echo those made in that report 24 years ago, but never implemented because the probability of an accidental loss of water was estimated to be too low to justify action.

Benjamin argues that we should have estimated the probability that sabotage or terrorist attack might cause a loss of water. Indeed, he seems to suggest that the probability can be calculated with some precision with methods that his company offers. While we believe that systematic analysis is useful in identifying vulnerabilities, we are skeptical about the predictive value of probabilistic calculations—especially for malevolent acts.

We respond more briefly to Benjamin's other comments below:

Magnitude of the release of ^{137}Cs. We looked at 10 and 100 percent releases—not just 100%.

Sensitivity to the constant-wind assumption. An estimate of the sensitivity of the contamination area to wind wander can be obtained by varying the opening angle in the wedge model calculation. Increasing the opening angle from 0.11 to 1 radians, for example, results in the area contaminated above 100 Ci/km2 increasing by about 20% for the 100% release and decreasing by about a factor of 3 for the 10% release.

Feasibility of totally draining the pool through valves and gates. We make no claim that this is possible. Rather we cite NRC staff concerns that a number of pools could be drained below the top of the spent fuel. This would result in very high radiation levels in the spent-fuel-pool building. Pools should therefore be equipped with sources of makeup water that can be turned on from a remote location.

Probabilities that terrorist attacks would put dense-packed fuel into a more coolable configuration and open-racked fuel into a less coolable configuration. Benjamin makes both assertions. The first is far from obvious. With regard to the second, we point out that the assumption that the geometry of the spent fuel is not changed is a limitation of our analysis—as it is of all other analyses of which we are aware. The NRC should commission studies of the implications for coolability of potential changes in geometry.

Omission of 8-day halflife ^{131}I and 2-year halflife ^{134}Cs in the consequence calculations. Shorter-lived isotopes such as ^{131}I and one-year halflife ^{106}Ru could make significant contributions to short-term doses downwind from a spent-fuel-pool fire. However, our analysis was limited to the long-term consequences of such an accident where, as the consequences of the Chernobyl accident demonstrate, 30-year halflife ^{137}Cs is the principle concern because it can force the evacuation of huge areas for decades.

Effectiveness of dry casks over the long term. We propose on-site dry-cask storage for about 30 years of older spent fuel that would, according to current plans, remain in pools for that length of time. Spent-fuel casks have already been in use for about 20 years and there is no evidence that they cannot last decades longer without significant deterioration.

Risks during spent-fuel transfer. We urge in the paper that these risks be carefully examined and minimized before the transfer begins. However, the fuel will have to be moved sooner or later in any case.

Availability of space for dry-cask storage. Nuclear power plants are surrounded by exclusion areas that provide ample space for a few tens of additional casks.

Acceleration of Yucca Mtn. Project. It would probably be counterproductive at this stage to try to significantly accelerate the licensing process of the Yucca Mountain underground spent-fuel repository. It would be worth exploring whether the delivery rate for spent-fuel could be increased above the current design rate of 3000 tons per year. However, there are so many political uncertainties associated with the transport of spent fuel to Yucca Mountain and so many technical issues that still have to be decided in its design and licensing process that speculation about possible acceleration should not be used as an excuse to ignore the relatively straightforward interim on-site storage option recommended in our paper.

Rulemaking Comments

From: John Runkle [jrunkle@pricecreek.com]
Sent: Tuesday, May 10, 2011 6:21 PM
To: Rulemaking Comments
Subject: Re: DOCKET ID NRC-2010-0131
Attachments: NAS Spent fuel storage.pdf

Part 2 of 2 (NAS report)

May 10, 2010

Attached please find the following

1. Union of Concerned Scientists, "Safer Storage of Spent Nuclear Fuel: The Problems of Spent Fuel Pools," revised March 24, 2011

2. Statement of David Lockbaum, Director, Nuclear Safety Project, before the U.S. Senate Energy and Natural Resources Committee, March 29, 2011

3. Alvarez et al., "Reducing the Hazardous from Stored Spent Power-Reactor Fuel in the United States," January 2003

4. Thompson, "Robust Storage of Spent Nuclear Fuel: A Neglected Issue of Homeland Security," January 2003.

5. National Academies of Science, "Safety and Security of Commerical Spent Nuclear Storage (Public Report)," 2006

Because of you size limitations, I am including document 5 in a separate email.

Together these document provide additional support that the AP1000 Certification rulemaking should be DENIED because of the inadequate spent fuel pools, and/or postponed or significantly extended to allow the NRC to develop and implement lessons learned from the Fukushima accident. As stated in the PETITION TO SUSPEND AP1000 DESIGN CERTIFICATION RULEMAKING PENDING EVALUATION OF FUKUSHIMA ACCIDENT IMPLICATIONS ON DESIGN AND OPERATIONAL PROCEDURES AND REQUEST FOR EXPEDITED CONSIDERATION, there was a significant backsliding from Revision 15 to Revision 18 by increasing the density of the spent fuel pools.

It is also readily apparent that some of the lessons learned from the Fukushima accident are:

a. spent fuel pools should not be densely packed b. there should be a robust containment around the fuel pools c. there should be redundant cooling systems for the fuel pools d. the build up of hydrogen in the fuel pools needs to be addressed e. there should be back up power for pumps, cooling systems and monitoring systems

Other lessons regarding the spent fuel pools may be learned after investigation.

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Committee on the Safety and Security of Commercial Spent Nuclear Fuel Storage, National Research Council

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Public Report

Committee on the Safety and Security of Commercial Spent Nuclear Fuel Storage
Board on Radioactive Waste Management
Division on Earth and Life Studies
NATIONAL RESEARCH COUNCIL *OF THE NATIONAL ACADEMIES*

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COMMITTEE ON THE SAFETY AND SECURITY OF COMMERCIAL SPENT NUCLEAR FUEL STORAGE

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[1] Drs. Cox and Wreathall resigned from the committee on February 26 and March 17, 2004, respectively.

BOARD ON RADIOACTIVE WASTE MANAGEMENT

[1] Dr. Meserve did not participate in the oversight of this study.

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This study would not have been possible without the help of several organizations and individuals who were called upon for information and advice. The committee would like to acknowledge especially the following organizations and individuals for their help:

- Congressional staff members Kevin Cook, Terry Tyborowski, and Jeanne Wilson (retired) for their guidance on the study task.
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- Department of Homeland Security staff member Jon MacLaren, who also served as a liaison to the committee.
- Steve Kraft and John Vincent (deceased) of the Nuclear Energy Institute and staff of Energy Resources International for providing information about spent fuel storage practices in industry.
- ENTERGY Corp., Exelon Corp, and Arizona Public Service Corp. staff for organizing tours of the Braidwood, Dresden, Indian Point, and Palo Verde nuclear generating stations.
- German organizations and individuals who helped organize a tour of spent fuel storage facilities in Germany. These organizations and individuals are explicitly acknowledged in Appendix C.
- Speakers (see Appendix A) and participants at committee meetings as well as those who sent written comments for providing their knowledge and perspectives on this important matter,

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as passible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The content of the review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report:

John F.Aheame, Sigma Xi and Duke University
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Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the report's conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Chris G.Whipple, ENVIRON International Corporation, and R.Stephen Berry, University of Chicago. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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NOTE TO READERS

This report is based on a classified report that was developed at the request of the U.S. Congress with sponsorship from the Nuclear Regulatory Commission and the Department of Homeland Security. This report contains all of the findings and recommendations that appear in the classified report. Some have been slightly reworded and other sensitive information that might allow terrorists to exploit potential vulnerabilities has been redacted to protect national security. Nevertheless, the National Research Council and the authoring committee believe that this report provides an accurate summary of the classified report, including its findings and recommendations

The authoring committee for this report examined the potential consequences of a large number of scenarios for attacking spent fuel storage facilities at commercial nuclear power plants. Some of these scenarios were developed by the Nuclear Regulatory Commission as part of its ongoing vulnerability analyses, whereas others were developed by the committee based upon the expertise of its members or suggestions from participants at the committee's open meetings. The committee focused its discussions about terrorist attacks on the concept of *maximum credible scenarios*. These are defined by the committee to be physically realistic classes of attacks that, if carried out successfully, would produce the most serious potential consequences within that class. In a practical sense they can be said to *bound* the consequences for a given type of attack. Such scenarios could in some cases be very difficult to carry out because they require a high level of skill and knowledge or luck on the part of the attackers, It was nevertheless useful to analyze these scenarios because they provide decision makers with a better understanding of the full range of potential consequences from terrorist attacks.

The committee uses the term *potential consequences* advisedly. It is important to recognize that a terrorist attack on a spent fuel storage facility would not necessarily result in the release of any radioactivity to the environment. The consequences of such an attack would depend not only on the nature of the attack itself, but also on the construction of the spent fuel storage facility; its location relative to surrounding features that might shield it from the attack; and the ability of the guards and operators at the facility to respond to the attack and/or mitigate its consequences. Facility-specific analyses are required to determine the potential vulnerability of a given facility to a given type of terrorist attack.

Congress asked the National Research Council for technical advice related to the vulnerability of spent fuel storage facilities to terrorist attacks. Congress, the Nuclear Regulatory Commission, and the Department of Homeland Security are responsible for translating this advice into policy actions. This will require the balancing of costs, risks, and benefits across the nation's industrial infrastructure. The committee was not asked to examine the potential vulnerabilities of other types of infrastructure to terrorist attacks or the consequences of such attacks. While such comparisons will likely be difficult, they will be essential for ensuring that the nation's limited resources are used judiciously in protecting its citizens from terrorist attacks.

SUMMARY FOR CONGRESS

The U.S. Congress asked the National Academies to provide independent scientific and technical advice on the safety and security of commercial spent nuclear fuel storage in the United States, specifically with respect to the following charges:

- Potential safety and security risks of spent nuclear fuel presently stored in cooling pools at commercial nuclear reactor sites.
- Safety and security advantages, if any, of dry cask storage versus wet pool storage at these reactor sites.
- Potential safety and security advantages, if any, of dry cask storage using various single-, dual-, and multi-purpose cask designs,
- The risks of terrorist attacks on these materials and the risk these materials might be used to construct a radiological dispersal device.

Congress requested that the National Academies produce a classified report that addresses these charges within 6 months and also provide an unclassified summary for unlimited public distribution. The first request was fulfilled in July 2004. This report fulfills the second request.

The highlights of the report are as follows:

(1) Spent fuel pools are necessary at all operating nuclear power plants to store recently discharged fuel.
(2) The committee judges that successful terrorist attacks on spent fuel pools, though difficult, are possible.
(3) If an attack leads to a propagating zirconium cladding fire, it could result in the release of large amounts of radioactive material.
(4) Additional analyses are needed to understand more fully the vulnerabilities and consequences of events that could lead to propagating zirconium cladding fires.
(5) It appears to be feasible to reduce the likelihood of a zirconium cladding fire by rearranging spent fuel assemblies in the pool and making provision for water-spray systems that would be able to cool the fuel, even if the pool or overlying building were severely damaged.
(6) Dry cask storage has inherent security advantages over spent fuel pool storage, but it can only be used to store older spent fuel
(7) There are no large security differences among different storage-cask designs.
(8) It would be difficult for terrorists to steal enough spent fuel from storage facilities for use in significant radiological dispersal devices (dirty bombs).

The statement of task does not direct the committee to recommend whether the transfer of spent fuel from pool to dry cask storage should be accelerated. The committee judges, however, that further engineering analyses and cost-benefit studies would be needed before decisions on this and other mitigative measures are taken. The report contains detailed recommendations for improving the security of spent fuel storage regardless of how it is stored.

EXECUTIVE SUMMARY

In the Fiscal Year 2004 Energy and Water Development Conference Report, the U.S. Congress asked the National Academies to provide independent scientific and technical advice on the safety and security[1] of commercial spent nuclear fuel storage in the United States, specifically with respect to the following four charges:

(1) Potential safety and security risks of spent nuclear fuel presently stored in cooling pools at commercial reactor sites.
(2) Safety and security advantages, if any, of dry cask storage versus wet pool storage at these reactor sites.
(3) Potential safety and security advantages, if any, of dry cask storage using various single-, dual-, and multi-purpose cask designs.
(4) The risks of terrorist attacks on these materials and the risk these materials might be used to construct a radiological dispersal device.

Congress requested that the National Academies produce a classified report that addresses these charges within 6 months and also provide an unclassified summary for unlimited public distribution. The first request was fulfilled in July 2004. This report fulfills the second request.

Spent nuclear fuel is stored at commercial nuclear power plant sites in two configurations:

- In water-filled pools, referred to as *spent fuel pools*.
- In *dry casks* that are designed either for storage (single-purpose casks) or both storage and transportation (dual-purpose casks). There are two basic cask designs: bare-fuel casks and canister-based casks, which can be licensed for either single- or dual-purpose use, depending on their design.

Spent fuel pools are currently in use at all 65 sites with operating commercial nuclear power reactors, at 8 sites where commercial power reactors have been shut down, and at one site not associated with an operating or shutdown power reactor. Dry-cask storage facilities have been established at 28 operating, shutdown, or decommissioned power plants. The nuclear industry projects that up to three or four nuclear power plants will reach full capacity in their spent fuel pools each year for at least the next 17 years.

The congressional request for this study was prompted by conflicting public claims about the safety and security of commercial spent nuclear fuel storage at nuclear power plants. Some analysts have argued that the dense packing of spent fuel in cooling pools at nuclear power plants does not allow a sufficient safety margin in the event of a loss-of-pool-coolant event from an accident or terrorist attack. They assert that such events could result in the release of large quantities of radioactive material to the environment If the zirconium cladding of the spent fuel overheats and ignites. To reduce the potential for such fires, these

[1] In the context of this study, *safety* refers to measures that protect spent nuclear fuel storage facilities against failure, damage, human error, or other accidents that would disperse radioactivity in the environment. *Security* refers to measures to protect spent fuel storage facilities against sabotage, attacks, or theft.

analysts have suggested that spent fuel more than five years old be removed from the pool and stored in dry casks, and that the remaining younger fuel be reconfigured in the pool to allow more space for air cooling in the event of a loss-of-pool-coolant event.

The committee that was appointed to perform the present study examined the vulnerability of spent fuel stored in pools and dry casks to accidents and terrorist attacks. Any event that results in the breach of a spent fuel pool or a dry cask, whether accidental or intentional, has the potential to release radioactive material to the environment. The committee therefore focused its limited time on understanding two issues: (1) Under what circumstances could pools or casks be breached? And (2) what would be the radioactive releases from such breaches?

To address these questions, the committee performed a critical review of the security analyses that have been carried out by the Nuclear Regulatory Commission and its contractors, the Department of Homeland Security, industry, and other independent experts to determine if they are objective, complete, and credible. The committee was unable to examine several important issues related to these questions either because it was unable to obtain needed information from the Nuclear Regulatory Commission or because of time constraints. Details are provided in Chapters 1 and 2.

The committee's findings and recommendations from this analysis are provided below, organized by the four charges of the study task. The ordering of the charges has been rearranged to provide a more logical exposition of results.

CHARGE 4: RISKS OF TERRORIST ATTACKS ON THESE MATERIALS AND THE RISK THESE MATERIALS MIGHT BE USED TO CONSTRUCT A RADIOLOGICAL DISPERSAL DEVICE

The concept of *risk* as applied to terrorist attacks underpins the entire statement of task for this study. Therefore, the committee examined this final charge first to provide the basis for addressing the remainder of the task statement. The committee's examination of Charge 4 is provided in Chapter 2, On the basis of this examination, the committee offers the following findings and recommendations numbered according to the chapters in which they appear

FINDING 2A: The probability of terrorist attacks on spent fuel storage cannot be assessed quantitatively or comparatively. Spent fuel storage facilities cannot be dismissed as targets for such attacks because it is not possible to predict the behavior and motivations of terrorists, and because of the attractiveness of spent fuel as a terrorist target given the well known public dread of radiation. Terrorists view nuclear power plant facilities as desirable targets because of the large inventories of radioactivity they contain. While it would be difficult to attack such facilities, the committee judges that attacks by knowledgeable terrorists with access to appropriate technical means are possible. It is important to recognize, however, that an attack that damages a power plant or its spent fuel storage facilities would not necessarily result in the release of *any* radioactivity to the environment. There are potential steps that can be taken to lower the potential consequences of such attacks.

FINDING 2B: The committee judges that the likelihood terrorists could steal enough spent fuel for use in a significant radiological dispersal device is small. Removal of a spent fuel assembly from the pool or dry cask would prove extremely difficult under almost any terrorist attack scenario. Attempts by a knowledgeable insider(s) to remove single rods and related debris from the pool might prove easier, but the amount of material that could be removed would be small. Moreover, superior materials could be stolen or purchased more easily from other sources. Even though the likelihood of spent fuel theft appears to be small, it is nevertheless important that the protection of these materials be maintained and improved as vulnerabilities are identified.

RECOMMENDATION: The Nuclear Regulatory Commission should review and upgrade, where necessary, its security requirements for protecting spent fuel rods not contained in fuel assemblies from theft by knowledgeable insiders, especially in facilities where individual fuel rods or portions of rods are being stored in pools.

FINDING 2C: A number of security improvements at nuclear power plants have been instituted since the events of September 11, 2001. However, the Nuclear Regulatory Commission did not provide the committee with enough information to evaluate the effectiveness of these procedures for protecting stored spent fuel. Surveillance and other human-factors related security procedures are just as important as the physical barriers in preventing and mitigating terrorist attacks. Although the committee did learn about some of the changes that have been instituted since the September 11, 2001, attacks, it was not provided with enough information to evaluate the effectiveness of procedures now in place.

RECOMMENDATION: Although the committee did not specifically investigate the effectiveness and adequacy of improved surveillance and security measures for protecting stored spent fuel, an assessment of current measures should be performed by an independent[2] organization.

CHARGE 1: POTENTIAL SAFETY AND SECURITY RISKS OF SPENT NUCLEAR FUEL STORED IN POOLS

The committee's examination of Charge 1 is provided in Chapter 3. On the basis of this examination, the committee offers the following findings and recommendations:

FINDING 3A: Pool storage is required at all operating commercial nuclear power plants to cool newly discharged spent fuel. Freshly discharged spent fuel generates too much decay heat to be passively air cooled. This fuel must be stored in a pool that has an active heat removal system (i.e., water pumps and heat exchangers) for at least one year before being moved to dry storage. Most dry storage systems are licensed to store fuel that has been out of the reactor for at least five years. Although spent fuel younger than five years could be stored in dry casks, the changes required for shielding and heat-removal

[2] That is, independent of the Nuclear Regulatory Commission and the nuclear industry.

could be substantial, especially for fuel that has been discharged for less than about three years.

FINDING 3B: The committee finds 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. Details are provided in the committee's classified report.

FINDING 3C: It appears to be feasible to reduce the likelihood of a zirconium cladding fire following a loss-of-pool-coolant event using readily implemented measures. The following measures appear to have particular merit: Reconfiguring the spent fuel in the pools (i.e., redistribution of high decay-heat assemblies so that they are surrounded by low decay-heat assemblies) to more evenly distribute decay-heat loads and enhance radiative heat transfer; limiting the frequency of offloads of full reactor cores into spent fuel pools, requiring longer shutdowns of the reactor before any fuel is offloaded, and providing enhanced security when such offloads must be made; and development of a redundant and diverse response system to mitigate loss-of-pool-coolant events that would be capable of operation even if the pool or overlying building were severely damaged.

FINDING 3D: The potential vulnerabilities of spent fuel pools to terrorist attacks are plant-design specific. Therefore, specific vulnerabilities can be understood only by examining the characteristics of spent fuel storage at each plant. As described in Chapter 3, there are substantial differences in the designs of spent fuel pools that make them more or less vulnerable to certain types of terrorist attacks.

FINDING 3E: The Nuclear Regulatory Commission and independent analysts have made progress in understanding some vulnerabilities of spent fuel pools to certain terrorist attacks and the consequences of such attacks for releases of radioactivity to the environment. However, additional work on specific issues is needed urgently. The analyses carried out to date provide a general understanding of spent fuel behavior in a loss-of-pool-coolant event and the vulnerability of spent fuel pools to certain terrorist attacks that could cause such events to occur. The work to date, however, has not been sufficient to adequately understand the vulnerabilities and consequences of such events. Additional analyses are needed to fill in the knowledge gaps so that well-informed policy decisions can be made.

> **RECOMMENDATION: The Nuclear Regulatory Commission should undertake additional best-estimate analyses to more fully understand the vulnerabilities and consequences of loss-of-pool-coolant events that could lead to a zirconium cladding fire. Based on these analyses, the Commission should take appropriate actions to address any significant vulnerabilities that are identified.** The committee provides details on additional analyses that should be carried out in its classified report. Cost-benefit considerations will be an important part of such decisions.

> **RECOMMENDATION: While the work described in the previous recommendation under Finding 3E, above, is being carried out, the Nuclear Regulatory Commission should ensure that power plant operators take prompt and effective measures to reduce the consequences of loss-of-pool-coolant**

events in spent fuel pools that could result in propagating zirconium cladding fires. The committee judges that there are at least two such measures that should be implemented promptly:

- Reconfiguring of fuel in the pools so that high decay-heat fuel assemblies are surrounded by low decay-heat assemblies. This will more evenly distribute decay-heat loads, thus enhancing radiative heat transfer in the event of a loss of pool coolant.
- Provision for water-spray systems that would be able to cool the fuel even if the pool or overlying building were severely damaged.

Reconfiguring of fuel in the pool would be a prudent measure that could probably be implemented at all plants at little cost, time, or exposure of workers to radiation. The second measure would probably be more expensive to implement and may not be needed at all plants, particularly plants in which spent fuel pools are located below grade or are protected from external line-of-sight attacks by exterior walls and other structures.

The committee anticipates that the costs and benefits of options for implementing the second measure would be examined to help decide what requirements would be imposed. Further, the committee does not presume to anticipate the best design of such a system—whether it should be installed on the walls of a pool or deployed from a location where it is unlikely to be compromised by the same attack—but simply notes the demanding requirements such a system must meet.

CHARGE 3: POTENTIAL SAFETY AND SECURITY ADVANTAGES, IF ANY, OF DIFFERENT DRY CASK STORAGE DESIGNS

The third charge to the committee focuses exclusively on the safety and security of dry casks. The committee addressed this charge first in Chapter 4 to provide the basis for the comparative analysis between dry casks and pools as called for in Charge 2.

FINDING 4A: Although there are differences in the robustness of different dry cask designs (e.g., bare-fuel versus canister-based), the differences are not large when measured by the absolute magnitudes of radionuclide releases in the event of a breach. All storage cask designs are vulnerable to some types of terrorist attacks, but the quantity of radioactive material releases predicted from such attacks is relatively small. These releases are not easily dispersed in the environment.

FINDING 4B: Additional steps can be taken to make dry casks less vulnerable to potential terrorist attacks. Although the vulnerabilities of current cask designs are already small, additional, relatively simple steps can be taken to reduce them as discussed in Chapter 4.

RECOMMENDATION: The Nuclear Regulatory Commission should consider using the results of the vulnerability analyses for possible upgrades of requirements in 10 CFR 72 for dry casks, specifically to improve their resistance to terrorist attacks. The committee was told by

Nuclear Regulatory Commission staff that such a step is already under consideration.

CHARGE 2: SAFETY AND SECURITY ADVANTAGES, IF ANY, OF DRY CASK STORAGE VERSUS WET POOL STORAGE

In Chapter 4, the committee offers the following findings and recommendations with respect to the comparative component of Charge 2:

FINDING 4C: Dry cask storage does not eliminate the need for pool storage at operating commercial reactors. Under present U.S. practices, dry cask storage can only be used to store fuel that has been out of the reactor long enough (generally greater than five years under current practices) to be passively air cooled.

FINDING 4D: Dry cask storage for older, cooler spent fuel has two inherent advantages over pool storage: (1) It is a passive system that relies on natural air circulation for cooling; and (2) it divides the inventory of that spent fuel among a large number of discrete, robust containers. These factors make it more difficult to attack a large amount of spent fuel at one time and also reduce the consequences of such attacks. The robust construction of these casks prevents large-scale releases of radioactivity in all of the attack scenarios examined by the committee in its classified report.

FINDING 4E: Depending on the outcome of plant-specific vulnerability analyses described in the committee's classified report, the Nuclear Regulatory Commission might determine that earlier movements of spent fuel from pools into dry cask storage would be prudent to reduce the potential consequences of terrorist attacks on pools at some commercial nuclear plants. The statement of task directs the committee to examine the risks of spent fuel storage options and alternatives for decision makers, not to recommend whether any spent fuel should be transferred from pool storage to cask storage. In fact, there may be some commercial plants that, because of pool designs or fuel loadings, may require some removal of spent fuel from their pools. If there is a need to remove spent fuel from the pools it should become clearer once the vulnerability and consequence analyses described in the classified report are completed. The committee expects that cost-benefit considerations would be a part of these analyses.

IMPLEMENTATION ISSUES

Implementation of the recommendations in Chapters 2–4 will require action and cooperation by a large number of parties. The final chapter of the report provides a brief discussion of two implementation issues that the committee believes are of special interest to Congress: *Timing Issues:* Ensuring that high-quality, expert analyses are completed in a timely manner; and *Communications Issues:* Ensuring that the results of the analyses are communicated to relevant parties so that appropriate and timely mitigating actions can be taken. This discussion leads to the following finding and recommendation.

FINDING 5A: Security restrictions on sharing of information and analyses are hindering progress in addressing potential vulnerabilities of spent fuel storage to

terrorist attacks. Current classification and security practices appear to discourage information sharing between the Nuclear Regulatory Commission and industry. They impede the review and feedback processes that can enhance the technical soundness of the analyses being carried out; they make it difficult to build support within the industry for potential mitigative measures; and they may undermine the confidence that the industry, expert panels such as this one, and the public place in the adequacy of such measures.

RECOMMENDATION: The Nuclear Regulatory Commission should improve the sharing of pertinent information on vulnerability and consequence analyses of spent fuel storage with nuclear power plant operators and dry cask storage system vendors on a timely basis.

The committee also believes that the public is an important audience for the work being carried out to assess and mitigate vulnerabilities of spent fuel storage facilities. While it would be inappropriate to share all information publicly, more constructive interaction with the public and independent analysts could improve the work being carried out and also increase public confidence in Nuclear Regulatory Commission and industry decisions and actions to reduce the vulnerability of spent fuel storage to terrorist threats.

1

INTRODUCTION AND BACKGROUND

In the Fiscal Year 2004 Energy and Water Development Conference Report, the U.S. Congress asked the National Academies to provide independent scientific and technical advice on the safety and security[1] of commercial spent nuclear fuel storage in the United States (see Box 1.1). The Nuclear Regulatory Commission and the Department of Homeland Security jointly sponsored this study, as directed by Congress.

Awareness and concerns about the threat of high-impact terrorism have become acute and pervasive since the attacks on September 11, 2001. The information gathered by the committee during this study led it to conclude that there were indeed credible concerns about the safety and security of spent nuclear fuel storage in the current threat environment. From the outset the committee believed that safety and security issues must be addressed quickly to determine whether additional measures are needed to prevent or mitigate attacks that could cause grave harm to people and cause widespread fear, disruption, and economic loss. The information gathered during this study reinforced that view. Any concern related to nuclear power plants[2] has added stakes: Many people fear radiation more than they fear exposure to other physical insults. This amplifies the concern over a potential terrorist attack involving radioactive materials beyond the physical injuries it might cause, and beyond the economic costs of the cleanup.

1.1 CONTEXT FOR THIS STUDY

The congressional request for this study was prompted by conflicting public claims about the safety and security of commercial spent nuclear fuel storage at nuclear power plants. Some have argued that the dense packing used for storing spent fuel in cooling pools at nearly every nuclear power plant does not provide a sufficient safety margin in the event of a pool breach and consequent water loss from an accident or terrorist attack.[3] In such cases, the potential exists for the fuel most recently discharged from a reactor to heat up sufficiently for its zirconium cladding to ignite, possibly resulting in the release of large amounts of radioactivity to the environment (Alvarez et al., 2003a). The Nuclear Regulatory Commission's own analyses have suggested that such zirconium cladding fires and releases of radioactivity are possible (e.g., USNRC, 2001 a).

To reduce the potential for such an event, Alvarez et al. (2003a) suggested that spent fuel more than five years old be removed from the pool and stored in dry casks, and

[1] In the context of this study, *safety* refers to measures that protect spent nuclear fuel storage facilities against failure, damage, human error, or other accidents that would disperse radioactivity in the environment. *Security* refers to measures to protect spent fuel storage facilities against sabotage, attacks, or theft.

[2] Safety and security of reactors at nuclear power plants are outside of the committee's statement of task and have been addressed only where they could not be separated from spent fuel storage. The distinctions between spent fuel storage and operating nuclear power reactors are sometimes blurred in public discussions of nuclear and radiological concerns.

[3] The committee refers to such occurrences as *loss-of-pool-coolant events* in this report.

that the remaining younger fuel be rearranged in the pool to allow more space for cooling (see also Marsh and Stanford, 2001; Thompson, 2003). The Nuclear Regulatory Commission staff, the nuclear industry, and some others have argued that densely packed pool storage can be carried out both safely and securely (USNRC, 2003a).

BOX 1.1 STATEMENT OF TASK

The issues to be addressed by this study are specified in the Energy and Water Development Conference Report and are as follows:

(1) Potential safety and security risks of spent nuclear fuel presently stored in cooling pools at commercial reactor sites (see Chapter 3).
(2) Safety and security advantages, if any, of dry cask storage versus wet pool storage at these reactor sites (see Chapter 4).
(3) Potential safety and security advantages, if any, of dry cask storage using various single-, dual-, and multi-purpose cask designs (see Chapter 4).
(4) In light of the September 11, 2001, terrorist attacks, this study will explicitly consider the risks of terrorist attacks on these materials and the risk these materials might be used to construct a radiological dispersal device (see Chapter 2),

Policy actions to improve the safety and security of spent fuel storage could have significant national consequences. Nuclear power plants generate approximately 20 percent of the electricity produced in the United States. The issue of its future availability and use is critical to our nation's present and future energy security. The safety and security of spent fuel storage is an Important aspect of the acceptability of nuclear power. Decisions that affect such a large portion of our nation's electricity supply must be considered carefully, wisely, and with a balanced view.

1.2 STRATEGY TO ADDRESS THE STUDY CHARGES

Congress directed the National Academies to produce a classified report that addresses the statement of task shown in Box 1.1 within 6 months and an unclassified summary for unlimited public dissemination within 12 months. This report, which has undergone a security review by the Nuclear Regulatory Commission and found to contain no classified national security or safeguards information, fulfills the second request.[4]

The National Research Council of the National Academies appointed a committee of 15 experts to carry out this study. Biographical sketches of the committee members are provided in Appendix B. The committee met six times from February to June 2004 to gather information and complete its classified report. The committee met again in August, October, and November 2004 and in January 2005 to develop this public report.

Details on the information-gathering sessions and speakers are provided in Appendix A. Most of the information-gathering sessions were not open to the public because they involved presentations and discussions of classified information. The committee recognized, however, that important contributions to this study could be made by industry representatives, independent analysts, and the public, so it scheduled open, unclassified

[4]The classified report was briefed to the agencies and Congress on July 15, 2004,

sessions at three of its meetings to obtain comments from interested organizations and individuals. Public comments at these meetings were encouraged and considered.

Subgroups of the committee visited several nuclear power plants to learn first-hand how spent fuel is being managed in wet and dry storage: the Dresden and Braidwood Nuclear Generating Stations in Illinois, which are owned and operated by Exelon Nuclear Corp.; the Indian Point Nuclear Generating Station in New York, which is owned and operated by ENTERGY Corp.; and the Palo Verde Nuclear Generating Station in Arizona, which is operated by Arizona Public Service Corp. A subgroup of committee members also traveled to Germany to visit spent fuel storage installations at Ahaus and Lingen and to talk with experts about the safety and security of German spent fuel storage. The German government has been concerned about security for a long time, and the German nuclear industry has made adjustments to spent fuel storage designs and operations that reduce their vulnerability to accidents and terrorist attacks. A summary of the trip to Germany is provided in Appendix C,

The statement of task for this study directed the committee to examine both the safety and the security of spent fuel storage. It is important to recognize that these are two sides of the same coin in the sense that any event that results in the breach of a spent fuel pool or a dry cask, whether accidental or intentional, has the potential to release radioactive material to the environment. The committee therefore focused its limited time on understanding two issues: (1) Under what circumstances could poots or casks be breached? And (2) what would be the radioactive releases from such breaches?

The initiating events that could lead to the *accidental* breach of a spent fuel pool are well known: A large seismic event or the accidental drop of a cask on the pool wall that could lead to the loss of pool coolant. The condition that could lead to an accidental breach of a dry storage cask is similarly well known: an accidental drop of the cask during handling operations. Current Nuclear Regulatory Commission regulations are designed to prevent such accidental conditions by imposing requirements on the design and operation of spent fuel storage facilities. These regulations have been in place for decades and have so far been effective in preventing accidental releases of radioactive materials from these facilities into the environment.

The initiating events that could lead to the *intentional* breach of a spent fuel pool or dry storage cask are not as well understood. The Nuclear Regulatory Commission has had long-standing requirements in place to deal with radiological sabotage (included in the "design basis threat"; see Chapter 2), but the September 11, 2001, terrorist attacks provided a graphic demonstration of a much broader array of potential threats. As described in the following chapters, the Nuclear Regulatory Commission is currently sponsoring studies to better understand the potential consequences of such terrorist attacks on spent fuel storage facilities.

Early on in this study, the committee made a judgment that it should focus most of its attention concerning such initiating events on the security aspects of its task statement. Many of the phenomena that follow an initiating event (e.g., loss of pool coolant or cask breach) would be the same whether it arose from an accident or terrorist attack, as noted previously. While the mitigation strategies for such events might be similar, they would require different kinds of preparation.

Given the relatively short time frame for this study, the committee focused its efforts on performing a critical review of the security analyses that have been carried out by the Nuclear Regulatory Commission and Its contractors, the Department of Homeland Security, industry (i.e., EPRI, formerly named the Electric Power Research Institute; ENTERGY Corp.; and dry cask vendors), and other independent experts to determine if they are objective, complete, and credible. The committee could only perform limited independent safety and security analyses based on the information it gathered.

The committee made many requests for information from the Nuclear Regulatory Commission, its Sandia National Laboratories contractor, and other organizations and individuals, often with little advance notice. For the most part, all parties responded well to these requests. The committee was able to access experts who could answer its technical questions and was pleased with the cooperation and information it received during its visits to spent fuel storage facilities. This cooperation was essential in enabling the committee to complete its task within the requested six-month timeframe,

The committee was forced to circumscribe some aspects of its examinations, however, due to time and/or information constraints. In particular, the committee did not pursue in-depth examinations of the following topics:

- Human factors issues involved in responding to terrorist attacks on spent fuel storage. These include surveillance activities to identify potential threats (both inside and outside the plant); the response of security forces; and the preparation of plant personnel to deploy mitigative measures in the event of an attack.
- The behavior of radioactive material after it enters the environment from a spent fuel pool or dry cask. The committee assumed that any large release of radioactivity from a spent fuel storage facility would be problematic even in the absence of knowledge of how it would disperse in the environment. The committee instead focused its efforts on understanding how much radioactive material would be released, if any, in the case of an attack.
- The economic consequences of potential terrorist attacks, except insofar as noting the possible magnitude of cleanup costs after a catastrophic release of radioactivity.
- The costs of potential measures to mitigate spent fuel storage vulnerabilities. The committee understands that the Nuclear Regulatory Commission would include cost-benefit considerations in decisions to impose any new requirements on industry for such measures.

The committee also did not examine the potential vulnerability of commercial spent fuel while being transported. That topic is not only outside of the committee's task, but there is another National Academies study currently underway to examine transportation issues.[5]

Because most of the studies on spent fuel storage vulnerabilities undertaken for the Nuclear Regulatory Commission are still in progress, the committee was not able to review completed technical documents. Instead, the committee had to rely on presentations by and discussions with technical experts. The committee does not believe that these difficulties prevented it from developing sound findings and recommendations from the information it

[5] Committee on Transportation of Radioactive Waste. See *http://nationalacademies.org/transportofradwaste*. That committee's final report is now planned for completion in the late summer of 2005.

did receive. The committee was able to draw upon other information sources both domestic and foreign,[6] including the experience and expertise of its members, to fill some of the information gaps.

1.3 REPORT ROADMAP

The sections that follow in this chapter provide background on storage of spent nuclear fuel, which may be helpful to non-experts in understanding the issues discussed in the following chapters. The other chapters are organized to explicitly address the four charges of the committee's statement of task:

- Chapter 2 addresses the last charge to the committee to "explicitly consider the risks of terrorist attacks on these materials and the risk these materials might be used to construct a radiological dispersal device."
- Chapter 3 addresses the first charge to the committee to examine the "potential safety and security risks of spent nuclear fuel presently stored in cooling pools at commercial reactor sites."
- Chapter 4 addresses the second and third charges to examine the "safety and security advantages, if any, of dry cask storage versus wet pool storage at these reactor sites" and the "potential safety and security advantages, if any, of dry cask storage using various single-, dual-, and multi-purpose cask designs."
- Chapter 5 concerns implementation of the recommendations in this report, specifically conceming timing and communication issues.

The appendixes provide supporting information, including a glossary and acronym list, descriptions of the committee's meetings, and biographical sketches of the committee members.

1.4 BACKGROUND ON SPENT NUCLEAR FUEL AND ITS STORAGE

This section is provided for readers who are not familiar with the technical features of spent nuclear fuel and its storage. Other readers should skip directly to Chapter 2.

Spent nuclear fuel is fuel that has been irradiated or "burned" in the core of a nuclear reactor, in power reactors, the energy released from fission reactions in the nuclear fuel heats water[7] to produce steam that drives turbines to generate electricity. Spent nuclear fuel from non-commercial reactors (such as research reactors, naval propulsion reactors, and Plutonium production reactors) is not considered in this study.

1.4.1 Nuclear Fuel

Almost all commercial reactor fuel in the United States is in the form of solid, cylindrical pellets of uranium dioxide. The pellets are about 0.4 to 0.65 inch (1.0 to 1.65 centimeters) in length and about 0.3 to 0.5 inch (0.3 to 1.25 centimeters) in diameter. The

[6] For example, the aforementioned visits to Lingen and Ahaus, in Germany.
[7] A different coolant can be used, but all power reactors now operating in the United States are water cooled.

pellets are loaded into tubes, called *fuel cladding,* made of a zirconium metal alloy, called zircaloy. A loaded tube, which is typically 11,5 to 14.75 feet (3.5 to 4.5 meters) in length, is called a *fuel rod* (also referred to as a *fuel pin* or *fuel element*). Fuel rods are bundled together, with a 0.12 to 0.18 inch (0.3 to 0.45 centimeter) space left between each for coolant to flow, to form a square fuel assembly (see FIGURE 1.1) measuring about 6 to 9 inches (15 to 23 centimeters) on a side.

Typical fuel assemblies for boiling water nuclear reactors (BWRs) hold 49 to 63 fuel rods, and fuel assemblies for pressurized water nuclear reactors (PWRs) hold 164 to 264 fuel rods.[8] Depending on reactor design, typically between 190 and 750 assemblies, each weighing from 275 to 685 kg (600 to 1500 pounds), make up a power reactor core. New fuel assemblies (i.e., those that have not been irradiated in a reactor) do not require special cooling or radiation shielding; they can be moved with a crane in open air. Once in the reactor, however, the fuel undergoes nuclear fission and begins to generate the radioactive fission products and activation products that require shielding and cooling.

The uranium oxide fuel essentially is composed of two isotopes of uranium: Initially, about 3–5 percent[9] by weight is fissile uranium (uranium-235), which is the component that sustains the fission chain reaction; and about 95–97 percent is uranium-238, which can capture a neutron to produce fissile plutonium and other radioactive heavy isotopes (actinides). Each fission event, whether in uranium or plutonium, releases energy and neutrons as the fissioning nucleus splits into two (and infrequently three) radioactive fragments, called fission products.

When the fissile material has been consumed to a level where it is no longer economically viable (typically 4.5 to 6 years of operation for current fuel designs), the fuel is considered *spent* and is removed from the reactor core. Spent fuel assemblies are highly radioactive. The decay of radioactive fission products and other constituents generates heat (called *decay heat*) and penetrating (gamma and neutron) radiation. Therefore cooling, shielding, and remote handling are required for spent nuclear fuel.

The amount of heat and radiation generated by a spent fuel assembly after its removal from a reactor depends on the number of fissions that have occurred in the fuel, called the *burn-up,* and the time that has elapsed since the fuel was removed from the reactor. The rate of decay-heat generation by spent reactor fuel and how it will change with time after the fuel is removed from the reactor can be calculated. The results of an example calculation are shown in FIGURE 1.2.

At discharge from the reactor, a spent fuel assembly generates on the order of tens of kilowatts of heat. Decay-heat production diminishes as very short-lived radionuclides decay away, dropping heat generation by a factor of 100 during the first year; dropping by another factor of 5 between year one and year five; and dropping about 40 percent between year five and year ten (see FIGURE 1.2). Within a year of discharge from the reactor, decay-heat production in spent nuclear fuel is dominated by four radionucfides: Ruthenium-106 (with a 372.6-day half-life), cerium-144 (284.4-day half-life), cesium-137 (30.2-year half-life),

[8] Technical specifications for the fuel assemblies are taken from the American National Standard document for pool storage of spent nuclear fuel (American Nuclear Society, 1988).

[9] With only a few exceptions, commercial nuclear power reactors in the United States have been fueled with low-enriched uranium, that is, less than 20 percent of the uranium is uranium-235. Uranium found in nature has about 0.71 percent uranium-235 by weight.

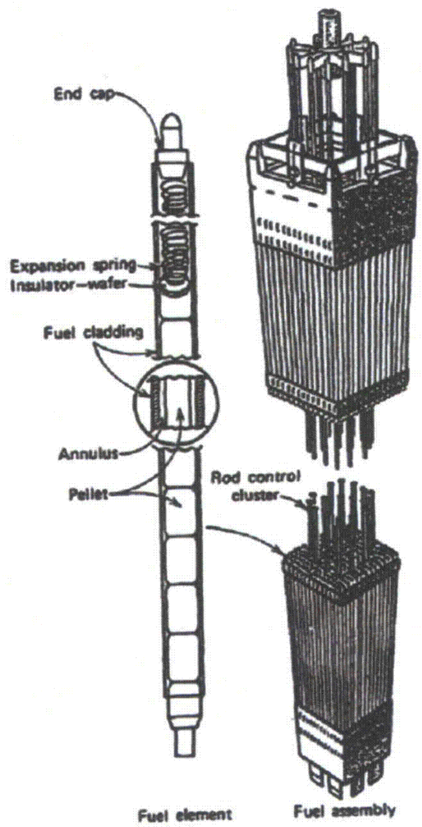


FIGURE 1.1 Fuel rods, also called fuel pins or elements, are bundled together into fuel assemblies as shown here. This fuel assembly is for a PWR reactor. SOURCE: Duderstadt and Hamilton (1976; Figure 3–7).

and cesium-134 (2.1-year half-life) and their short-lived decay products contribute nearly 90 percent of the decay heat from a spent fuel assembly.

Longer-lived radionuclides persist in the spent fuel even as the decay heat drops further. Cesium-137 decays to barium-137, emitting a beta particle and a high-energy gamma ray. The cesium-137 half-life of 30.2 years is sufficiently long to ensure that this radionuclide will persist during storage. It and other materials present in the fuel will form small particles, called *aerosols,* in a zirconium cladding fire.

Shorter-lived radionuclides decay away rapidly after removal of the spent fuel from the reactor. One of these is iodine-131, which is of particular concern in reactor core accidents because it can be taken up in large quantities by the human thyroid. This radionuclide has a half-life of about 8 days and typically persists in significant quantities in spent fuel only on the order of a few months.

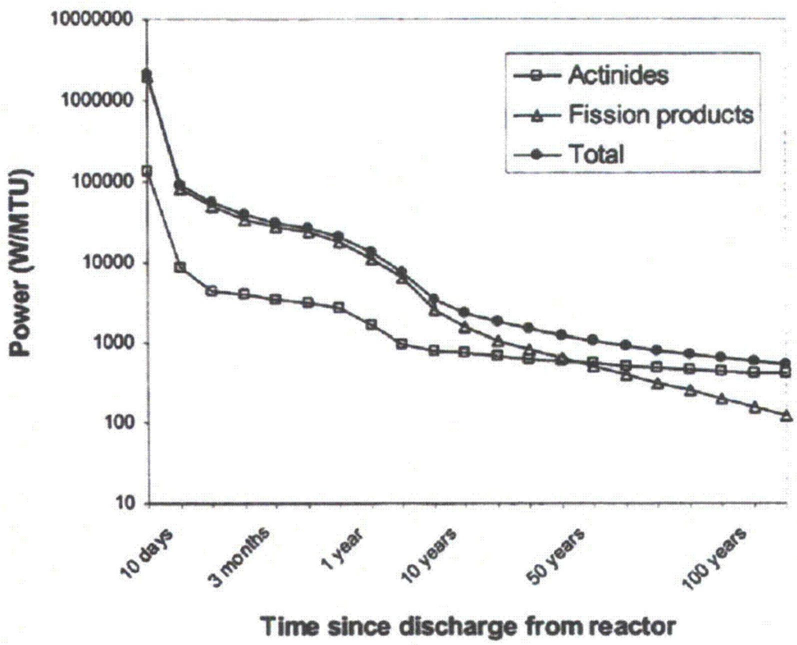


FIGURE 1.2 Decay-heat power for spent fuel (measured in watts per metric ion of uranium) plotted on a logarithmic scale as a function of time after reactor discharge. Note that the horizontal axis is a data series, not a scale. SOURCE: Based on data from USNRC (1984).

1.4.2 Storage of Spent Nuclear Fuel

Storage technologies for spent nuclear fuel have three primary objectives:

- Cool the fuel to prevent heat-up to high temperatures from radioactive decay.
- Shield workers and the public from the radiation emitted by radioactive decay in the spent fuel and provide a barrier for any releases of radioactivity.
- Prevent criticality accidents (uncontrolled fission chain reactions).

After the fuel assemblies are unloaded from the reactor they are stored in water pools, called *spent fuel pools*. The water in the pools provides radiation shielding and cooling and captures all but noble gas radionuclides in case of fuel rod leaks.[10] The geometry of the fuel and neutron absorbers (such as boron, hafnium, and cadmium) within the racks that hold the spent fuel or in the cooling water help prevent criticality events.[11] The water in the pool is circulated through heat exchangers for cooling and ion exchange filters to capture any radionuclides and other contaminants that get into the water. Makeup water is also added to the pool to replace pool water lost to evaporation. The operation of the pumps and heat exchangers is especially important during and immediately after reactor

[10] If the cladding in the fuel rods is breached some radioactive materials will be released into the pool.

[11] See the Glossary (Appendix E) for a definition of criticality. Most of the fuel's capacity for sustaining criticality is expended in the reactor as the uranium and plutonium are fissioned.

refueling operations, because this is when larger quantities of higher heat-generating spent fuel are placed into the pool.

Current U.S. regulations require that spent fuel be stored in the power plant's fuel pool for at least one year after its discharge from the reactor before being moved to dry storage. After that time the spent fuel can be moved, but only with active cooling. Active cooling is generally necessary for about three years after the spent fuel is removed from the reactor core (USNRC, 2003b).

When a spent fuel pool is filled to capacity, older fuel, which has lower decay-heat, is moved to other pools or placed into dry casks Heat generated in the loaded dry casks is removed by air convection and thermal radiation. The cask provides shielding of penetrating radiation and confinement of the radionuclides in the spent fuel. As with pool storage, criticality control is accomplished by placing the fuel in a fixed geometry and separating individual fuel assemblies with neutron absorbers. Standard industry practice is to place in dry storage only spent fuel that has cooled for five years or more after discharge from the reactor,[12] Most spent fuel in wet or dry storage is located at nuclear power plant sites (i.e., on-site storage).

There are significant differences in the design and construction of wet and dry storage installations at commercial nuclear power plants. The characteristics depend on the type of the nuclear power plant, the age of the spent fuel storage installation, or the type of dry casks used. The design and features of spent fuel pools and dry storage facilities are discussed in Chapters 3 and 4, respectively.

1.4.3 Spent Fuel Inventories

As of 2003, approximately 50,000 MTU (metric tons of uranium) of spent fuel have been generated over the past four decades in the United States. A typical nuclear power plant generates about 20 MTU per year. The entire U.S. nuclear industry generates about 2000 MTU per year.

Of the approximately 50,000 MTU of commercial spent fuel in the United States, 43,600 MTU are currently stored in pools and 6200 MTU are in dry storage. Pool storage exists at all 65 sites with operating commercial nuclear power reactors[13] and at 8 sites where commercial power reactors are no longer operating (i.e., they have been shut down or decommissioned) (FIGURE 1.3). Additionally, there is an away-from-reactor spent fuel pool operating at the G.E.Morris Facility in Illinois (see Appendix D).

Of the spent fuel in dry storage, 4500 MTU are in storage at 22 sites with operating commercial nuclear power reactors, and 1700 MTU are in storage at 6 sites where the commercial reactors are no longer operating. An additional dry-storage facility is operated by the federal government at the Idaho National Laboratory. It stores most of the damaged fuel from the Three Mile Island Unit 2 reactor accident.

[12] Fuel aged as little as three years could be stored in passively cooled casks, but fewer assemblies could be accommodated in each cask because of the higher heat load.

[13] There are 103 operating commercial nuclear power reactors in the United States. Many sites have more than one operating reactor.

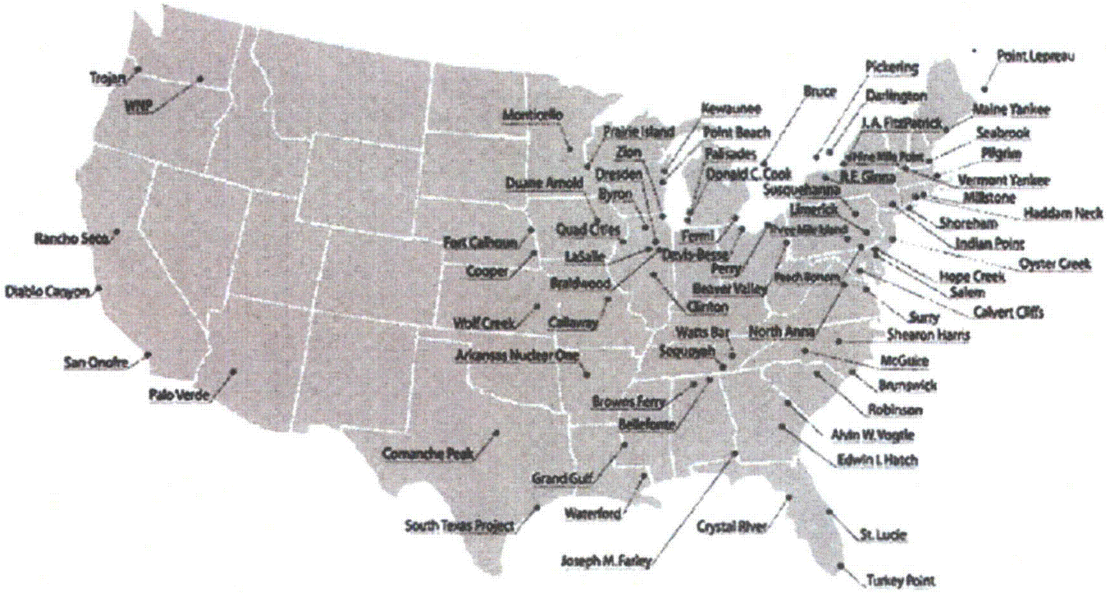


FIGURE 1.3 Locations of spent fuel storage facilities in the United States.

TABLE 1.1 provides a listing of the 30 operating Independent Spent Fuel Storage InstalEations (ISFSIs14) in the United States. These ISFSIs include the dry storage facilities at operating and shutdown commercial power reactor sites as well as the storage facilities at the Morris and Idaho sites, as described above. The committee did not examine the Morris and Idaho facilities as part of this study. At-reactor pool storage is not considered to be an ISFSI because it operates under the power reactor license.

1.4.4 History of Spent Fuel Storage

Spent fuel pools at commercial nuclear power plants were not designed to accommodate all the fuel used during the operating lifetime of the reactors they service. Most commercial power plants were designed with small pools under the assumption that fuel would be cooled for a short period of time after discharge from the reactor and then be sent offsite for recycling (i.e., reprocessing).[15] A commercial reprocessing industry never developed, however, for the reasons discussed in Appendix D. Newer power plants were designed with larger pool storage capacities. Even plants with larger-capacity pools will run out of pool space if they operate beyond their initial 40-year licenses. In 2000, the nuclear power industry projected that roughly three or four plants per year would run out of needed storage space in their pools without additional interim storage capacity (see FIGURE 1.4).

Another development that logically could reduce the demand for storage of spent nuclear fuel at the sites of power plants is the availability of a geologic repository for

[14] An ISFSI is a facility for storing spent fuel in wet pools or dry casks and is defined in Title 10, Part 72 of the Code of Federal Regulations.

[15] Residual uranium-235 and plutonium in the spent fuel would be recovered for the manufacture of new fuel. The waste products in the fuel, principally the fission products, would be immobilized in solid matrices and stored for eventual disposal.

TABLE 1.1: Operating ISFSIs in the United States as of July 2004

Name	Location
Palo Verde	Arizona
Arkansas Nuclear One	Arkansas
Rancho Seco	California
San Onofre	California
Diablo Canyon	California
Fort St. Vrain [1]	Colorado
Edwin L. Hatch	Georgia
DOE-INL [2]	Idaho
G.E. Morris [3]	Illinois
Dresden	Illinois
Duane Arnold	Iowa
Maine Yankee	Maine
Calvert Cliffs	Maryland
Big Rock Point	Michigan
Palisades	Michigan
Prairie Island	Minnesota
Yankee Rowe	Massachusetts
Oyster Creek	New Jersey
J.A. FitzPatrick	New York
McGuire	North Carolina
Davis-Besse	Ohio
Trojan	Oregon
Susquehanna	Pennsylvania
Peach Bottom	Pennsylvania
Robinson	South Carolina
Oconee	South Carolina
North Anna	Virginia
Surry	Virginia
Columbia Gen. Station	Washington
Point Beach	Wisconsin

NOTES:

[1]The Fort St. Vrain ISFSI stores fuel from a commercial gas-cooled reactor. The facility is operated by the Department of Energy.

[2]The DOE-INL facility stores fuel from the Three-Mile Island Unit 2 reactor. The facility is operated by the Department of Energy.

[3]The G.E.Morris ISFSI is a wet storage facility.

SOURCES: Data from the USNRC (2004).

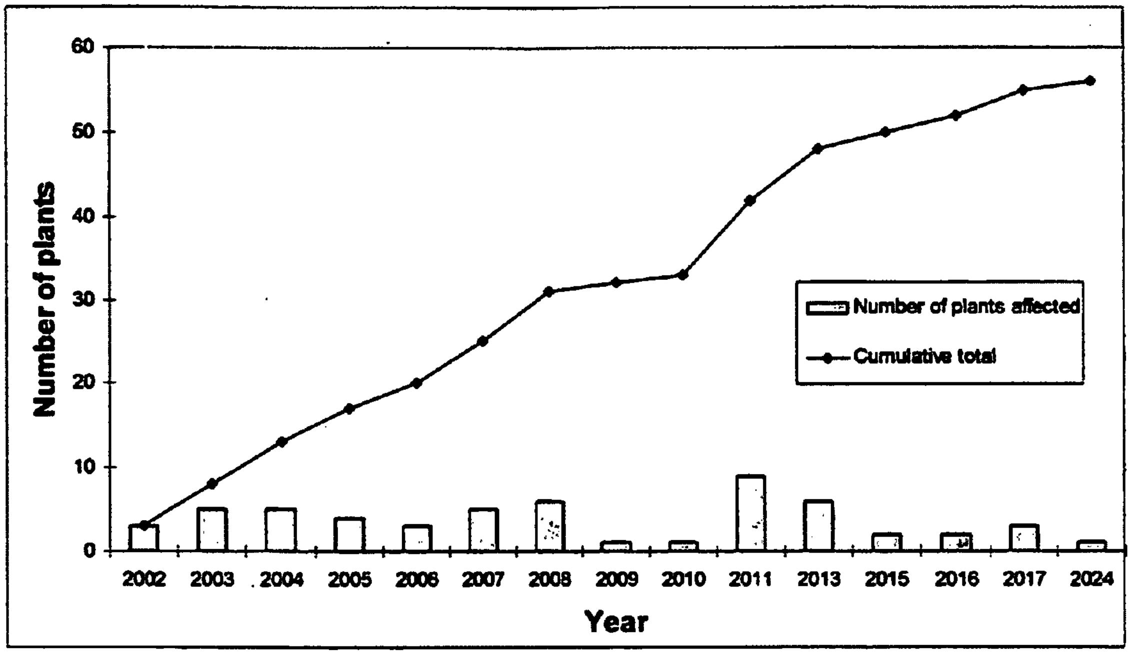


FIGURE 1.4 Projection of the number of commercial nuclear power plants that will run out of needed space in their spent fuel pools in coming years if they do not add interim storage. These data, looking only at plants that did not already use dry cask storage, were provided to the Nuclear Regulatory Commission in 2000. SOURCE: USNRC (2001b).

disposal of spent nuclear fuel. But a nuclear waste repository is not expected to be in operation until at least 2010, and even then It will take several decades for all of the spent fuel to be shipped for disposal. Thus, onsite storage of spent fuel is likely to continue for at least several decades,

Power plant operators have made two changes in spent fuel storage procedures to increase the capacity of onsite storage. First, starting in the late 1970s, plant operators began to install high-density racks that enable more spent fuel to be stored in the pools. This has increased storage capacities in some pools by up to about a factor of five (USNRC, 2003b). Second, as noted above, many plant operators have moved older spent fuel from the pools into dry cask storage systems (see Chapter 4) or into other pools when available to make room for freshly discharged spent fuel and to maintain the capacity for a full-core offload,[16]

The original spent fuel racks, sometimes called "open racks," were designed to store spent fuel in an open array, with open vertical and lateral channels between the fuel assemblies to promote water circulation. The high-density storage racks eliminated many of the channels so that the fuel assemblies could be packed closer together (FIGURE 1.5). This configuration does not allow as much water (or air circulation in loss-of-pool-cootant events) through the spent fuel assemblies as the original open-rack design.

[16] Although not required by regulation, it is standard practice in the nuclear industry to maintain enough open space in the spent fuel pool to hold the entire core of the nuclear reactor. This provides an additionsl margin of safety should the fuel have to be removed from the reactor core in an emergency or for maintenance purposes.

Several nuclear utilities have already submitted license applications to the Nuclear Regulatory Commission to build 16 new ISFSIs, Among the potential new ISFSIs, a consortium of utilities has submitted a license for a private fuel storage facility (PFS) in Utah for interim dry storage of up to 40,000 metric tons of spent fuel.

Most or all pools store some spent fuel that has aged more than five years after discharge from the reactor, and so could be transferred to dry-cask storage. The amount that could be transferred depends on plant-specific information such as pool size and configuration, operating history of the reactor, the enrichment and burn-up level in the fuel, and availability of an ISFSI.

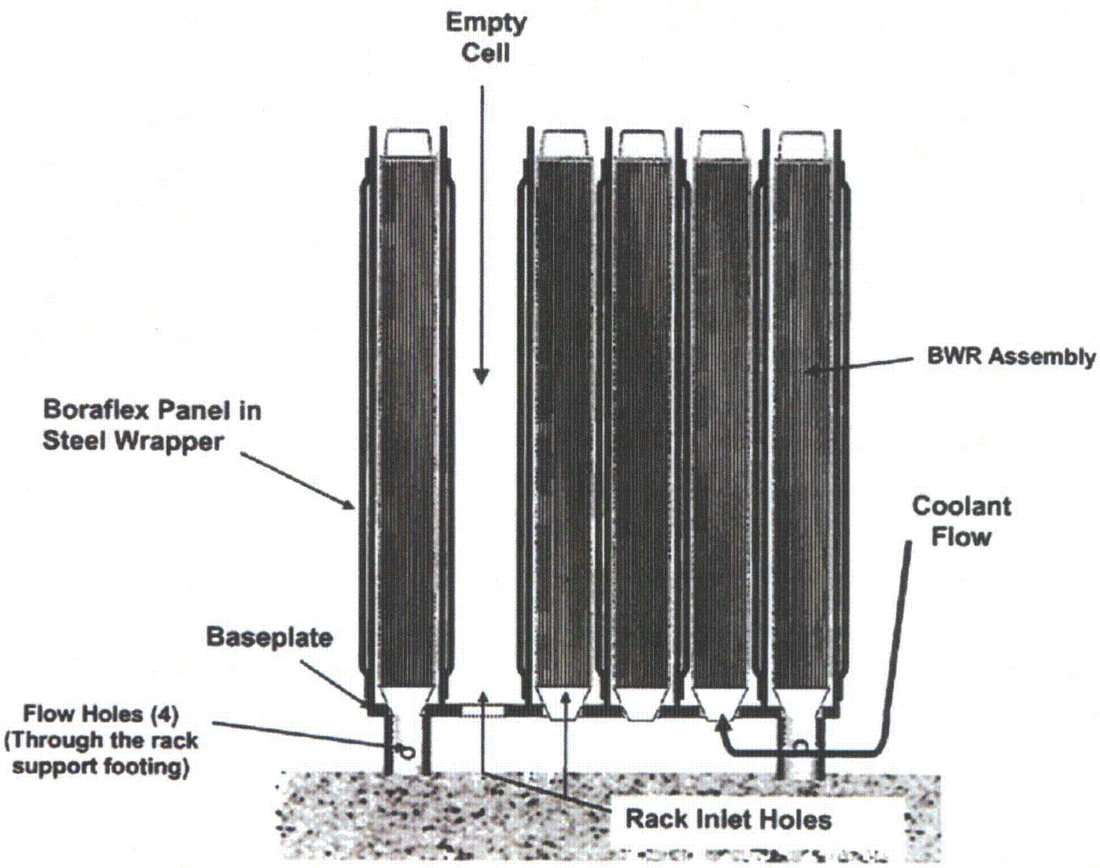


FIGURE 1.5 Dense spent fuel pool storage racks for BWR fuel. This cross-sectional illustration shows the principal elements of the spent fuel rack, which sits on the bottom of the pool. SOURCE: Nuclear Regulatory Commission briefing materials (2004).

2

TERRORIST ATTACKS ON SPENT FUEL STORAGE

This chapter addresses the final charge to the committee to "explicitly consider the risks of terrorist attacks on [spent fuel] and the risk these materials might be used to construct a radiological dispersal device." The concept of *risk* as applied to terrorist attacks underpins the entire statement of task for this study. Therefore, the committee addresses this final charge first to provide the basis for addressing the remainder of the task statement.

The chapter is organized into the following sections:

- Background on risk.
- Terrorist attack scenarios.
- Risks of terrorist attacks on spent fuel storage facilities.
- Findings and recommendations.

2.1 BACKGROUND ON RISK

"Risk" is a function of three factors (Kaplan and Garrick, 1981):

- The *scenario* describing the undesirable event,
- The *probability* that the scenario will occur.
- The *consequences* if the scenario should occur.

In the context of the present report, a *scenario* describes the modes and mechanisms of a possible terrorist attack against a spent fuel storage facility. For example, a scenario might involve a suicide attack with a hijacked civilian airliner. Another might involve a ground assault with a truck bomb. Several such scenarios are described later in this chapter and discussed in more detail in the committee's classified report.

Probability is a dimensionless quantity that expresses the likelihood that a given scenario will occur over a specified time period. If the occurrence of a scenario is judged to be impossible, it would have a probability of 0.0. On the other hand, if the scenario were judged to be certain, it has a probability of 1.0. A scenario that had a 50 percent chance of occurrence during the period contemplated would have a probability of 0.5.

Consequences describe the undesirable results if the scenario were to occur. For example, a terrorist attack on a spent fuel storage facility could release ionizing radiation to the environment.[1] The exposure of the public to this radiation could have both deterministic and stochastic effects. The former would occur from short-term exposures to very high doses of ionizing radiation, the latter to smaller doses that might have no immediate effects

[1] Terrorist scenarios and consequences are being described here for the sake of Illustration. One should not conclude from this description that the committee believes that such consequences would necessarily occur as the result of a terrorist attack on a spent fuel storage facility.

but could result in cancer induction some years or decades later.[2] Consequences also could be described in terms of economic damage. These could arise, for example, from the loss of use of the facility and surrounding areas or costs to clean up those areas. There also could be severe psychological consequences that could drive changes in public acceptance of commercial nuclear energy.

The quantitative expression for the risk of a particular scenario, for example a suicide terrorist attack with a hijacked airliner, is

$$\text{Risk}_{\text{airliner attack}} = \text{Probability}_{\text{airliner attack}} \times \text{Consequences}_{\text{airliner attack}} \qquad (1)$$

The total risk would be the sum of the risks for all possible independent attack scenarios. For example, if a spent fuel storage facility was determined to be vulnerable to attacks using airliners, truck bombs, and armed assaults, the total risk would be calculated as

$$\text{Risk}_{\text{total}} = \text{Risk}_{\text{airliner attack}} + \text{Risk}_{\text{truck bomb attack}} + \text{Risk}_{\text{armed assault attack}} \qquad (2)$$

Such equations are routinely used to calculate the risks of various industrial accidents, including accidents at nuclear power plants, through a process known as *probabilistic risk assessment*. Each accident is assigned a numerical probability based on a careful analysis of the sequence of failures (e.g., human or mechanical failures) that could produce the accident. The consequences of such accidents are typically expressed in terms of injurles, deaths, or economic losses.

It is possible to estimate the risks of industrial accidents because there are sufficient experience and data to quantify the probabilities and consequences. This is not the case for terrorist attacks. To date, experts have not found a way to apply these quantitative risk equations to terrorist attacks because of two primary difficulties: The first is to develop a complete set of bounding scenarios for such attacks; the second is to estimate their probabilities. These depend on impossible-to-quantify factors such as terrorist motivations, expertise, and access to technical means.[3] They also depend on the effectiveness of measures that might prevent or mitigate such attacks.

In the absence of quantitative information on risks, one could attempt to make qualitative risk comparisons. Such comparisons could estimate, for example, the relative risks of attacks on spent fuel storage facilities versus attacks on commercial nuclear power reactors or other critical infrastructure such as chemical plants. Although a comparison of such risks is beyond the scope of this study, the committee recognizes that policy decisions about spent fuel storage may need to take into account such comparative risk issues,

[2] Such cancers would likely not be directly traceable to the radiation dose received from a terrorist attack and would likely be indistinguishable from the large population of cancers that result from other causes.

[3] Political scientists and counter-terror specialists have argued whether terrorists seek headlines, casualties, or both (e.g., Jenkins 1975, 1985), The September 11, 2001, attacks in the United States and the March 11, 2004, attacks in Spain demonstrate that some terrorists, particularly those of al-Qaida and its allies, intend to commit mass murder and/or mass economic disruption, both of which may have important political consequences. Further information about the motivation of terrorists is provided in NRC (2002).

especially for decisions regarding the expenditure of limited societal resources to address terrorist threats.

The 2002 National Research Council report *Making the Nation Safer: The Role of Science and Technology in Countering Terrorism* framed this issue as follows (NRC, 2002, P. 43):

> The potential vulnerabilities of NPPs [nuclear power plants] to terrorist attack seem to have captured the imagination of the public and the media, perhaps because of a perception that a successful attack could harm large populations and have severe economic and environmental consequences. There are, however, many other types of large industrial facilities that are potentially vulnerable to attack, for example, petroleum refineries, chemical plants, and oil and liquefied natural gas supertankers. These facilities do not have the robust construction and security features characteristic of NPPs, and many are located near highly populated urban areas.

Groups seeking to carry out high-impact terrorism will likely choose targets that have a high probability of being attacked successfully.[4] If success is measured by the number of people killed and injured or the permanent destruction of property, then spent fuel storage facilities may not make good terrorist targets owing to their relatively robust construction (see Chapters 1 and 3) and security. Industrialized societies like the United States provide terrorists a large number of "soft" (i.e., unprotected) targets that could be attacked more easily with greater effect than spent fuel storage facilities. These include chemical plants, refineries, transportation systems, and other facilities where large numbers of people gather (see NRC, 2002).

On the other hand, there are other success criteria that might influence a terrorist's decision to attack a "hard" (i.e., robust or well protected) target such as a commercial nuclear power plant and its spent fuel storage facilities. Such attacks could spread panic and shut down the power plant for an extended period of time even with no loss of life. Moreover, an attack that resulted in the release of radioactive material could threaten the viability of commercial nuclear power.

These considerations led the committee to conclude that it could not address its charge using quantitative and comparative risk assessments. The committee decided instead to examine a range of possible terrorist attack scenarios in terms of (1) their potential for damaging spent fuel pools and dry storage casks; and (2) their potential for radioactive material releases. This allowed the committee to make qualitative judgments about the vulnerability of spent fuel storage facilities to terrorist attacks and potential measures that could be taken to mitigate them.

[4] This point was made to the committee in a briefing by the Department of Homeland Security, where "success" means that the terrorist was able to achieve the goals of the attack, whatever they might be.

2.2 TERRORIST ATTACK SCENARIOS

It is possible to imagine a wide range of terrorist attacks against spent fuel storage facilities. Each would have a range of potential consequences depending on the characteristics of the attack and the facility being targeted as well as any post-attack mitigative actions to prevent or reduce the release of radioactive material. The committee focused its discussions about terrorist attacks around the concept of a *maximum credible scenario*—that is, an attack that is physically possible to carry out and that produces the most serious potential consequences within a given class of attack scenarios.

The following example illustrates the concept: One of the scenario classes considered by the committee in this chapter involves suicide attacks against spent fuel storage facilities with civilian passenger aircraft. The physics of such attacks are well understood: In general, heavier and higher-speed aircraft produce greater impact forces than lighter and slower aircraft, all else being equal. Consequently, the maximum credible scenario for suicide attacks involving civilian passenger aircraft would utilize the largest civilian passenger aircraft widely used in the United States flying at maximum cruising speed and hitting the facility at its most vulnerable point. Such an attack provides an upper bound to the damage that could be inflicted by this type of aircraft attack.

The maximum credible scenario is particularly useful for obtaining a general understanding of the damage that could be inflicted, but it would not necessarily apply to every spent fuel storage facility. To be judged a "credible" scenario, the terrorist must be able to successfully carry it out as designed—for example, to hit a spent fuel storage facility with the largest civilian aircraft at its most vulnerable point. This would rule out attacks that are physically impossible, such as flying a large civilian aircraft into a facility that is located below ground level or protected by surrounding hills or buildings. This also would rule out attacks invoking weapons that are not available to terrorists (e.g., aircraft-launched weapons such as "bunker-buster" bombs or nuclear weapons).

This is not intended, however, to rule out attacks that are judged to have a low probability for success simply because terrorists might lack the skill and knowledge or luck to carry them out. In fact, if the consequences of such attacks were severe, policy makers might still decide that prudent mitigating actions should be taken regardless of their low probabilities of occurrence.[5] This might be especially true if quick, inexpensive fixes could be implemented. The main benefit of analyzing the maximum credible scenario is that it provides decision makers with a better characterization of the full range of potential consequences so that sound policy judgments can be made.

The analyses carried out for the Nuclear Regulatory Commission (described in the committee's classified report) do not consider maximum credible scenarios. Instead, the analyses employ *reference scenarios* that are based either on the characteristics of previous terrorist attacks or on qualitative judgments of the technical means and methods that might be employed in attacks against spent fuel storage facilities. Although such reference scenarios are useful for gaining Insights on potential consequences of terrorist attacks, they

[5] The Department of Energy, for example, routinely examines the consequences of very low probability events involving nuclear weapons safety and security; see, for example, AL 56XB Development and Production Manual published by the U.S. Department of Energy, National Nuclear Security Administration. See *http://prp.lanl.gov/documents/d_p_manual.asp*.

are not necessarily bounding. This becomes important when the reference scenario attack results in damage to a facility that verges on failure.

The committee prefers a maximum credible scenario approach for one important reason: It believes that terrorists who choose to attack hardened facilities like spent fuel storage facilities would choose weapons capable of producing maximum destruction. **Of course, once the consequences of such attacks are known, an element of expert judgment is required to determine whether such attacks have a high likelihood of being carried out as designed. Such judgment is especially important when making policy decisions about actions to reduce the vulnerabilities of facilities to such attacks.**

The consequences of terrorist attacks can be described in terms of either *maximum credible releases* or *best-estimate releases.* The former describes the largest releases of radioactive material following an attack based on quantitative analytical models (e.g., the MELCOR computer code described in Chapter 3). The latter describes the median estimates from such models. In both cases, the estimates may not account for mitigative actions that could be taken after an attack to reduce or even eliminate releases. The Nuclear Regulatory Commission analyses reviewed by the committee in its classified report are best-estimate releases for various terrorist attack scenarios. The estimates in NUREG-1738 (USNRC, 2001 a) and Alvarez et al. (2003a). on the other hand, describe maximum-credible to worst-case releases.[6]

The committee considered four classes of terrorist attack scenarios in this study:

- Air attacks using large civilian aircraft or smaller aircraft laden with explosives.
- Ground attacks by groups of well-armed and well-trained individuals.
- Attacks involving combined air and land assaults,
- Thefts of spent fuel for use by terrorists (including knowledgeable insiders) in radiological dispersal devices.

The committee devoted time at its meetings discussing these scenarios, it also received briefings on possible scenarios from Nuclear Regulatory Commission staff and suggestions for scenarios from the Department of Homeland Security (DHS), other experts, and the public. Some scenarios were dismissed by the committee as not credible. An example of such a scenario is an attack on a spent fuel storage facility with a nuclear weapon. Such weapons would be relatively difficult[7] for terrorists to build or steal. Even if such a weapon could be obtained, the committee can think of no reason that it would be used against a spent fuel storage facility rather than another target. There are easier ways to attack spent fuel storage facilities, as discussed in the classified report, and there are more attractive targets for nuclear weapons, for example, large population centers.

[6] Worst-case releases are based on the most unfavorable conditions that could occur in a given scenario, regardless of whether those conditions were physically realistic. For example, a worst-case estimate of the radionuclide releases from an attack on a spent fuel pool might assume that all of the volatile radionuclides contained in the spent fuel would be released, even if quantitative analytical models showed that such releases were very unlikely to occur

[7] Difficult but certainly not impossible. See Chapter 2 in NRC (2002).

Given the experience of September 11, 2001, and the attacks that have occurred in other parts of the world, it is clear to the committee that the ability of the most capable terrorists to carry out attacks is limited only by their access to technical means. It is probably not limited by the ability of terrorist organizations to recruit or train attackers or bring them and any needed equipment into the United States—if indeed they are not already here. Moreover, the demonstrated willingness of terrorists to carry out suicide attacks greatly expands the scenarios that need to be considered when analyzing potential threats.

As is discussed in some detail in Chapters 3 and 4, the facilities used to store spent fuel at nuclear power plants are very robust. Thus, 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. This further restricts the scenarios that need to be considered. For example, attacks using rocket-propelled grenades (RPGs) of the type that have been carried out in Iraq against U.S. and coalition forces would not likely be successful if the intent of the attack is to cause substantial damage to the facility. Of course, such an attack would get the public's attention and might even have economic consequences for the attacked plant and possibly the entire commercial nuclear power industry.

The threat scenarios summarized in this chapter are based on documents provided to the committee, briefings received at committee meetings, and the committee's own expert judgment.[8] Further overview and information on nuclear and radiological threats in general can be found in the NRC (2002) report and references therein.

2.2.1 Air Attacks

The September 11, 2001, attacks[9] demonstrated that terrorists are capable of successfully attacking fixed infrastructure with large civilian jetliners. The security of civilian passenger airliners has been improved since these attacks were carried out, and the vulnerability of civilian passenger aircraft to highjacking has been reduced. Nevertheless, the committee judges, based on the evidence made available to it during this study, that attacks with civilian aircraft remain a credible threat. Such aircraft are used routinely in freight and charter services, and large numbers of such aircraft enter the United States from other countries each day. Improvements to ground security or cargo inspection would likely not eliminate the threat posed by an air crew willing to stage a suicide attack with a chartered air freighter.

Although the September 11, 2001, attacks utilized Boeing 757 and 767 airliners, larger aircraft (Boeing 747, 777; Airbus 340) are in routine use around the world, and an even larger aircraft (Airbus 380) is entering production. Assaults by such large aircraft could impart enormous energy impulses to spent fuel storage facilities. Additionally, attacks with

[8] The committee found limited information in the open literature on various scenarios for terrorist attacks on nuclear plants and their spent fuel storage facilities.

[9] The al-Qaida terrorist organization hijacked and crashed two Boeing 767 airliners into Towers 1 and 2 of the World Trade Center building in New York and a Boeing 757 airliner into the Pentagon building in Arlington, Virginia. A second Boeing 757, which was believed to be targeted either on the White House or the U.S. Capitol (see National Commission on Terrorist Attacks Upon the United States, Staff Statement No, 16 [Outline of the 9/11 Plot], pages 18–19) crashed in an open field near Jennerstown, Pennsylvania.

aircraft carrying large fuel loads could produce fires that would greatly complicate rescue and recovery efforts.

Previous studies on aircraft crash impacts (Droste et at., 2002; Lange et al., 2002; HSK, 2003; RBR Consultants, 2003; Thomauske, 2003) suggest that the consequences of a heavy aircraft crash on a nuclear installation depend on factors such as the following:

- Type and design of the aircraft.
- Speed of the aircraft.
- Fuel loading of the aircraft and total weight at impact.
- Angle-of-attack and point-of-impact on the facility.
- Construction of the facility.
- Location of the target with respect to ground level (i.e., below or above grade).[10]
- The presence of surrounding buildings and other obstacles (e.g., hills, transmission lines) that might block certain potential flight paths into the facility.

In other words, the consequences of such attacks are scenario- and plant-design specific. It is not possible to make any general statements about spent fuel storage facility vulnerabilities to air attacks that would apply to all U.S. commercial nuclear power plants

U.S. commercial nuclear power plants are not required by the Nuclear Regulatory Commission to defend against air attacks. The Commission believes that it is the responsibility of the U.S. government to implement security measures to prevent such attacks. The commercial nuclear industry shares this view. The Nuclear Regulatory Commission staff informed the committee that the Commission has directed power plant operators to take steps to reduce the likelihood of serious consequences should such attacks occur. The staff also informed the committee that the Commission may issue additional directives once the vulnerability analyses it is sponsoring at Sandia National Laboratories are completed. These analyses are described in the committee's classified report (see also Chapters 3 and 4 in this report).

2.2.2 Ground Attacks

Ground attacks on a nuclear facility could take three forms: (1) a direct assault on the facility by armed groups, (2) a stand-off attack using appropriate weapons, or (3) an assault having both air and ground components. The direct assault would likely be carried out by a group of well-armed and trained attackers, perhaps working with the assistance of an insider. The objective of such an attack would likely be to gain entry to protected and vital areas of the plant (FIGURE 2.1) to carry out radiological sabotage. The attackers would need to have knowledge of the design, location, and operation of the spent fuel facility to carry out such an attack successfully.

Commercial nuclear power plants are required by the Nuclear Regulatory Commission to maintain a professional guard force at each plant to defend against a Commission-developed design basis threat (DBT), which includes a ground assault. The protective force is a critical part of a nuclear power plant's security system for deterring,

[10] All current dry cask storage facilities in the United States are constructed at ground level, whereas spent fuel pools can be located above or below grade, depending on plant design (see Chapter 3).

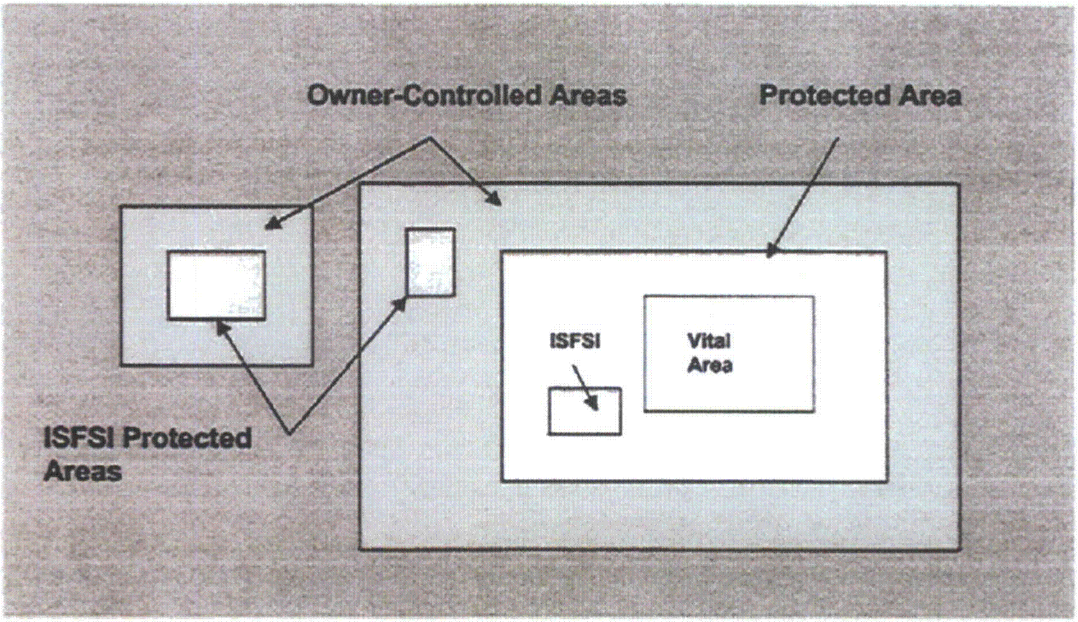


FIGURE 2.1 Commercial nuclear power plant sites are demarcated as shown for security purposes. The part of the power plant site over which the plant operator exercises control is referred to as the *owner-controlled area*. This usually corresponds to the boundary of the site. Located within this area are one or more *protected areas* to which access is restricted using guards, fences, and other barriers. Dry cask storage facilities, formally referred to as independent Spent Fuel Storage Installations (ISFSIs), are located within these areas. The *vital area* of the plant contains the reactor core, support buildings, and the spent fuel pool. It is the most carefully controlled and guarded part of the plant site. SOURCE: Modified from Nuclear Regulatory Commission briefing materials (2004).

detecting, thwarting, or impeding attacks. The Commission staff declined to provide a formal briefing to the committee on the DBT for radiological sabotage, asserting that the committee did not have a need to know this information. Nevertheless, the committee was able to discern the details of the DBT from a series of presentations made by Nuclear Regulatory Commission staff. Commission staff also provided a fact check of this information as the classified report was being finalized.

Power plant operators are required to demonstrate to the Commission's satisfaction that there is "high assurance" that their guard forces can thwart the Commission-defined DBT assault. This guard force also must be able to provide deterrence against a beyond-DBT attack depending on the adversarial force. Reinforcing forces would be provided by local and state law enforcement as well as federal forces. The Commission staff also informed the committee that since the September 11, 2001, attacks, the Commission has been working with DHS to improve coordination procedures with federal, state, and local agencies to improve their response capabilities in the event of an attack. DHS also is making grants to local law enforcement agencies around power plant sites to raise their capabilities to respond to requests for assistance.

Since the September 11, 2001, attacks, the Nuclear Regulatory Commission has issued directives to power plant operators to enhance protection against vehicle bombs. The Commission also has issued directives to power plant operators to enhance protection against insider threats.

The committee does not have enough information to judge whether the measures at power plants are in fact sufficient to defend against either a DBT or a beyond-DBT attack on spent fuel storage. The Nuclear Regulatory Commission declined to provide detailed briefings to the committee on surveillance, security procedures, and security training at commercial nuclear power plants. Consequently, the committee was unable to evaluate their effectiveness, A recent General Accounting Office report (GAO, 2003) was critical of some of these procedures, but the committee has no basis for judging whether these criticisms were justified. Nevertheless, the committee judges that surveillance and security procedures at commercial nuclear power plants are just as important as physical barriers in preventing successful terrorist attacks and mitigating their consequences.

2.2.3 Attacks Having Both Air and Ground Components

Hybrid attacks that combine aspects of both air and ground attacks also could be mounted by terrorists. These could deliver attacking forces directly to a spent fuel storage facility, bypassing the security perimeters and security personnel deployed to protect against a ground attack. The committee considered various scenarios for such attacks. The committee judges that some scenarios are feasible. Details are provided in the classified report.

2.2.4 Terrorist Theft of Spent Fuel for Use in a Radiological Dispersal Device (RDD)

An RDD, or so-called dirty bomb, is a device that disperses radioactive material using chemical explosives or other means (NRC. 2002) RDDs do not involve flssion-induced explosions of the kind associated with nuclear weapons. While RDD attacks can be carried out with any source of radioactivity, this discussion is confined to scenarios that involve the theft of spent fuel for such use.[11] A crude RDD device could be fabricated simply by loading stolen spent fuel onto a truck carrying high explosives. The truck could be driven to another location and detonated. The dispersal of radioactivity from such an attack would be unlikely to cause many immediate deaths, but there could be fatalities from the chemical explosion as well as considerable cleanup costs and adverse psychological effects.

It would be difficult for terrorists to steal a large quantity of spent fuel (e.g., a single spent fuel assembly) for use in an RDD for three reasons. First, spent fuel is highly radioactive and therefore requires heavy shielding to handle. Second, the use of heavy equipment would be required to remove spent fuel assemblies from a pool or dry cask. Third, controls are in place at plants to deter and detect such thefts. Additional details on these controls are provided in the classified report.

Theft and removal of an assembly or individual fuel rods during an assault on the plant might be easier, because the guard force would likely be preoccupied defending the plant. However, the amount of material that could be removed would be small, and getting it

[11] An attack on a spent fuel facility that resulted in the direct release of radioactivity would be an act of radiological sabotage of the kind considered previously in this chapter.

out of the plant would be time consuming and obvious to the plant defenders and other responding forces.

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. Pieces of fuel rods also are sometimes intentionally removed from assemblies for offsite laboratory analysis. Some plants have misplaced fuel rod pieces.[12] A knowledgeable insider might be able to retrieve some of this material from the pool, but getting it out of the plant under normal operating conditions would be difficult.

Even the successful theft of a part of a spent fuel rod would provide a terrorist with only a relatively small amount of radioactive material. Superior materials could be obtained from other facilities. This material also can be purchased (Zimmerman and Loeb, 2004).

Moreover, even with explosive dissemination, it is unlikely that much of the spent fuel will be aerosolized unless it is incorporated into a well-designed RDD. More likely, such an event would break up and scatter the fuel pellets in relatively large chunks, which would not pose an overwhelming cleanup challenge.

Even though the likelihood of spent fuel theft appears to be small, it is nevertheless important that the protection of these materials be maintained and improved as vulnerabilities are identified.

2.3 RISKS OF TERRORIST ATTACKS ON SPENT FUEL STORAGE FACILITIES

Nuclear Regulatory Commission staff told the committee that it believes that the consequences of a terrorist attack on a spent fuel pool would likely unfold slowly enough that there would be time to take mitigative actions to prevent a large release of radioactivity. They also pointed out that since the September 11, 2001, attacks, the Nuclear Regulatory Commission has issued several orders that contain Interim Compensatory Measures that require power plant operators to consider potential mitigative actions in the event of such an attack. The committee received a briefing on some of these measures at one of its meetings. According to Commission staff, such measures provide an additional margin of safety.

The nuclear industry and the Nuclear Regulatory Commission have also asserted that the robust construction and stringent security requirements at nuclear power plants[13] make them less vulnerable to terrorist attack than softer targets such as chemical plants and refineries (e.g., Chapin et al., 2002). They argue that scarce resources should be devoted to

[12] For example, at the Millstone and Vermont Yankee plants in 2000 and 2003, respectively. In the case of Millstone, the Nuclear Regulatory Commission determined on the basis of extensive analysis that these rods were likely disposed of as low-level waste. After the committee's classified report was published, Commission staff informed the committee that Vermont Yankee had accounted for the missing rod segments and that Humbolt Bay had uncovered and is investigating an inventory discrepancy involving spent fuel rod segments.

[13] These arguments tend to be generic in nature and do not differentiate spent fuel pools from the rest of the power plant.

upgrading security at these other critical facilities rather than at already well-protected nuclear plants.

There are two unstated propositions in the argument that nuclear plants are less vulnerable than other facilities. The first speaks to the probability of terrorist attacks on such facilities; the second speaks to the consequences:

- *Proposition 1:* Nuclear power plants (and their spent fuel facilities) are less desirable as terrorist targets because they are robust and well protected,
- *Proposition 2:* If attacked, nuclear plants (and their spent fuel storage facilities) are likely to sustain little or no damage because they are robust and well protected.

The committee obtained a briefing from the Department of Homeland Security to address the first proposition. Details are provided in the classified report.

While the committee's classified report was in review, the National Commission on Terrorist Attacks Upon the United States issued a staff paper (Staff Statement No. 16, Outline of the 9/11 Plot, pages 12–13) suggesting that al-Qaida initially included unidentified nuclear plants among an expanded list of targets for the September 11, 2001, attacks. According to that report, these plants were eliminated from the target list along with several other facilities when the terrorist organization scaled back the number of planned attacks. Nevertheless, if this information is correct, it provides further indications that commercial nuclear power plants are of interest to terrorist groups,[14] even though softer targets may have a higher priority with many terrorists.

With respect to the first proposition, the committee judges that it is not prudent to dismiss nuclear plants, including their spent fuel storage facilities, as undesirable targets for attacks by terrorists.

As to the second proposition that terrorist attacks are likely to cause little or no damage, a poorly designed attack or an attack by unsophisticated terrorists might produce little physical damage to the plant There could, however, be severe adverse psychological effects from such an attack that could have considerable economic consequences. On the other hand, attacks by knowledgeable terrorists with access to advanced weapons might cause considerable physical damage to a spent fuel storage facility, especially in a suicide attack.

It is important to recognize that an attack that damages a power plant or its spent fuel facilities would not necessarily result in the release of *any* radioactivity to the environment. While It may not be possible to deter such an attack, there are many potential mitigation steps that can be taken to lower its potential consequences should an attack occur. These are discussed in some detail in the committee's classified report (see also Chapters 3 and 4 in this report).

[14] In another example of concern, police in Toronto, Canada, detained 19 men in August 2003 based on suspicious activities that included surveillance and flying lessons that would take them over a nuclear power plant (Ferguson et al., 2004).

In summary, the committee judges that the plausibility of an attack on a spent fuel storage facility, coupled with the public fear associated with radioactivity, indicates that the possibility of attacks cannot be dismissed.

2.4 FINDINGS AND RECOMMENDATIONS

With respect to the committee's task to "explicitly consider the risks of terrorist attacks on [spent fuel] and the risk these materials might be used to construct a radiological dispersal device," the committee offers the following findings and recommendations:

FINDING 2A: The probability of terrorist attacks on spent fuel storage cannot be assessed quantitatively or comparatively. Spent fuel storage facilities cannot be dismissed as targets for such attacks because it is not possible to predict the behavior and motivations of terrorists, and because of the attractiveness of spent fuel as a terrorist target given the well-known public dread of radiation.

Terrorists view nuclear power plant facilities as desirable targets because of the large inventories of radionuclides they contain. The committee believes that knowledgeable terrorists might choose to attack spent fuel pools because (1) at U.S. commercial power plants, these pools are less well protected structurally than reactor cores; and (2) they typically contain inventories of medium- and long-lived radionuclides that are several times greater than those contained in individual reactor cores.

FINDING 2B: The committee judges that the likelihood terrorists could steal enough spent fuel for use in a significant radiological dispersal device is small.

Spent fuel assemblies in pools or dry casks are large, heavy, and highly radioactive. They are too large and radioactive to be handled by a single individual. Removal of an assembly from the pool or dry cask would prove extremely difficult under almost any terrorist attack scenario. Attempts by a knowledgeable insider(s) to remove single rods and related debris from the pool might prove easier, but it would likely be very difficult to get it out of the plant under normal operating conditions. Theft and removal during an assault on the plant might be easier because the guard force would likely be occupied defending the plant. However, the amount of material that could be removed would be small. Moreover, there are other facilities from which highly radioactive material could be more easily stolen, and this material also can be purchased. Even though the likelihood of spent fuel theft appears to be small, it is nevertheless important that the protection of these materials be maintained and improved as vulnerabilities are identified.

RECOMMENDATION: The Nuclear Regulatory Commission should review and upgrade, where necessary, its security requirements for protecting spent fuel rods not contained in fuel assemblies from theft by knowledgeable insiders, especially in facilities where individual fuel rods or portions of rods are being stored in pools.

FINDING 2C: A number of security improvements at nuclear power plants have been instituted since the events of September 11, 2001. The Nuclear Regulatory Commission did not provide the committee with enough information to evaluate the effectiveness of these procedures for protecting stored spent fuel.

Surveillance and security procedures are just as important as physical barriers in preventing and mitigating terrorist attacks. The Nuclear Regulatory Commission declined to provide the committee with detailed briefings on the surveillance and security procedures that are now in place to protect spent fuel facilities at commercial nuclear power plants against terrorist attacks. Although the committee did learn about some of the changes that have been instituted since the September 11, 2001, attacks, it was not provided with enough information to evaluate the effectiveness of procedures now in place.

RECOMMENDATION: Although the committee did not specifically investigate the effectiveness and adequacy of improved surveillance and security measures for protecting stored spent fuel, an assessment of current measures should be performed by an independent[15] organization.

[15] That is, independent of the Nuclear Regulatory Commission and the nuclear industry.

3

SPENT FUEL POOL STORAGE

This chapter addresses the first charge of the committee's statement of task to assess "potential safety and security risks of spent nuclear fuel presently stored in cooling pools at commercial reactor sites."[1] As noted in Chapter 1, storage of spent fuel in pools at commercial reactor sites has three primary objectives:

- Cool the fuel to prevent heat-up to high temperatures from radioactive decay.
- Shield workers and the public from the radiation emitted by radioactive decay in the spent fuel and provide a barrier for any releases of radioactivity.
- Prevent criticality accidents.

The first two of these objectives could be compromised by a terrorist attack that partially or completely drains the spent fuel pool.[2] The committee will refer to such scenarios as "loss-of-pool-coolant" events. Such events could have several deleterious consequences; Most immediately, ionizing radiation levels in the spent fuel building rise as the water level in the pool falls. Once the water level drops to within a few feet (a meter or so) of the tops of the fuel racks, elevated radiation fields could prevent direct access to the immediate areas around the lip of the spent fuel pool building by workers. This might hamper but would not necessarily prevent the application of mitigative measures, such as deployment of fire hoses to replenish the water in the pool.

The ability to remove decay heat from the spent fuel also would be reduced as the water level drops, especially when it drops below the tops of the fuel assemblies. This would cause temperatures in the fuel assemblies to rise, accelerating the oxidation of the zirconium alloy (zircaloy) cladding that encases the uranium oxide pellets. This oxidation reaction can occur in the presence of both air and steam and is strongly exothermic—that is, the reaction releases large quantities of heat, which can further raise cladding temperatures. The steam reaction also generates large quantities of hydrogen:

Reaction in air:	$Zr+O_2 \rightarrow ZrO_2$	heat released=1.2×10^7 joules/kilogram
Reaction in steam:	$Zr+2H_2O \rightarrow ZrO_2+2H_2$	heat released=5.8×10^6 joules/kilogram

[1] A basic description of pool storage can be found in Chapter 1 and historical background can be found in Appendix D. Section 3.1 provides additional technical details about pool storage,

[2] The committee could probably design configurations in which fuel might be deformed or relocated to enable its re-criticality, but the committee judges such an event to be unlikely. Also, the committee notes that while re-criticality would certainly be an undesirable outcome, criticality accidents have happened several times at locations around the world and have not been catastrophic offsite. An accompanying breach of the fuel cladding would still be the chief concern.

These oxidation reactions can become locally self-sustaining (i.e., autocatalytic[3]) at high temperatures (i.e., about a factor of 10 higher than the boiling point of water) if a supply of oxygen and/or steam is available to sustain the reactions. (These reactions will not occur when the spent fuel is under water because heat removal prevents such high temperatures from being reached). The result could be a runaway oxidation reaction—referred to in this report as a *zirconium cladding fire*—that proceeds as a burn front (e.g., as seen in a forest fire or a fireworks sparkler) along the axis of the fuel rod toward the source of oxidant (i.e., air or steam). The heat released from such fires can be even greater than the decay heat produced in newly discharged spent fuel.

As fuel rod temperatures increase, the gas pressure inside the fuel rod increases and eventually can cause the cladding to balloon out and rupture. At higher temperatures (around 1800°C [approximately 3300°F]), zirconium cladding reacts with the uranium oxide fuel to form a complex molten phase containing zirconium-uranium oxide. Beginning with the cladding rupture, these events would result in the release of radioactive fission gases and some of the fuel's radioactive material in the form of aerosols into the building that houses the spent fuel pool and possibly into the environment. If the heat from one burning assembly is not dissipated, the fire could spread to other spent fuel assemblies in the pool, producing a propagating zirconium cladding fire.

The high-temperature reaction of zirconium and steam has been described quantitatively since at least the early 1960s (e.g., Baker and Just, 1962), The accident at the Three Mile Island Unit 2 reactor and a set of experiments (e.g., CORA, FPT 1–6, CODEX, ORNL-VI, VERCORS) have provided a basis for understanding the phenomena of zirconium cladding fires and fission-product releases from irradiated fuel in a reactor core accident. This understanding and data from the experiments form the foundation for computer simulations of severe accidents involving nuclear fuel. These experiments and computer simulations are for inside-reactor vessel events rather than events in an open-air spent fuel pool array.

This chapter examines possible initiating factors for such loss-of-pool-coolant events and the potential consequences of such events. It is organized into the following four main sections:

- Background on spent fuel pool storage.
- Previous studies on safety and security of pool storage.
- Evaluation of the potential risks of pool storage.
- Findings and recommendations.

[3] That is, the reaction heat will increase temperatures in adjacent areas of the fuel rod, which in turn will accelerate oxidation and release even more heat. Autocatalytic oxidation leading to a "runaway" reaction requires a complex balance of heat and mass transfer, so assigning a specific ignition temperature is not possible. Empirical equations have been developed to predict the reaction rate as a function of temperature when steam and oxygen supply are not limited (see, e.g., Tong and Weisman, 1996, p. 223). Numerous scaled experiments have found that the oxidation reaction proceeds very slowly below approximately 900° C (1700°F).

3.1 BACKGROUND ON SPENT FUEL POOL STORAGE

After a power reactor is shut down, its nuclear fuel continues to produce heat from radioactive decay (see FIGURE 1.2). 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[4] 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.

Pool heat loads can be quite high, as exemplified by a "typical" boiling water reactor (BWR) which was used in some of the analyses discussed elsewhere in this chapter (this BWR is hereafter referred to as the "reference BWR"). This pool has approximately 3800 locations for storage of spent fuel assemblies, about 3000 of which are occupied by four-and-one-third reactor cores (13 one-third-core offloads) in a pool approximately 35 feet wide, 40 feet long, and 39 feet deep (10.7 meters wide, 12.2 meters long, and 11.9 meters deep) with a water capacity of almost 400,000 gallons (1.51 million liters). According to Nuclear Regulatory Commission staff, the total decay heat in the spent fuel pool is 3.9 megawatts (MW) ten days after a one-third-core offload. The vast majority of this heat is from decay in the newly discharged spent fuel. Heat loads would be substantially higher in spent fuel pools that contained a full-core offload.

Although spent fuel pools have a variety of designs, they share one common characteristic: Almost all spent fuel pools are located outside of the containment structure that holds the reactor pressure vessel.[5] In some reactor designs, the spent fuel pools are contained within the reactor building,[6] which is typically constructed of about 2 feet of reinforced concrete (see FIGURE 3.1). 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 (see FIGURE 3.2). As described in more detail below, some pools are built at or below grade, whereas others are located at the top of the reactor building.

The enclosing superstructures above the pool are typically steel, industrial-type buildings designed to house cranes that are used to move reactor components, spent fuel, and spent fuel casks. These superstructures above the pool are designed to resist damage from seismic loads but not from large tomado-bome missiles (e.g., cars and telephone poles), which would usually impact the superstructures at low angles (i.e-, moving horizontally). In contrast the typical spent fuel pool is robust. The pool walls and the external walls of the building housing the pool (these external walls may incorporate one or more pool walls in some plants) are designed for seismic stability and to resist horizontal

[4] A 1996 survey by the Nuclear Regulatory Commission (USNRC, 1996) found that the majority of commercial power reactors routinely offload their entire core to the spent fuel pool during refueling outages. The practice is more common among PWRs than BWRs, which tend to offload only that fuel that is to be replaced, but some BWRs do offload the full core. In response to a committee inquiry, an Energy Resources International staff member confirmed that this is still the case today.

[5] The exceptions in the United States are the Mark III BWRs, which have two pools, one of which is inside the containment As discussed in Appendix C, spent fuel pools at German commercial nuclear power plants also are located inside reactor containment structures.

[6] A PWR containment structure is a large, domed building that houses the reactor pressure vessel, the steam generators, and other equipment. In a BWR, the containment structure houses less equipment, is located closer in to the pressure vessel, and sits inside a building called the reactor building, which also houses the spent fuel pool and safety-related equipment to support the reactor.

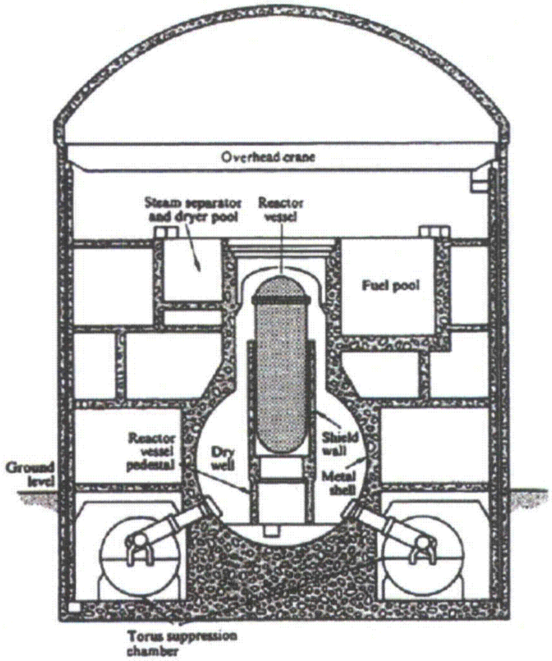


FIGURE 3.1 Schematic section through a G.E.Mark I BWR reactor plant. The spent fuel pool is located in the reactor building well above ground level. This diagram is for a BWR with a reinforced concrete superstructure (roof). Most designs have thin steel superstructures, SOURCE: Lamarsh (1975, Figure 11.3).

strikes of tomado missiles. The superstructures and pools were not, however, specifically designed to resist terrorist attacks.

The typical spent fuel pool is about 40 feet (12 meters) deep and can be 40 or more feet (12 meters) in each horizontal dimension. The pool walls are constructed of reinforced concrete typically having a thickness between 4 and 8 feet (1.2 to 2.4 meters). The pools contain a ¼– to ½–inch-thick (6 to 13 mrn) stainless steel liner, which is attached to the walls with studs embedded in the concrete. The pools also contain vertical storage racks for holding spent and fresh fuel assemblies, and some pools have a gated compartment to hold a spent fuel storage cask while it is being loaded and sealed (see Chapter 4).

The storage racks are about 13 feet (4 meters) in height and are installed near the bottom of the spent fuel pool. The racks have feet to provide space between their bottoms and the pool floor. There is also space between the sides of the rack and the steel pool liners for circulation of water (FIGURE 3.3), There are about 26 feet (8 meters) of water above the top of the spent fuel racks. This provides substantial radiation shielding even when an assembly is being moved above the rack. Transfers of spent fuel from the reactor core to the spent fuel pool or from the pool to storage casks are carried out underwater to provide shielding and cooling.

The general elevation of the spent fuel pool matches that of the vessel containing the reactor core. Pressurized water reactor designs use comparatively shorter reactor

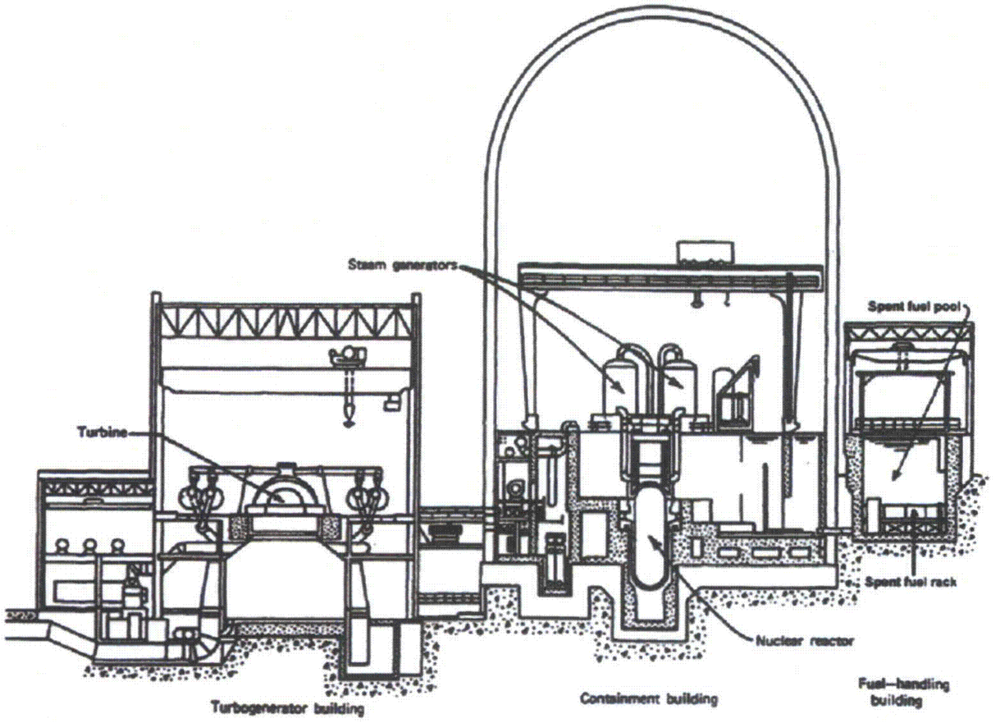


FIGURE 3.2 Schematic section through a PWR reactor plant. The spent fuel pool is located in the fuel-handling building next to the domed reactor containment building at or slightly below ground level, SOURCE: Modified from Duderstadt and Hamilton (1976, Figure 3–4).

vessels closer to ground level (grade) and also have spent fuel pools that are close to grade (FIGURE 3.2). The design shown in this figure is typical of the fuel pool arrangement for PWRs, Nuclear power plant sites that contain two reactors are usually arranged in a mirror-image fashion, with the two spent fuel pools (or a shared pool) located in a common area adjoining both reactor buildings. For single-plant or two-plant arrangements, the building covering the spent fuel pool and crane structures is typically an ordinary steel industrial building. There are 69 PWRs currently in operation in the United States; 6 PWRs have been decommissioned but continue to have active spent fuel pool storage.

In contrast, in boiling water reactor designs, the reactor vessel is at a higher elevation, and the BWR vessels are somewhat taller than PWR vessels,[7] Consequently, BWRs have more elevated spent fuel pools, generally well above grade. FIGURE 3.1 shows the general design for the 22 BWR Mark I plants operating in the United States.

Nuclear Regulatory Commission staff is conducting a survey of the plants to obtain a better understanding of the variations in design of spent fuel pools across the nation. The following information was provided to the committee from that survey:

[7] The higher elevation accommodates control mechanisms that sit under the reactor, and the extra height accommodates steam separation and drying equipment at the top of the vessel. The fuel is about the same length as PWR fuel.

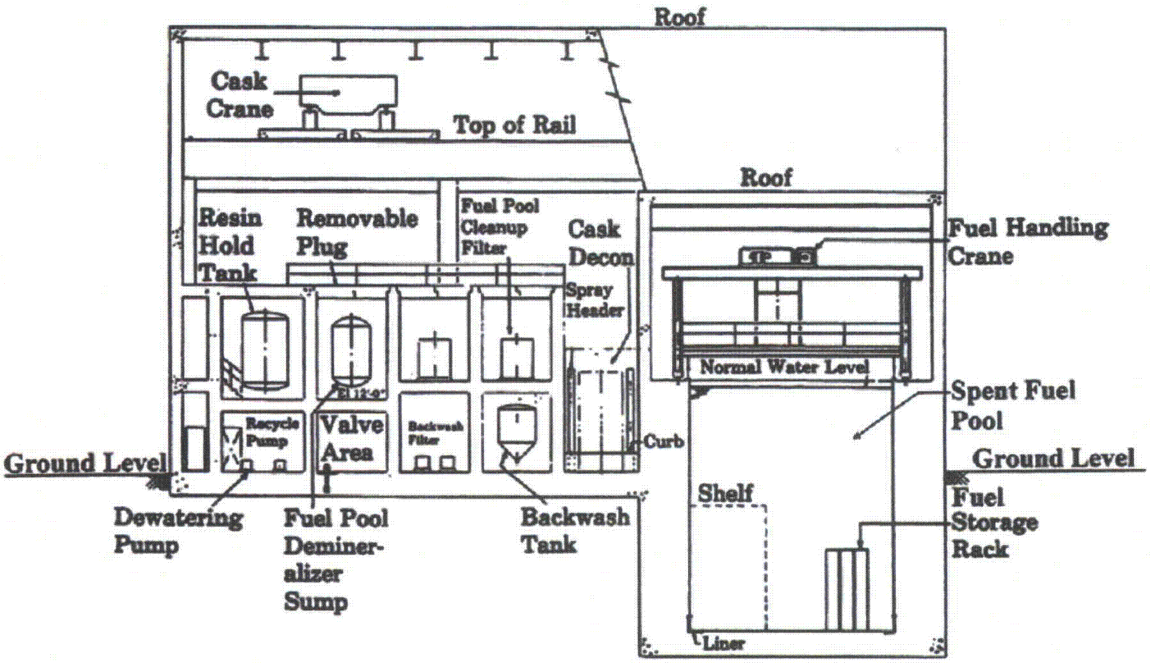


FIGURE 3.3 Example of a section of a PWR spent fuel pool and support facilities. The pool is located to the right in the figure; the support equipment to the left. SOURCE: American Nuclear Society (1988),

- PWR spent fuel pools: Spent fuel pools are located in buildings adjoining the reactor containment buildings at PWR plants (see FIGURE 3.2). Some pools are positioned such that their spent fuel is below grade. As shown in Figure 3.2, some pool walls also serve as the external walls of the spent fuel pool buildings. Some plants have structures surrounding the spent fuel pool building that would provide some shielding of the pools from low-angle line-of-sight attacks. A more complete plant survey would be needed to establish the extent of pool exposure to such attacks.
- BWR spent fuel pools: MARK I and II BWR plants are located above grade and are shielded by at least one exterior building wall. Some pools are also shielded by the reactor buildings. Some pools are also shielded by "significant" surrounding structures, and some have supplemental floor and column supports.

The vulnerability of a spent fuel pool to terrorist attack depends in part on its location with respect to ground level as well as its construction. Pools are potentially susceptible to attacks from above or from the sides depending on their elevation with respect to grade and the presence of surrounding shielding structures.

As noted in Chapter 1, nearly all pools contain high-density spent fuel racks. These racks allow approximately five times as many assemblies to be stored in the pool as would have been possible with the original racks, which had open lateral channels between the fuel assemblies to enhance water circulation.

3.2 PREVIOUS STUDIES ON SAFETY AND SECURITY OF POOL STORAGE

Several reports have been published on the safety of spent fuel pool storage. One of the earliest analyses was contained in the *Reactor Safety Study* (U.S. Atomic Energy Commission, 1975). which concluded that spent fuel pool safety risks were very much smaller than those involving the cores of nuclear reactors. This conclusion is not surprising: The cooling system in a spent fuel pool is simple. The coolant is at atmospheric pressure; the spent fuel is in a subcritical configuration and generates little heat relative to that generated in an operating reactor; and the design and location of piping in the pool make a severe loss-of-pool-coolant event unlikely during normal operating conditions. Despite changes in reactor and fuel storage operations, such as longer fuel residence times in the core and higher-density pool storage, the conclusions of that study are still broadly applicable today. It is important to recognize, however, that the *Reactor Safety Study* did not address the consequences of terrorist attacks.

The Nuclear Regulatory Commission and its contractors have periodically reanalyzed the safety of spent nuclear fuel storage (see Benjamin et al., 1979; BNL, 1987, 1997; USNRC, 1983, 2001a, 2003b). All of these studies suggest that a loss-of-pool-coolant event could trigger a zirconium cladding fire in the exposed spent fuel. The Nuclear Regulatory Commission considered such an accident to be so unlikely that no specific action was warranted, despite changes in reactor operations that have resulted in increased fuel burn-ups and fuel storage operations that have resulted in more densely packed spent fuel pools,

In 2001, the Nuclear Regulatory Commission published NUREG-1738, *Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants,* to provide a technical basis for rulemaking for power plant decommissioning (USNRC, 2001a). A draft of the study was issued for public comments, including comments by the Advisory Committee on Reactor Safeguards and a quality review of the methods, assumptions, and models used in the analysis was carried out by the Idaho National Engineering and Environmental Laboratory.

The study provided a probabilistic risk assessment that identified severe accident scenarios and estimated their consequences. The analysis determined, for a given set of fuel characteristics, how much time would be required to boil off enough water to allow the fuel rods to reach temperatures sufficient to initiate a zirconium cladding fire.

The analysis suggested that large earthquakes and drops of fuel casks from an overhead crane during transfer operations were the two event initiators that could lead to a loss-of-pool-coolant accident. For cases where active cooling (but not the coolant) has been lost, the thermal-hydraulic analyses suggested that operators would have about 100 hours (more than four days) to act before the fuel was uncovered sufficiently through boiling of cooling water in the pool to allow the fuel rods to ignite. This time was characterized as an "underestimate" given the simplifications assumed for the loss-of-pool-coolant scenario.

The overall conclusion of the study was that the risk of a spent fuel pool accident leading to a zirconium cladding fire was low despite the large consequences because the predicted frequency of such accidents was very low. The study also concluded, however, that the consequences of a zirconium cladding fire in a spent fuel pool could be serious and, that once the fuel was uncovered, it might take only a few hours for the most recently discharged spent fuel rods to ignite.

A paper by Alvarez et al. (2003a; see also Thompson, 2003) took the analyses in NUREG-1738 to their logical ends in fight of the September 11, 2001, terrorist attacks: Namely, what would happen if there were a loss-of-pool-coolant event that drained the spent fuel pool? Such an event was not considered in NUREG-1738, but the analytical results in that study were presented in a manner that made such an analysis possible.

Alvarez and his co-authors concluded that such an event would lead to the rapid heat-up of spent fuel in a dense-packed pool to temperatures at which the zirconium alloy cladding would catch fire and release many of the fuel's fission products, particularly cesium-137. They suggested that the fire could spread to the older spent fuel, resulting in long-term contamination consequences that were worse than those from the Chemobyl accident. Citing two reports by Brookhaven National Laboratory (BNL, 1987, 1997), they estimated that between 10 and 100 percent of the cesium-137 could be mobilized in the plume from the burning spent fuel pool, which could cause tens of thousands of excess cancer deaths, loss of tens of thousands of square kilometers of land, and economic losses in the hundreds of billions of dollars. The excess cancer estimates were revised downward to between 2000 and 6000 cancer deaths in a subsequent paper (Beyea et at., 2004) that more accurately accounted for average population densities around U.S. power plants.

Alvarez and his co-authors recommended that spent fuel be transferred to dry storage within five years of discharge from the reactor. They noted that this would reduce the radioactive inventories in spent fuel pools and allow the remaining fuel to be returned to open-rack storage to allow for more effective coolant circulation, should a loss-of-pool-coolant event occur. The authors also discussed other compensatory measures that could be taken to reduce the consequences of such events.

The Alvarez et al. (2003a) paper received extensive attention and comments, including a comment from the Nuclear Regulatory Commission staff (USNRC, 2003a; see Alvarez et al., 2003b, for a response). None of the commentators challenged the main conclusion of the Alvarez et al. (2003a) paper that a severe loss-of-pool-coolant accident might lead to a spent fuel fire in a dense-packed pool. Rather, the commentators challenged the likelihood that such an event could occur through accident or sabotage, the assumptions used to calculate the offsite consequences of such an event, and the cost-effectiveness of the authors' proposal to move spent fuel into dry cask storage. One commentator summarized these differences in a single sentence (Benjamin, 2003, p. 53): "In a nutshell, [Alvarez et al.] correctly identify a problem that needs to be addressed, but they do not adequately demonstrate that the proposed solution is cost-effective or that it is optimal."

The Nuclear Regulatory Commission staff provided a briefing to the committee that provides a further critique of the Alvarez et al. (2003a) analysis that goes beyond the USNRC (2003a) paper. Commission staff told the committee that the NUREG-1738 analyses attempted to provide a bounding analysis of current and conceivable future spent fuel pools at plants undergoing decommissioning and therefore relied on conservative assumptions. The analysis assumed, for example, that the pool contained an equivalent of three-and-one-half reactor cores of spent fuel, including the core from the most recent reactor cycle. The staff also asserted that NUREG-1738 did not provide a realistic analysis of consequences. Commission staff concluded that "the risks and potential societal cost of [a] terrorist attack on spent fuel pools do not justify the complex and costly measures proposed in Alvarez et al. (2003) to move and store 1/3 of spent fuel pools [sic] inventory in dry storage casks,"[8]

The committee provides a discussion of the Alvarez et al. (2003a) analysts in its classified report. The committee judges that some of their release estimates should not be dismissed.

The 2003 Nuclear Regulatory Commission (USNRC, 2003b) staff publication NUREG-0933, *A Prioritization of Generic Safety Issues,*[9] discusses beyond-design-basis accidents in spent fuel pools. The study draws some of the same consequence conclusions as the Alvarez et al. (2003a) paper. It notes that in a dense-packed pool, a zirconium cladding fire "would probably spread to most or all of the spent fuel pool" (p. 1). This could drive what the report refers to as "borderline aged fuel" into a molten condition leading to the release of fission products comparable to molten fuel in a reactor core.

The NUREG-0933 report (USNRC, 2003b) summarizes technical analyses of the frequencies of severe accidents for three BWR scenarios. The report concludes that the greatest risk is from a beyond-design-basis seismic event. While the consequences of such accidents are considerable, the report concludes that their frequencies are no greater than would be expected for reactor core damage accidents due to seismic events beyond the design basis safe shutdown earthquake.

An analysis of spent fuel operating experience by the Nuclear Regulatory Commission staff (USNRC, 1997) showed that several accidental partial-loss-of-pool-coolant events have occurred as a result of human error. Two of these involved the loss of more than 5 feet of water from the pool, but none had serious consequences. Nevertheless, Commission staff suggested that plant-specific analyses and corrective actions should be taken to reduce the potential for such events in the future.

It is important to recognize that with the exception of the Alvarez et al. (2003a) paper, all of the previous U.S. work reviewed by the committee has focused on safety risks, not security risks. The Nuclear Regulatory Commission analyses of spent fuel storage vulnerabilities were not completed by the time the committee finalized its information gathering for this report, but the committee did receive briefings on this work. In addition, analyses have been undertaken of external impacts on power plant structures by aircraft for the few commercial power plants that are located close enough to airports to consider hardening of the plant design to resist accidental aircraft crashes. These analyses were done as part of the plants' licensing safety analyses. The committee did not look further into these few plants because the aircraft considered were smaller and the impact velocities considered were much lower than those that might be brought to bear in a well-planned terrorist attack.

The committee did learn about work to assess the risks of spent fuel storage to terrorist attacks in Germany (see Appendix C for a description). However, the details of this work are classified by the German government and therefore are unavailable to the

[8]The quote is from a PowerPoint presentation made by Nuclear Regulatory Commission staff to the committee at one of its meetings,

[9] NUREG-0933 is a historical record that provides a yearly update of generic safety issues. It does not provide any additional technical analysis of these issues.

committee for review. Consequently, the committee was unable to provide a technical assessment.

3.3 EVALUATION OF THE POTENTIAL RISKS OF POOL STORAGE

Prior to the September 11, 2001, terrorist attacks, spent fuel pool analyses by the Nuclear Regulatory Commission were focused almost exclusively on safety. On the basis of these analyses, the Commission concluded that spent fuel storage carried risks that were no greater (and likely much lower) than risks for operating nuclear reactors, as discussed in the previous section of this chapter.

The September 11, 2001, terrorist attacks raised the possibility of a new kind of threat to commercial power plants and spent fuel storage: premeditated, carefully planned, high-impact attacks by terrorists to damage these facilities for the purpose of releasing radiation to the environment and spreading fear and panic among civilian populations. The Commission informed the committee that Its conclusions about risks of spent fuel storage are now being reevaluated in light of these new threats.

Prior to September 11, the Nuclear Regulatory Commission viewed the most credible sabotage event as a violent external land assault by small groups of well-trained, heavily armed individuals aided by a knowledgeable insider.[10] The Commission has long-established requirements for physical protection systems at power plants to thwart such assaults. The committee was told that these requirements have been increased since the September 11, 2001, attacks. To the committee's knowledge, there are currently no requirements in place to defend against the kinds of larger-scale, premeditated, skillful attacks that were carried out on September 11, 2001, whether or not a commercial aircraft is involved. Staff from the Nuclear Regulatory Commission and representatives from the nuclear industry repeatedly told the committee that they view detecting, preventing, and thwarting such attacks as the federal government's responsibility.

It is important to recognize that nuclear power plants in the United States and most of the rest of the world[11] were designed primarily with safety, not security, in mind.[12] The reinforced concrete containment buildings that house the reactors were designed to contain internal pressures of up to about 4 atmospheres in case steam is released in the event of various hypothetical reactor accidents. These and other plant structures were not specifically designed to resist external terrorist attacks, although their robust construction would certainly provide significant protection against external assaults with airplanes or other types of weapons. Moreover, commercial power plants are substantially more robust than other critical infrastructure such as chemical plants, refineries, and fossil-fuel-fired electrical generating stations.

[10] This is known as the "design basis threat" for radiological sabotage of nuclear power plants. See Chapter 2.

[11] Spent fuel storage facilities in Germany are designed to survive the impact of a Phantom military jet without a significant release of radiation. Since September 11, 2001, the Germans have also examined the impact of a range of aircraft, including large civilian airliners, on these facilities, A discussion is provided in Appendix C.

[12] No nuclear power plant ordered after the mid-1970s has been built in the United States, so the designs were developed long before domestic terrorism of the kind seen on September 11, 2001, became a concern.

In the wake of the September 11, 2001, attacks, a great deal of additional work has been or is being carried out by government and private entities to assess the security risks posed by terrorist attacks against nuclear power plants and spent fuel storage. The committee provides a discussion of these studies in the following subsections. Some of these studies are still in progress.

The committee's discussion of this work in the following subsections is organized around the following two questions:

(1) Could an accident or terrorist attack lead to a loss-of-pool-coolant event that would partially or completely drain a spent fuel pool?
(2) What would be the radioactive releases if a pool were drained?

3.3.1 Could a Terrorist Attack Lead to a Loss-of-Pool-Coolant Event?

A terrorist attack that either disrupted the cooling system for the spent fuel pool or damaged or collapsed the pool itself could potentially lead to a loss-of-pool-coolant event. The cooling system could be disrupted by disabling or damaging the system that circulates water from the pool to heat exchangers to remove decay heat. This system would not likely be a primary target of a terrorist attack, but it could be damaged as the result of an attack on the spent fuel pool or other targets at the plant (e.g., the power for the pumps could be interrupted). The loss of cooling capacity would be of much greater concern were it to occur during or shortly after a reactor offloading operation, because the pool would contain a large amount of high decay-heat fuel.

The consequences of a damaged cooling system would be quite predictable: The temperature of the pool water would rise until the pool began to boil. Steam produced by boiling would carry away heat, and the steam would cool as it expanded into the open space above the pool.[13] Boiling would slowly consume the water in the pool, and if no additional water were added the pool level would drop. It would likely take several days of continuous boiling to uncover the fuel. Unless physical access to the pool were completely restricted (e.g., by high radiation fields or debris), there would likely be sufficient time to bring in auxiliary water supplies to keep the water level in the pool at safe levels until the cooling system could be repaired. This conclusion presumes, of course, that technical means, trained workers, and a sufficient water supply were available to implement such measures. The Nuclear Regulatory Commission requires that alternative sources of water be identified and available as an element of each plant's operating license.

The pool-boiling event described above could result in the release of small amounts of radionuclides that are normally present in pool water.[14] These radionuclides would likely have little or no offsite impacts given their small concentrations in the steam and their subsequent dilution in air once released to the environment. Moreover, as long as the spent fuel is covered with a steam-water mixture, it would not heat up sufficiently for the cladding to ignite.

A loss-of-pool-coolant event resulting from damage or collapse of the pool could

[13] The building above the spent fuel pool contains blow-out panels that could be removed to provide additional ventilation.
[14] This contamination may enter the water from damaged fuel or from neutron-activated materials that build up on the external surfaces of the fuel assemblies. The latter material is referred to as "crud."

have more severe consequences. Severe damage of the pool wall could potentially result from several types of terrorist attacks, for instance:

(1) Attacks with large civilian aircraft,
(2) Attacks with high-energy weapons.
(3) Attacks with explosive charges.

The committee reviewed two independent analyses of aircraft impacts on power plant structures: A study sponsored by EPRI completed in 2002 provides a generic analysis of civilian airliner impacts on commercial power plant structures (EPRI, 2002). A study in progress by Sandia National Laboratories for the Nuclear Regulatory Commission examines the consequences of an aircraft impact on an actual BWR power plant.

The EPRI and Sandia analyses used different finite element and finite difference codes that are in common use in research and industry.[15] Both sets of analyses attempted to validate the codes against physical tests, such as the Sandia "slug tests" that impacted water barrels into a concrete test wall at high speeds. EPRI's analysis used a Riera impact loading condition, which models the aircraft impact on a rigid structure and is a slightly conservative assumption because the structures are in fact deformable. The Sandia analysis was carried out on powerful computers that allowed the aircraft to be included explicitly in the calculations.

The committee also reviewed the preliminary results of Nuclear Regulatory Commission studies on the response of thick reinforced concrete walls such as those used in spent fuel pools to attacks involving simple explosive charges and other high-energy devices. The details of the analyses were not provided and therefore could not be evaluated quantitatively. However, some of these preliminary results are described in the committee's classified report.

The results of these aircraft and assault studies are classified or safeguards information. The committee has concluded that there are some scenarios that could lead to the partial failure of the spent fuel pool wall, thereby resulting in the partial or complete loss of pool coolant. A zirconium cladding fire could result if timely mitigative actions to cool the fuel were not taken. Details are provided in the classified report.

3.3.2 What would be the Radioactive Releases if a Pool Were Drained?

There are two ways in which an attack on a spent fuel pool could spread radioactive contamination: mechanical dispersion and zirconium cladding fires. An explosion or high-energy impact directly on the spent fuel could mechanically pulverize and loft fuel out of the pool. This would contaminate the plant and surrounding site with pieces of spent fuel. Large-scale

[15] The EPRI analyses used several finite element models (ABAQUS, LS DYNA, ANACAP, and WINFRITH) and Riera impact functions. The Sandia analyses used the CTH finite difference model and the Pronto3D finite element analysis model. The CTH code has been used for a wide range of impact penetration and explosive detonation problems by the Department of Energy, the Department of Defense, and industry during the past decade CTH results have been compared extensively with experimental results. As an Eulerian code (where material flows through a fixed grid) it can readily handle severe distortions. It also has a variety of computational material models for dynamic (high-strain-rate) conditions, although it is limited in that it does not explicitly model structural members, such as rebar and metal liners in the concrete structure, because of computational requirements.

offsite releases of the radioactive constituents would not occur, however, unless they were mobilized by a zirconium cladding fire that melted the fuel pellets and released some of their radionuclide inventory. Such fires would create thermal plumes that could potentially transport radioactive aerosols hundreds of miles downwind under appropriate atmospheric conditions.

The Nuclear Regulatory Commission is now sponsoring work at Sandia National Laboratories to improve upon the analyses in NUREG-1738 (USNRC, 2001a), and in particular to obtain an improved phenomenological understanding of the thermal and hydraulic processes that would occur in a spent fuel pool from a loss-of-pool-coolant event. The committee received briefings on this work from Commission and Sandia staff during the course of this study. Additionally, the committee received a briefing from ENTERGY Corp. staff and its consultants under contract to analyze and understand the consequences of a loss-of-pool-coolant event in a spent fuel pool in a PWR plant.

The Sandia analyses were carried out on the reference BWR described in Section 3.1. Sandia's analysis of a PWR spent fuel pool had only just begun by the end of May 2004 and has not yet yielded any results. The committee had less opportunity to examine ENTERGY's approach and results. Because of these limitations, the committee was unable to examine in any detail the effects of the differences between BWR and PWR pools and fuel, except as noted with respect to their locations relative to grade.

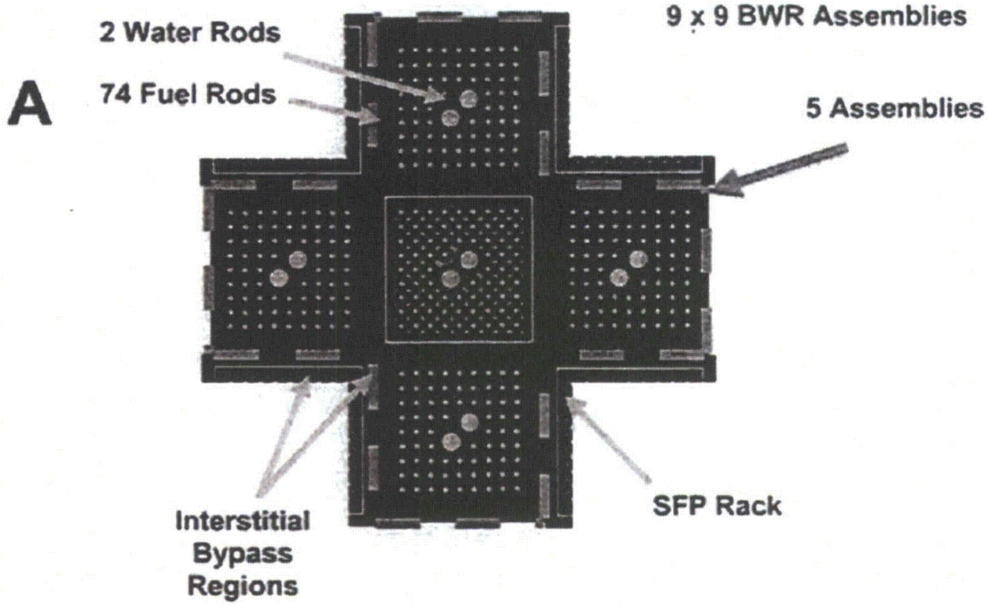
The analyses were carried out using several well-established computer codes. The MELCOR code, which was developed by Sandia for use in analyzing severe reactor core accidents, was used to model fluid flow, heat transfer, fuel cladding oxidation kinetics, and fission product release phenomena associated with spent fuel assemblies. This code has been benchmarked against data from experiments (e.g., the FPT experiments on the Phébus test facility, and the VERCORS, CORA, and ORNL VI experiments)[16] that involve zirconium oxidation kinetics and fission product release. However, none of the experiments was designed to simulate the physical conditions in a spent fuel pool. Many of the phenomena are not significantly different in a reactor core and in a spent fuel pool, but a few important differences, particularly concerning fire propagation from hotter fuel assemblies to cooler fuel assemblies and nuclear fuel volatilities, warrant more detailed analyses or further experiments. In principle, MELCOR can perform "best-estimate" calculations that address a range of accident evolutions, accounting for temperature, availability of oxidizing air and steam,[17] and speciation and transport of radionuclides.

Sandia calculated the decay heat in the assemblies using the ANSI/ANS 5.1 code based on actual characteristics of the spent fuel (i.e., actual fuel ages, burn-ups, and locations) in the reference BWR pool. Flow and mixing behavior in the pool and reactor building enclosing the pool were modeled using a separate computational fluid dynamics (CFD) code.

Two types of analyses were carried out. A "separate effects" analysis was undertaken to examine the thermal responses of a spent fuel assembly (FIGURE 3.4) in a

[16] These experiments were designed to examine phenomena that occur in reactor cores during severe accidents. The phenomena include core degradation.

[17] Oxygen feeds the zirconium reaction and enhances release and transport of ruthenium-106, and the steam reaction releases hydrogen; whereas limited availability of oxygen starves the reaction. Steam can also entrain released fission products.



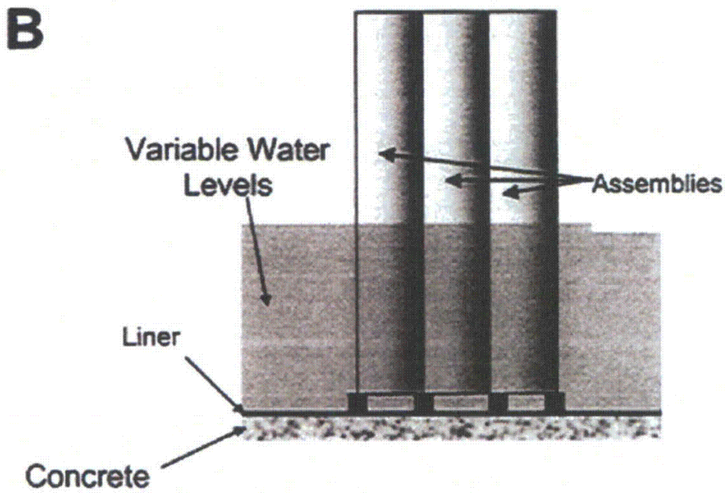


FIGURE 3.4 Configuration of fuel assemblies used for separate effects analysis, (A) Top view of BWR spent fuel assemblies used in the model. (B) Side view showing spent fuel assemblies in the pool. SOURCE: Nuclear Regulatory Commission briefing materials (2004).

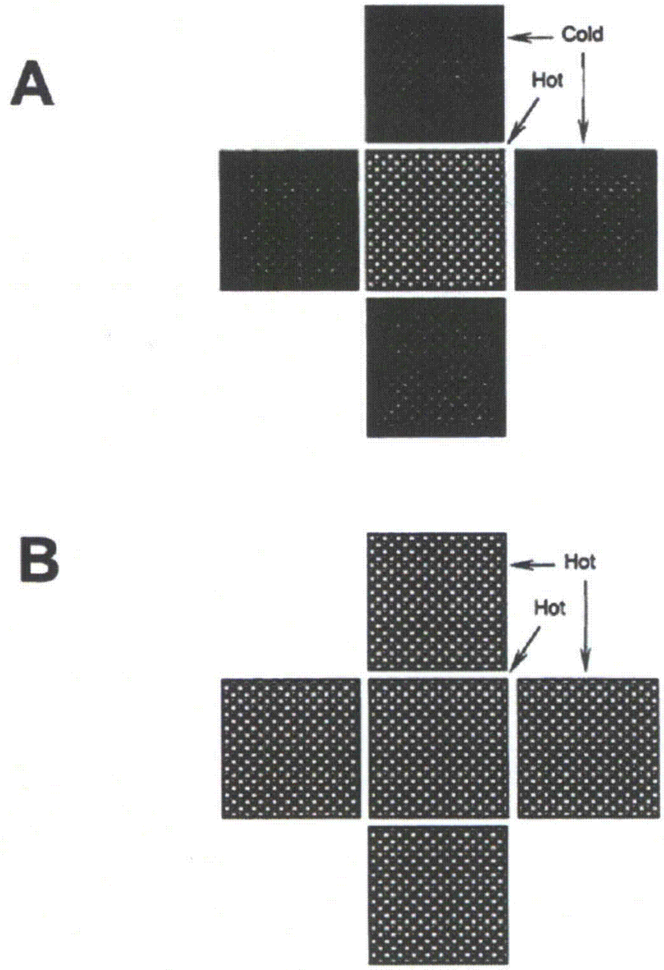


FIGURE 3.5 Two configurations used in the separate effects models shown in FIGURE 3.4: (A) Center hot spent fuel assembly surrounded by four cold assemblies; and (B) center hot spent fuel assembly surrounded by four hot assemblies. SOURCE: Nuclear Regulatory Commission briefing materials (2004).

loss-of-pool-coolant event. This analysis was used to understand how thermal behavior is influenced by factors such as decay heat in the fuel assembly, heat transfer with adjacent assemblies, and heat transfer to circulating air or steam in a drained spent fuel pool. This analysis was used to guide the development of "global response" models to examine the thermal-hydraulic behavior of an entire spent fuel pool.

The separate effects analysis examined the thermal behavior of a high decay-heat BWR spent fuel assembly surrounded either by four low decay-heat assemblies (FIGURE 3.5A) or four high decay-heat assemblies (FIGURE 3.5B). This analysis showed that the potential for heat build-up in a fuel assembly sufficient to initiate a zirconium cladding fire depends on its decay heat (which is related to its age) and on the rate at which heat can be transferred to adjacent assemblies and to circulating air or steam.

In the configuration shown in FIGURE 3.5A, the low decay-heat assemblies act as thermal radiation heat sinks, thereby allowing the more rapid transfer of heat away from the center fuel assembly than would be the case if the center assembly were surrounded by high decay-heat assemblies. The results from this analysis indicate that this configuration can be air cooled sufficiently to prevent the initiation of a zirconium cladding fire within a relatively short time after the center fuel assembly is discharged from the reactor. In the configuration shown in FIGURE 3.5B, heat transfer away from the center assembly is reduced and heat build-up is more rapid. Results indicate that this configuration cannot be air cooled for a significantly longer time after the center fuel assembly is discharged from the reactor,

The global analysis modeled the actual design and fuel loading pattern of the reference BWR spent fuel pool. The pool was divided into seven regions based on fuel age. Within each of those seven regions, the model for the fuel racks was subdivided into 16 zones. The grouping of assemblies into zones reduced the computational requirements compared to modeling every assembly.[18] Two scenarios were examined: (1) a complete loss-of-pool-coolant scenario in which the pool is drained to a level below the bottom of spent fuel assemblies; and (2) a partial-loss-of-pool-coolant scenario in which water levels in the pool drain to a level somewhere between the top and bottom of the fuel assemblies. In the former case, a convective air circulation path can be established along the entire length of the fuel assemblies, which promotes convective air cooling of the fuel, in the latter case, an effective air circulation path cannot form because the bottom of the assembly is blocked by water. Steam is generated by boiling of the pool water, and the zirconium cladding oxidation reaction produces hydrogen gas. This analysis suggests that circulation blockage has a significant impact on thermal behavior of the fuel assemblies. The specific impact depends on the depth to which the pool is drained.

The global analysis examined the thermal behavior of fuel assemblies in the pool at 1, 3, and 12 months after the offloading of one-third of a core of spent fuel from the reactor. Sensitivity studies were carried out to assess the importance of radiation heat transfer between different regions of the pool, the effects of building damage on releases of radioactive material to the environment, and the effects of varying the assumed location and size of the hole in the pool wall.

The results of these analyses are provided in the committee's classified report. For some scenarios, the fuel could be air cooled within a relatively short time after its removal from the reactor. If a loss-of-coolant event took place before the fuel could be air cooled, however, a zirconium cladding fire could be initiated if no mitigative actions were taken. Such fires could release some of the fuel's radioactive material inventory to the environment in the form of aerosols.

For a partial-loss-of-pool-coolant event, the analysis indicates that the potential for zirconium cladding fires would exist for an even greater time (compared to the complete-loss-of-pool-coolant event) after the spent fuel was discharged from the reactor because air circulation can be blocked by water at the bottom of the pool. Thermal coupling between adjacent assemblies will be due primarily to radiative rather than convective heat transfer. However, this heat transfer mode has been modeled simplistically in the MELCOR runs

[18] The global-response model runs took between 10 and 12 days on the personal computers used in the Sandia analyses.

performed by Sandia.[19]

If the water level is above the top of the fuel racks, decay heat in the fuel could cause the pool water to boil. Once water levels fall below a certain level in the fuel assembly, the exposed portion of the fuel cladding might heat up sufficiently to ignite if no mitigative actions were taken. This could result in the release of a substantial fraction of the cesium inventory to the environment in the form of aerosols.

A zirconium cladding fire in the presence of steam could generate hydrogen gas over the course of the event. The generation and transport of hydrogen gas in air was modeled in the Sandia calculations as was the deflagration of a hydrogen-air mixture in the closed building space above the spent fuel pool The deflagration of hydrogen could enhance the release of radioactive material in some scenarios.

Sandia was just beginning to carry out a similar set of analyses for a "reference" PWR spent fuel pool when the committee completed information gathering for its classified report. There are reasons to believe that the results for a PWR pool could be somewhat different and possibly more severe, than for a BWR pool: PWR assemblies are larger, have somewhat higher burn-ups, and some assemblies sit directly over the rack feet, which may impede cooling. While PWR fuel assemblies hold more fuel, they also have more open channels within them for water circulation. The committee was told that as part of this work, a sensitivity analysis will be carried out to understand how design differences among U.S. PWRs will influence the model results.

ENTERGY Corp. has carried out independent separate-effects modeling of a PWR spent fuel pool using the MELCOR code. The analyses addressed both partial and complete loss-of-pool-coolant events for its PWR spent fuel assemblies in a region of the pool where there are no water channels in the spent fuel racks. The analyses were made for relatively fresh spent fuel assemblies (i.e., separate models were run for assemblies that had been discharged from the reactor for 4, 30, and 90 days) surrounded by four "cold" assemblies that had been discharged for two years. In general, the ENTERGY results are similar to those from the Sandia separate-effects analyses mentioned above.

Several steps could be taken to mitigate the effects of such loss-of-pool-coolant events short of removal of spent fuel from the pool. Among these are the following:

- The spent fuel assemblies in the pools can be reconfigured in a "checkerboard" pattern so that newer, higher decay-heat fuel elements are surrounded by older, lower decay-heat elements. The older elements will act as radiation heat sinks in the event of a coolant loss so that the fuel is air coolable within a short time of its discharge from the reactor. Alternatively, newly discharged fuel can be placed near the pool wall, which also acts as a heat sink. ENTERGY staff estimates that reconfiguring the fuel in one of its pools into a checkerboard pattern would take only about 10 hours of extra work, but would not extend a refueling outage. Reconfiguring of fuel already in the pool could be done at any time. It does not require a reactor outage.

[19] In a reactor core accident, heat transfer by thermal radiation is not important because all of the fuel assemblies are at approximately the same temperature. Consequently, there is no net heat transfer between them. But spent fuel pools contain assemblies of different ages, burn-ups, and decay-heat production. The hotter assemblies will radiate heat to cooler assemblies.

- If there is sufficient space in the pool, empty slots can also be arranged to promote natural air convection in a complete-loss-of-pool-coolant event. The cask loading area in some pools may serve this purpose if it is in communication with the rest of the pool.
- Preinstalled emergency water makeup systems in spent fuel pools would provide a mechanism to replace pool water in the event of a coolant loss.
- Preinstalled water spray systems above or within the pool could also be used to cool the fuel in a loss-of-pool-coolant event.[20] The committee carried out a simple aggregate calculation suggesting that a water spray of about 50 to 60 gallons (about 190 to 225 liters) per minute for the whole pool would likely be adequate to prevent a zirconium cladding fire in a loss-of-pool-coolant event. A simple, low-pressure spray distribution experiment could verify what distribution of coolant would be sufficient to cool a spent fuel pool. Such a system would have to be designed to function even if the spent fuel pool or building were severely damaged in an attack.[21]
- Limiting full-core offloads to situations when such offloads are required would reduce the decay heat load in the pool during routine refueling outages. Alternatively, delaying the offload of fuel to the pool after a reactor shutdown would reduce the decay-heat load in the pool.
- The walls of spent fuel pools could be reinforced to prevent damage that could lead to a loss-of-pool-coolant event.
- Security levels at the plant could be increased during outages that involve core offloads.

Of course, damage to the pool and high radiation fields could make It difficult to take some of these mitigative measures. Multiple redundant and diverse measures may be required so that more than one remedy is available to mitigate a loss-of-pool-coolant event, especially when access to the pool is limited by damage or high radiation fields. Cost considerations might be significant, particularly for measures such as installing hardened spray systems and lengthening refueling outages, but the committee did not examine the costs of these measures.

3.3.3 Discussion

The Sandia and ENTERGY analyses described in this chapter were still in progress when the committee completed its classified report. As noted previously, draft technical documents describing the work were not available at the time this study was being completed. Consequently, the committee's understanding of these analyses is based on briefing materials (i.e., PowerPoint slides) presented before the committee by Nuclear

[20] There is an extensive analytic and experimental experience base confirming that spray systems are effective in providing emergency core cooling in BWR reactor cores, which generate much more decay heat than spent fuel. Detailed experiments have shown that some minimum amount of water must be delivered on top of each assembly, and if that is provided, the assembly will be cooled adequately even if there is significant blockage of the cooling channels.

[21] ENTERGY staff mentioned the possible use of a specially equipped fire engine to provide spray cooling. The committee does not know whether this would deliver sufficient spray cooling where it is needed or would provide sufficient protection if terrorists are attempting to prevent emergency response, but the strategy is worth further examination.

Regulatory Commission and ENTERGY staff and consultants, discussions with these experts, and the committee's own expert judgment,

The committee judges that these analyses provide a start for understanding the behavior of spent fuel pools in severe environments. The analyses were carried out by qualified experts using well-known analytical methods and engineering codes to model system behaviors. Although this is a start, the analyses have important limitations.

The aircraft attack scenarios consider one type of aircraft. Heavier aircraft could be used in such attacks. These planes are in common use in passenger and/or cargo operations, and some of these planes can be chartered.

Equally limiting assumptions were made in the analyses of spent fuel pool thermal behavior. To make the analysis tractable, it was assumed that the fuel in the pool was in an undamaged condition when the loss-of-pool-coolant event occurred. This is not necessarily a valid assumption. Whether such damage would change the outcome of the analyses described in this chapter is unknown.

Simplistic modeling assumptions were made about the fuel assembly geometry (e.g., individual fuel bundles were not modeled in the global effects calculation), convective cooling flow paths and mechanisms, thermal radiation heat transfer, propagation of cladding fires to low-power bundles, and radioactivity release mechanisms. In addition, flow blockage due to fission-gas-induced clad ballooning[22] was not considered. The thermal analysis experts on the committee judge that these simplistic assumptions could produce results that are more severe (i.e., overconservative) than would be the case had more realistic assumptions been used.

More sophisticated models, which involve clad ballooning and detailed thermal-hydraulics, including radiative heat transfer, have been developed for the analysis of severe in-core accidents. These models can be evaluated using more powerful computers. MELCOR appears to have sufficient capability to evaluate more sophisticated models of the spent fuel pool and Sandia has access to large, sophisticated computers. State-of-the-art calculations of this type are needed for the analysis of spent fuel pools so that more informed regulatory decisions can be made.

The analyses also do not consider the possibility of an attack that ejects spent fuel from the pool. The ejection of freshly discharged spent fuel from the pool might lead to a zirconium cladding fire if immediate mitigative actions could not be taken. The application of such measures could be hindered by the high radiation fields around the fuel.

While the committee judges that some attacks involving aircraft would be feasible to carry out, it can provide no assessment of the probability of such attacks. Nevertheless, analyzing their consequences is useful for informing policy decisions on steps to be taken to protect these facilities from terrorist attack.

[22] If a fuel rod reaches relatively high temperatures, the gases inside can cause the cladding to balloon out, restricting and even blocking coolant flow through the spaces between the rods within the assembly.

3.4 FINDINGS AND RECOMMENDATIONS

Based on its review of spent fuel pool risks, the committee offers the following findings and recommendations.

FINDING 3A: Pool storage is required at all operating commercial nuclear power plants to cool newly discharged spent fuel.

Operating nuclear power plants typically discharge about one-third of a reactor core of spent fuel every 18–24 months. Additionally, the entire reactor core may be placed into the spent fuel pool (offloaded) during outage periods for refueling. The analyses of spent fuel thermal behavior described in this chapter demonstrate that freshly discharged spent fuel generates too much decay heat to be passively air cooled. The Nuclear Regulatory Commission requires that this fuel be stored in a pool that has an active heat removal system (i.e,, water pumps and heat exchangers) for at least one year as a safety matter. Current design practices for approved dry storage systems require five years' minimum decay in spent fuel pools. Although spent fuel younger than five years could be stored in dry casks, the changes required for shielding and heat removal could be substantial, especially for fuel that has been discharged for less than about three years.

FINDING 3B: The committee finds 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 Details are provided in the committee's classified report.

It is not possible to predict the precise magnitude of such releases because the computer models have not been validated for this application.

FINDING 3C: It appears to be feasible to reduce the likelihood of a zirconium cladding fire following a loss-of-pool-coolant event using readily implemented measures.

There appear to be some measures that could be taken to mitigate the risks of spent fuel zirconium cladding fires in a loss-of-pool-coolant event. The following measures appear to have particular merit.

- Reconfiguring of spent fuel in the pools (i.e., redistribution of high decay-heat assemblies so that they are surrounded by low decay-heat assemblies) to more evenly distribute decay-heat loads. The analyses described elsewhere in this chapter suggest that the potential for zirconium cladding fires can be reduced substantially by surrounding freshly discharged spent fuel assemblies with older spent fuel assemblies in "checkerboard" pattems. The analyses suggest that such arrangements might even be more effective for reducing the potential for zirconium cladding fires than removing this older spent fuel from the pools. However, these advantages have not been demonstrated unequivocally by modeling and experiments.
- Limiting the frequency of offloads of full cores into spent fuel pools, requiring longer shutdowns of the reactor before any fuel is offloaded to allow decay-heat levels to be managed, and providing enhanced security when such offloads must

be made. The offloading of the reactor core into the spent fuel pool during reactor outages substantially raises the decay-heat load of the pool and increases the risk of a zirconium cladding fire in a loss-of-pool-coolant event. Of course, any actions that increase the time a power reactor is shut down incur costs, which must be considered in cost-benefit analyses of possible actions to reduce risks.

- Development of a redundant and diverse response system to mitigate loss-of-pool-coolant events. Any mitigation system, such as a spray cooling system, must be capable of operation even when the pool is drained (which would result in high radiation fields and limit worker access to the pool) and the pool or overlying building, including equipment attached to the roof or walls, is severely damaged.

FINDING 3D: The potential vulnerabilities of spent fuel pools to terrorist attacks are plant-design specific. Therefore, specific vulnerabilities can be understood only by examining the characteristics of spent fuel storage at each plant.

As described in the classified report, there are substantial differences in the design of PWR and BWR spent fuel pools. PWR pools tend to be located near or below grade, whereas BWR pools typically are located well above grade but are protected by exterior walls and other structures. In addition, there are plant-specific differences among BWRs and PWRs that could increase or decrease the vulnerabilities of the pools to various kinds of terrorist attacks, making generic conclusions difficult.

FINDING 3E: The Nuclear Regulatory Commission and independent analysts have made progress in understanding some vulnerabilities of spent fuel pools to certain terrorist attacks and the consequences of such attacks for releases of radioactivity to the environment. However, additional work on specific issues listed in the following recommendation is needed urgently.

The analyses carried out to date for the Nuclear Regulatory Commission by Sandia National Laboratories and by other independent organizations such as EPRI and ENTERGY have provided a general understanding of spent fuel behavior in a loss-of-pool-coolant event and the vulnerability of spent fuel pools to certain terrorist attacks that could cause such events to occur. The work to date, however, has not been sufficient to adequately understand the vulnerabilities and consequences. This work has addressed a small number of plant designs that may not be representative of U.S. commercial nuclear power plants as a whole. It has considered only a limited number of threat scenarios that may underestimate the damage that can be inflicted on the pools by determined terrorists. Additional analyses are needed urgently to fill in the knowledge gaps so that well-informed policy decisions can be made.

RECOMMENDATION: The Nuclear Regulatory Commission should undertake additional best-estimate analyses to more fully understand the vulnerabilities and consequences of loss-of-pool-coolant events that could lead to a zirconium cladding fire. Based on these analyses, the Commission should take appropriate actions to address any significant vulnerabilities that are identified. The analyses of the BWR and PWR spent fuel pools should be extended to consider the consequences of loss-of-pool-coolant events that are described in the committee's classified report.

The consequence analyses should address the following questions:

- **To what extent would such attacks damage the spent fuel in the pool, and what would be the thermal consequences of such damage?**
- **Is it feasible to reconfigure the spent fuel within pools to prevent zirconium cladding fires given the actual characteristics (i.e., heat generation) of spent fuel assemblies in the pool, even if the fuel were damaged in an attack? Is there enough space in the pools at all commercial reactor sites to implement such fuel reconfiguration?**
- **In the event of a localized zirconium cladding fire, will such rearrangement prevent its spread to the rest of the pool?**
- **How much spray cooling is needed to prevent zirconium cladding fires and prevent propagation of such fires? Which of the different options for providing spray cooling are effective under attack and accident conditions?**

Sensitivity analyses should also be undertaken to account for the full range of variation in spent fuel pool designs (e.g., rack designs, capacities, spent fuel burn-ups, and ages) at U.S. commercial nuclear power plants.

RECOMMENDATION: While the work described in the previous recommendation under Finding 3E, above, is being carried out, the Nuclear Regulatory Commission should ensure that power plant operators take prompt and effective measures to reduce the consequences of loss-of-pool-coolant events in spent fuel pools that could result in propagating zirconium cladding fires. The committee judges that there are at least two such measures that should be implemented promptly:

- Reconfiguring of fuel in the pools so that high decay-heat fuel assemblies are surrounded by low decay-heat assemblies. This will more evenly distribute decay-heat loads, thus enhancing radiative heat transfer in the event of a loss of pool coolant.
- Provision for water-spray systems that would be able to cool the fuel even if the pool or overlying building were severely damaged.

Reconfiguring of fuel in the pool would be a prudent measure that could probably be implemented at all plants at little cost, time, or exposure of workers to radiation. The second measure would probably be more expensive to implement and may not be needed at all plants, particularly plants in which spent fuel pools are located below grade or are protected from external line-of-sight attacks by exterior walls and other structures.

The committee anticipates that the costs and benefits of options for implementing the second measure would be examined to help decide what requirements would be imposed. Further, the committee does not presume to anticipate the best design of such a system—whether it should be installed on the walls of a pool or deployed from a location where it is unlikely to be compromised by the same attack—but simply notes the demanding requirements such a system must meet.

4

DRY CASK STORAGE AND COMPARATIVE RISKS

This chapter addresses the second and third charges of the committee's statement of task:

- The safety and security advantages, if any, of dry cask storage[1] versus wet pool storage at reactor sites.
- Potential safety and security advantages, if any, of dry cask storage using various single-, dual-, or multi-purpose cask designs.

The second charge calls for a comparative analysis of dry cask storage versus pool storage, whereas the third charge focuses exclusively on dry casks. The committee will address the third charge first to provide the basis for the comparative analysis.

By the late 1970s, the need for alternatives to spent fuel pool storage was becoming obvious to both commercial nuclear power plant operators and the Nuclear Regulatory Commission. The U.S. government made a policy decision at that time not to support commercial reprocessing of spent nuclear fuel (see Appendix D). At the same time, efforts to open an underground repository for permanent disposal of commercial spent fuel were proving to be more difficult and time consuming than originally anticipated.[2] Commercial nuclear power plant operators had no place to ship their growing inventories of spent fuel and were running out of pool storage space.

Dry cask storage was developed to meet the need for expanded onsite storage of spent fuel at commercial nuclear power plants. The first dry cask storage facility in the United States was opened in 1986 at the Surry Nuclear Power Plant in Virginia. Such facilities are now in operation at 28 operating and decommissioned nuclear power plants. In 2000, the nuclear power industry projected that up to three or four plants per year would run out of needed storage space in their pools without additional interim storage capacity.

This chapter is organized into the following sections:

- Background on dry cask storage.
- Evaluation of potential risks of dry cask storage.
- Potential advantages of dry storage over wet storage.
- Findings and recommendations.

[1] This storage system is referred to as "dry" because the fuel is stored out of water.

[2] The Nuclear Waste Policy Act of 1982 and the Amendments Act of 1987 laid out a process for identifying a site for a geologic repository. That repository was to be opened and operating by the end of January 1998. The federal government now hopes to open a repository at Yucca Mountain, which is located in southwestern Nevada, by the end of 2010,

4.1 BACKGROUND ON DRY CASK STORAGE

The storage of spent fuel in dry casks has the same three primary objectives as pool storage (Chapter 3):

- Cool the fuel to prevent heat-up to high temperatures from radioactive decay.
- Shield workers and the public from the radiation emitted by radioactive decay in the spent fuel and provide a barrier for any releases of radioactivity.
- Prevent criticality accidents.

Dry casks are designed to achieve the first two of these objectives without the use of water or mechanical systems. Fuel cooling is passive: that is, it relies upon a combination of heat conduction through solid materials and natural convection or thermal radiation through air to move decay heat from the spent fuel into the ambient environment. Radiation shielding is provided by the cask materials: Typically, concrete, lead, and steel are used to shield gamma radiation, and polyethylene, concrete, and boron-impregnated metals or resins are used to shield neutrons. Criticality control is provided by a lattice structure, referred to as a *basket*, which holds the spent fuel assemblies within individual compartments in the cask (FIGURE 4.1). These maintain the fuel in a fixed geometry, and the basket may contain boron-doped metals to absorb neutrons.[3]

Passive cooling and radiation shielding are possible because these casks are designed to store only older spent fuel. This fuel has much lower decay heat than freshly discharged spent fuel as well as smaller inventories of radionuclides.

The industry sometimes refers to these casks using the following terms:

- Single-, dual-, and multi-purpose casks.
- Bare-fuel and canister-based casks.

The terms in the first bullet indicate the application for which the casks are intended to be used. Single-purpose cask systems are licensed[4] only to store spent fuel. Dual-purpose casks are licensed for both storage and transportation. Multi-purpose casks are intended for storage, transportation, and disposal in a geologic repository. No true multi-purpose casks exist in the United States (or in any other country for that matter) because specifications for acceptable containers for geologic disposal have yet to be finalized by the Department of Energy. Current plans for Yucca Mountain do not contemplate the use of multi-purpose casks.

Nevertheless, some cask vendors still refer to their casks as "multi-purpose." These are at best dual-purpose casks, however, because they have been licensed only for storage and transport. **Because true multi-purpose casks do not now exist and are not likely to exist in the future, the committee did not consider them further in this study.**

[3] Criticality control is less of an issue in dry casks because there is no water moderator present after the cask is sealed and drained.

[4] Authority for licensing dry cask storage rests with the Nuclear Regulatory Commission.

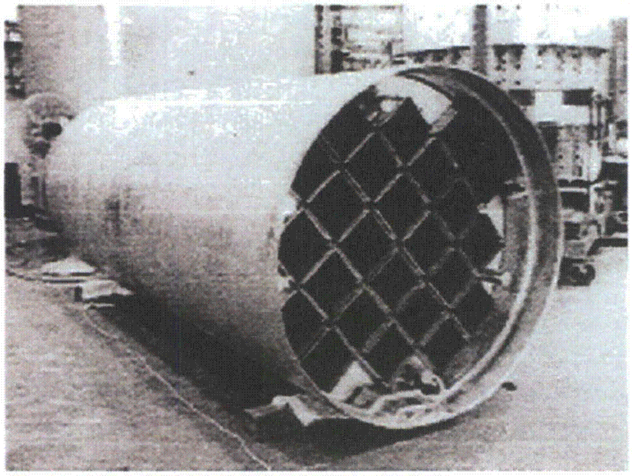


FIGURE 4.1 Photo of NUHOMS canister showing the internal basket for holding the spent fuel assemblies in a fixed geometry. This canister is shown for illustrative purposes only.
SOURCE: Courtesy of Transnuclear, Inc., an Areva Company.

The terms in the second bullet indicate how spent fuel is loaded into the casks. In bare-fuel[5] casks, spent fuel assemblies are placed directly into a basket that is integrated into the cask itself (see FIGURE 4.3B), The cask has a bolted lid closure for sealing. In canister-based casks, spent fuel assemblies are loaded into baskets integrated into a thin-wall (typically 1/2-inch [1.3-centimeter] thick) steel cylinder, referred to as a *canister* (see FIGURE 4.1 and 4.3A), The canister is sealed with a welded lid. The canister can be stored or transported if it is placed within a suitable overpack. This overpack is closed with a bolted lid.

Bare-fuel and canister-based systems are sometimes referred to as "thick-walled" and "thin-walled" casks, respectively, by some cask vendors. This designation is not strictly correct because the overpacks in canister-based systems have thick walls. The only thin-walled component is the canister, which is designed to be stored or transported within the overpack.

The designation of a cask as single- or dual-purpose often has less to do with its design and more to do with licensing decisions. Indeed, bare-fuel and canister-based casks can be licensed for either single or dual purposes. Consequently, one should not expect the performance of a cask in accidents or terrorist attacks to depend on its designation as single- or dual-purpose. Rather, performance will depend on the type of attack and construction of the cask. For the purposes of discussion in this chapter, therefore, the committee uses the designations "bare-fuel" and "canister-based," rather than single- or dual-purpose, when referring to various cask designs.

All bare-fuel casks in use in the United States are designed to be stored vertically. Most canister-based systems also are designed for vertical storage, but one overpack

[5] The term *bare fuel* refers to the entire fuel assembly, including the uranium pellets within the fuel rods.

system is designed as a horizontal concrete module (FIGURE 4.2).[6] The principal characteristics of dry cask storage systems are summarized in TABLE 4.1, which is located at the end of this chapter.

Dry casks are designed to hold up to about 10 to 15 metric tons of spent fuel. This is equivalent to about 32 pressurized water nuclear reactor (PWR) spent fuel assemblies or 68 boiling water nuclear reactor (BWR) spent fuel assemblies. Although the dimensions vary among manufacturers, fuel types (i.e., BWR or PWR fuel), and amounts of fuel stored, the casks are typically about 19 feet (6 meters) in height, 8 feet (2.5 meters) in diameter, and weigh 100 tons or more when loaded.

The casks (for bare-fuel designs) or canisters (for canister-based designs) are placed directly into the spent fuel pool for loading. After they are loaded, the canisters or casks are drained, vacuum dried, and filled with an inert gas (typically helium). The loaded canisters or casks are then removed from the pool, their outer surfaces are decontaminated,[7] and they are moved to the dry storage facility on the property of the reactor site. Loading of a single cask or canister can take up to one week. The vacuum drying process is the longest step in the loading process.

In the United States, dry casks are stored on open concrete pads within a protected area of the plant site.[8,9] This protected area may be contiguous with the protected area of the plant itself or may be located some distance away in its own protected area (see FIGURE 2.1).

According to the information provided to the committee by cask vendors, nuclear power plant operators are currently purchasing mostly dual-purpose casks for spent fuel storage. The horizontal NUHOMS cask design is one of the most-ordered designs at present (TABLE 4.3). The vendors informed the committee that cost is the chief consideration for their customers when making purchasing decisions. Cost considerations are driving the cask industry away from all-metal cask designs and toward concrete designs for storage.

[6] In addition, there is one modular concrete vault design in the United States: the Fort St. Vrain, Colorado, Independent Spent Fuel Storage Installation, which stores spent fuel from a high-temperature gas-cooled reactor. This reactor operated until 1989 and is now decommissioned. Because this is a one-of-a-kind facility, and the time available to the committee was short, it was not examined in this study.

[7] Small amounts of radioactive contamination are present in the cooling water in the spent fuel pool. Some of this contamination is transferred to the cask or canister surfaces when it is immersed in the pool for loading.

[8] There may be exceptions in the future. Private Fuel Storage has requested a license from the Nuclear Regulatory Commission to construct a dry cask storage facility in Utah that will store fuel from multiple reactor sites. An underground dry cask storage facility has been proposed at the Humbolt Bay power plant in California to store old, low decay-heat fuel. The underground design is being proposed primarily because the site has very demanding seismic design requirements and is possible only because the fuel to be stored generates little heat.

[9] In Germany, dry casks are stored in reinforced concrete buildings. These buildings were originally designed to provide additional radiation shielding (beyond what is provided by the cask itself) to reduce doses at plant site boundaries to background levels. Some of these buildings are sufficiently robust to provide protection against crashes of large aircraft. A subgroup of the committee visited spent fuel storage sites at Ahaus and Lingen during this study. See Appendix C for details.

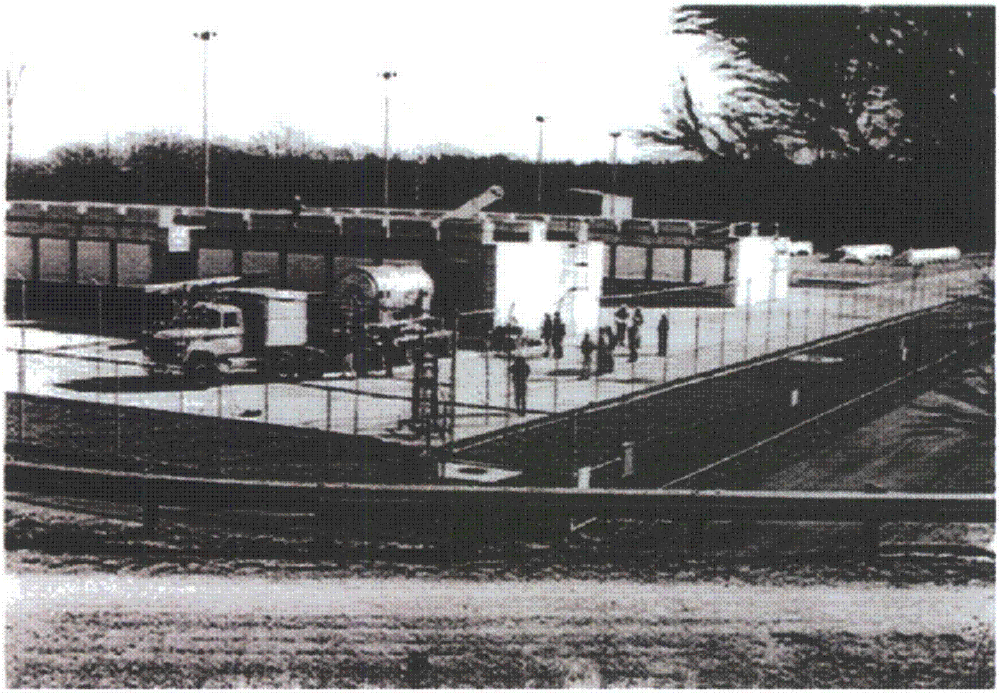


FIGURE 4.2 Photo showing a canister being loaded into a NUHOMS horizontal storage module. SOURCE: Courtesy of Transnuclear, Inc., an Areva Company.

4.2 EVALUATION OF POTENTIAL RISKS OF DRY CASK STORAGE

Dry casks were designed to ensure safe storage of spent fuel,[10] not to resist terrorist attacks. The regulations for these storage systems, which are given in Title 10, Part 72 of the Code of Federal Regulations (i.e., 10 CFR 72), are designed to ensure adequate passive heat removal and radiation shielding during normal operations, off-normal events, and accidents. The latter include, for example, accidental drops or tip-overs during routine cask movements. The robust construction of these casks provides some passive protection against external assaults, but the casks were not explicitly designed with this factor in mind.[11]

The regulations in 10 CFR 72 require that dry cask storage facilities (formally referred to as Independent Spent *Fuel* Storage Installations, or ISFSIs) be located within a protected area of the plant site (see FIGURE 2.1). However, the protection requirements for these installations are lower than those for reactors and spent fuel pools. The guard force is required to carry side arms, and its main function is surveillance: to detect and assess threats and to summon reinforcements. If the ISFSI is within the protected area of the plant

[10] Dual-purpose casks also were designed for safe transport under the requirements of Title 10, Part 71 of the Code of Federal Regulations. The committee did not examine transport of spent fuel in this study.
[11] A recent study by the German organization GRS (Gesellschaft für Anlagen- und Reaktorsicherheit, MBH) examined the vulnerability of CASTOR-type casks to large-aircraft impacts.

it would come directly under the protection of plant's guard forces. The protected area is surrounded by vehicle barriers to protect against the detonation of a design basis threat vehicle bomb.[12]

A terrorist attack that breached a dry cask could *potentially* result in the release of radioactive material from the spent fuel into the environment through one or both of the following two processes: (1) mechanical dispersion of fuel particles or fragments; and (2) dispersion of radioactive aerosols (e.g., cesium-137). As described in Chapter 3, the latter process would have greater offsite radiological consequences. The committee evaluates the potential for both of these processes later in this chapter.

In the wake of the September 11, 2001, attacks, additional work has been or is being carried out by government and private entities to assess the security risks to dry casks from terrorist attacks. Sandia National Laboratories is currently analyzing the response of dry casks to a number of potential terrorist attack scenarios at the request of the Nuclear Regulatory Commission. The committee was briefed on these analyses at two of its meetings.

Sandia is analyzing the responses of three vertical cask designs and one horizontal design to a variety of terrorist attack scenarios (FIGURE 4.3). These designs are considered to be broadly representative of the dry casks currently licensed for storage in the United States by the Nuclear Regulatory Commission (see TABLE 4.1 at the end of this chapter). The committee received briefings on these studies by Nuclear Regulatory Commission and Sandia staff.

Several attack scenarios are being considered in the Sandia analyses. They include large aircraft impacts and assaults with various types and sizes of explosive charges and other energetic devices. Details on the large aircraft impact scenarios are provided in the classified report.

Most of this work is still in progress and has not yet resulted in reviewable documents. Consequently, the committee had to rely on discussions with the experts who are carrying out these studies and its own expert judgment in assessing the quality and completeness of this work.

4.2.1 Large Aircraft Impacts

Sandia analyzed the impact of an airliner traveling at high speed into the four cask designs shown in FIGURE 4.3. These analyses examined the consequences of impacts of the fuselage and the "hard" components of the aircraft (i.e., the engines and wheel struts) into individual casks and arrays of casks on a storage pad. The latter analysis examined the potential consequences of cask-to-cask interactions resulting from cask sliding or partial tip-over The objectives of the analyses were first to determine whether the casks would fail (i.e., the containment would be breached) and, if so, to estimate the radioactive material releases and their health consequences.

[12] As noted in Chapter 2, the committee did not examine surveillance requirements or the placement or effectiveness of vehicle barriers and guard stations at commercial nuclear plants.

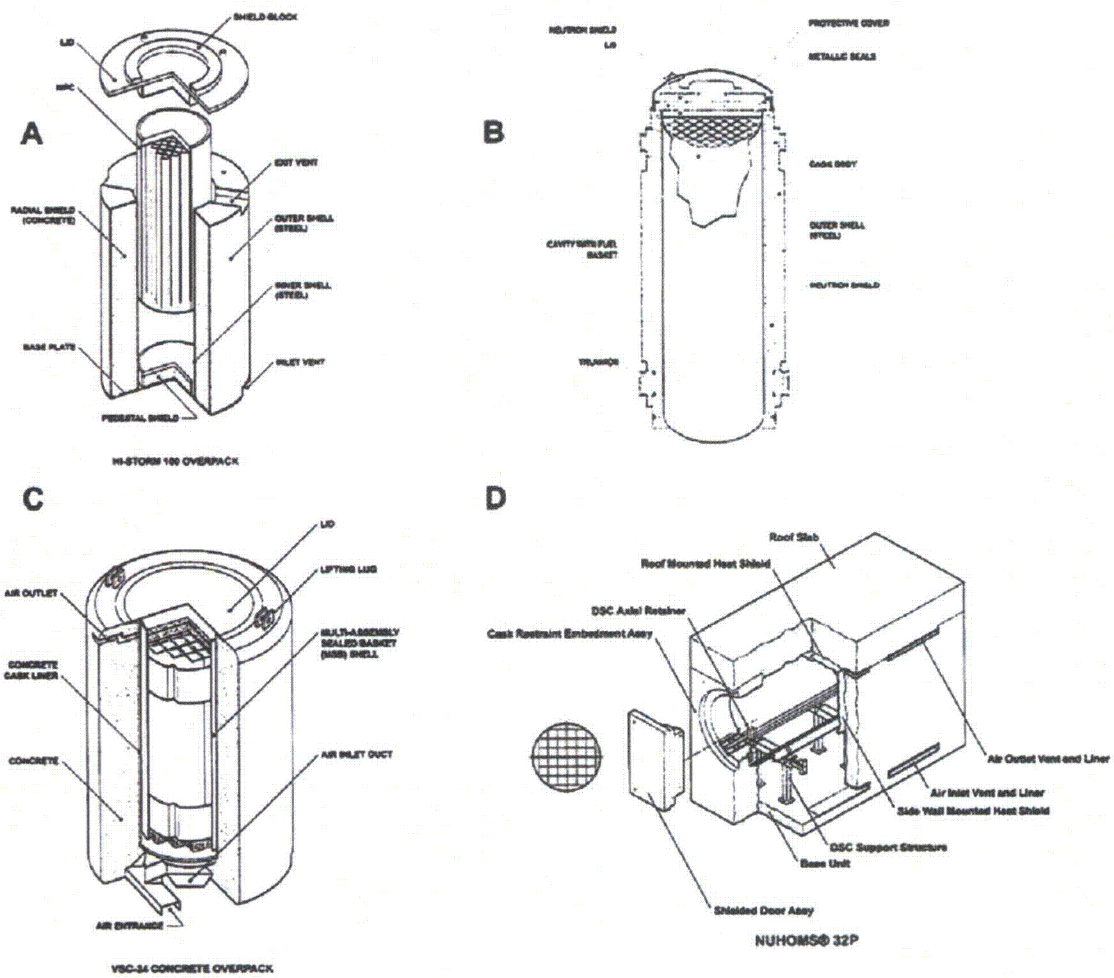


FIGURE 4.3 Four cask systems used in the Sandia analyses described in this chapter: (A) HI-STORM-100, (B) TN-68, (C) VSC-24, (D) NUHOMS-32P. The casks shown in A, C, and D are canister-based casks; the cask shown in B is a bare-fuel cask. SOURCE: Nuclear Regulatory Commission briefing materials (2004).

The aircraft was modeled using Sandia-developed Eulerian CTH code (see footnote 15 in Chapter 3). The aircraft manufacturer (Boeing Corp.) was consulted to ensure that the aircraft model used in the analyses was accurate. The casks were modeled with standard finite element codes using the published characteristics of the casks. The casks were assumed to be filled with high-burn-up, 10-year-old spent fuel. The fuel rods were assumed to fail (rupture) if the strains in the cladding exceeded 1 percent, which is a conservative assumption. Sandia evaluated the release of radioactive materials from the spent fuel pellets inside the fuel rods when such cladding failures occurred. Radiological consequences of such releases were calculated for "representative" (with respect to weather and population) site conditions for each cask based on the actual average conditions at the site that currently stores the most spent fuel in that cask type.[13] Site conditions differed for each cask.

The effects of jet fuel fires also were not considered in the analyses. Based on an analysis of actual aircraft accidents, Sandia determined that jet fuel would likely be dispersed over a large area in a low-angle impact. Consequently, the resulting petroleum fire would likely be of short duration (generally less than 15 minutes according to Sandia researchers). Long-duration fires that could damage the casks or even ignite the cladding of the spent fuel were not seen to be credible for the aircraft impact scenarios considered by Sandia.[14]

The results of these analyses, which are considered by the Nuclear Regulatory Commission to be classified or safeguards information, are detailed in the classified report. In general, the analyses show that some types of impacts will damage some types of casks. For some scenarios there could be substantial cask-to-cask interactions, including collisions and partial tip-overs.

Nevertheless, predicted releases of radioactive material from the casks, mainly noble gases, were relatively small for all of the scenarios considered by Sandia. The analyses show that the releases were governed by design-specific features of the casks Sandia noted that the modeling of such releases is difficult and requires expert judgment for several elements of the calculation. Detailed calculations of the consequences were still in progress when the committee was briefed on these analyses.

4.2.2 Other Assaults

Analyses are also being carried out to understand the consequences of other types of assaults on the cask designs shown in FIGURE 4.3. These include assaults using explosives and certain types of high-energy devices. The analyses were still underway when the committee was briefed on these analyses, and the results were characterized by the Nuclear Regulatory Commission as preliminary. Details are provided in the classified report.

4.2.3 Discussion

As noted previously, the dry cask vulnerability analyses were still underway when the committee's classified study was completed. Based on the analyses it did receive, the committee judges that no cask provides complete protection against all types of terrorist attacks. The committee judges that releases of radioactive material from dry casks are low for the scenarios it examined with one possible exception as discussed in the classified report. It is not clear to the committee whether it is credible to assume that this "exceptional" scenario could actually be carried out.

[13] As noted in Chapter 1, the committee did not concern itself with how radioactive materials would be transported through the environment once they were released from a dry cask. Rather, the committee confined its examination to whether and how much radioactive material might be released from a dry cask in the event of a terrorist attack.

[14] The committee subgroup that visited Germany was briefed on a fire test on the Castor cask that involved a fully engulfing one-hour petroleum fire. The cask maintained its integrity during and after this test. See Appendix C. The results of this test do not necessarily translate to casks having other designs.

In the committee's opinion, there are several relatively simple steps that could be taken to reduce the likelihood of releases of radioactive material from dry casks in the event of a terrorist attack:

- Additional surveillance could be added to dry cask storage facilities to detect and thwart ground attacks.[15]
- Certain types of cask systems could be protected against aircraft strikes by partial earthen berms. Such berms also would deflect the blasts from vehicle bombs.
- Visual barriers could be placed around storage pads to prevent targeting of individual casks by aircraft or standoff weapons,[16] These would have to be designed so that they would not trap jet fuel in the event of an aircraft attack.
- The spacing of vertical casks on the storage pads can be changed, or spacers (shims) can be placed between the casks, to reduce the likelihood of cask-to-cask interactions in the event of an aircraft attack.
- Relatively minor changes in the design of newly manufactured casks could be made to improve their resistance to certain types of attack scenarios.

4.3 POTENTIAL ADVANTAGES OF DRY STORAGE OVER WET STORAGE

Based on the analyses presented in Chapter 3 and previously in this chapter, the committee judges that dry cask storage has several potential safety and security advantages over pool storage. These differences can best be illustrated using scenarios for both storage systems based on the Sandia analyses reviewed by the committee. **The use of such scenarios should not be taken to imply that the committee believes that these scenarios are likely or even possible at all storage facilities. They are used only for illustrative purposes.**

The following statements can be made about the comparative advantages of dry-cask storage and pool storage based on the Sandia analyses:

Less spent fuel is at risk in an accident or attack on a dry storage cask than on a spent fuel pool. An accident or attack on a dry cask storage facility would likely affect at most a few casks and put a few tens of metric tons of spent fuel at risk. An accident or attack on a spent fuel pool puts the entire inventory of the pool, potentially hundreds of metric tons of spent fuel, at risk.

The potential consequences of an accident or terrorist attack on a dry cask storage facility are lower than those for a spent fuel pool. There are several reasons for this difference:

(1) There is less fuel in a dry cask than in a spent fuel pool and therefore less radioactive material available for release.
(2) *Measured on a per-fuel-assembly basis,* the inventories of radionuclides available

[15] As noted in Chapter 1, the committee did not examine surveillance activities at nuclear power plants and has no basis to judge whether current activities at dry cask storage facilities are adequate.
[16] The ISFSI at the Palo Verde Nuclear Power Plant in Arizona, which was visited by a subgroup of committee members, incorporates a berm into its design to provide a visual barrier.

for release from a dry cask are lower than those from a spent fuel pool because dry casks store older, lower decay- heat fuel.

(3) Radioactive material releases from a breach in a dry cask would occur through mechanical dispersion. [17] Such releases would be relatively small. Certain types of attacks on spent fuel pools could result in a much larger dispersal of spent fuel fragments. Radioactive material releases from a spent fuel pool also could occur as the result of a zirconium cladding fire, which would produce radioactive aerosols. Such fires have the potential to release large quantities of radioactive material to the environment.

The recovery from an attack on a dry cask would be much easier than the recovery from an attack on a spent fuel pool. Breaches in dry casks could be temporarily plugged with radiation-absorbing materials until permanent fixes or replacements could be made. The most significant contamination would likely be confined largely to areas near the cask storage pad and could be detected and decontaminated. The costs of recovery could be high, however, especially if the cask could not be repaired or the spent fuel could not be removed with equipment available at the plant. A special facility might have to be constructed or brought onto the site to transfer the damaged spent fuel to other casks.

Breaches in spent fuel pools could be much harder to plug, especially if high radiation fields or the collapse of the overlying building prevented workers from reaching the pool. Complete cleanup from a zirconium cladding fire would be extraordinarily expensive, and even after cleanup was completed large areas downwind of the site might remain contaminated to levels that prevented reoccupation (see Chapter 3).

It is the potential for zirconium cladding fires in spent fuel pools that gives dry cask storage most of its comparative safety and security advantages. This comparative advantage can be reduced by lowering the potential for zirconium cladding fires in loss-of-pool-coolant events. As discussed in Chapter 3, the committee believes that there are at least two steps that can be implemented immediately to lower the potential for such fires.

4.4 FINDINGS AND RECOMMENDATIONS

With respect to the committee's task to examine potential safety and security advantages of dry cask storage using various single-, dual-, or multi-purpose cask designs, the committee offers the following findings and recommendations:

FINDING 4A: Although there are differences in the robustness of different dry cask designs (e.g., bare-fuel versus canister-based), the differences are not large when measured by the absolute magnitudes of radionuclide releases in the event of a breach.

All storage cask designs are vulnerable to some types of terrorist attacks for which radionuclide releases would be possible. The vulnerabilities are related to the specific

[17] Since the committee's classified report was published, the committee received an additional briefing from the Nuclear Regulatory Commission suggesting that a radioactive aerosol could be released in one type of terrorist attack. However, the scenario in question does not appear to the committee to be credible.

design features of the casks, but the committee judges that the quantity of radioactive material releases predicted from such attacks is still relatively small.

FINDING 4B: Additional steps can be taken to make dry casks less vulnerable to potential terrorist attacks.

Although the vulnerabilities of current cask designs are already small, additional, relatively simple steps can be taken to reduce them. Such steps are listed in Section 4.2.3.

RECOMMENDATION: The Nuclear Regulatory Commission should consider using the results of the vulnerability analyses for possible upgrades of requirements in 10 CFR 72 for dry casks, specifically to improve their resistance to terrorist attacks.

The committee was told by Nuclear Regulatory Commission staff that such a step is already under consideration. Based on the material presented to the committee, there appear to be minor changes that can be made by plant operators and cask vendors to increase the resistance of existing and new casks to terrorist attacks (see Section 4.2.3).

With respect to the committee's task to examine the safety and security advantages of dry cask storage versus wet pool storage at reactor sites, the committee offers the following findings and recommendations:

FINDING 4C: Dry cask storage does not eliminate the need for pool storage at operating commercial reactors.

Newly discharged fuel from the reactor must be stored in the pool for cooling, as discussed in detail in Chapter 3. Under current U.S. practices, dry cask storage can be used only to store fuel that has been out of the reactor long enough (generally greater than five years under current practices) to be air cooled. The fuel in dry cask storage poses less of a risk in the event of a terrorist attack than newly discharged fuel in pools because there is substantially reduced probability of initiating a cladding fire.

FINDING 4D: Dry cask storage for older, cooler spent fuel has two inherent advantages over pool storage: (1) It is a passive system that relies on natural air circulation for cooling; and (2) it divides the inventory of that spent fuel among a large number of discrete, robust containers. These factors make it more difficult to attack a large amount of spent fuel at one time and also reduce the consequences of such attacks.

Each storage cask holds no more than about 10 to 15 metric tons of spent fuel, compared to the several hundred metric tons of spent fuel that is commonly stored in reactor pools. The robust construction of these casks prevents large-scale releases of radionuclides in all of the attack scenarios examined by the committee. Some of the attacks could breach the casks, but many of these breaches would be small and could probably be more easily plugged than a perforated spent fuel pool wall because radiation fields would be lower and there would be no escaping water to contend with. Even large breaches of the cask would result only in the mechanical dispersal of some of its radionuclide inventory in the immediate vicinity of the cask.

FINDING 4E: Depending on the outcome of plant-specific vulnerability analyses described in the committee's classified report, the Nuclear Regulatory Commission might determine that earlier movements of spent fuel from pools Into dry cask storage would be prudent to reduce the potential consequences of terrorist attacks on pools at some commercial nuclear plants.

The statement of task directs the committee to examine the risks of spent fuel storage options and alternatives for decision makers, not to recommend whether any spent fuel should be transferred from pool storage to cask storage. In fact, there may be some commercial plants that, because of pool designs or fuel loadings, may require some removal of spent fuel from their pools, If there is a need to remove spent fuel it should become clearer once the vulnerability and consequence analyses described in Chapter 3 are completed. The committee expects that cost-benefit considerations would be a part of these analyses.

TABLE 4.1 Dry Casks Used for Spent Fuel Storage in the United States

Cask design used for storage	License holder	Type	Fuel type	Construction	Closure system	Number of casks used to date; sites; and number of casks on order[1]
CASTOR V/21	GNSI (General Nuclear Systems, Inc.)	Bare-fuel, storage-only	BWR	Ductile cast iron	Primary lid (44 bolts), secondary lid (48 bolts)	25 loaded (Surry); 0 purchased
CASTOR X/33	GNS (Gesellschaft für Nuklear-Service mbH)	Bare-fuel, storage-only	PWR	Ductile cast iron	Primary lid (44 bolts), secondary lid (70 cup screws)	1 loaded (Surry); 0 purchased
NAC S/T	NAC International	Bare-fuel, storage-only	PWR	Inner and outer stainless steel shells	Closure lid (24 bolts)	2 loaded (Surry); 0 purchased
MC-10	Westinghouse	Bare-fuel, storage-only	PWR	Stainless and carbon steel	One shield lid and two sealing lids, all bolted (number of bolts not available)	1 loaded (Surry); 0 purchased
TN-32, TN-40	Transnuclear Inc.	Bare-fuel, storage-only	PWR	Carbon steel	One lid (48 bolts)	61 loaded (4 sites); 22 purchased
TN-68	Transnuclear Inc.	Bare-fuel, dual-purpose	BWR	Carbon steel	One lid (48 bolts)	24 loaded (Peach Bottom); 20 purchased
Fuel Solution W-150 Storage Cask	BNFL Fuel Solutions	Canister-based, dual-purpose	PWR, BWR	Reinforced concrete with inner steel shell	Canister lid, welded cask lid (12 bolts)	7 loaded (Big Rock Point); 0 purchased
HI-STORM 100	Holtec International	Canister-based, storage-only module	PWR, BWR	Stainless steel shells with un-reinforced concrete filler	Canister lid, welded cask lid (4 bolts)	58 loaded (7 sites); 177 on order
HI-STAR 100	Holtec International	Canister-based, dual-purpose	PWR, BWR	Carbon steel shells with neutron absorber polymer	Canister lid, welded cask lid (54 bolts)	7 loaded (2 sites[1]); 5 on order

VSC-24 Ventilated Concrete Cask	BNFL Fuel Solutions	Canister-based, storage-only	PWR	Reinforced concrete with inner steel shell	Canister lid, welded cask lid (6 bolts)	58 loaded (3 sites); 4 purchased[2]
NAC-MPC	NAC International	Canister-based, dual-purpose	PWR	Metal canister surrounded by storage overpack. Storage overpack consists of an inner steel liner 3.5 in. thick, two rebar cages, and concrete	Canister lid, welded cask lid over a shield plug (6 high-strength bolts)	21 loaded (Yankee Rowe and CT Yankee); 59 purchased
NAC-UMS	NAC International	Canister-based, dual-purpose	PWR, BWR	Metal canister surrounded by storage overpack. Storage overpack consists of inner steel liner 2.5 in. thick, two rebar cages, and concrete	Canister lid, welded cask lid over a shield plug (6 high-strength bolts)	80 loaded (2 sites); 165 purchased
Holtec MPC 24E/EF	Holtec International	Canister based, dual-purpose	PWR, BWR	Metal canister surrounded by storage overpack. Storage overpack consists of inner and outer steel liners, a double-rebar cage, and concrete	Canister lid, welded cask lid, shield plug plus 48 bolts	34 loaded (Trojan); 0 purchased
NUHOMS 24P, 52B, 61BT, 24PT1, 24PT2, 32PT	Transnuclear Inc.	Canister-based, dual-purpose	PWR, BWR	Horizontal reinforced concrete storage module with shielded canister	Canister lid, welded storage module lid, reinforced concrete	239 loaded (10 sites); >150 purchased

NOTES:

[1]The Humboldt Bay Power Plant is licensing a site-specific variation of the HI-STAR System called HI-STAR HE.

[2] Some licensees have purchased additional casks that have not yet been loaded, nor are they planned for loading.

SOURCES: Data compiled from cask license holders (2004).

5

IMPLEMENTATION ISSUES

Implementation of the recommendations in this report will require actions and cooperation by a large number of parties. This chapter provides a brief discussion of two implementation issues that the committee believes will be of interest to Congress:

(1) Timing Issues: Ensuring that high-quality, expert analyses are completed in a timely manner.
(2) Communication Issues: Ensuring that the results of the analyses are communicated to industry so that appropriate and timely mitigating actions can be taken.

5.1 TIMING ISSUES

The September 11, 2001, terrorist attacks forced the nation to begin a reexamination of the vulnerability of its critical infrastructure to high-impact suicide attacks by terrorists. The Nuclear Regulatory Commission was no exception. The Commission began a top-to-bottom review of security procedures at commercial nuclear power plants. This review resulted in the issuance of numerous directives to power plant operators to upgrade their security practices. The Commission also began a series of vulnerability analyses of spent fuel storage to terrorist attacks. These analyses are described in Chapters 3 and 4,

More than three years have passed since the September 11, 2001, attacks. Vulnerability analyses of spent fuel pool storage to attacks with large aircraft have been performed by EPRI (Chapter 3), and analyses of vulnerabilities of dry cask storage to large aircraft attacks have been completed by the German organization GRS (Gesellschaft für Anlagen- und Reaktorsicherheit, mbH). However, the Nuclear Regulatory Commission's analyses of spent fuel storage vulnerabilities have not yet been completed, and actions to reduce vulnerabilities, such as those described in Chapter 3, on the basis of these analyses have not yet been taken. Moreover, some important additional analyses remain to be done. The slow pace in completing this work is of concern given the enormous potential consequences as described elsewhere in this report.

The committee does not know the reason for this delay, nor was it asked by Congress for an evaluation. It is important to note that the Nuclear Regulatory Commission's analyses are addressing a much broader range of vulnerabilities than just spent fuel storage. The committee nevertheless raises this issue because it appears to be having an impact on the timely completion of critical work and implementation of appropriate mitigative actions for spent fuel storage.

5.2 COMMUNICATION ISSUES

During the course of this study, the committee had the opportunity to interact with representatives of the nuclear power industry to discuss their concerns about safety and security issues. The committee received numerous comments from industry representatives about the lack of information sharing by the Nuclear Regulatory Commission on the vulnerability analyses described in Chapter 3. These representatives noted that information flow was predominately in one direction: from the industry to the Commission. The Commission was not providing a reciprocal flow of information that could help the industry better understand and take early actions to address identified vulnerabilities.

Restrictions on information sharing by the Commission have resulted in missed opportunities in at least two cases observed by the committee. Analyses of aircraft impacts into power plant structures described in Chapter 3 were being carried out independently by Sandia for the Commission and by EPRI for the nuclear power industry. Because of classification restrictions, EPRI was not provided with information about the Sandia work, including the results of physical tests that would have helped EPRI validate its models. Both Sandia and the industry would have benefited had their analysts been able to talk with each other about their models, assumptions, and results while the analyses were in progress. When the EPRI work was completed the Commission declared it to be safeguards information.[1] As a consequence, some of the EPRI analysts who generated the results no longer had access to them, and the results could not be shared widely within industry.

A similar situation exists with respect to the ENTERGY Corp, spent fuel pool separate effects analyses described in Chapter 3. ENTERGY is using similar approaches and models as Sandia but has received little or no guidance from Commission staff about whether the results are realistic or consistent. The ENTERGY analysts told the committee that they would have benefited had they been able to compare and discuss their approaches and results with Sandia analysts. Sandia analysts were prevented from doing so because of classification issues. Sharing of ENTERGY's results within the company or across industry may be problematical if they are determined to be classified or safeguards information by the Commission.

Several Nuclear Regulatory Commission staff also privately expressed to the committee their frustration at the difficulty in sharing information that they know would be useful to industry. In fact, from the contacts the committee had, there does not appear to be a lack of willingness to share information at the working staff level within the Commission. Rather, it seems to be an issue of getting permission from upper management and addressing the classification restrictions.

Much of the difficulty in sharing this information appears to arise because the information is considered by the Nuclear Regulatory Commission to be safeguards information or in some cases even classified national security information. Industry analysts and decision makers generally do not have the appropriate personal security clearances[2] to access this information. The committee learned that the Commission is making efforts to share more of this information with some industry representatives. The industry will be responsible for implementing any changes to spent fuel storage to make it less vulnerable to terrorist attack. Clearly, therefore, the industry needs to understand the results of the

[1] Safeguards information is defined in section 147 of the Atomic Energy Act and in the Code of Federal Regulations, Title 10, Part 73.2. See the glossary for a definition. Authority for designation of safeguards resides with the Nuclear Regulatory Commission.

[2] In fact, a personnel security clearance is not required to access safeguards information. One only needs to be of "good character" and have a "need to know" as determined by the Nuclear Regulatory Commission.

Commission's vulnerability analyses to ensure that effective implementation strategies are adopted.

The committee also received complaints during this study from members of the public about the lack of information sharing. Commission staff have responded to these complaints by stating that such sharing could reveal sensitive information to terrorists and that the public does not have a "need to know" this information.

The committee fully agrees that information that could prove useful to terrorists should not be released. On the other hand, the committee believes that there is information that could be shared without compromising national security. For example, general information about the kinds of threats being considered and general steps being taken to reduce vulnerabilities could be shared with the public. Information about specific vulnerabilities of spent fuel pools and dry storage casks to terrorist attacks as well as potential mitigative actions could be shared with industry without revealing the details about how such attacks might be carried out. Sharing information with industry is essential for ensuring that mitigative actions to reduce vulnerabilities are carried out. Sharing information with the public is essential in a nation with strong democratic traditions for sustaining public confidence in the Commission as an effective regulator of the nuclear industry, and for reducing the potential for severe environmental, health, economic, and psychological consequences from terrorist attacks should they occur.

5.3 FINDING AND RECOMMENDATION

FINDING 5A: Security restrictions on sharing of information and analyses are hindering progress in addressing potential vulnerabilities of spent fuel storage to terrorist attacks.

Current classification and security practices appear to discourage information sharing between the Nuclear Regulatory Commission and industry. During the course of the study the committee received comments from power plant operators, their contractors, and Nuclear Regulatory Commission staff about the difficulties of sharing the information on the vulnerability of spent fuel storage. Indeed, even the committee found it difficult and in some cases impossible to obtain needed information (e.g., information on the design basis threat). Such restrictions have several negative consequences: They Impede the review and feedback processes that can enhance the technical soundness of the analyses being carried out; they make it difficult to build support within the industry for potential mitigative measures; and they may undermine the confidence that the industry, expert panels such as this one, and the public place in the adequacy of such measures.

RECOMMENDATION: The Nuclear Regulatory Commission should improve the sharing of pertinent information on vulnerability and consequence analyses of spent fuel storage with nuclear power plant operators and dry cask storage system vendors on a timely basis.

Implementation of this recommendation will allow timely mitigation actions. Certain current security practices may have to be modified to carry out this recommendation.

The committee also believes that the public is an important audience for the work being carried out to assess and mitigate vulnerabilities of spent fuel storage facilities. While it would be inappropriate to share all information publicly, more constructive interaction with the public and independent analysts could improve the work being carried out and also increase public confidence in Nuclear Regulatory Commission and industry decisions and actions to reduce the vulnerability of spent fuel storage to terrorist threats.

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A

INFORMATION-GATHERING SESSIONS

The committee organized several meetings and tours to obtain information about the safety and security of spent fuel storage. A list of these meetings and tours is provided below. The committee held several *data-gathering sessions not open to the public* to obtain classified and safeguards information about the safety and security of spent fuel storage. The committee also held several *data-gathering sessions open to the public* to receive unclassified briefings from industry, independent analysts, and other interested parties including members of the public. The written materials (e.g., PowerPoint presentations and written statements) obtained by the committee at these open sessions are posted on the web site for this project: *http://dels.nas.edu/sfs.*

A.1 FIRST MEETING, FEBRUARY 12–13, 2004, WASHINGTON, D.C.

The objective of this meeting was to obtain background information on the study request from staff of the House Committee on Appropriations, Energy and Water Development Subcommittee. The committee also was briefed by one of the sponsors of the study and by two independent experts. The following is the list of topics and speakers for the open session:

- Background on the congressional request for this study. Speaker Kevin Cook, Professional Staff, House Committee on Appropriations, Energy and Water Development Subcommittee.
- Reducing the hazard from stored spent power-reactor fuel in the United States. Speakers: Frank von Hippel, Princeton University, and Klaus Janberg, independent consultant, co-authors of the paper entitled "Reducing the Hazard from Stored Spent Power-Reactor Fuel in the United States" (Alvarez et al., 2003).
- Nuclear power plants and their fuel as terrorist targets. Speaker: Ted Rockwell, MPR Associates, Inc., co-author of the paper entitled "Nuclear Power Plants and Their Fuel as Terrorist Targets" (Chapin et al., 2002).
- Nuclear Regulatory Commission analyses of spent fuel safety and security. Speaker: Farouk Eltawila, director, Division of Systems Analysis and Regulatory Effectiveness, Office of Research, Nuclear Regulatory Commission.

On the second day of the meeting, the committee held a data-gathering session not open to the public to obtain classified briefings from the U.S. Nuclear Regulatory Commission about its ongoing analyses of spent fuel storage security.

A.2 SECOND MEETING, MARCH 4–6, 2004, ARGONNE, ILLINOIS

During the second meeting, the committee held a data-gathering session not open to the public to receive classified briefings on spent fuel storage security from the U.S. Nuclear Regulatory Commission. The committee also toured the Dresden and Braidwood Nuclear

Generating Stations to see first-hand how spent fuel is managed and stored. The two plants were chosen because of the differences in their spent fuel storage facilities.

A.3 THIRD MEETING, APRIL 15–17, 2004, ALBUQUERQUE, NEW MEXICO

During the third meeting, the committee held a data-gathering session not open to the public to receive a briefing from EPRI on spent fuel storage vulnerabilities. The committee also held a data-gathering session open to the public to receive briefings on dry cask storage systems and radioactive releases from damaged spent fuel storage casks.

- Speakers on dry cask storage systems: William McConaghy (GNB-GNSI); Steven Sisley (BNFL); Alan Hanson (Transnuclear Inc.); Charles Pennington (NAC international); and Brian Gutherman (Hoitec International, via telephone).
- Radionuclide releases from damaged spent fuel. Speaker: Robert Luna, Sandia National Laboratories (retired).

A.4 TOUR OF SELECTED SPENT FUEL STORAGE INSTALLATIONS IN GERMANY

On April 25–28, 2004, a group of committee members traveled to Germany to meet with German officials and to visit selected spent fuel storage installations. The agenda of the tour was as follows:

- Meeting with Michael Sailer, chairman of the German reactors safety commission (RSK, Reaktorsicherheitskommission).
- Visit to the dry cask manufacturer GNB (Gesellschaft für Nuklear-Behälter mbH) headquarters in Essen and the cask assembly facility and test museum in Mülheim.
- Tour of the Ahaus intermediate dry storage facility.
- Meeting with Florentin Lange, GRS (Gesellschaft für Anlagen- und Reaktorsicheheit mbH), co-author of the study entitled "Safety Margins of Transport and Storage Casks for Spent Fuel Assemblies and HAW Canisters Under Extreme Accident Loads and Effects from External Events" (Lange et al., 2002),
- Tour of the Lingen nuclear power plant and its spent fuel storage facilities.

A summary of information gathered during the tour is provided in Appendix C.

A.5 FOURTH MEETING, MAY 10–12, 2004, WASHINGTON, D.C.

During the fourth meeting, the committee held a data-gathering session not open to the public to hold in-depth technical discussions with Sandia National Laboratories staff and contractors on their spent fuel storage vulnerability analyses. The committee also received an intelligence briefing from Department of Homeland Security staff on terrorist capabilities and from the U.S. Nuclear Regulatory Commission staff on terrorist scenarios.

The meeting also included a data-gathering session open to the public that included the following briefings:

- Summary of the field trip to Germany. Speaker: Louis Lanzerotti (committee chair).
- Vulnerabilities of spent nuclear fuel pools to terrorist attacks: issues with the design basis threat. Speaker: Peter Stockton, Project on Government Oversight.
- Consequences of a major release of ^{137}Cs into the atmosphere. Speaker: Jan Beyea, Consulting in the Public Interest.

A.6 FIFTH MEETING, MAY 26–28, 2004, WASHINGTON, D.C.

The objective of this closed meeting (i.e., open only to committee members and staff) was to finalize the classified report for National Research Council review.

A.7 TOURS OF SELECTED SPENT FUEL STORAGE FACILITIES AT U.S. NUCLEAR POWER PLANTS

On June 11 and June 14, 2004, respectively, committee subgroups visited the Palo Verde Nuclear Generating Station in Arizona and the Indian Point Nuclear Generating Station in New York.

A.8 SIXTH MEETING, JUNE 28–29, 2004

The objective of this closed meeting was to complete work on the classified report.

A.9 SEVENTH MEETING, AUGUST 12–13, 2004

The objective of this closed meeting was to develop a public version of the committee's report. The committee also held a data-gathering session not open to the public to receive a briefing from the Department of Homeland Security on steps being taken to address the findings and recommendations in the classified report.

A.10 EIGHTH MEETING, OCTOBER 28–29, 2004

The objective of this closed meeting was to continue work to develop a public version of the committee's report. The committee also held a data-gathering session not open to the public to receive a briefing from the Nuclear Regulatory Commission on steps being taken to address the findings and recommendations in the classified report.

A.11 NINTH MEETING, NOVEMBER 29–30, 2004

The objective of this closed meeting was to continue work to develop a public version of the committee's report.

A. 12 TENTH MEETING, JANUARY 24–25, 2005

The objective of this closed meeting was to continue work to develop a public version of the committee's report. The committee also held a data-gathering session not open to the public to meet with three commissioners from the Nuclear Regulatory Commission (Chairman Nils Diaz and members Edward McGaffigan and Jeffrey Merrifield) to discuss what additional information the commission might be willing to make available to the committee on human-factors-related issues.

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B

BIOGRAPHICAL SKETCHES OF COMMITTEE MEMBERS

LOUIS J. LANZEROTTI, *Chair,* is an expert in geophysics and electromagnetic waves and a veteran of over 40 National Research Council (NRC) studies. He currently consults for Bell Laboratories, Lucent Technologies, and is a distinguished professor for solar-terrestrial research at the New Jersey Institute of Technology. Previously, he was a distinguished member of the technical staff at Bell Labs. His research interests include space plasmas and engineering problems related to the impacts of atmospheric and space processes on telecommunications on commercial satellites and transoceanic cables. He has been associated with numerous National Aeronautics and Space Administration (NASA) space missions as well, including Voyager, Ulysses, Galileo, and Cassini, and with commercial space satellite missions to research design and operational problems associated with spacecraft and cable operations. In 1988, he was elected to the National Academy of Engineering for his work on energetic particles and electromagnetic waves in the earth's magnetosphere, including their impact on space and terrestrial communication systems. He has twice received the NASA Distinguished Public Service Medal and has a geographic feature in Antarctica named in his honor He was appointed to the National Science Board by President George W. Bush in 2004. Dr. Lanzerotti holds a Ph.D. in physics from Harvard University.

CARL A.ALEXANDER is an expert in the behavior of nuclear material at high temperatures and also in biological and chemical weapons. He is chief scientist and senior research leader at the Battelle Memorial Institute in Columbus, Ohio. Dr. Alexander worked on fuel design and behavior for the aircraft nuclear propulsion program and several space nuclear power projects, including the Viking, Voyager, and Cassini missions. He helped analyze the evolution of the Three Mile Island accident and is involved in the French Phebus fission product experiments, which are to reproduce all of the phenomena involved during a nuclear power reactor core meltdown accident He has served as a consultant to the Nuclear Regulatory Commission and, in the 1970s, worked on the first experiments on the effects of an attack on spent fuel shipping containers using shaped charges. He currently leads research projects on agent neutralization and collateral effects for weapons of mass destruction for the Defense Threat Reduction Agency and the Navy, and on lethality of missile defense technologies for the Missile Defense Agency. Dr. Alexander has taught materials science and engineering at the Ohio State University and has served as graduate advisor and adjunct professor at the Massachusetts Institute of Technology, University of Southampton in the United Kingdom, and the University of Maryland. He has authored over 100 peer-reviewed articles and technical reports, many of which are classified. He holds a Ph.D. in materials science from Ohio State University.

ROBERT M.BERNERO is a nuclear engineering and regulatory expert. He is now an independent consultant after retiring from the U.S. Nuclear Regulatory Commission (USNRC) in 1995. In 23 years of service for the USNRC Mr. Bernero held numerous positions in reactor licensing, fuel cycle facility licensing, engineering standards development, risk assessment research, and waste management. His final position at USNRC was as director of the Office of Nuclear Materials Safety and Safeguards, Prior to joining the USNRC he worked for the General Electric Company in nuclear technology for 13 years. He has served as a member of the Commission of Inquiry for an International

Review of Swedish Nuclear Regulatory Activities, and he currently consults on nuclear safety-related matters, particularly regarding nuclear materials licensing and radioactive waste management. Mr, Bernero received his B.A. degree from St. Mary of the Lake (Illinois), a B.S. degree from the University of Illinois, and an M.S, degree from Rensselaer Polytechnic Institute.

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KENNETH K.KUO is an expert in combustion, rocket propulsion, ballistics, and fluid mechanics. He is a Distinguished Professor of Mechanical Engineering at the Pennsylvania State University. He is also the leader and director of the university's High Pressure Combustion Laboratory, a laboratory with advanced instrumentation and data acquisition devices. Dr. Kuo has directed team research projects in propulsion and combustion studies for 32 years. He has edited eight books and authored one book on combustion, published over 300 technical articles, and served as principal investigator for more than 70 projects, including a Multidisciplinary University Research Initiative (MURI) grant from the U.S. Army on "Ignition and Combustion of High Energy Materials," He is now serving as principal investigator and co-principal investigator for two MURI programs on rocket and energetic materials. In 1991, he was elected fellow of American Institute of Aeronautics and Astronautics and has received several awards for his work on solid propellants combustion processes. Dr. Kuo holds a Ph.D. in aerospace and mechanical sciences from Princeton University.

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KATHLEEN R.MEYER has expertise in health physics and radio logic risk assessment. She is a principal of Keystone Scientific, Inc., and is currently involved in risk assessments for public health and the environment from radionuclides and chemicals at several U.S. Department of Energy sites. Other work includes an assessment of the interim radionuclide soil action levels adopted by the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency, and the Colorado Department of Health and Environment for cleanup at the Rocky Flats Environmental Technology Site. She has been a member of the National Council on Radiation Protection and Measurements Historical Dose Evaluation Committee. Dr. Meyer has authored or co-authored several peer-reviewed articles, including papers on cancer research, historical evaluation of past radionuclide and chemical releases, and risk assessment of radionuclides and chemicals. She holds a Ph.D. in radiological health sciences from Colorado State University.

FREDRICK J. MOODY is an expert thermal hydraulics and two-phase flow in nuclear power reactors. In 1999, he retired after 41 years of service at General Electric Company and 28 years as an adjunct professor of mechanical engineering at San Jose State University. Dr. Moody was the recipient of several prestigious career awards, including the General Electric Power Sector Award for Contributions to the State-of-the-Art for Two-Phase Flow and Reactor Accident Analysis. He has served as a consultant to the Nuclear Regulatory Commission's Advisory Committee on Reactor Safeguards, teaches thermal hydraulics for General Electric's Nuclear Energy Division, and continues to review thermal analyses for General Electric. Dr. Moody is a fellow of the American Society of Mechanical Engineers, which awarded him the George Westinghouse Gold Medal in 1980, and the Pressure Vessels and Piping Medal in 1999. He has also received prestigious career awards from General Electric and was elected to the Silicon Valley Engineering Hall of Fame. Dr. Moody was elected to the National Academy of Engineering in 2001 for pioneering and vital contributions to the safety design of boiling water reactors and for his role as educator. He has published three books and more than 50 papers. Dr. Moody holds a Ph.D in mechanical engineering from Stanford University.

TIMOTHY R.NEAL is an expert in weapons technology and explosives. He began his career at Los Alamos National Laboratory in 1967 and has led programs addressing weapon hydrodynamics, explosions inside structures and above ground, image analysts, and dynamic testing. He also has held several management positions within the Laboratory's nuclear weapons arena, including leadership of the Explosives Technology and Applications Division and of the Advanced Design and Production Technologies Initiative. He spearheaded Los Alamos' Stockpile Stewardship and Management Programmatic

Environmental impact Statement and helped establish the U.S. Department of Energy's new Stockpile Stewardship Program. More recently, he has served as a senior technical advisor to the U.S. Department of Energy on nuclear explosive safety, and he has worked closely with the Pantex Plant for nuclear weapons production in Amarillo, Texas, in establishing a new formal basis for operational safety. Dr. Neal has received four DOE excellence awards, including one for hydrodynamics, and authored various technical papers and reports as well as one book on explosive phenomena. He holds a Ph.D. in physics from Camegie-Mellon University.

LORING A.WYLLIE, JR. is an expert in structural engineering and senior principal of Degenkolb Engineers. His work has included seismic evaluations, analysis, and design of strengthening measures to improve seismic performance. He has performed seismic assessments and proposed strengthening solutions for several buildings within the U.S. Department of Energy weapons complex and for civilian buildings, some of which have historical significance. Mr. Wyllie's expertise is also recognized in several countries, including the former Soviet Union where he worked on an Exxon facility. Mr. Wyllie is a past president of the Earthquake Engineering Research Institute. His contributions to the profession of structural engineering were recognized by his election to the National Academy of Engineering in 1990 and his honorary membership in the Structural Engineers Association of Northern California. In recognition of Mr. Wyllie's expertise in concrete design and performance, the American Concrete Institute named him an honorary member in 2000. Mr. Wyllie also was elected an honorary member of the American Society of Civil Engineers in 2001. He holds a M.S. degree from the University of California, Berkeley.

PETER D.ZIMMERMAN is an expert in nuclear physics and terrorism. He is currently the chair of science and security and director of the Centre for Science & Security Studies at King's College in London. He previously served as the chief scientist of the Senate Foreign Relations Committee, where his responsibilities included nuclear testing, nuclear arms control, cooperative threat reduction, and bioterrorism. Previously, he served as science advisor for arms control in the U.S. State Department, where he provided advice directly to Assistant Secretary for Arms Control and the Undersecretary for Arms Control and International Security. His responsibilities included technical aspects of the Comprehensive Test Ban Treaty, biological arms control, missile defense, and strategic arms control. Dr. Zimmerman spent many years in academia as professor of physics at Louisiana State University. He is the author of more than 100 articles on basic physics as well as arms control and national security. His most recent publication is the monograph "Dirty Bombs: The Threat Revisited," which was published by the National Defense University in the Defense Horizons series. Dr. Zimmerman holds a Ph.D. in experimental nuclear and elementary particle physics from Stanford University and a Fil. Lic. degree from the University of Lund, Sweden. He is a fellow of the American Physical Society and a member of its governing council. He is a recipient of the 2004 Joseph A, Burton/ Forum award for physics in the public interest.

C

TOUR OF SELECTED SPENT FUEL STORAGE-RELATED INSTALLATIONS IN GERMANY

On April 25–28, 2004, six committee members visited spent fuel storage-related installations in Germany. The following is a summary of some of the pertinent information obtained from that trip.

Several organizations and individuals worked with committee staff to make this trip possible. The committee would especially like to acknowledge Alfons Lührmann and William McConaghy of GNB/GNSI (Gesellschaft für Nuklear-Behälter, mbH/General Nuclear Systems, Inc.), who organized site visits; Klaus Janberg (STP engineering); Michael Sailer, chairman of RSK (Reaktorsicherheitskommission—reactor safety commission); Holger Broeskamp manager of GNS (Gesellchaft für Nuklear-Service, mbH—Germany's nuclear industry consortium) and his staff; Wolfgang Sowa, managing director of GNB (Gesellschaft für Nuklear-Behälter, mbH) and his staff; Florentin Lange of GRS (Gesellschaft für Anlagen-und Reaktorsicherheit, mbH); and Hubertus Flügge, vice-president of the RWE Power AG plants in Lingen and his staff, who allowed the committee to visit the reactor building and the site's spent fuel storage facility.

C.1 GERMAN COMMERCIAL NUCLEAR POWER PLANTS

Germany currently has 18 operating commercial nuclear power reactors at 12 sites. Approximately one-third of the reactors are boiling water reactors (BWRs) and two-thirds are pressurized water reactors (PWRs).

The design for PWR plants is illustrated schematically in FIGURE C.1. It consists of a dome-shaped reactor building constructed of reinforced concrete and a spherical inner containment structure constructed of steel. The reactor core, spent fuel pool, and steam generators are located within the inner containment. The emergency core-cooling systems are located outside the inner containment but within the reactor building.

The German BWR reactor building design is generally similar to a PWR, However, the spent fuel pool is outside the inner containment structure but within the reactor building. The reactor building is also a different shape (rectangular or cylindrical).

There are three generations of commercial nuclear power plants in Germany, each having increasingly thick walls:

- First-generation plants have reactor building walls that are less than 1 meter thick. There are four plants of this type.
- Second-generation plants have reactor building walls that are slightly more than 1 meter thick. There are five plants of this type.
- Third-generation plants have reactor building walls that are about 2 meters thick, There are nine plants of this type.[1]

[1] The committee subgroup visited one of these plants (the Lingen power plant) during its tour.

Some first- and second-generation plants have independent emergency systems in a bunkered building that contains some safety trains and a control room. These systems are capable of delivering water to the reactor after an accident or attack if the pipe systems within the reactor building survive.

Second- and third-generation plants were designed to withstand the crash of military fighter jets. Second-generation plants were designed to withstand the crash of a Starfighter jet at the typical landing speed. Third-generation plants were designed to withstand the crash of a Phantom jet at the typical cruising speed. This is considered to be part of the "design basis threat" for nuclear power plants in Germany. This information on the design basis threat has been made available to the public by the German government.

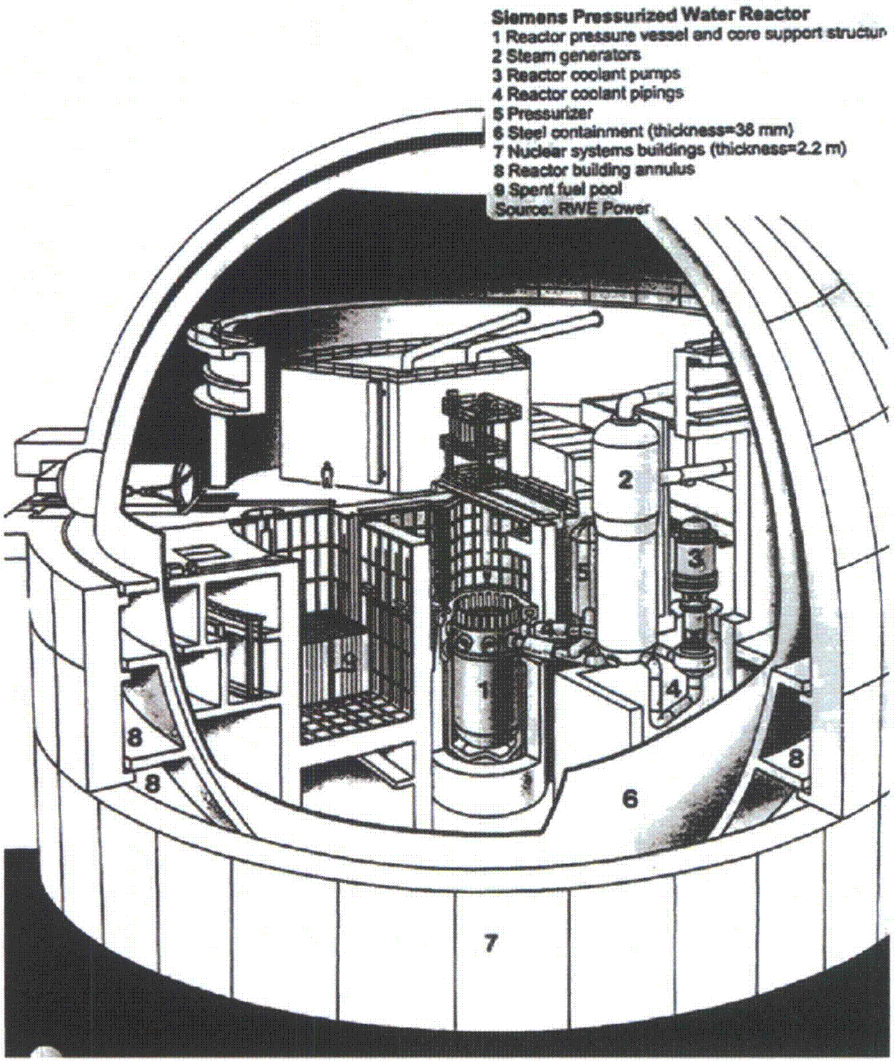

FIGURE C.1 Schematic illustration of the Lingen PWR power plant, a third-generation power plant design. SOURCE: RWE Power.

Plant operators must show that of the four safety trains (each train contains 50 percent of the safety system) at the plant, at least two will survive such a crash. The crash parameters (e.g,, aircraft type, speed, and angle) have been established by RSK. The crash parameters have been published and the public knows about them. Each plant must perform an independent analysis of each reactor building. Sometimes two separate analyses have to be provided for the same site if there are two or more reactors with different designs.

In 1998, the German government decided to phase out nuclear energy. Commercial nuclear plants will be allowed to generate an agreed-to amount of electricity before shutdown. Currently, the Lingen and the Neckarwestheim-2 plants have the highest remaining electricity production allowance and will be shutdown in 2021 or 2022, should no revision of this political decision be implemented.

C.2 SPENT FUEL STORAGE

Until recently, all spent fuel at German plants was stored in the reactor pools until it could be sent to Sellafield (U.K.) or La Hague (France) for reprocessing. In the 1980s, plants began to re-rack their spent fuel pools to increase storage capacities (the older German nuclear plants were designed to contain one full reactor core plus one third of a core). Regulators became concerned that the emergency cooling systems were not sufficient to handle the increased heat loads in spent fuel pools from this re-racking. Some plants added additional cooling circuits to address this concern. Only one power plant (an older plant at Obrigheim) has wet interim pool storage in a bunkered building.

A discussion of alternative spent fuel storage options began in 1979. A reprocessing plant had been proposed at Gorleben that would have had several thousand metric tons of pool storage. The German government concluded that while there were no major technical issues for reprocessing, wet fuel storage was a potential problem because cooling systems could be disrupted in a war. GNS decided to shift from wet to dry storage for centralized storage facilities.

There are two centralized storage facilities in Germany: Gorleben and Ahaus. Gorleben is designed to store vitrified high-level waste from spent fuel reprocessing and spent fuel from commercial power reactors. Ahaus is designed to store spent fuel from test reactors and other special types of fuel. Ahaus currently stores 305 casks of reactor fuel from the decommissioned Thorium High Temperature Reactor, three casks of PWR spent fuel from the Neckarwestheim site, and three casks of BWR spent fuel from the Gundremmingen site. The latter shipment produced large public demonstrations and required the deployment of 35,000 police officers to maintain security.

At the end of 2001, the German utility companies and the German federal government agreed to avoid all transport of spent fuel in Germany because of intense public opposition. The German government recently passed a law making it illegal to transport spent nuclear fuel to reprocessing plants in France and the United Kingdom after June 30, 2005. However, there is no legal restriction concerning the transport of spent fuel from power reactors to other destinations (e.g., to dry storage facilities). The government and power plant operators have negotiated an agreement to develop dry cask storage facilities at each of the 12 nuclear power plant sites to avoid the need for offsite spent fuel transport.

These dry cask storage facilities are to be constructed by 2006. They are licensed to store fuel for 40 years. There are three dry cask storage facility designs in Germany:

1. WTI design: The walls and roof are constructed of 80 and 50 centimeters, respectively, of reinforced concrete.
2. STEAG design: The wails and roof are constructed of 1.2 and 1.3 meters, respectively, of reinforced concrete. This design is used at the Lingen Nuclear Power Plant dry storage facility visited by the committee (FIGURE C.2).
3. GNK design: This is a tunnel design and is under construction at the Neckarwestheim nuclear power plant.

The use of reinforced concrete in these facilities was originally intended for radiation protection and structural support, not for terrorist attacks.

In 1999, RSK issued guidelines for dry storage, which were released in 2001 (RSK, 2001). Licensing a dry storage facility in Germany requires several safety demonstrations and analyses. As part of the licensing procedures for a storage facility, the license applicant must do independent calculations that demonstrate how the building features meet the safety standards and the design basis threat. This threat includes an armed group of intruders and the impact of a Phantom 2 military jet. It also includes a shaped charge. The scenario of a deliberate crash of a large civilian airplane has been considered and analyzed as part of the recent licensing of onsite dry storage facilities but is not established as part of the design basis threat. There are public hearings during which the license applicant explains the safety features of the storage facility. The public is aware of the design basis threat, and it is provided with the results of the analysis but not with the details.

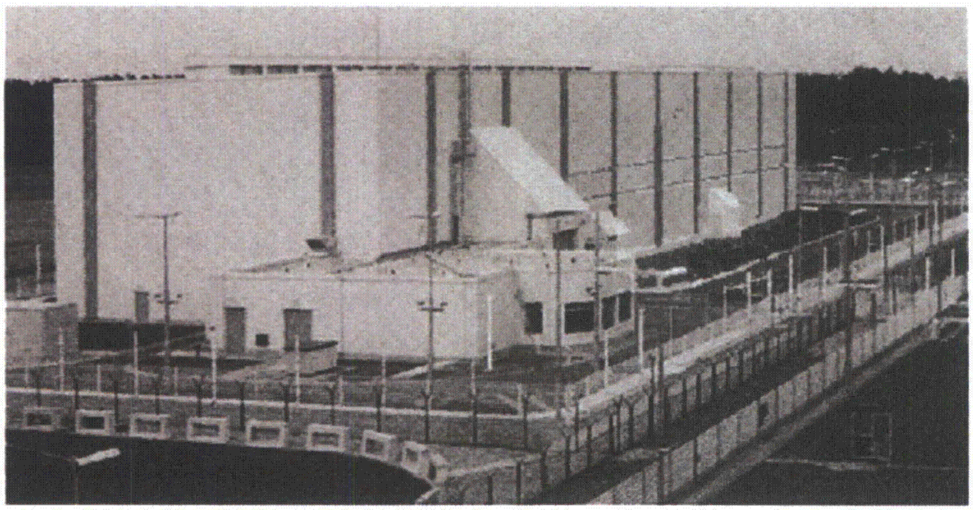

FIGURE C.2 Dry cask spent fuel storage building at the Lingen Nuclear Power Plant.
SOURCE: RWE Power.

There are six temporary (i.e., five- to seven-year) storage facilities in use at reactor sites until these dry cask storage facilities become available. The casks in these temporary storage facilities are stored horizontally and are protected by concrete "garages" designed to withstand the impact of a Phantom military jet.

Spent commercial fuel is stored in CASTOR® casks (FIGURE C.3) that were originally designed and developed by the German utility-owned company GNB.[2] These casks can store either PWR or BWR spent fuel assemblies. The design consists of a ductile cast iron cylindrical cask body with integral circumferential fins machined into the outer surface to maximize heat transfer; inside, the spent fuel assemblies are inserted in a borated stainless steel basket. The cask has a double-lid system that is protected by a third steel plate. The cask complies with the international regulations of the International Atomic Energy Agency (IAEA) as a type B(U) package.

Spent fuel is typically cooled for five years in a pool before it is put in dry cask storage; some other custom-made cask designs can hold fuel that has been cooled for shorter (minimum two years) or longer times depending on the fuel characteristics and fuel burn-up. Current fuel burn-ups in Germany (52 to 55 gigawatt-days per metric ton) are similar to those in the United States.

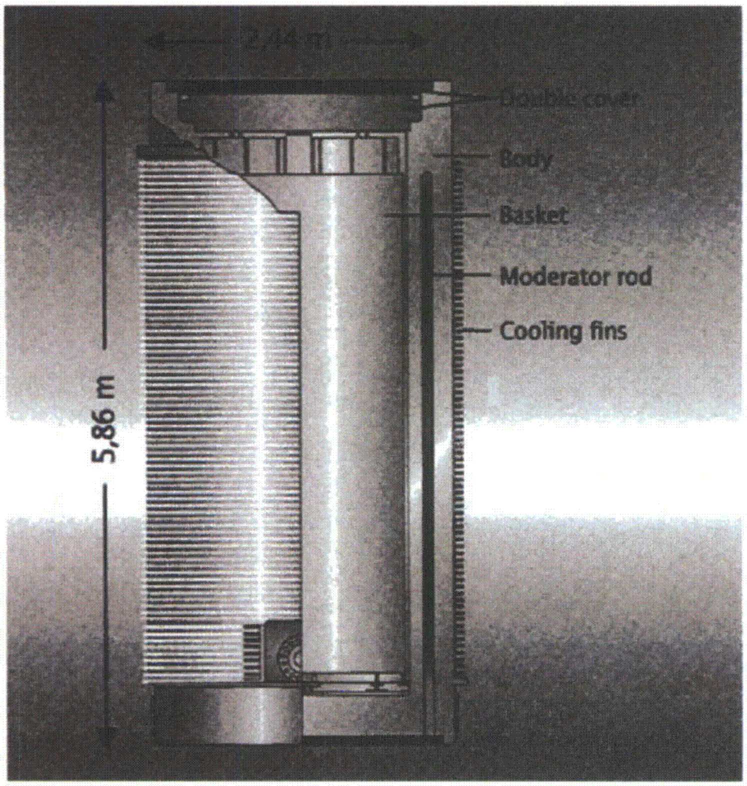

FIGURE C.3 Typical features of a CASTOR cask used at the Lingen Nuclear Power Plant.
SOURCE: RWE Power AG Lingen Nuclear Power Plant.

[2]Gesellschaft für Nuklear-Behälter, mbH.

C.3 RESPONSE TO THE SEPTEMBER 11, 2001, TERRORIST ATTACKS IN THE UNITED STATES

The September 11, 2001, terrorist attacks on the United States caused the German government to reassess the security of its nuclear power plants and spent fuel storage facilities. RSK held meetings starting in October 2001 to discuss the implications of the September 11 attacks for German commercial nuclear power plants. It issued a short statement recommending that an analysis be carried out on each plant to assess its vulnerability to September 11-type attacks. These analyses have not yet been undertaken. Plant operators assert that terrorist attacks are a general risk of society and should be treated like attacks on other infrastructure (e.g., chemical facilities). The Länder (state) governments, which are responsible for licensing commercial power plants in Germany, do not require these analyses. RSK recommended that the federal government develop a checklist for such an analysis, but this also has not been done.

A general analysis of the impact of the different civilian aircraft on commercial nuclear plants was requested by BMU[3] and has been carried out by GRS.[4] The result of the discussions between RSK and BMU on the basis of this report was that plant specific sensitivity analyses are needed. GRS was also involved in the framing of the recent German licensing process in the analysis of the consequences of civilian aircraft attacks on STEAG-and WTI-design spent fuel storage facilities using three sizes of aircraft (ranging from Airbus A320- to Boeing 747-size aircraft).

C.4 TESTS ON GERMAN CASKS

The casks that are used in German dry cask storage facilities have been subjected to several tests that simulate accidents and terrorist attacks. The following types of tests were performed on these casks or cask materials.

Airplane crash test simulations with military aircraft (Phantom type) are part of the licensing requirements for both casks and storage facilities. Between 1970 and 1980 a number of tests on storage casks were carried out at the Meppen military facility in Germany. A one-third scale model of a GNB cask was used to simulate the impact of a turbine shaft of a military aircraft using a hollow-tube projectile. Two different impact orientations were used: perpendicular to upright cask body (lateral impact) and perpendicular to center of lid system. The projectile completely disintegrated in the test, but the cask sustained only minor damage.

The jet aircraft tests were carried out because of safety concerns, but after September 11, 2001, intentional crashes of aircraft also were considered. Investigations by BAM (Bundesanstalt für Materialforschung und -prüfung) and GRS concluded that CASTOR-type casks would maintain their integrity when intentionally hit by a commercial aircraft.

[3] Bundesministerlum für Umwelt Naturschutz and Reaktorsicherheit (Federal Ministry for Environment, Nature Protection, and Nuclear Safety and Security).

[4]Gesellschaft für Anlagen- und Reaktorsicherheit (GRS), mbH (Company for Installation and Reactor Safety). GRS is Germany's main research institution on nuclear safety. It is an independent, nonprofit organization, founded in 1977, and has about 450 employees. GRS funds its work through research contracts. Some have compared GRS to Sandia National Laboratories in the United States.

Other types of terrorist attacks have been a long-standing concern to the German government because of terrorism activities in Europe in the 1970s and 1980s. A series of tests simulating terrorist attacks on casks were done in Germany, France, the United States (for the German government), and Switzerland (for the Swiss government). Additional tests may have been done that are not publicly acknowledged.

In 1979–1980 at the German Army facility in Meppen, a "hollow charge" (i.e., shaped charge) weapon was fired at a ductile cast iron plate and fuel assembly dummy to simulate a CASTOR cask. The cask plate was perforated but release fractions from the fuel assembly were not examined. From this experiment, the German government concluded that the wall thickness of the cask should not be less than 300 millimeters.

Other tests were carried out at the Centre d'Etude de Gramat in France in 1992 on behalf of the Germany Federal Ministry of Environment, Nature Protection and Nuclear Safety (BMU) (Lange et al,, 1994), These tests involved shaped charges directed at a CASTOR cask (type CASTOR Ila, the cask was one third of the regular length) filled with nine fuel element dummies with depleted uranium. The fuel rods were pressurized to 40 bars to simulate fuel burn-up, but the cask interior was at atmospheric pressure or at reduced pressure of 0.8 bar. The shaped charge perforated the cask and penetrated fuel elements. This damaged the fuel and resulted in the release of fuel particles from the cask.

These particles were collected, and their particle size distribution was measured. About 1 gram of uranium was released in particles of less than 12.5-microns aerodynamic diameter, and 2.6 grams of uranium were released in particles with a size range between 12.5 and 100 microns. If the pressure inside the cask was reduced to 0.8 bar (to simulate the conditions during interim storage of spent fuel in Germany), the releases were reduced by two-thirds: 0.4 gram for particle sizes less than 12.5 microns and about 0.3 gram for particles between 12.5 and 100 microns.

In 1998, a demonstration was carried out at the Aberdeen Proving Ground in the United States using an anti-tank weapon on a CASTOR cask. The purpose of this demonstration was to show that a concrete jacket on the exterior of the cask could prevent perforation. The weapon was first fired at the cask without the jacket. It perforated the front wall of the cask. The concrete Jacket was effective in preventing perforation of the cask. Committee members saw a specimen of this cask at the GNB workshop (see FIGURE C.4).

Also in 1999, explosion of a liquid gas tank next to a cask was performed by the German BAM (Federal Office of Material Research and Testing) to study the effect of accidents involving fire or explosions in the vicinity of the cask during transportation or storage. The gas tank and the CASTOR cask were initially about 8 feet (2.5 meters) apart. Explosion of the tank generated a fire ball 330 to 500 feet (100 to 150 meters) in diameter. The explosion projected the cask 23 feet (7 meters) away and tilted it by 180 degrees, causing it to hit the ground on the lid side. Examination after the explosion showed no change in the containment properties of the lid system.

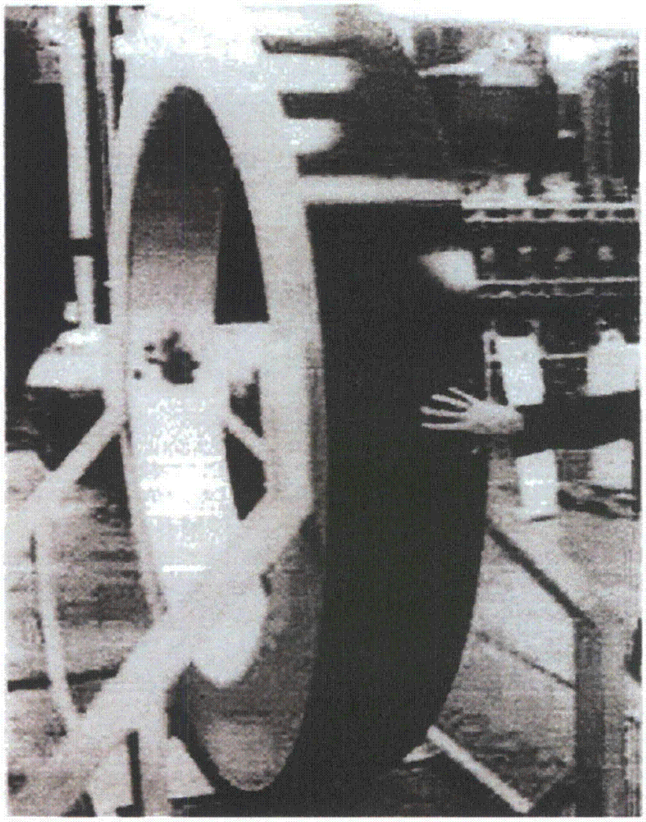

FIGURE C.4 Section of a CASTOR cask showing the perforation made by a shaped charge at the Aberdeen Proving Ground. SOURCE: Courtesy of GNB/GNSI.

REFERENCE

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D

HISTORICAL DEVELOPMENT OF CURRENT COMMERCIAL POWER REACTOR FUEL OPERATIONS

There are 103 commercial power reactors operating in the United States at this time. Almost all of them are operating with spent fuel pools that are too small to accommodate cumulative spent fuel discharges. This short appendix was prepared to provide a historical background for power reactor fuel operations and pool and dry-cask storage of spent fuel.

D.1 DESIGN FOR A CLOSED FUEL CYCLE

The first large generation of commercial reactors in the United States were almost all light water reactors (LWRs), that is, nuclear reactors that use ordinary water to cool the core and to moderate the neutrons emitted by fission. The hydrogen atoms in the water coolant moderate, or slow down the fission-emitted neutrons to an energy level that is more likely to cause fission when the neutron strikes a fissile atom. These reactors were designed, developed, and licensed in the 1960s and 1970s, although many were not completed until the 1980s. Their design power output increased rapidly, as it did for non-nuclear power plants, in order to achieve economies of scale. Thus, the earlier plants in this generation were designed to produce 500–900 megawatts of electrical power (MWe) while later units increased to 1000–1200 MWe. The number of LWRs built and ordered by the U.S. industry began to approach 200. All of these plants were being designed for a closed fuel cycle, that is, for the uranium oxide fuel, enriched to 2–5 percent uranium-235, to be loaded and "burned" to a level of 20–30 gigawatt-days per metric ton of uranium (GWd/MTU), then reprocessed in commercial plants to separate the still usable fissionable, or fissile, materials in the spent fuel from the radioactive waste. The reprocessing plants would recover the fissile plutonium-239 formed from uranium-238 during reactor operations and residual fissile uranium-235 for use as fuel in LWRs and later in breeder reactors (USNRC, 1976).

By the mid-1970s commercial reprocessing plants were built, under construction, or planned in New York, Illinois, South Carolina, and Tennessee, with a combined projected capacity to reprocess more than 6000 MTU of spent fuel per year. For comparison, a large LWR discharges about 20 MTU of spent fuel at a refueling. By this time the price of fresh uranium was dropping and the cost of fuel reprocessing made it difficult for recycle fuel to compete with fresh fuel. Also, there was controversy about the risk of fissile material diversion if recycled plutonium was moved in commercial traffic. Both existing fuel reprocessing plants withdrew from licensing for technical reasons and then, on April 7, 1977, President Carter issued a policy statement that "we will defer indefinitely the commercial reprocessing and recycling of the plutonium produced in the U.S. nuclear power programs." The statement went on to say: "The plant at Barnwell, South Carolina, will receive neither federal encouragement nor funding for its completion as a reprocessing facility." After consultation with the White House, the U.S. Nuclear Regulatory Commission (USNRC) terminated its Final Generic Environmental Statement on the Use of Recycled Plutonium in Mixed Oxide Fuel in Light-Water Cooled Reactors (GESMO) proceedings.

Thus, the U.S. nuclear industry was immediately changed from a closed fuel cycle, with recycle, to an open or once-through fuel cycle with the fuel loaded into the reactor in several consecutive locations to obtain maximum economic use of the fuel before it was finally removed as waste. The USNRC changed the legal definition of high-level radioactive waste to include the high-level waste from both nuclear fuel reprocessing and spent nuclear fuel.

For this study, the significance of this closed fuel cycle design is that this entire generation of more than 100 reactors was designed with small spent fuel pools, relying on prompt shipment away from the reactor to the reprocessing plant to make room for later discharges of spent fuel. Early spent fuel shipping casks were being designed with active cooling systems to support shipment of fuel less than a year out of the reactor to a reprocessing plant. BOX D.1 discusses the spent nuclear fuel at reprocessing plants. Supplementary wet and dry storage systems had to be developed to receive the older spent fuel to make room for fresh spent fuel from the reactor. Many plants had to remove and modify the storage racks in their spent fuel pools to accommodate more spent fuel in the pool itself until licensed supplementary systems were available.

D.2 RETRENCHMENT OF U.S. REACTOR PLANS

As noted in Section D.1, in the 1970s the United States was building reactors at a high rate. Then, in the late 1970s, three factors produced a retrenchment in power reactor plans: rising interest rates, reversal of the U.S. fuel reprocessing policy, and the Three Mile Island-2 accident.

D.2.1 Effect of Interest Rates

Commercial power reactors have characteristically high initial capital costs. The regulated public utilities have had to raise the capital with various debt instruments; to build, license, and operate the finished plant for a time before it can be declared commercial; and to change the electricity rates charged consumers to retire the debt on the capital cost. The soaring interest rates in the United States during the late 1970s drove the costs of new nuclear plants that were under construction to extreme heights. This, combined with slackening demand for electricity, led to the cancellation of many plants, some even in advanced stages of construction.

D.2.2 Effect of Reversal of U.S. Fuel Reprocessing Policy

President Carter enunciated a change in U.S. policy for reprocessing of spent nuclear fuel in early 1977. Those reactors then operating and those under construction had to begin modifying their reactor fuel cycle design to go from the closed (reprocessing) cycle to a "once-through" fuel cycle. This induced the designers to go to higher levels of uranium-235 enrichment in the new fuel, but still within the 5 percent licensing limit. It also induced the designers to revise the core loading and operating plans in order to burn or use the fissile content of the fuel to the greatest extent economically possible since the fissile residue could not be retrieved by reprocessing. As a result, spent fuel burnup levels rose to levels that are now almost double the 20–30 GWd/MTU characteristic of the original closed fuel cycle. This results in an increase in the decay-heat power of the spent fuel assembly by the time it is put into the spent fuel pool.

BOX D.1 SPENT FUEL AT NUCLEAR FUEL REPROCESSING PLANTS

Up until the mid-1970s the commercial nuclear industry was expected to operate several nuclear fuel reprocessing plants to recover fissile plutonium from virtually all of the commercial spent fuel from U.S. reactors. These plants would use aqueous reprocessing methods developed by the Atomic Energy Commission (AEC). The recovered plutonium was to be used as mixed oxide fuel (PuO2 and UO_2) in water reactors and, later, as fuel in breeder reactors. Each reprocessing plant had one or two storage pools to receive and store the fuel temporarily until it was reprocessed. No long-term storage of the spent fuel from commercial reactors was planned. Only two commercial reprocessing sites have received spent fuel, West Valley, New York, and G.E.-Morris, Illinois,

The first commercial reprocessing plant began operations by the Nuclear Fuel Services Company on a site in West Valley, New York, owned by the State of New York. The State of New York licensed a low-level radioactive waste disposal site adjacent to the reprocessing plant. The West Valley plant had a reprocessing capacity of about 1 metric ton of uranium (MTU) per day. It operated at reduced capacity because there was not yet much commercial spent fuel to reprocess. In fact, about half of the spent fuel reprocessed there was from the last in the series of plutonium production reactors, the N-Reactor, at the AEC site in Hartford, Washington. This spent fael was provided to the West Valley plant to keep it working in the early days when little commercial spent fuel was available. The West Valley plant suspended operations in 1972 in order to expand its capacity to about 3 MTU per day. The work and the re-licensing effort went on until 1976 when the company withdrew its application for the new license and terminated reprocessing operations. The U.S. Department of Energy (DOE) took over the task of high-level radioactive waste retrieval and decommissioning under the West Valley Demonstration Project Act of 1980. About 137 MTU of commercial spent fuel remaining in the cooling pool was returned to its owners (USNRC, 1987). In 2003 the last of this spent fuel, about 25 MTU in two shipping casks, was shipped to the DOE-Idaho National Lab where it remains in dry storage in those casks.

The General Electric Company built a nuclear fuel reprocessing plant at Morris. Illinois, near the Dresden Nuclear Power Station. The plant was expected to reprocess 3 MTU per day. When the G.E.-Morris plant was in its final testing in 1975, the company determined that its performance would not be acceptable without extensive modifications. The request for a reprocessing plant operating license was withdrawn and the plant was licensed only to possess the spent nuclear fuel that it was under contract to reprocess. After modifying the storage system in its below-grade pool to hold more spent fuel, G.E.-Morris has received and stores 700 MTU of spent fuel for various owners.

Power reactors are refueled, and spent fuel is discharged to the storage pool, every one to two years. The decay-heat power of recently discharged spent fuel dominates the heat load of all the spent fuel in the pool, both freshly discharged and old, since the decay heat from a spent fuel assembly decreases by one to two orders of magnitude in the first year after it is removed from the reactor increasing the capacity of the spent fuel pool by reracking, that is, modifying the storage racks to provide for closer spacing of the fuel assemblies,[1] allows older fuel to be accumulated in the pool rather than being removed for shipment or dry storage. Re-racking can make it more difficult to cool the freshly discharged fuel if there is catastrophic loss of the fuel pool water.

D.2.3 Effect of the Three Mile Island Accident

The final factor driving the retrenchment of the nuclear power industry was the Three Mile Island-2 (TMI-2) accident that occurred on March 28, 1979, in Pennsylvania (Walker, 2004). In that accident a small failure in the reactor coolant system was compounded by operator errors to result in catastrophic damage; a partial core melt occurred. The inability of the operators to understand and control the events, and the confusion among the state, the USNRC, and other responsible agencies about public protection had a devastating effect on public trust in the safety of nuclear power. The USNRC escalated safety requirements after the TMI–2 accident. These new requirements substantially modified the operation of licensed plants, delayed completion of new plants, and further increased their construction costs. The accident also resulted in the retrenchment of nuclear power in the 1980s and led to the cancellation of many plants, decommissioning of some plants, and the sale of some plants to other owners. The fleet of operating U.S. reactors was reduced to the presently operating 103 described here.

D.3 COMMERCIAL POWER REACTORS CURRENTLY OPERATING IN THE UNITED STATES

All of the commercial power reactors operating in the United States are light water reactors. BOX D.2 describes the LWRs that are currently operating in the United States.

D.3.1 Pressurized Water Reactors

About two-thirds of the U.S. reactors are pressurized-water reactors (PWRs), dual-cycle plants in which the primary cooling water is kept under a pressure of about 2000 pounds per square inch absolute (psia) as it circulates to remove fission and decay heat from the reactor fuel in the core and carry that energy to the steam generators, to generate steam in the lower-pressure secondary loop. The reactor, primary loop piping, and steam generators are all located in the containment structure; the steam lines penetrate the containment carrying the steam to the turbine to generate electrical power.

About one-third of the U.S. reactors are boiling-water reactors (BWRs), single-cycle plants in which the primary coolant of the reactor core is operated at about 1000 psia as it recirculates within the reactor core. The fission and decay heat generated in the core cause a substantial amount of the reactor coolant water to boil into steam that passes out directly from the reactor pressure vessel to the turbine-generator system. Plant differences stem initially from the different designs of the nuclear steam system supplier, the different designs of the architect-engineers that built the plants, and the owners that often specified additional modifications.

[1]The capacity of spent fuel pools has typically been increased by replacing the original storage racks with racks that hold the spent fuel assemblies closer together. The fuel assembly channels in these replacement racks typically have solid metal walls with neutron-absorbing material for nuclear safety reasons. This configuration inhibits water or air circulation more than the earlier configuration.

BOX D.2 U.S. NUCLEAR POWER PLANTS

In the United States, 32 utility companies are licensed to manage the 103 operating reactors. There are also 27 shutdown reactors in storage or decommissioning. These reactors are situated at 65 nuclear power plant sites across the United States; a plant site may have 1, 2, or 3 reactors.

The fleet of 103 operating reactors in the United States is composed of the following:

- 69 pressurized water reactors (PWRs) and
- 34 boiling water reactors (BWRs).

The containment design for PWRs is divided into dry (56 reactors), ice condenser (9 reactors), and sub-atmospheric (4 reactors) containments. Among the BWR containment designs, 22 reactors are of design type Mark I, 8 of Mark II, and 4 of Mark III,

The PWRS operating in the United States were designed by three different nuclear steam system suppliers; Westinghouse Electric, Combustion Engineering, and Babcock & Wilcox. Most PWRs have what are called farge dry containments, that is, containment structures of about 2 million cubic feet volume that can absorb the rapid release of steam and hot water from a postulated rupture of the primary coolant system without exceeding an internal pressure of about 4 atmospheres. FIGURE D.1 illustrates a PWR in a large dry containment. Some PWR containments are essentially as large but use ventilation fans to maintain the initial containment pressure mildly sub-atmospheric to provide an additional pressure margin. Finally, one set of nine Westinghouse PWRs uses ice-condenser containment structures, in which the containment has about the same pressure capability but is smaller, relying on massive baskets of ice maintained in the containment to condense steam releases and mitigate the pressure surge.

D.3.2 Boiling Water Reactors

The BWRs in operation today were designed by the General Electric Company. They all use pressure suppression containments, two-chamber systems with the reactor located in a dry well that is connected to a wet well containing a large pool of water.

In the event of a rupture of the reactor system in the dry well, the steam and hot water released are channeled into the water in the wet well, condensing and cooling the steam to mitigate the pressure surge. BOX D.2 lists the three successive generations of BWR containment design, and the number of each still operating. FIGURE D.2 illustrates three types of BWR containments: Mark I. Mark II, and Mark III, The Mark I containment is the most common type with 22 in operation. The reactor pressure vessel, containing the reactor core is located in a dry well of the containment in the shape of an inverted incandescent light bulb.

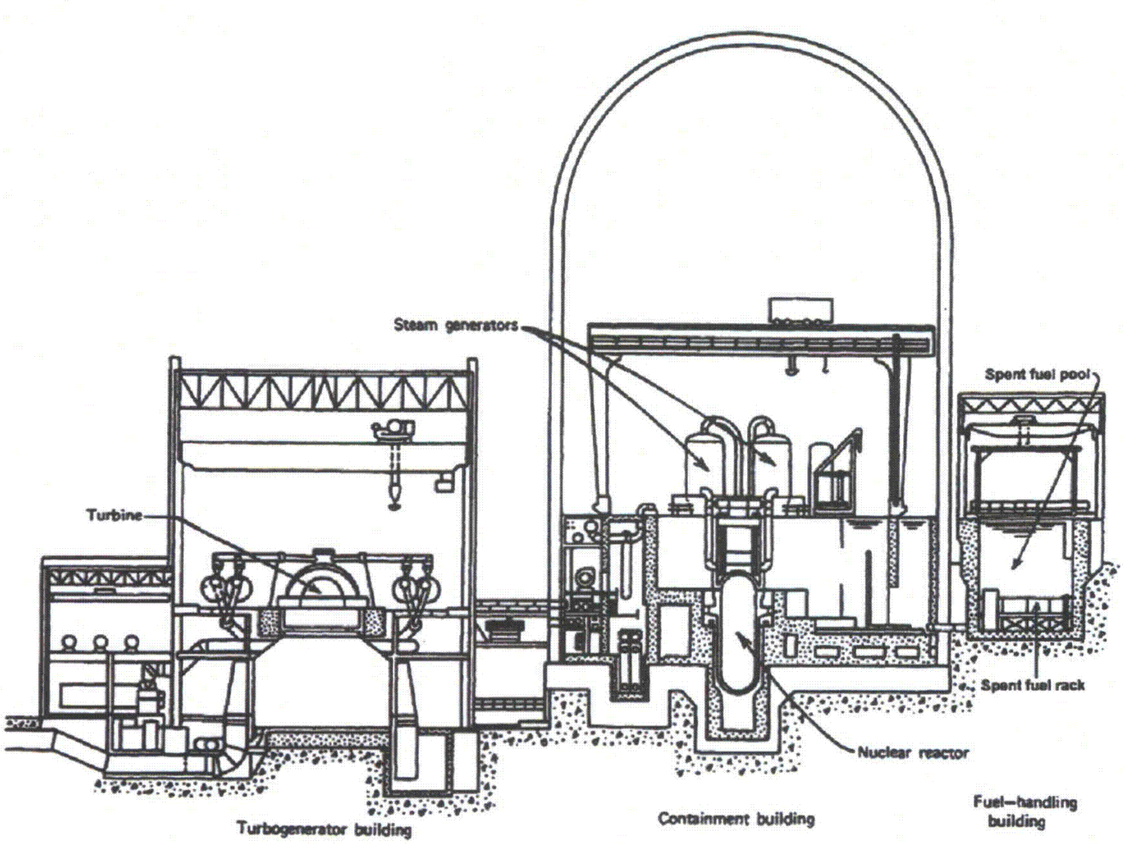

FIGURE D.1 A PWR in a large dry containment. SOURCE: Modified from Duderstadt and Hamilton (1976, Figure 3–4).

The dry well is connected by large ducts to the wet well, a large toroidal (i.e., doughnut-shaped) part of the containment that is partially filled with water. Gas and steam releases from an accident in the dry well would be passed through the connecting ducts into the water in the wet well, cooling the gas and condensing the steam to mitigate the accident pressure rise in the containment. The containment building Mark II BWR is similar to the Mark I except that in the Mark II containment the conical dry well is directly above the cylindrical wet well. Nine Mark II reactors are still operating in the United States. In the Mark III, the dry well around the reactor vessel is vented to the top of a cylindrical wet well that surrounds it.

Four Mark III BWRs are currently operating. The entire dry well-wet well system is contained within a large steel containment shell and a concrete shield building.

D.3.3 Reactor Fuel and Reactor Control

TABLE D.1 presents the range of dimensions and weights for a wide variety of the LWR fuel assemblies used in the operating reactors. The spent fuel pools and the dry storage systems used at a reactor must be tailored to the specific fuel design for that reactor.

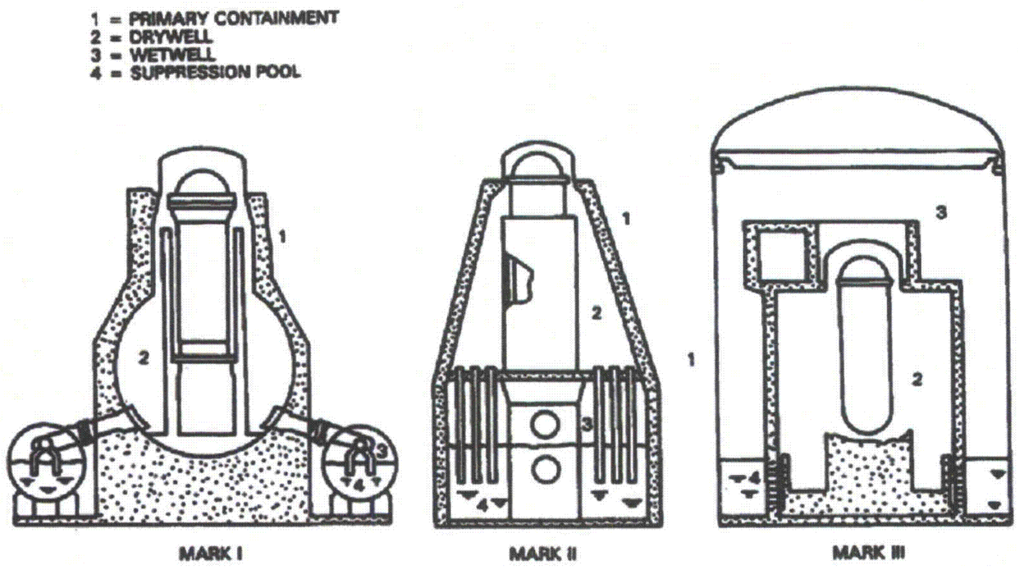

FIGURE D.2 Three types of BWR containment system: Mark I, Mark II, and Mark III. SOURCE: Modified from Lahey and Moody (1993, Figure 1–9).

The fission process is controlled by the reactor operators through the use of neutron-absorbing materials. The primary control is an array of control rods or blades that can be withdrawn from the core to the degree needed. In the PWRs, the control rods are moved within selected empty tubes within the assembly. In the BWRs, cruciform (cross-shaped) control blades are moved across the faces of the fuel assembly, typically narrower than those in a PWR fuel assembly. Reactor fuel designers also use burnable poisons within the fuel assembly to control the fission process. These poisons are placed in appropriate amounts within the fuel assembly so that they burn away, making the fuel assembly more reactive, as the continued fission process is making it less reactive. PWRs also use neutron control by dissolving neutron-absorbing sodium borate in the reactor coolant, gradually lowering the concentration from the peak after refueling to the minimum before the next refueling.

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TABLE D.1 Range of Dimensions and Weights for Light Water Reactor Fuel Assemblies Used in Operating Reactors in the United States.

Physical Characteristics of Typical LWR Fuel Assemblies

Reactor Type	BWR	BWR	PWR	PWR	PWR	PWR	PWR	PWR	PWR	PWR	PWR	PWR
Fuel Designer	GE	GE	B&W	B&W	GE	GE	W	W	W	W	W	W
Fuel Rod Array	7x7	8x8	15x15	17x17	14x14	16x16	14x14	14x14	15x15	15x15	17x17	17x17
Active Fuel Length (in.)	144	144	144	143	137	150	120	144	121	144	144	168
Nominal Envelope (in.)[2]	5.438	5.47	8.536	8.536	8.25	8.25	7.763	7.763	8.449	8.426	8.426	8.426
Fuel Assembly Length (in.)	176	176	166	166	157	177	137	161	137	160	160	—
Weight (lbs.)	600	600	1,516	1,502	581 kg	—	501 kg	573 kg	594 kg	654 kg	665 kg	—
Fuel Rod												
Number	49	63	208	264	164	224-236	180	179	204	204	264	264
Length (in.)	163	—	153	—	147	161	127	152	127	152	152	—
Pitch, Square (in.)	0.738	0.640	0.568	0.501	0.580	0.506	0.556	0.556	0.563	0.563	0.496	0.496
O.D. (in.)	0.570	0.493	0.430	0.379	0.440	0.382	0.422	0.422	0.422	0.422	0.374	0.360
Clad Thickness (mils.)	35.5	34	26.5	23.5	26	25	16.5	24.3	16.5	24.3	22.5	22.5
Clad Material	Zr 2	Zr 2	Zr 4	Zr 4	Zr 4	Zr 4	sst	Zr 4	sst	Zr 4	Zr 4	Zr 4
Pellet O.D. (in.)	0.488	0.416	0.370	0.3232	0.3795	0.325	0.3835	0.3659	0.3835	0.3659	0.3225	0.3088
Pellet Length (in.)	—	—	—	0.375	0.650	0.390	0.600	0.600	0.600	0.600	0.530	0.530
Gap, Radial (mils.)	5.5	4.5	3.5	3.1	4.3	3.5	2.8	3.8	2.8	3.8	3.3	3.3
Density (STD)	—	—	92.5-95.0	93.5-95.0	93.0-95.0	94.75	93.0-94.0	92.0	93.0-94.0	92.0	95.0	95.0
Poison	Gd_2O_3	Gd_2O_3	None	None	B_4C/Al_2O_3	B_4C/Al_2O_3	—	—	—	—	—	—
Nonfueled Rods												
Number	0	1	17	25	6	6	16	17	21	21	25	25
Material	—	Zr 2	Zr 4	Zr 4	Zr 4	Zr 4	304 sst	Zr 4	304 sst	Zr 4	Zr 4	Zr 4
Spacer Grids												
Number	7	7	8	8	8	12	—	—	—	—	—	—
Material	Inconel X	Inconel X	Inconel 718	Inconel 718	Zr 4	Zr 4	—	—	—	—	—	—

SOURCE: American Nuclear Society (1988).

E

GLOSSARY

Actinide: Any of a series of chemically similar radioactive elements with atomic numbers ranging from 89 (actinium) through 103 (lawrencium). This group includes uranium and plutonium.

Alpha particle: Two neutrons and two protons bound as a single particle (a helium nucleus) emitted from certain radioactive isotopes when they undergo radioactive decay.

Bare-fuel cask: See *Cask.*

Beta particle: A charged particle consisting of a positron or electron emitted from certain radioactive isotopes when they undergo radioactive decay.

Beyond-design-basis accidents: Technical expression describing accident sequences outside of those used as design criteria for a facility. Beyond-design-basis accidents are generally more severe but are judged to be too unlikely to be a basis for design.

Boiling water reactor (BWR): A type of nuclear reactor in which the reactor's water coolant is allowed to boil to produce steam. The steam is used to drive a turbine and electrical generator to produce electricity.

Burn-up: Measure of the number of fission reactions that have occurred in a given mass of nuclear fuel, expressed as thermal energy released multiplied by the period of operation and divided by the mass of the fuel. Typical units are megawatt-days per metric ton of uranium (MWd/MTU) or gigawatt-days per metric ton of uranium (GWd/MTU).

Canister-based cask: See *Cask*

Cask: Large, typically cylindrical containers constructed of steel and/or reinforced concrete that are used to store and/or transport spent nuclear fuel. Casks designed for storage of spent nuclear fuel can be of two types: "bare-fuel" or "canister-based." In bare-fuel casks, spent fuel is stored in a fuel basket surrounded by a heavily shielded and leak-tight container. In canister-based casks, the fuel is enclosed in a leak-tight steel cylinder, called a canister, which has a welded lid. The canister is placed in a heavily shielded cask overpack. Casks can be single-, dual-, or multiple-purpose, indicating that they can be used, respectively, for storage (also called storage-only casks), for storage and transportation, and for storage, transportation, and geologic disposal. There are no true multi-purpose casks for spent fuel currently available on the market.

Cesium-137: Radioactive isotope that is one of the products of nuclear fission

Chain reaction: A series of fission reactions wherein the neutrons released in one fission event stimulate the next fission event or events.

Cladding: Thin-walled metal tube that forms the outer jacket of a nuclear fuel rod. It prevents corrosion of the nuclear fuel and the release of fission products into the coolant. Zirconium alloys (also called *zircaloy*, see below) are common cladding materials in commercial nuclear fuel.

Conduction: In the context of heat transfer, the transfer of heat within a medium through a diffusive process (i.e., molecular or atomic collisions),

Containment structure: A robust, airtight shell or other enclosure around a nuclear reactor core to prevent the release of radioactive material to the environment in the event of an accident.

Convection: Heat transfer by the physical movement of material within a fluid medium.

Cooling time: The amount of time elapsed since spent fuel was discharged from a nuclear reactor.

Core: That portion of a nuclear reactor containing the fuel elements.

Criticality: Term used in reactor physics to describe the state in which the number of neutrons released by the fission process is exactly balanced by the neutrons being absorbed and escaping the reactor core. At Criticality, the nuclear fission chain reaction is self-sustaining,

Decay heat: Heat produced by the decay of radioactive isotopes contained in nuclear fuel.

Decay, radioactive: Disintegration of the nucleus of an unstable element by the spontaneous emission of charged particles (alpha, beta, positron) or photons of energy (gamma radiation) from the nucleus, spontaneous fission, or electron capture.

Depleted uranium: Uranium enriched in the element uranium-238 relative to uranium-235 compared to that usually found in nature. Also, uranium in which the uranium-235 content has been reduced through a physical process.

Design basis phenomena: Earthquakes, tornadoes, hurricanes, floods, and other events that a nuclear facility must be designed and built to withstand without loss of systems, structures, and components necessary to ensure public health and safety.

Design basis threat: In the context of this study, hypothetical ground assault threat against a commercial nuclear power plant. Some generic elements of the design basis threat are described in Title 10, Section 73.1(a) of the Code of Federal Regulations (10 CFR73.1(a)).

Dirty bomb: See *Radiological Dispersal Device.*

Dry storage: Out-of-water storage of spent nuclear fuel in heavily shielded casks.

Drywell: The containment structure enclosing a boiling water nuclear reactor vessel. The drywell is connected to a pressure suppression system and provides a barrier to the release of radioactive material to the environment under accident conditions.

Dual-purpose cask: See *Cask.*

Fissile material: Material that undergoes fission from thermal (slow) neutrons. Although sometimes used as a synonym for fissionable material, the term "fissile" has acquired this more restricted meaning in nuclear reactor technology. The three primary fissile materials are uranium-233, uranium-235, and plutonium-239.

Fission: Splitting of a nucleus into at least two nuclei accompanied by the release of neutrons and a relatively large amount of energy.

Fissionable: Material that is capable of undergoing fission from fast neutrons. Fission products: Nuclei resulting from the fission of elements such as uranium.

Fuel assembly: A square array of fuel rods.

Fuel pellet: A small cylinder of uranium usually in a ceramic form (uranium dioxide, UO_2), typically measuring about 0.4 to 0.65 inches (1.0 to 1.65 centimeters) tall and about 0.3 to 0.5 inch (0.8 to 1.25 centimeters) in diameter.

Fuel reprocessing: Chemical processing of reactor fuel to separate the unused fissionable material (uranium and plutonium) from waste material,

Fuel rod: Sometimes referred to as a *fuel element* or *fuel pin.* A long, slender tube that holds the uranium fuel pellets. Fuel rods are assembled into bundles called *fuel assemblies.*

Gamma ray: Electromagnetic radiation (high-energy photons) emitted from certain radioactive isotopes when they undergo radioactive decay.

Half-life (radioactive): Time required for half the atoms of a radioactive substance to undergo radioactive decay. Each radioactive isotope has a unique half-life. For example, cesium-137 decays with a half-life of 30.2 years, and plutonium-239 decays with a half-life of 24,065 years.

Independent Spent Fuel Storage Installation (IS-FSI): A facility for storing spent fuel in wet pools or dry casks as defined in Title 10, Part 72 of the Code of Federal Regulations.

Irradiation: Process of exposing material to radiation, for example, the exposure of nuclear fuel in the reactor core to neutrons.

Isotope: Elements that have the same number of protons but different numbers of neutrons. For example, uranium-235 and uranium-238 are different isotopes of the element uranium.

Loss-of-pool-cootant event: A postulated accidental or malevolent event that results in a loss of the water coolant from a spent fuel pool at a rate in excess of the capability of the water makeup system to restore it.

Megawatt: One million watts.

MELCOR: A computer code developed by Sandia National Laboratories for use in analyzing severe reactor core accidents. The code has been adapted to model fluid flow, heat transfer, fuel cladding oxidation kinetics, and fission product release phenomena associated with spent fuel assemblies in spent fuel pools in loss-of-pool-coolant events.

Metric ton: Weight unit corresponding to 1000 kg or approximately 2200 pounds.

Metric tons of uranium: See *MTU.*

Moderator: Material, such as ordinary water, heavy water, or graphite, used in a reactor to slow down high-energy neutrons.

MTU (metric tons of uranium): Unit of measurement of the mass for spent nuclear fuel. also expressed in metric tons of heavy metal (MTHM). It refers to the initial mass of uranium that is contained in a fuel assembly. It does not include the mass of fuel cladding (zirconium alloy) or the oxygen in the fuel compound.

Multi-purpose cask: See *Cask,*

MWe: Megawatts of electrical energy output from a power plant

MWt: Megawatts of thermal energy output from a power plant.

Neutron: Uncharged subatomic particle contained in the nucleus of an atom. Neutrons are emitted from the nucleus during the fission process.

Open rack: A storage rack in a spent fuel pool that has open space and lateral channels between the cells for storing spent fuel assemblies to permit water circulation.

Overpack: Metal or concrete cask used for storage or transportation of a canister containing spent nuclear fuel. See Cask.

Owner-controlled area: That part of the power plant site over which the plant operator exercises control. This usually corresponds to the boundary of the site.

Pellet: See *Fuel pellet.*

Penetrate: To pass into, but not completely through, a solid object.

Perforate: To produce a hole that goes completely through a solid object.

Plutonium-239: A fissile isotope of plutonium that contains 94 protons and 145 neutrons.

Pressurized water reactor (PWR): A type of nuclear reactor in which the reactor's water coolant is kept at high pressure to prevent it from boiling. The coolant transfers its heat to a secondary water system that boils into steam to drive the turbine and generator to produce electricity,

Probabilistic risk assessment: A systematic, quantitative method to assess risk (see below) as it relates to the performance of a complex system.

Protected area: A zone located within the owner-controlled area of a commercial nuclear power plant site in which access is restricted using guards, fences, and other barriers.

psia: Unit of pressure, pounds per square inch absolute, that is the total pressure including the pressure of the atmosphere.

Radioactivity: Spontaneous transformation of an unstable atom, often resulting in the emission of particles (alpha and beta) or gamma radiation. The process is referred to as radioactive decay.

Radiological Dispersal Device (RDD): A terrorist device in which sources of radioactive material are dispersed by explosives or other means. Also referred to as a *dirty bomb.*

Radiological sabotage: Any deliberate act directed against a nuclear power plant or spent fuel in storage or transport that could directly or indirectly endanger the public health and safety by exposure to radiation.

Radionuclide: Any form of an isotope of an element that is radioactive.

Re-racking: Replacement of the existing racks in a spent fuel pool with new racks that increase the number of spent fuel assemblies that can be stored.

Risk: The potential for an adverse effect from an accident or terrorist attack. This potential can be estimated quantitatively if answers to the following three questions can be obtained: (1) What can go wrong? (2) How likely is it? (3) What are the consequences?

Safety: In the context of spent fuel storage, measures that protect storage facilities against failure, damage, human error, or other accidents that would disperse radioactivity in the environment

Safeguards: As used in the regulation of domestic nuclear facilities and materials, the use of material control and accounting programs to verify that all nuclear material is properly controlled and accounted for, and also the use of physical protection equipment and security forces to protect such material.

Safeguards information: Information not otherwise classified as National Security Information or Restricted Data that specifically identifies a U.S. Nuclear Regulatory Commission licensee's or applicant's detailed (1) security measures for the physical protection of special nuclear material or (2) security measures for the physical protection and location of certain plant equipment vital to the safety of production or utilization facilities (10 CFR 73.2). The U.S. Nuclear Regulatory Commission has the authority to determine whether information is "safeguards information."

Security: In the context of spent fuel storage, measures to protect storage facilities against sabotage, attacks, or theft.

Shaped charge: A demolition and wall penetration or perforation device that uses high explosive to create a high-velocity jet of material.

Single-purpose cask: See *Cask,*

Special nuclear material: Fissile elements such as uranium and plutonium.

Spent fuel: See *Spent nuclear fuel.*

Spent fuel pool: A water-filled pool that is used at all commercial nuclear reactors for storage of spent (used) fuel elements after their removal from a nuclear reactor Spent fuel pools are constructed of reinforced concrete and lined with stainless steel. The inside of the pool has storage racks to hold the spent fuel assemblies and may contain a gated compartment to hold a spent fuel cask while it is being loaded and sealed.

Spent (or used or irradiated fuel) nuclear fuel: Fuel that has been "burned" in the core of a nuclear reactor and is no longer efficient for producing electricity. After discharge from a reactor, spent fuel is stored in water-filled pools (see *Wet storage*) for shielding and cooling.

Storage-only cask: See *Cask.*

Thermal power: Total heat output from the core of a nuclear reactor.

Uranium-235: A fissile isotope of uranium that contains 92 protons and 143 neutrons. It is the principal nuclear fuel in nuclear power reactors.

Uranium-238: An isotope of uranium that contains 92 protons and 146 neutrons.

Vital area: A zone located within the protected area of a commercial nuclear power plant site that contains the reactor control room, the reactor core, support buildings, and the spent fuel pool. It is the most carefully controlled and guarded part of the plant site.

Watt: Unit of power.

Watt-hour: Energy unit of measure equal to one watt of power supplied for one hour

Wet storage: Storage of spent nuclear fuel in spent fuel pools.

Zircaloy: Zirconium alloy used as cladding for uranium oxide fuel pellets in reactor fuel assemblies.

Zirconium cladding fire: A self-sustaining, exothermic reaction caused by rapid oxidation of zirconium fuel cladding (zircaloy) at high temperatures.

F

ACRONYMS

ACRS: Advisory Committee on Reactor Safeguards
BAM: Bundesanstalt für Materialforschung und -prüfung
BMU: Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit
BNL: Brookhaven National Laboratory
BWR: Boiling Water Nuclear Reactor (see Appendix E)
CFD: Computational Fluid Dynamics
DBT: Design Basis Threat (see Appendix E)
DHS: United States Department of Homeland Security
DOE: United States Department of Energy
EPRI: Formerly referred to as the Electric Power Research Institute
GAO: United States Government Accountability Office (formerly the General Accounting Office)
GESMO: Final Generic Environmental Statement on the Use of Recycled Plutonium in Mixed Oxide Fuel in Light-Water Cooled Reactors
GNB: Gesellschaft für Nuklear-Behälter, mbH
GNS: Gesellschaft für Nuklear-Servlce, mbH
GNSI: General Nuclear Systems, Inc.
GRS: Gesellschaft für Anlagen- und Reaktorsicherheit, mbH
GWd/MTU: Gigawatt-Days per Metric Ton of Uranium (see *Burn-up* in Appendix E)
INL: Idaho National Laboratory (formerly Idaho National Engineering and Environmental Laboratory)
ISFSI: Independent Spent Fuel Storage Installation
HSK: Die Hauptabteilung für die Sicherheit der Kemaniagen
MTU: Metric Tons of Uranium (see Appendix E)
MWd/MTU: Megawatt-Days per Metric Ton of Uranium (see *Burn-up* in Appendix E)
NPP: Nuclear Power Plant
NRC: National Research Council
PFS: Private Fuel Storage
PWR: Pressurized Water Nuclear Reactor (see Appendix E)
ROD: Radiological Dispersal Device (see Appendix E)
RPG: Rocket-Propelled Grenade

RSK: Reaktorsicherheitskommission

TOW: Tube-Launched, Optically Tracked, Wire Guided [Missile] (see Appendix E)

USNRC: United States Nuclear Regulatory Commission

NRO REQUEST FOR COMMISSIONERS' ASSISTANTS BRIEFING:

Subject: NRO requests a briefing of the Commission Technical Assistants on the topic of changes during construction (CdC).

Summary: The purpose of the briefing is inform the Technical Assistants (TAs) of NRO's plan to include a license condition that will provide a process for licensees to proceed with construction of changes to their design basis pending review of the associated license amendment request. The staff will describe industry's basis for requesting this process and the staff's progress in addressing this issue.

Rationale for the Request: Once an applicant completes the "licensing" process and receives a Combined License (COL), they become an NRC "licensee." One of the principal impacts of that transition is the establishment of a "licensing basis" and a licensee's immediate assumption of responsibility for maintaining the plant's licensing basis. Licensing basis maintenance during construction is a new challenge—for both the NRC and the expected licensees. Over the past year, the staff has been discussing these potential issues with industry regarding the challenges that will be faced by licensees, constructors, and regulators in dealing with licensing processes such as 50.59-like screenings and evaluations, exemptions, and 50.90 amendments.

Key Messages:

- Staff's proposal for effective processing of licensee plant changes and modifications during the construction period under a Part 52 COL,
- Staff's progress in determining the activities that can be performed by licensees during construction while the NRC is reviewing requested changes to the licensing basis (license amendments)

Proposed times: Possible briefing times are

May 18th – 9:00-10:00, 11:00-12:00, 3:00-4:00
May 19th – 10:00-11:00, 2:00-3:00