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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

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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]

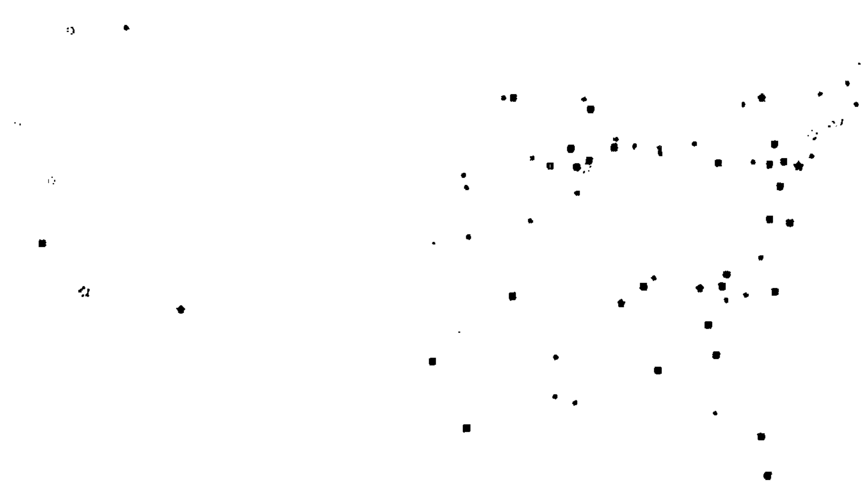

Figure 1: Locations of nuclear power plants in the United States. Circles represent sites with one reactor, squares represent plants with two; and stars represent plants with three. Open symbols represent sites with at least one shutdown reactor. Only the plant in Zion, Illinois has more than one shutdown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

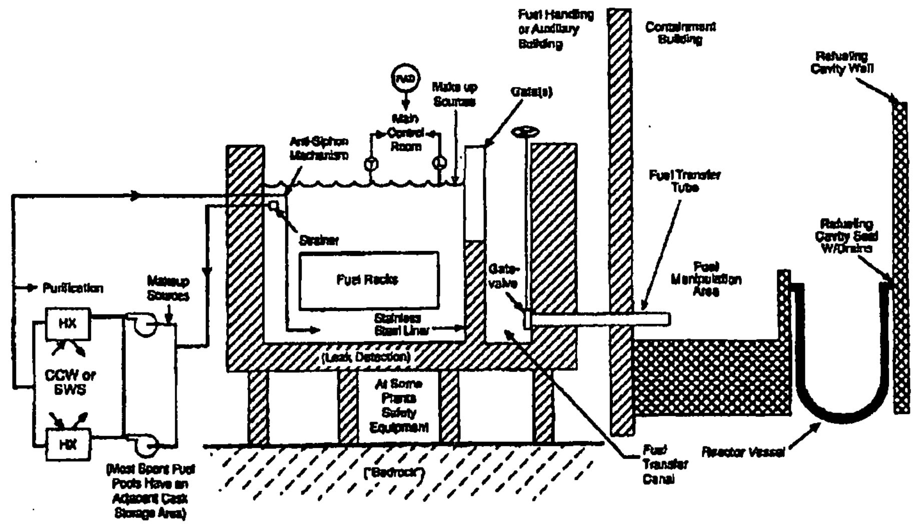

Figure 2a: Layout of spent fuel pool and transfer system for pressurized water reactors (*Source:* NUREG-1275, 1997).

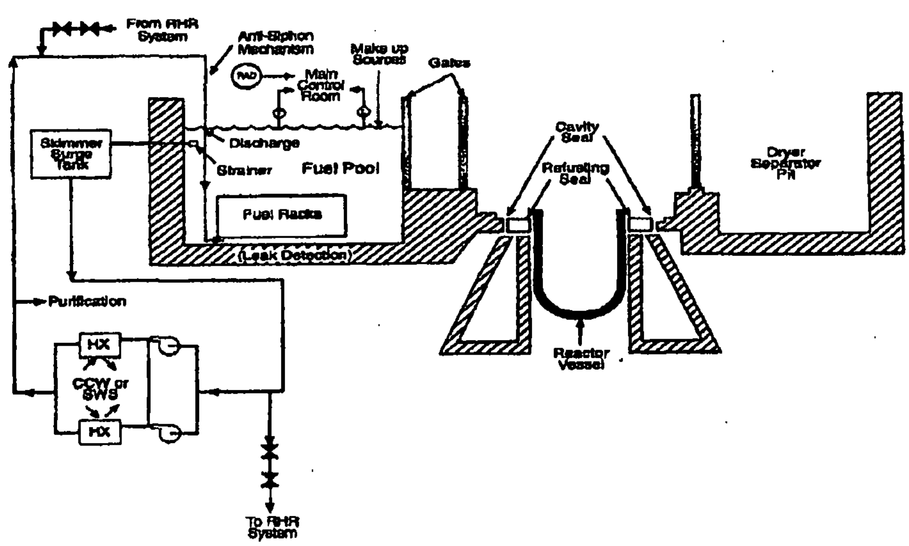

Figure 2b: Layout of spent fuel pool and transfer system for boiling water reactors (*Source:* NUREG-1275, 1997).

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

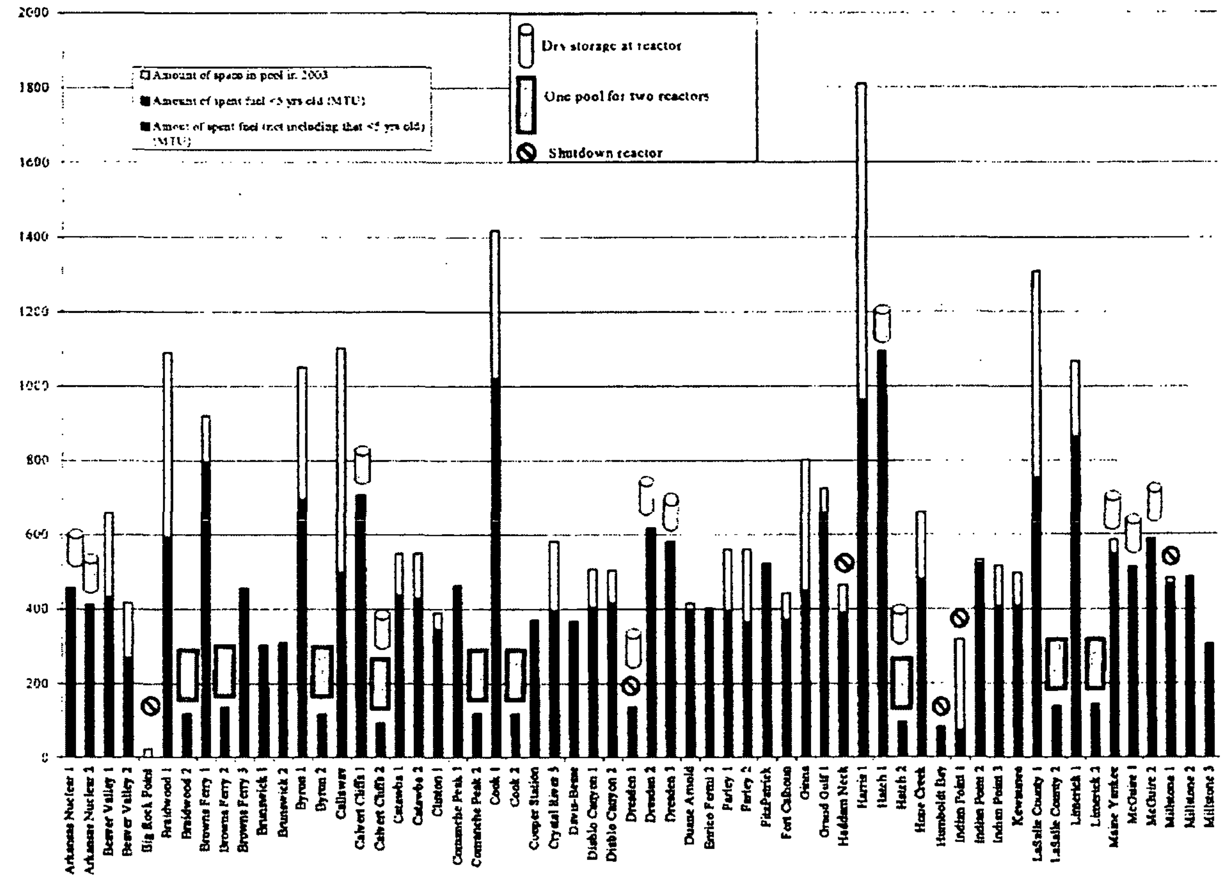

Figure 3: Estimated 2003 spent fuel inventory at each U.S. spent-fuel pool, measured in metric tons of contained uranium. Height of bar indicates total licensed capacity (1998, with some updates). Shading indicates estimated tonnage of spent fuel in pool as of 2003. Dark shading indicates the estimated 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)*

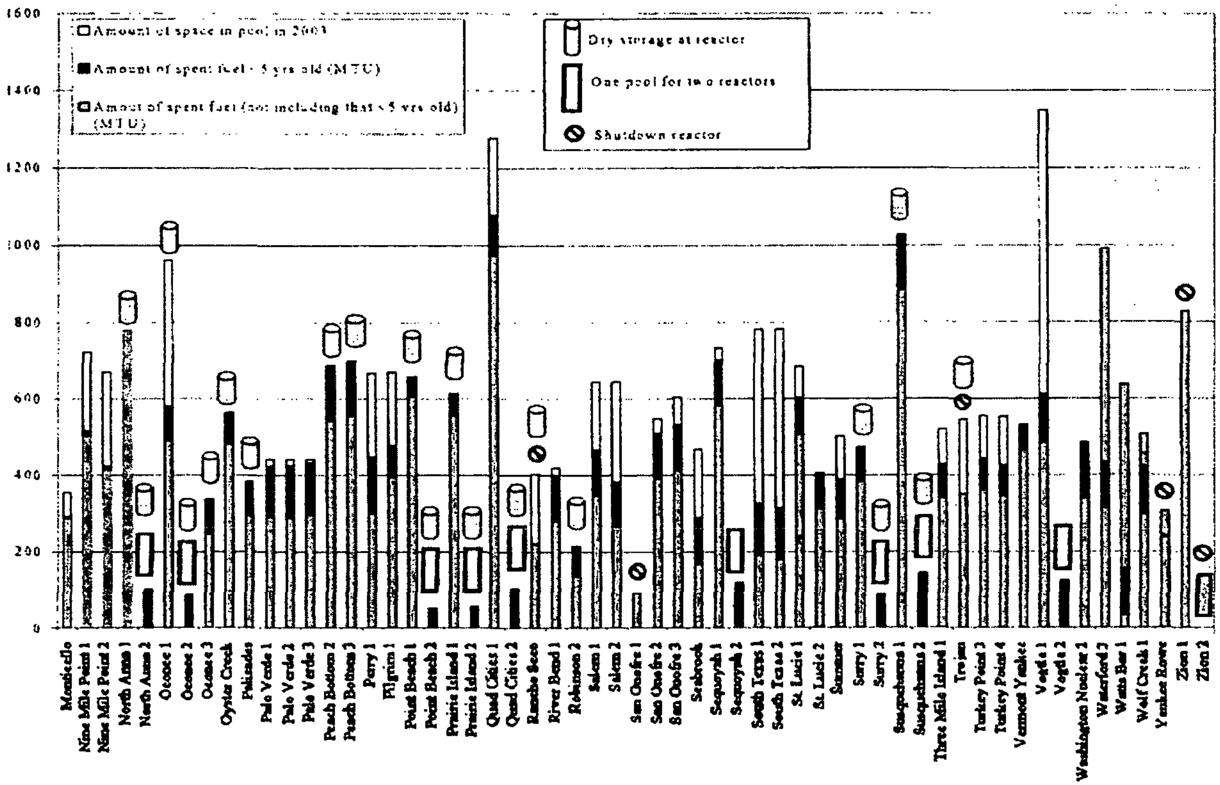

Figure 3: (Continued)

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.

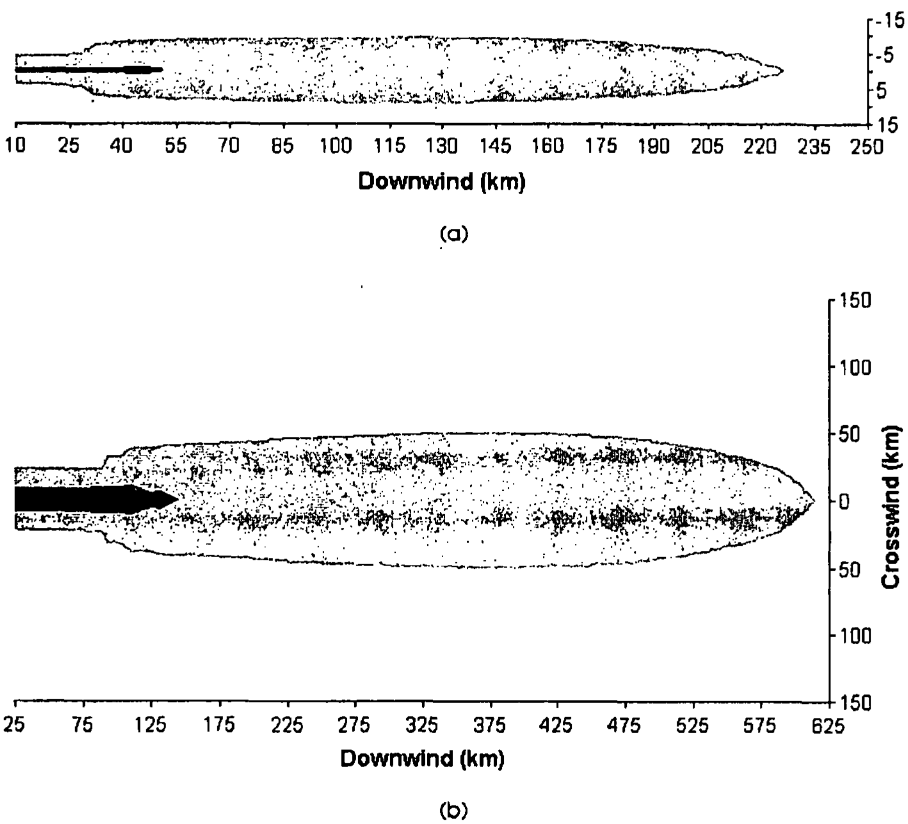

Figure 4: Typical areas contaminated above 100 (shaded) and 1000 (black) Ci/km^2 for release of (a) 3.5 MCi and (b) 35 MCi of ^{137}Cs. The added chance of cancer death for a person living within the shaded area for 10 years is estimated very roughly as between 1 and 10 percent. For someone living within 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.

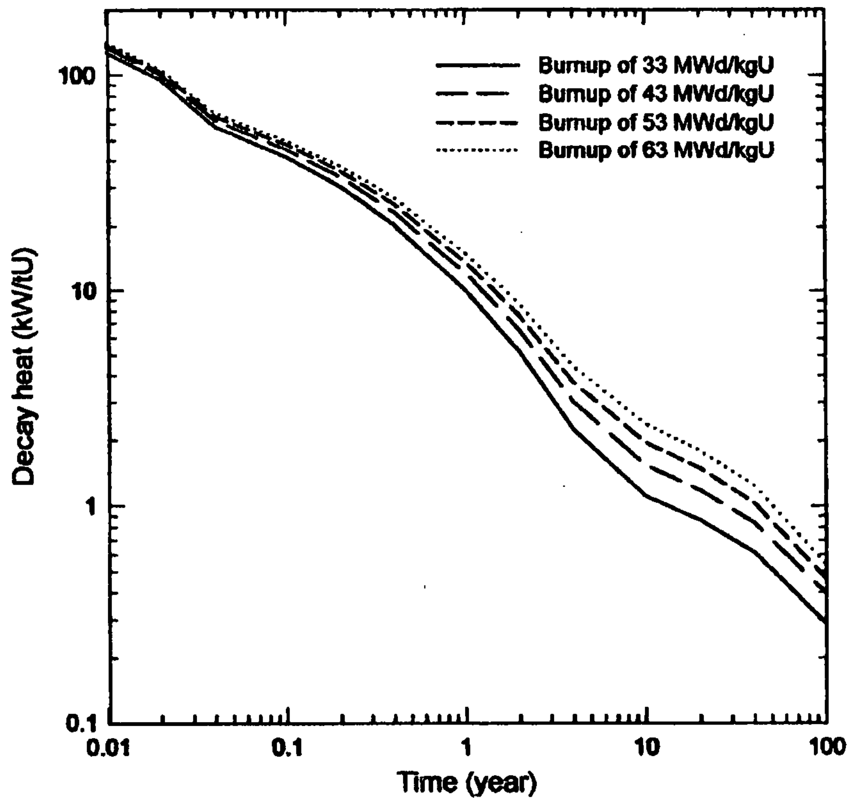

Figure 5: Decay heat as a function of time from 0.01 years (about 4 days) to 100 years for spent-fuel burnups of 33, 43, 53 and 63 MWd/kgU. The lowest burnup was typical for the 1970s. Current burnups are around 50 MWd/kgU (*Source:* authors[38]).

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

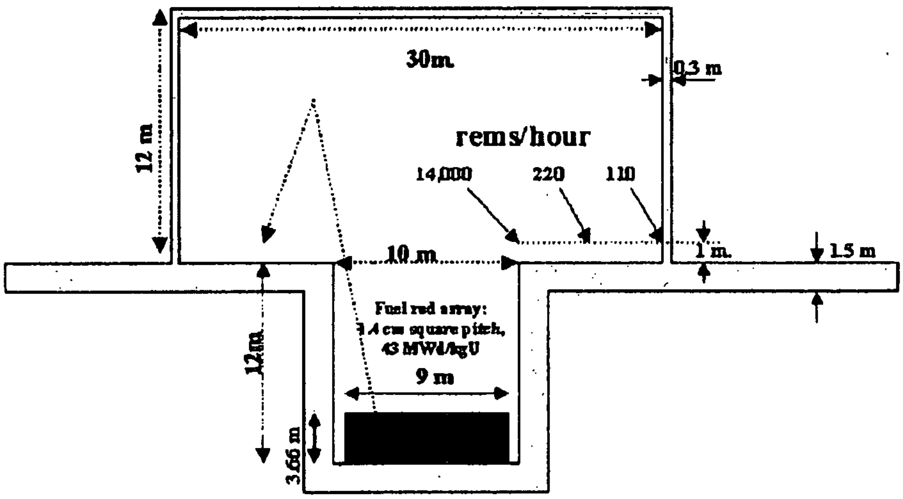

Figure 6: Calculated radiation levels from a drained spent-fuel pool one meter above the level of the floor of a simplified cylindrically-symmetric spent-fuel-pool building. Even out of direct sight of the spent fuel, the radiation dose rates from gamma rays scattered by the air, roof and walls are over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

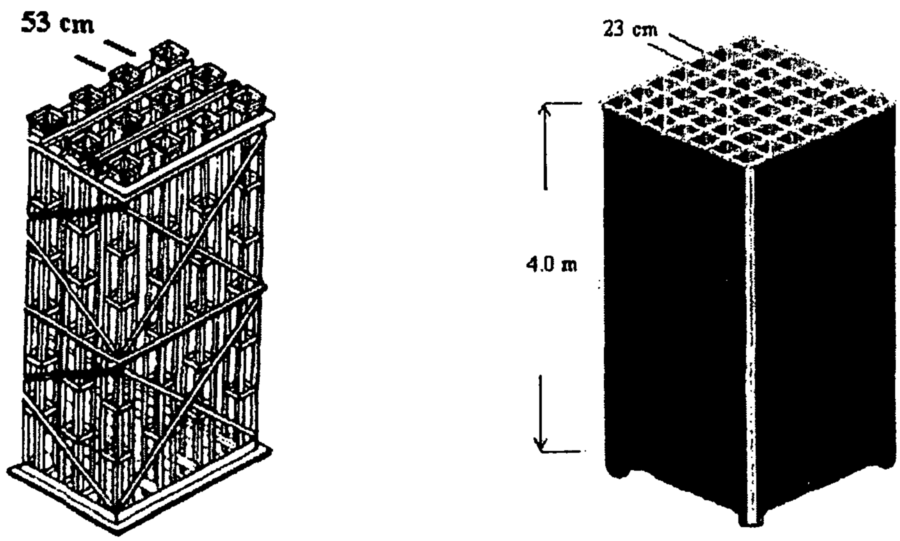

Figure 7: Open and dense-pack PWR spent-fuel racks (*Sources:* Left: NUREG/CR-0649, SAND77-1371, 1979; right: authors).

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 ($= 5.67 \times 10^{-12}\ T_K^4\ Watts/cm^2$) 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.

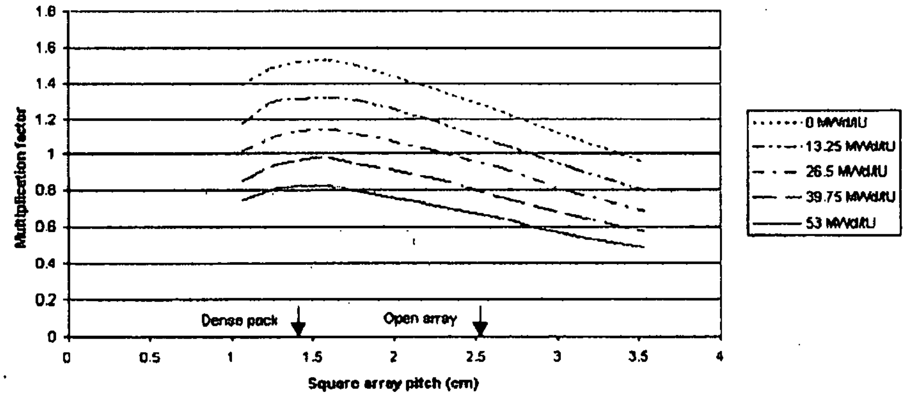

Figure 8: Neutron multiplication as a function of array pitch in an infinite square array of 4.4% enriched fuel rods with a design burnup of 53 MWd/kgU for 0, 25, 50, 75 and 100% irradiation (*Source:* authors).

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 $\Delta T = 100$°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 over-pack 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.)

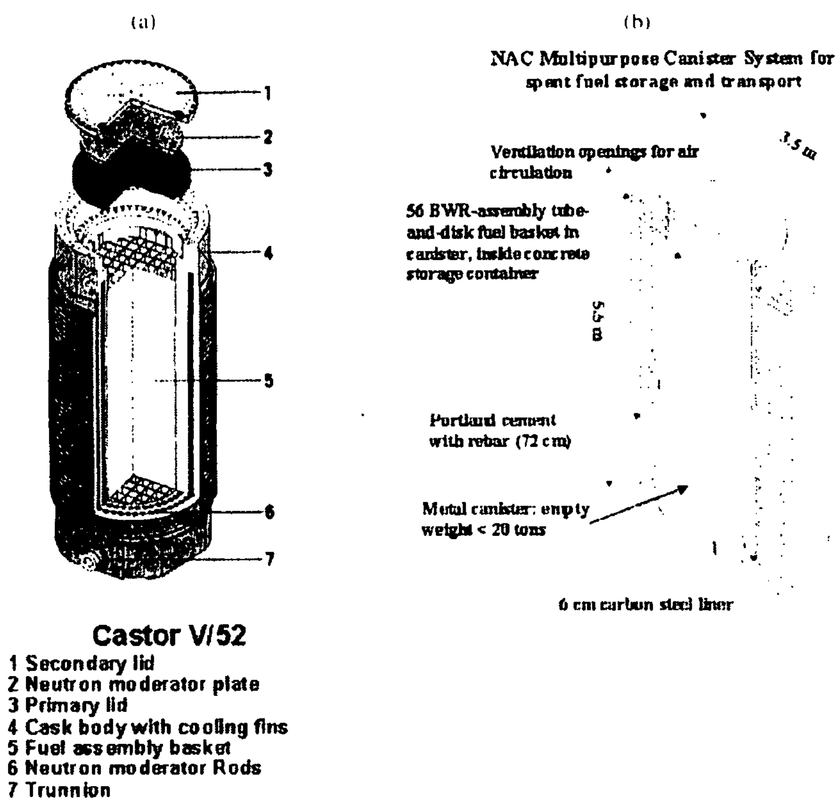

Figure 9: (a) Thick-walled cask[103] and (b) Cask with overpack.[104] (*Sources:* GNB and NAC).

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 x 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.

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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, $K_o\exp(-E_a/RT) = 1.1 \times 10^{-6}$ (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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Dr. Benjamin was formerly a Distinguished Member of the Technical Staff at Sandia National Laboratories.

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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 half-life ^{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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Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report

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

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SAFETY AND SECURITY OF COMMERCIAL SPENT NUCLEAR FUEL STORAGE

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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- 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:

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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.

CONTENTS

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 concerning 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.

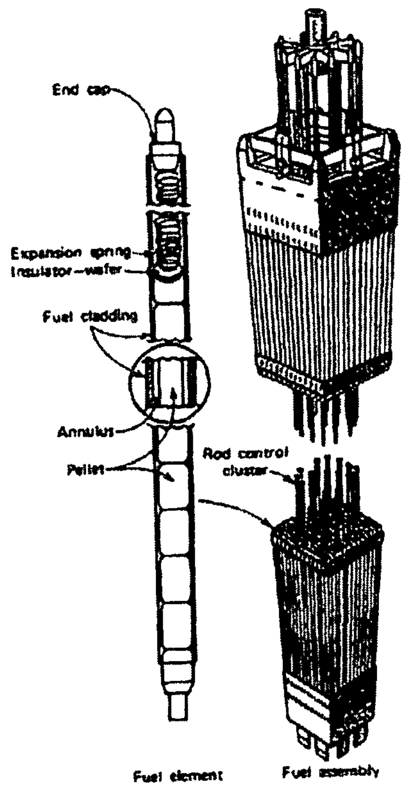

FIGURE 1.1 Fuel rods, also called fuel pins or elements, are bundled together into fuel assemblies as shown here. This fuel assembly is for a PWR reactor. SOURCE: Duderstadt and Hamilton (1976: Figure 3–7).

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.

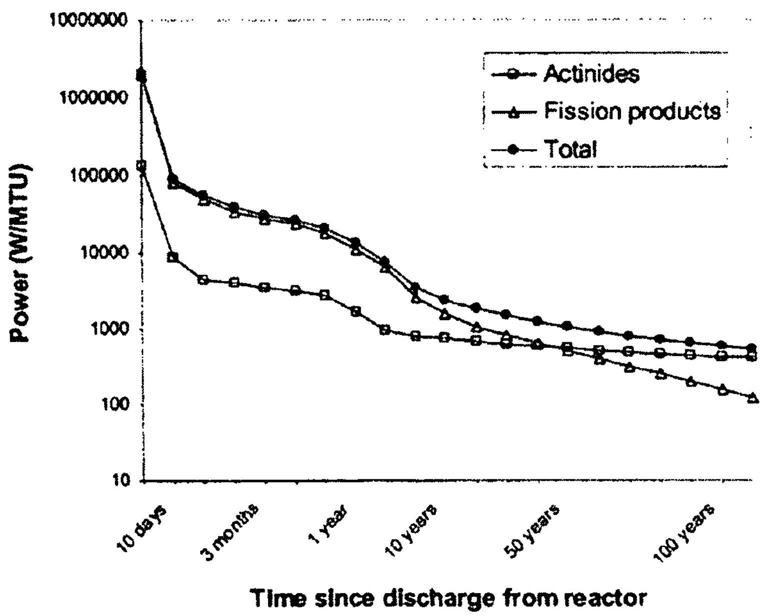

FIGURE 1.2 Decay-heat power for spent fuel (measured in watts per metric ion of uranium) plotted on a logarithmic scale as a function of time after reactor discharge. Note that the horizontal axis is a data series, not a scale. SOURCE: Based on data from USNRC (1984).

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.

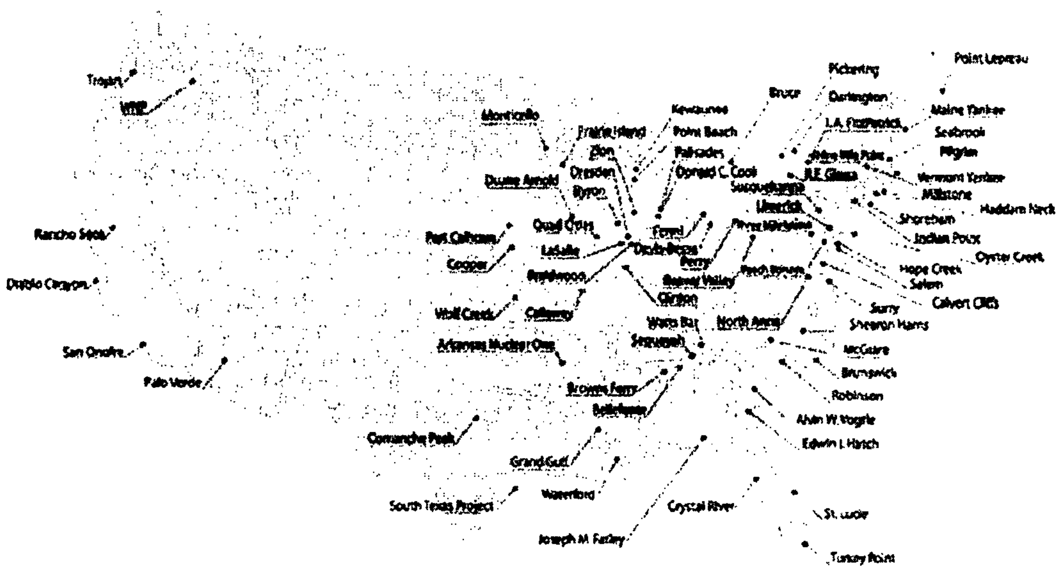

FIGURE 1.3 Locations of spent fuel storage facilities in the United States.

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).

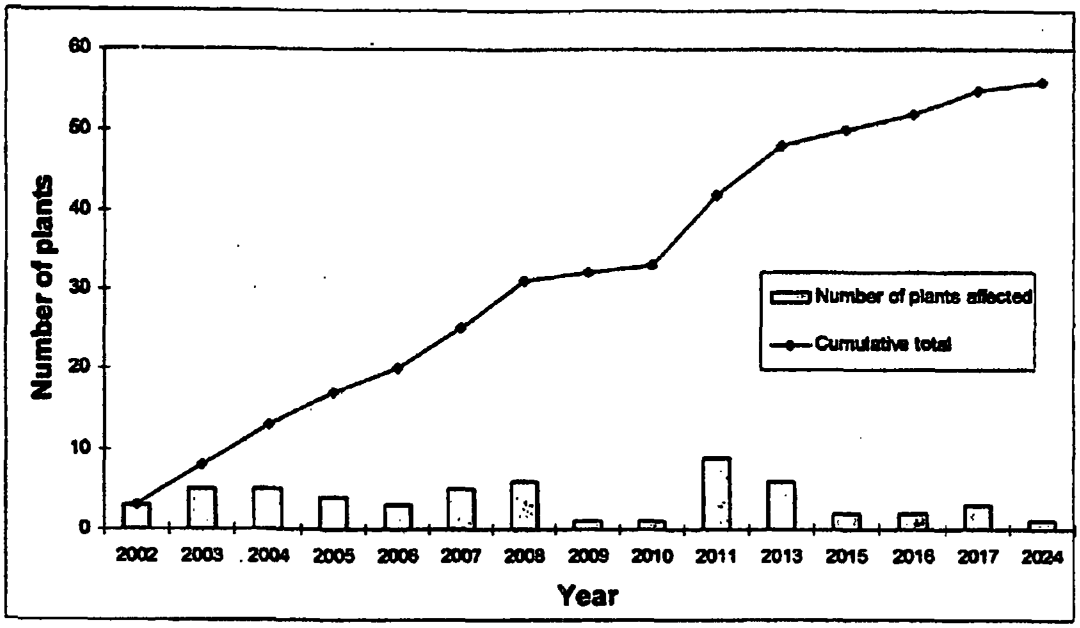

FIGURE 1.4 Projection of the number of commercial nuclear power plants that will run out of needed space in their spent fuel pools in coming years if they do not add interim storage. These data, looking only at plants that did not already use dry cask storage, were provided to the Nuclear Regulatory 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.

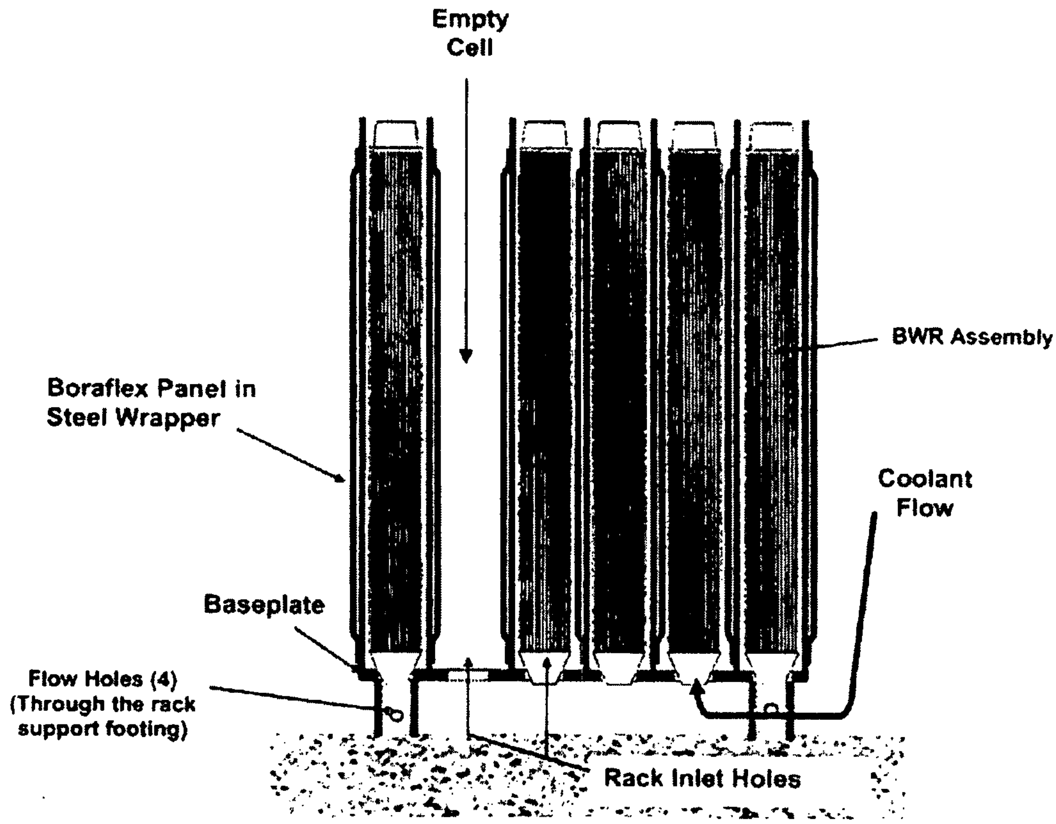

FIGURE 1.5 Dense spent fuel pool storage racks for BWR fuel. This cross-sectional illustration shows the principal elements of the spent fuel rack, which sits on the bottom of the pool. SOURCE: Nuclear Regulatory Commission briefing materials (2004).

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).

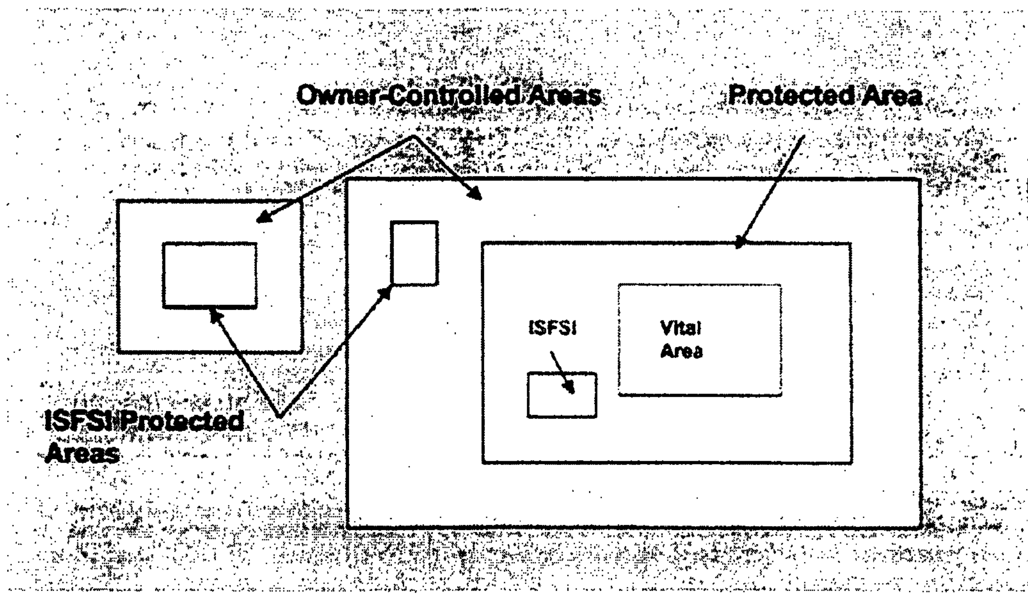

FIGURE 2.1 Commercial nuclear power plant sites are demarcated as shown for security purposes. The part of the power plant site over which the plant operator exercises control is referred to as the *owner-controlled area*. This usually corresponds to the boundary of the site. Located within this area 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 fission-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.

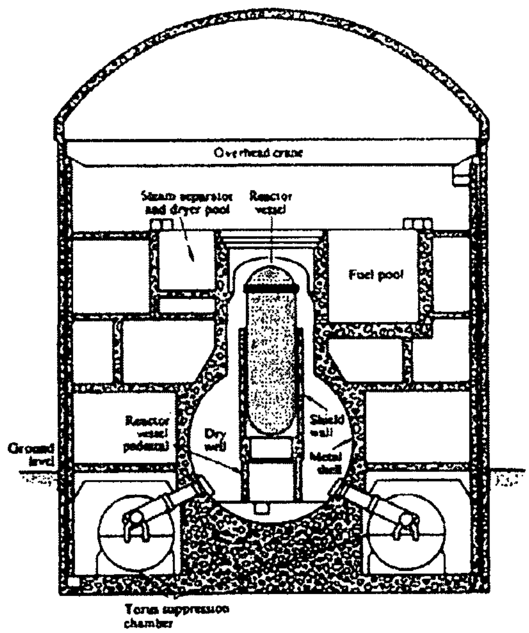

FIGURE 3.1 Schematic section through a G.E.Mark I BWR reactor plant. The spent fuel pool is located in the reactor building well above ground level. This diagram is for a BWR with a reinforced concrete superstructure (roof). Most designs have thin steel superstructures. SOURCE: Lamarsh (1975, Figure 11.3).

strikes of tornado 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 mm) 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

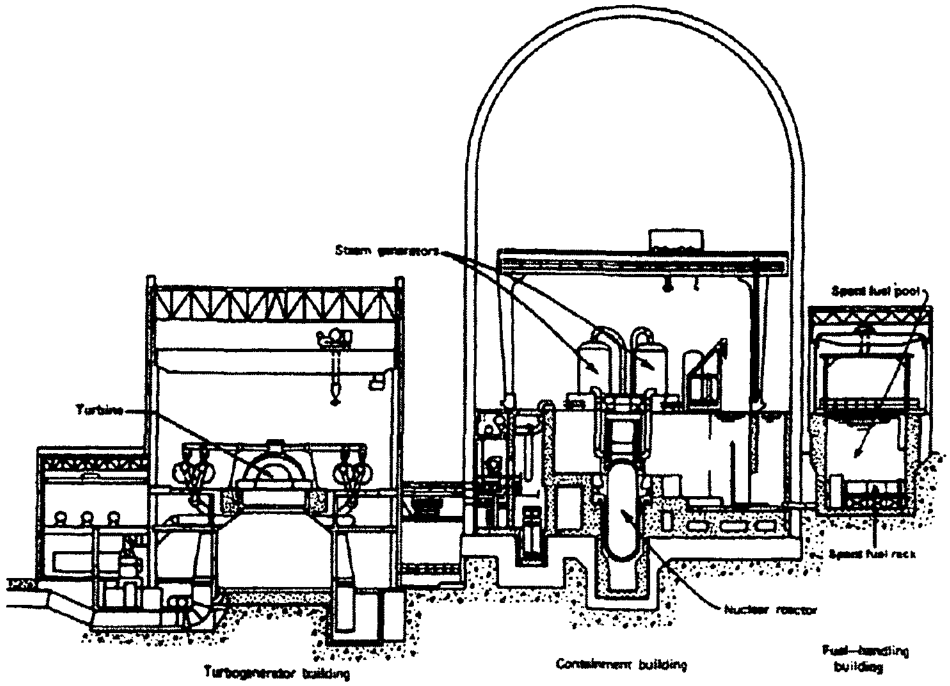

FIGURE 3.2 Schematic section through a PWR reactor plant. The spent fuel pool is located in the fuel-handling building next to the domed reactor containment building at or slightly below ground level. SOURCE: Modified from Duderstadt and Hamilton (1976, Figure 3–4).

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.

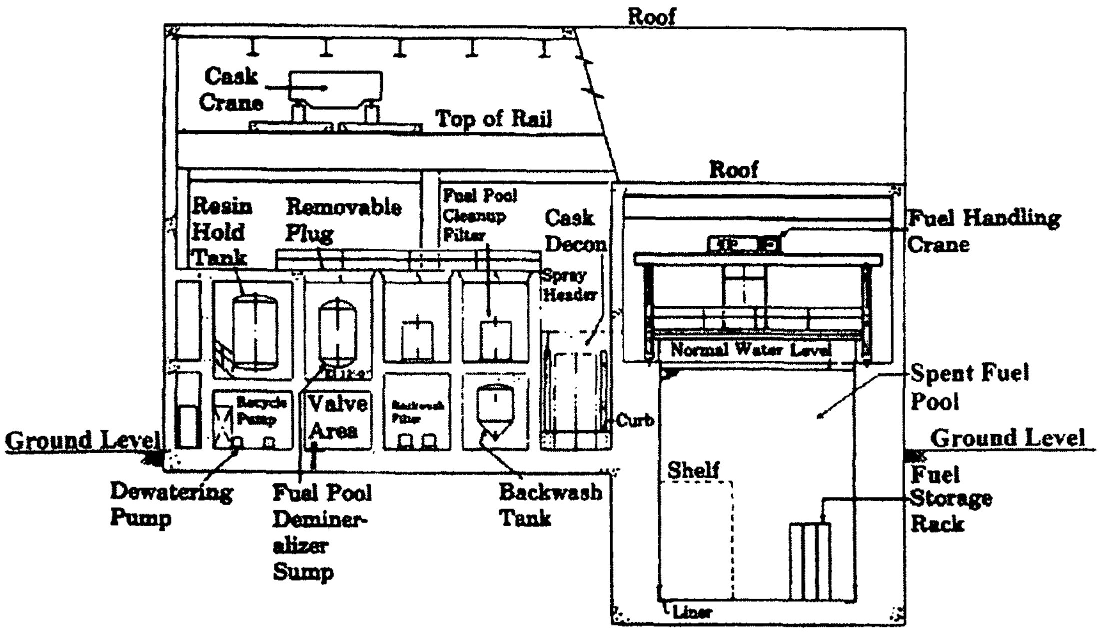

FIGURE 3.3 Example of a section of a PWR spent fuel pool and support facilities. The pool is located to the right in the figure: the support equipment to the left. SOURCE: American Nuclear Society (1988).

- 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.

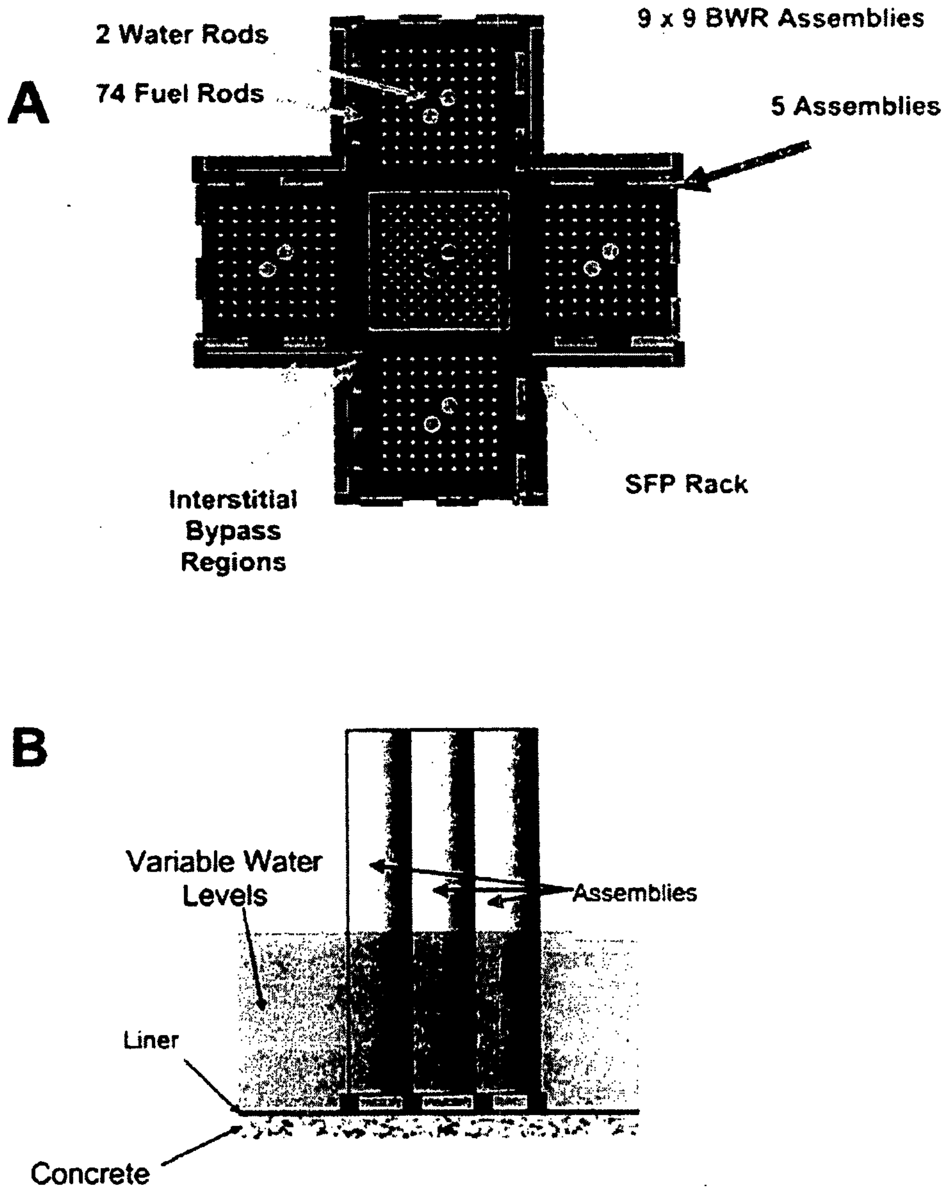

FIGURE 3.4 Configuration of fuel assemblies used for separate effects analysis. (A) Top view of BWR spent fuel assemblies used in the model. (B) Side view showing spent fuel assemblies in the pool. SOURCE: Nuclear Regulatory Commission briefing materials (2004).

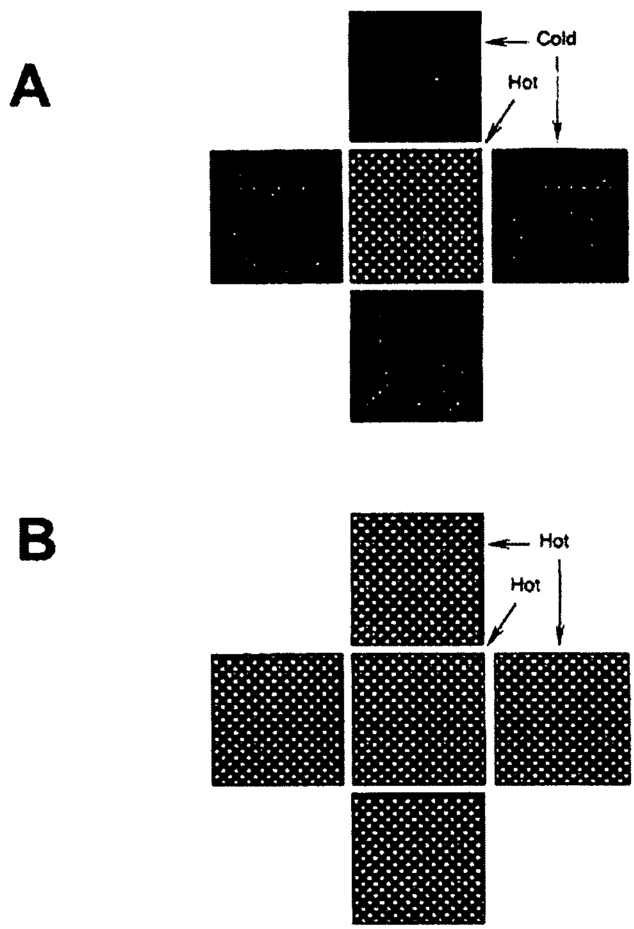

FIGURE 3.5 Two configurations used in the separate effects models shown in FIGURE 3.4: (A) Center hot spent fuel assembly surrounded by four cold assemblies; and (B) center hot spent fuel assembly surrounded by four hot assemblies. SOURCE: Nuclear Regulatory Commission briefing materials (2004).

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" patterns. 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.

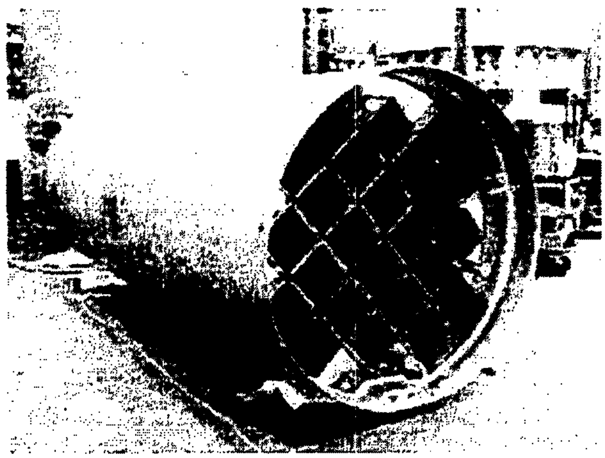

FIGURE 4.1 Photo of NUHOMS canister showing the internal basket for holding the spent fuel assemblies in a fixed geometry. This canister is shown for illustrative purposes only.
SOURCE: Courtesy of Transnuclear, Inc., an Areva Company

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.

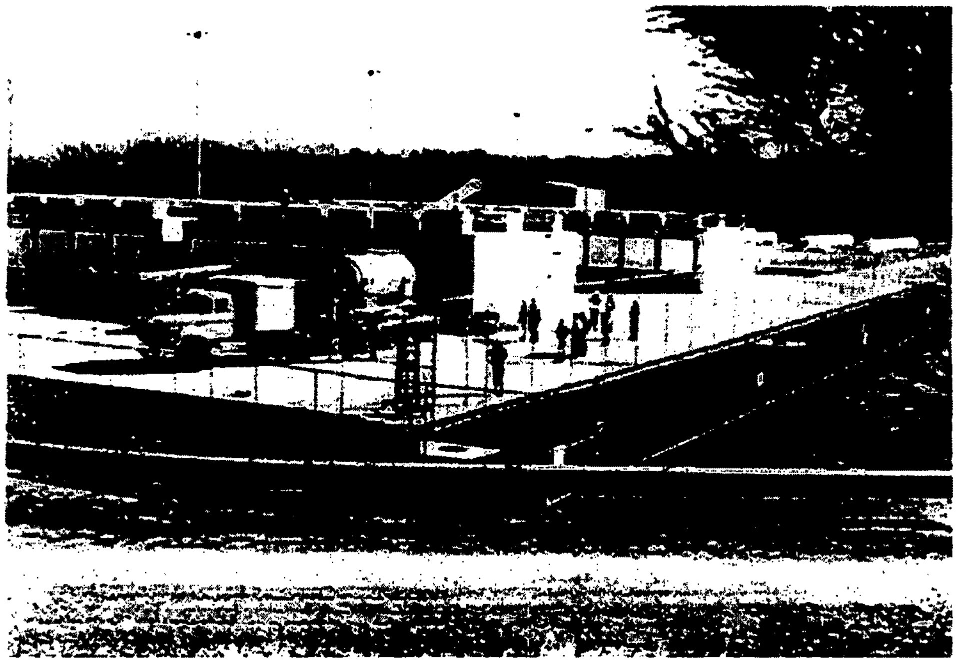

FIGURE 4.2 Photo showing a canister being loaded into a NUHOMS horizontal storage module. SOURCE: Courtesy of Transnuclear, Inc., an Areva Company.

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.

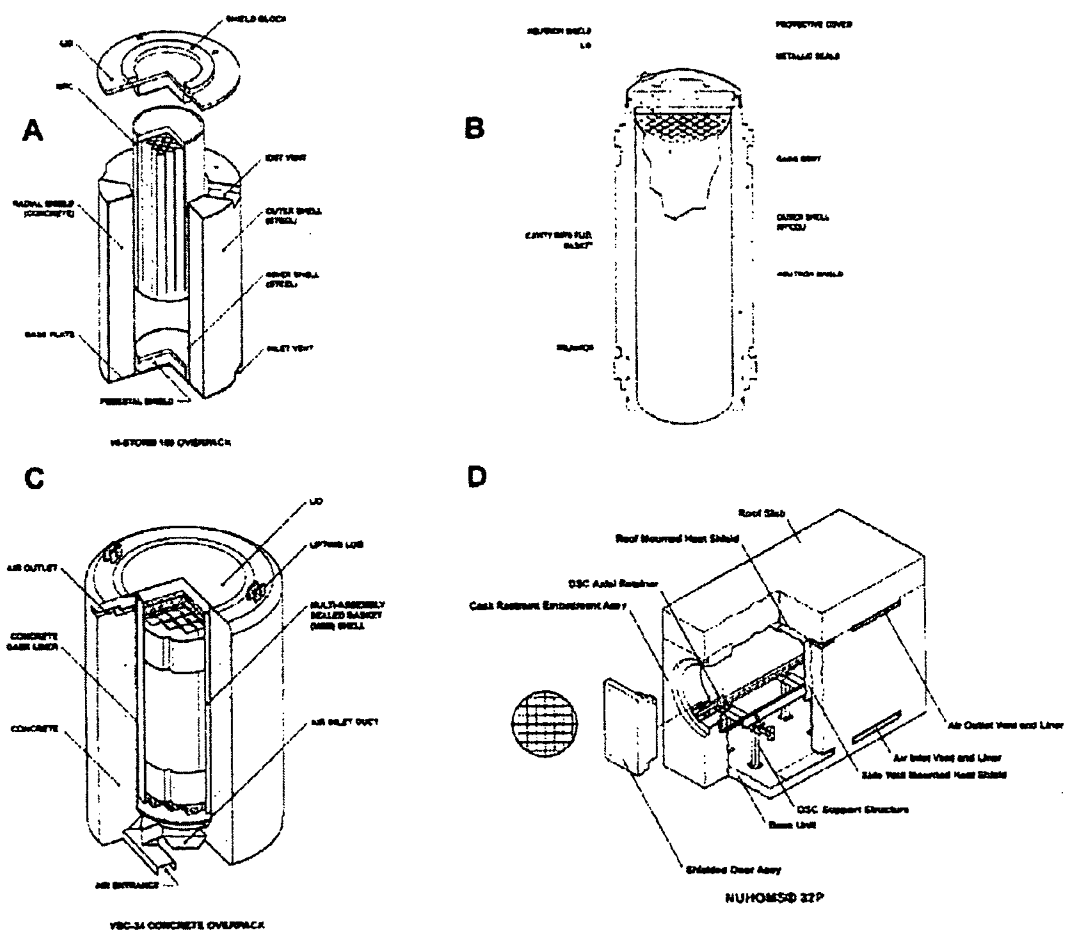

FIGURE 4.3 Four cask systems used in the Sandia analyses described in this chapter: (A) HI-STORM-100, (B) TN-68, (C) VSC-24, (D) NUHOMS-32P. The casks shown in A, C, and D are canister-based casks; the cask shown in B is a bare-fuel cask. SOURCE: Nuclear Regulatory Commission briefing materials (2004).

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.

M.QUINN BREWSTER is an expert in energetic solids and heat transfer. He is currently the Hermia G. Soo Professor of Mechanical Engineering at the University of Illinois at Urbana-Champaign. He is involved in the Academic Strategic Alliance Program, whose objective is to develop integrated software simulation capability for coupled, system simulation of solid rocket motors including internal ballistics (multi-phase, reacting flow) and structural response (propellant grain and motor case). Dr. Brewster has authored one book on thermal radiative transfer and chapters in four other books as well as several publications on combustion science. He is a fellow of the American Society of Mechanical Engineers and associate fellow of the American Institute of Aeronautics and Astronautics. Dr. Brewster holds a Ph.D. in mechanical engineering from the University of California at Berkeley.

GREGORY R.CHOPPIN is an actinide elements and radiochemistry expert. He is currently the R.O.Lawton Distinguished Professor Emeritus of Chemistry at Florida State University. His research interests involve the chemistry and separation of the f-elements and the physical chemistry of concentrated electrolyte solutions. During a postdoctoral period at the Lawrence Radiation Laboratory, University of California. Berkeley, he participated in the discovery of mendelevium, element 101. His research and educational activities have been recognized by the American Chemical Society's Award in Nuclear Chemistry, the Southern Chemist Award of the American Chemical Society, the Manufacturing Chemist Award in Chemical Education, the Chemical Pioneer Award of the American Institute of Chemistry, a Presidential Citation Award of the American Nuclear Society, the Becquerel Medal, British Royal Society, and honorary D.Sc. degrees from Loyola University and the Chalmers University of Technology (Sweden). Dr. Choppin previously served on the NRC's Board on Chemical Sciences and Technology and Board on Radioactive Waste Management He holds a Ph.D. in inorganic chemistry from the University of Texas, Austin.

NANCY J.COOKE is an expert in the development, application, and evaluation of methodologies to elicit and assess individual and team knowledge. She is currently a professor in the applied psychology program at Arizona State University East. She also holds a National Research Council Associateship position with Air Force Research Laboratory and serves on the board of directors of the Cognitive Engineering Research Institute in Mesa, Arizona. Her current research areas are the following: cognitive engineering, knowledge elicitation, cognitive task analysis, team cognition, team situation awareness, mental models, expertise, and human-computer interaction. Her most recent work includes the development and validation of methods to measure shared knowledge and team situation awareness and research on the impact of cross- training, distributed mission environments, and workload on team knowledge, process, and performance. This work has been applied to team cognition in unmanned aerial vehicle and emergency operation center command-and-control. She contributed to the creation of the Cognitive Engineering Research on Team Tasks Laboratory to develop, apply, and evaluate measures of team cognition. She has authored or co-authored over 70 articles, chapters, and technical reports on measuring team cognition, knowledge elicitation, and human-computer interaction. Dr. Cooke holds a Ph.D. in cognitive psychology from New Mexico State University, Las Cruces.

GORDON R.JOHNSON is an expert in penetration mechanics and computational mechanics. He is currently a senior scientist and manager of the solid mechanics group at Network Computing Services. His recent work has included the development of computational mechanics codes that include finite elements and meshless particles. He has also developed computational material models to determine the strength and failure characteristics of a variety of materials subjected to large strains, strain rates, temperatures, and pressures. His work for the U.S. Departments of Energy and Defense has included a wide range of intense impulsive loading computations for high-velocity impact and explosive detonation. He was a chief engineering fellow during his 35 years at Alliant Techsystems (formerly Honeywell). He has served as a technical advisor for university contracts with the Army Research Office, and an industry representative for its strategic planning, and was a member of the founding board of directors for the Hypervelocity Impact Society. Dr. Johnson holds a Ph.D. in structures from the University of Minnesota, Minneapolis.

ROBERT P.KENNEDY has expertise in structural dynamics and earthquake engineering. He is currency an independent consultant in structural mechanics and engineering. Dr. Kennedy has worked on static and dynamic analysis and the design of special-purpose civil and mechanical-type structures, particularly for the nuclear, petroleum, and defense industries. He has designed structures to resist extreme loadings, including seismic loadings, missile impacts, extreme winds, impulsive loads, and nuclear environmental effects, and he has developed computerized structural analysis methods. He also served as a peer reviewer for an EPRI study on aircraft impacts on nuclear power plants. In 1991, he was elected to the National Academy of Engineering for developing design procedures for civil and mechanical structures to resist seismic and other extreme loading conditions. Dr. Kennedy holds a Ph.D. in structural engineering from Stanford University.

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.

RICHARD T.LAHEY, JR., is an expert in multiphase flow and heat transfer technology, nuclear reactor safety, and the use of advanced technology for industrial applications. He is currently the Edward E.Hood Professor of Engineering at Rensselaer Polytechnic Institute (RPI) and was previously chair of the Department of Nuclear Engineering and Science, director of the Center for Multiphase Research, and the dean of engineering at RPI. Previously, Dr. Lahey held several technical and managerial positions with the General Electric Company, including overall responsibility for all domestic and foreign R&D programs associated with boiling water nuclear reactor thermal-hydraulic and safety technology. He has chaired several committees for the American Society of Mechanical Engineering, American Nuclear Society, American Institute for Chemical Engineering, American Society for Engineering Education, and NASA. His current research is funded by the Department of Energy's Naval Reactors Program, the Office of Naval Research, the National Science Foundation, the New York State Energy Research and Development Authority, Oak Ridge National Laboratory, and the Defense Advanced Research Projects Agency. He currently consults on nuclear reactor safety problems and the chemical processing of non-nuclear materials and is a member of the Board of Managers of PJM Interconnection, LLC. In 1994, he was elected to the National Academy of Engineering for his contributions to the fields of multiphase flow and heat transfer and nuclear reactor safety technology. In 1995, he became a member of the Russian Academy of Sciences-Baskortostan and he is a fellow of the American Nuclear Society and of the American Society of Mechanical Engineers. He has authored or co-authored over 300 technical publications, including 10 books or handbooks and 160 journal articles. Dr. Lahey holds a Ph.D. in mechanical engineering from Stanford University.

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.

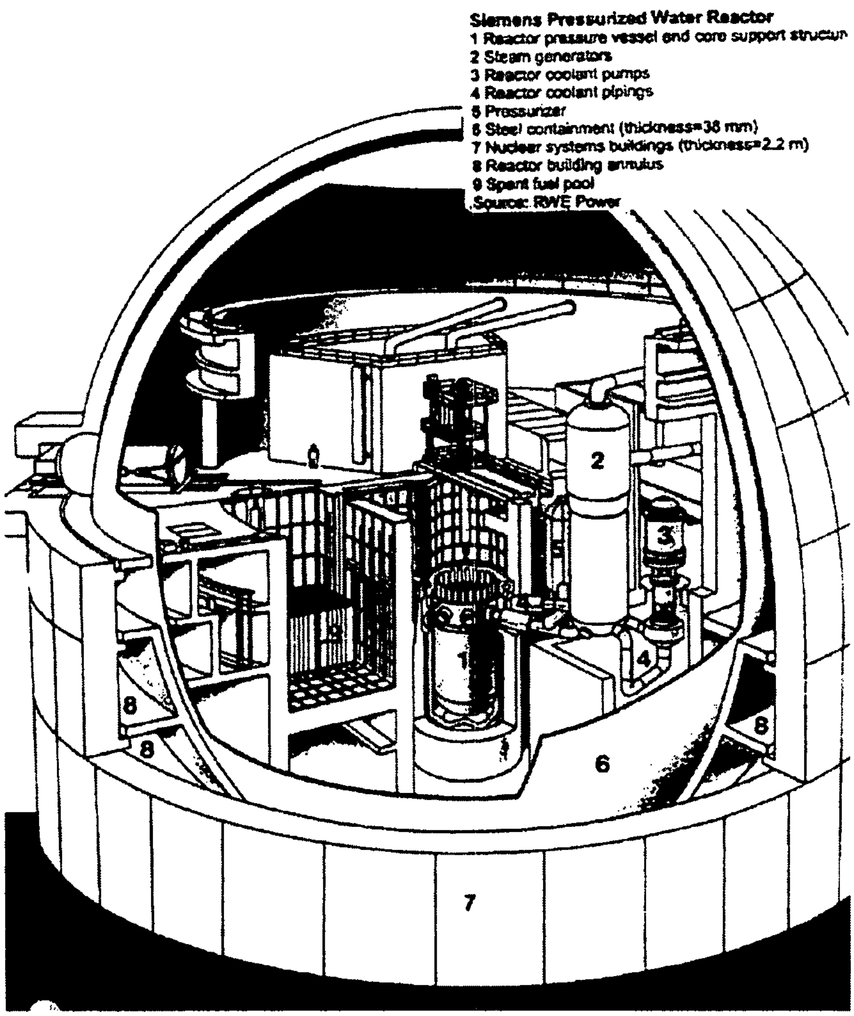

FIGURE C.1 Schematic illustration of the Lingen PWR power plant, a third-generation power plant design. SOURCE: RWE Power.

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 walls 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.

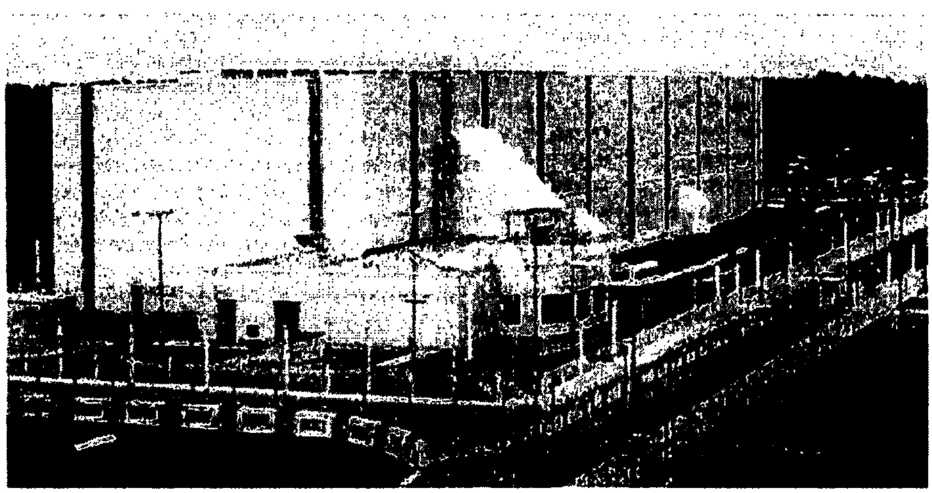

FIGURE C.2 Dry cask spent fuel storage building at the Lingen Nuclear Power Plant.
SOURCE: RWE Power.

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.

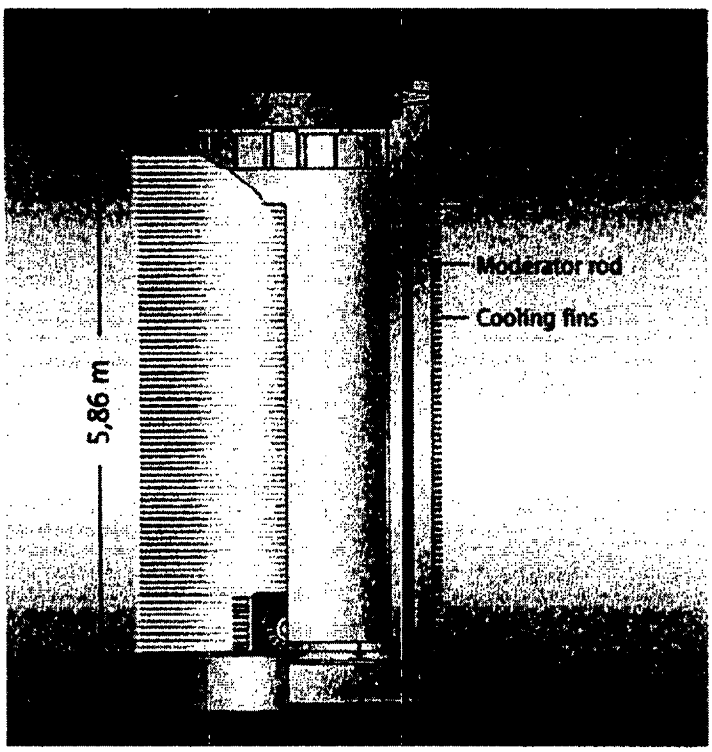

FIGURE C.3 Typical features of a CASTOR cask used at the Lingen Nuclear Power Plant.
SOURCE: RWE Power AG Lingen Nuclear Power Plant.

[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 lla, 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.

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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.

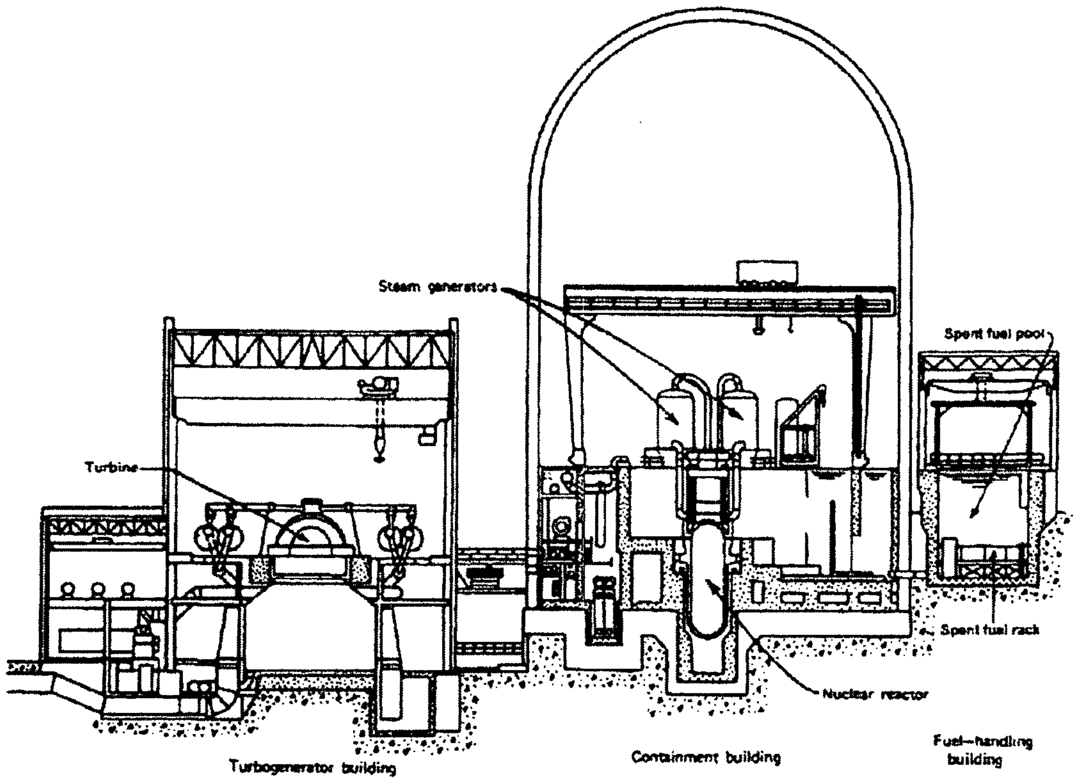

FIGURE D.1 A PWR in a large dry containment. SOURCE: Modified from Duderstadt and Hamilton (1976, Figure 3-4).

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.

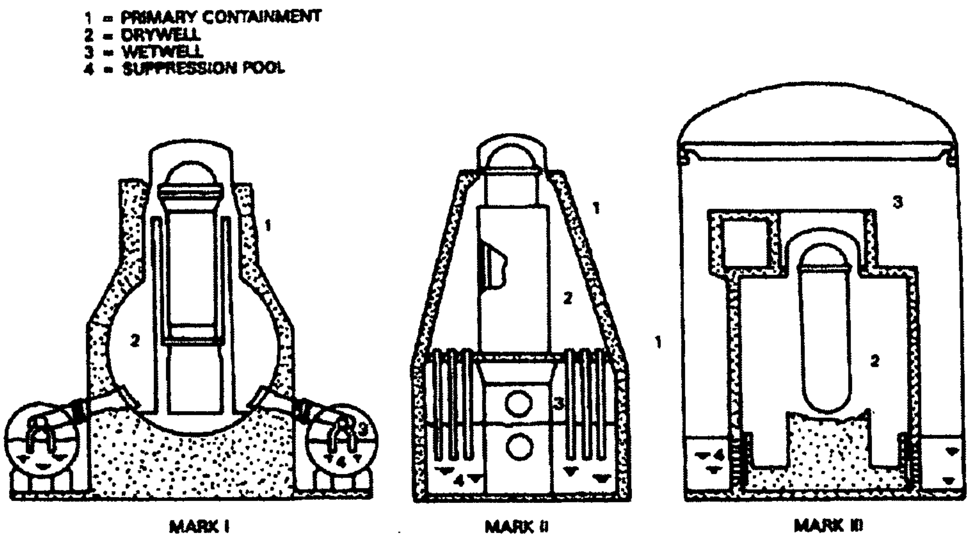

FIGURE D.2 Three types of BWR containment system: Mark I, Mark II, and Mark III. SOURCE: Modified from Lahey and Moody (1993, Figure 1-9).

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	CE	CE	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.)	178	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	28	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.)	—	—	—	0.378	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	4.2	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 (ISFSI): 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

PR 52
(76FR10269)

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Blue Ridge Environmental Defense League

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May 10, 2011

DOCKETED
USNRC

May 11, 2011 (9:00 am)

OFFICE OF SECRETARY
RULEMAKINGS AND
ADJUDICATIONS STAFF

Secretary, U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
ATTN: Rulemakings and Adjudications Staff
E-mail: Rulemaking.Comments@nrc.gov
301-415-1677

RE: Docket ID: NRC-2010-0131
Advanced Passive (AP) 1000 Design Certification Amendment
76 FR 10269, 10 CFR 52

To the Commission:

On behalf of the Blue Ridge Environmental Defense League, I submit the following remarks.

First, in light of the tragedy in Japan, we call upon the Nuclear Regulatory Commission to re-visit all nuclear issues—power, waste and mining. Earthquakes are not unusual in Japan. If an advanced, industrial nation like Japan with nuclear safeguards in place can be blind-sided by such an event, the United States should question all its assumptions about nuclear technology. This is the least we can do to honor the brave souls who sacrificed their lives to control the disaster in Fukushima, and to commemorate the the terrible loss of life among the innocent. 1

Second, the Commission should release undisclosed information and tell the truth. We recommend the following: Stop hiding computer codes, financial and commercial data, and other technical information under the cloak of "proprietary" and "SUNSI"[1] designations. Do an energetics model of nuclear power and a comparable one for all alternative energy sources; release the results. Discuss the threats to a democratic society posed buy a plutonium economy. Talk about the ethics of consuming electricity from fission reactors and saddling 20,000 future generations with the social and environmental problems of high-level radioactive waste.[2] The nuclear disaster at Fukushima has made these actions more necessary than ever. We agree with the following critique: 2

- You say you'd rather not? You don't have a choice.
- We critics discuss these problems all the time.
- The more you ignore us, the less credible you become.

[1] SUNSI: sensitive, unclassified non-safeguards information. According to the Nuclear Regulatory Commission, "SUNSI" means any information of which the loss, misuse, modification, or unauthorized access can reasonably be foreseen to harm the public interest, the commercial or financial interests of the entity or individual to whom the information pertains, the conduct of NRC and Federal programs, or the personal privacy of individuals. *See* http://www.nrc.gov/reading-rm/doc-collections/commission/comm-secy/2005/2005-0054comscy-attachment2.pdf

Esse quam videre

- Perhaps you fear that a full and frank discussion of these issues will result in no further use of light-ware fission reactors for generating electricity.
- So be it. That is the price of living in a democratic republic.
- "But the nation's economic health demands use of nuclear power, regardless of how a majority of the public feels about it." Is that your belief?
- You have just had an insight into your own totalitarian tendencies.[2]

"If the first tiny droplet of truth has exploded like a psychological bomb, what will happen in our country when waterfalls of Truth come crashing down?"[3]

Background

The U.S. Nuclear Regulatory Commission proposes to amend its regulations to certify an amendment to the Westinghouse AP1000 standard plant design. The purpose of the amendment is to replace the combined license (COL) information items and design acceptance criteria (DAC) with specific design information, address the effects of the impact of a large commercial aircraft, incorporate design improvements, and increase standardization of the design. On January 20, 2010, Westinghouse submitted to NRC design changes that would be included in Revision 18 of the AP1000 DCD (ADAMS Accession No. ML100250888). Subsequently, Westinghouse narrowed the focus of the changes, and on December 1, 2010 submitted Revision 18 (ADAMS Accession No. ML103480572).

Comments

What is perhaps most troubling about the AP1000 design approval is the lack of final NRC review. The Commission states: 3

> No technical review of Revision 18 by the NRC is necessary, because only [confirmatory items] and design changes pursuant to [interim staff guidance] previously accepted by the NRC are contained in Revision 18 to the DCD.[4]

The purpose of the cited interim staff guidance (DC/COL-ISG-011) is to finalize the review of the design. Although it may clarify things for license applicants, its effect is to freeze out the interested public's ability to bring new issues before the Commission. The guidance document states:

> The NRC is issuing its Final Interim Staff Guidance (ISG) DC/COL-ISG-011 (Agencywide Documents Access and Management System (ADAMS) Accession No. ML092890623). This ISG is to clarify the NRC staff position on finalizing licensing basis information at a point during the licensing review, a 4

[2] Adapted or copied from "A Critic Looks at Industry Credibility," David Dinsmore Comey, Director of Environmental Research Businessmen for the Public Interest, paper presented to the Atomic Industrial Forum, February 5, 1975
[3] Aleksandr Solzhenitsyn, *Id*
[4] Federal Register /Vol. 76, No. 37 /Thursday, February 24, 2011 / Proposed Rules 10269

so-called freeze point, and the control of licensing basis information during and following the initial review of applications for design certifications (DCs) or combined licenses (COLs). The NRC staff issues COL/DC-ISGs to facilitate timely implementation of current staff guidance and to facilitate activities associated with review of applications for DCs and COLs by the Office of New Reactors (NRO). The NRC staff intends to incorporate the final approved DC/COL-ISG-011 into the next revision of Regulatory Guide 1.206, "Combined License Applications for Nuclear Power Plants." 4

The flawed nature of the Westinghouse AP1000 should not be frozen at this time. At present, fourteen AP-1000s are planned in the United States and twelve more in China. Among the specific technical issues which are yet unresolved is "Extension of Seismic Spectra to Soil Sites and Changes to Stability and Uniformity of Subsurface Materials and Foundations." In the wake of the Fukushima disaster, the NRC cannot certify the AP1000 without further review and analysis. The following pages outline some of the design weaknesses and safety flaws. 5

Flawed Design

The proposed Westinghouse AP1000 nuclear power reactor should rightly be re-named *inherently dangerous*. Based our review of the so-called inherently safe design, the reactors, if constructed, would be accidents waiting to happen.

The AP-1000 is based on an earlier design, the AP-600, which was deemed too expensive to be competitive in today's energy market.[5] To bring down costs, they added more, larger fuel assemblies and a bigger reactor core, raising power from 1,933 megawatts-thermal to 3,400 MWt, a 76% increase. Westinghouse has worked for a decade to get the new AP-1000 design approved, but has run into a series of stumbling blocks. Today, it's in its 17th revision.

The two basic problems with the AP-1000 are: 6
1) Modular construction of the reactor shield building and an 800,000 gallon tank of water suspended above the reactor core, subjecting it to severe stress and instability in the event of an earthquake, tornado or hurricane; 7
2) A ventilation system which allows the free flow of air from inside the reactor containment building to outside air, allowing radiation to escape in the event of a reactor core breach. 8

Modular Construction

One of the cost-cutting measures employed by Westinghouse is modular construction of the reactor containment structure. Older plants cast the concrete structure as a unit. Making matter worse is an emergency cooling water tank holding eight hundred thousand gallons of water. This tank would weigh 3,334 tons. For comparison, the total weight of

[5] *A Roadmap to Deploy New Nuclear Power Plants in the United States by 2010*, Volume II, Main Report, Appendix D: Design Description AP-1000, US Department of Energy, October 31, 2001

the nuclear reactor vessel itself is 417 tons.[6] The water tank would sit atop the modular structure of the AP-1000 building.

Nuclear reactor shield buildings are supposed to guard against shocks from the outside
and provide a barrier to radiation from the inside. Federal regulations require nuclear 9
power plants to withstand earth tremors, severe weather and impacts from missiles and
aircraft. In October 2009 the Nuclear Regulatory Commission sent Westinghouse back
to the drawing board because the company had not demonstrated the ability of the AP-
1000 structure to meet these standards. NRC said, "Specifically, the design of the steel
and concrete composite structural module (SC module) must demonstrate the ability to
function as a unit during design basis events."[7] In response to a question about the AP-
1000, the chairman of the NRC replied, "Changes need to be made and additional
information needs to be provided."[8] However, NRC itself is a leaky vessel for hope. At
the Plant Vogtle nuclear power station in Georgia, Southern Company is pushing to build
two AP-1000s. It will require effective action on the part of residents, activists, elected
officials and others to prevent an aggressive company with powerful political support
from riding roughshod over safety issues.

Reactor Containment System

To reduce expensive plumbing, pumps and other hardware, the AP-1000 relies on so-
called passive safety systems; that is, in the event of an accident, the reactor is to be
cooled and controlled without electrical power and would "require no operator actions for 10
72 hours."[9] However, this passive design feature is the source of a fundamental
weakness so far overlooked by the Nuclear Regulatory Commission.

According to a comprehensive review of the AP1000 by Arnold Gundersen, reactor containment failures at Florida's Crystal River and Pennsylvania's Beaver Valley reactors reveal fundamental problems which point to a dangerous design flaw in the freestanding steel and concrete containment system of the new AP-1000.[10] Gundersen stated the danger bluntly:

> The unique AP1000 containment design allows it to develop a preexisting 11
> condition that could lead to a reduction in its wall thickness that would result in
> a rapid release of radiation. This scenario is likely and is not anticipated in the
> current design basis AP1000 analysis nor in the SAMDA analysis. 12

(SAMDA means severe accident mitigation design alternatives.) According to

[6] AP1000 Design Control Document Reactor Coolant System and Connected Systems 5.3.4.1, Revision 15
[7] Letter to Westinghouse From Dave Matthews to Rob Sisk regarding AP1000 Shield Building Design, 10/15/2009, ADAMS ML092320205
[8] "NRC chairman says Vogtle design needs safety changes" *The Atlanta Journal-Constitution*, David Markiewicz, November 5, 2009
[9] *Roadmap*
[10] Arnold Gundersen is the Chief Engineer with Fairewinds Associates, Inc., specializing in nuclear safety, engineering, and reliability issues. Gundersen is a nuclear engineer with more than 38 years of experience in nuclear power plant operation, management and design.

Gundersen, the NRC underestimates the radiation dose consequences of containment failure in the AP-1000. Corrosion, cracking and leakage in nuclear reactor containment 13
structures are more serious than anticipated by the NRC. And the high-oxygen and high-moisture environment in the AP-1000 makes it even more susceptible to corrosion in inaccessible locations than older plants. The AP-1000 design would siphon radiation leakage from the reactor containment to the atmosphere unfiltered and unmonitored. And this leakage path is more dangerous than those previously identified. In the Crystal River and Beaver Valley plants, the steel and concrete containment have no gap between them; a breach of the steel structure would be blocked by the concrete. But an accident releasing radioactive gases from the AP-1000 reactor vessel would not be kept inside the 13
containment structure because there is an annular gap between the steel containment and the concrete building. This gap is designed to draw air up and release it through the top of the building.

Post-9/11 Violation

In response to the terrorist attack on September 11, 2001, The Commission required nuclear reactor builders to make changes to withstand airplane impacts. In October 2010 the NRC issues a notice of violation to Westinghouse for failing to meet these safety standards in its AP1000 design. Specifically, NRC found failures to fully protect from fire the plant's concrete and steel shield building which houses the nuclear reactor. However, the violation carried no penalty.

Information Kept Secret

On September 29, 2010 the Division of New Reactors approved three related requests to withhold information from public disclosure.[11] These actions centered on withholding 14
information on the AP1000 nuclear reactor's containment shield building. We believe these requests were improper, contrary to the interests of public health and safety and, coming at this time, an attempt to circumvent scrutiny by the affected public.

As you may also know, on June 25, 2010 Arnold Gundersen[12] briefed the Advisory Committee on Reactor Safeguards about serious design flaws in the AP1000 shield building, the steel and concrete structures which are supposed to contain radiation in the event of an accident. The ACRS determined that the issue would need to be addressed in both generic and site-specific proceedings; that is, during both overall design certification and individual license applications. On August 12, 2010 we filed a new contention in our Plant Vogtle license intervention based on this information.

In June, the Chairman of the Advisory Committee on Reactor Safeguards, Harold B. Ray, said that specific issues relating to accessibility, inspections and maintenance of the

---

[11] ADAMS Accession Nos. ML102660263, ML102670260 and ML102660378

[12] Arnold Gundersen is the Chief Engineer with Fairewinds Associates, Inc., specializing in nuclear safety, engineering, and reliability issues. Gundersen is a nuclear engineer with more than 38 years of experience in nuclear power plant operation, management and design.

containment should be addressed not in the pending generic review of the AP1000 design by the ACRS, but within individual combined operating license proceedings.

However, the Nuclear Regulatory Commission granted the request to withhold information from the public which is directly related to the ongoing determination of safety measures at Plant Vogtle. Even if such withheld information were deemed proprietary, which we dispute, the withholding should not have been permitted because it impaired procedural rights.[13] 15

Further, under 10 CFR § 2.390, the Commission may deny a request for withholding of information from the public. The relevant regulation states:[14]

> The procedures in this section must be followed by anyone submitting a document to the NRC who seeks to have the document, or a portion of it, withheld from public disclosure because it contains trade secrets, privileged, or confidential commercial or financial information.
>
> If the Commission determines, under paragraph (b)(4) of this section, that the record or document contains trade secrets or privileged or confidential commercial or financial information, the Commission will then determine whether the right of the public to be fully apprised as to the bases for and effects of the proposed action outweighs the demonstrated concern for protection of a competitive position, and whether the information should be withheld from public disclosure under this paragraph. <u>If the record or document for which withholding is sought is deemed by the Commission to be irrelevant or unnecessary to the performance of its functions, it will be returned to the applicant</u>. (emphasis added)

The purpose of the requests by Westinghouse was to withhold information on steel welding inspections and benchmarking, analysis, testing, design and audits of the reactor containment shield building. Shield building maintenance and inspection issues were and central to our intervention. The withheld AP1000 information was relevant and necessary for the licensing proceedings before the Atomic Safety and Licensing Board. Withholding relevant and material information in this matter was improper and outrageous. 16

Conclusion

If the NRC's response to technical problems is a cloak of secrecy, how can people have any confidence in the next generation of nuclear power? The problems with the AP1000 center on an inherently unsafe technology. Other problems are political: a deceitful marketing strategy and an oversight agency which mixes promotion with regulation.

---

[13] 42 USC 2231, Atomic Energy Act, Chapter 16, Sec.181

[14] 10 CFR § 2.390(b)(5) Public inspections, exemptions, requests for withholding

Respectfully,

Louis A. Zeller

Louis A. Zeller

Rulemaking Comments

From:	bredl [bredl@skybest.com]
Sent:	Tuesday, May 10, 2011 11:56 PM
To:	Rulemaking Comments
Cc:	Gallagher, Carol
Subject:	Docket ID: NRC-2010-0131
Attachments:	110510 BREDL comments DCR.pdf

May 10, 2011

Secretary, U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
ATTN: Rulemakings and Adjudications Staff
E-mail: Rulemaking.Comments@nrc.gov
301-415-1677

RE: Docket ID: NRC-2010-0131
Advanced Passive (AP) 1000 Design Certification Amendment
76 FR 10269, 10 CFR 52

To the Commission:

On behalf of the Blue Ridge Environmental Defense League, I submit the attached remarks.

Respectfully,

Louis Zeller
Blue Ridge Environmental Defense League
BREDL@skybest.com
336-982-2691

PR 52
(76FR10269)

59

PUBLIC SUBMISSION

As of: May 11, 2011
Received: May 10, 2011
Status: Pending_Post
Tracking No. 80c6bdf5
Comments Due: May 10, 2011
Submission Type: Web

Docket: NRC-2010-0131
AP1000 Design Certification Amendment

Comment On: NRC-2010-0131-0001
AP1000 Design Certification Amendment

Document: NRC-2010-0131-DRAFT-0030
Comment on FR Doc # 2011-03989

DOCKETED
USNRC

May 11, 2011 (9:00 am)

OFFICE OF SECRETARY
RULEMAKINGS AND
ADJUDICATIONS STAFF

Submitter Information

Name: Kenneth Schrader
Address:
1279 Ironbark St.
San Luis Obispo, CA, 93401

General Comment

I recommend Commission approval of the design certification rule for the Westinghouse AP1000 design.

The Westinghouse AP1000 is a world leading advanced nuclear reactor design with the capability to provide base load electricity generation without the emission of air pollutants or greenhouse gasses. The AP1000 was designed using supercomputers to maximize safety and. incorporates technology developed based on thousands of years of combined nuclear reactor operating experience.

The AP1000 incorporates extensive use of passive safety systems that use natural gravity, conduction, and convection to mitigate events and remove residual core decay heat. The passive safety systems do not require offsite power or onsite diesel generators to operate. The passive safety systems have been fully tested at facilities throughout the world to ensure they operate as designed. As a result of use of passive safety systems and built in automation, the AP1000 provides walk away safety for three days, with no human intervention required.

The AP1000 passive safety systems are especially effective during an event that all AC electricity is lost (station blackout), such as what occurred at the Fukushima Daiichi plant in Japan when offsite power was lost and the diesel generators were damaged by a tsunami. The AP1000 response to a similar scenario would be uneventful, since the reactor core would be cooled by gravity driven flow from permanent water tanks located inside the containment.

The AP1000 is already being built in China. Commission approval of the design certification rule for the Westinghouse AP1000 will allow the US to benefit from a leading advanced nuclear reactor.

Template = SECY-067 **DS 10**

Rulemaking Comments

From: Gallagher, Carol
Sent: Wednesday, May 11, 2011 8:16 AM
To: Rulemaking Comments
Subject: Comment on Proposed Rule - AP1000 Design Certification Amendment
Attachments: NRC-2010-0131-DRAFT-0030.pdf

Van,

Attached for docketing is a comment from Kenneth Schrader on the above noted proposed rule (3150-AI81; 76 FR 10269) that I received via the regulations.gov website on 5/10/11.

Thanks,
Carol

PR 52
(76FR10269)

60

Rulemaking Comments

From: tomclements329@cs.com
Sent: Wednesday, May 11, 2011 9:02 PM
To: Rulemaking Comments
Subject: DOCKET ID NRC-2010-0131, AP1000 rulemaking
Attachments: Sterret to NRC 5.11.2011.pdf

DOCKETED
USNRC

May 12, 2011 (9:10 am)

OFFICE OF SECRETARY
RULEMAKINGS AND
ADJUDICATIONS STAFF

To Whom it Concerns:

I hereby submit the following memo for the AP1000 rulemaking docket. This memo, submitted in an earlier AP1000 docket and still relevant, requires a full response by the NRC staff in the current AP1000 rulemaking docket..

Obviously, your response or non-response will become part of the AP1000 rulemaking docket and will thus comprise the record upon which a legal challenge to the AP1000 rulemaking is made, if such action develops.

I request that this message and the attachment be made part of the record for DOCKET ID NRC-2010-0131 and be posted in ADAMS.

Sincerely,

Tom Clements
Friends of the Earth
Columbia, SC

Template-SECY-067

DS10

3

DOCKET NUMBER
PROPOSED RULE PR 52
(70 FR 20062)

201 West Duke Building
Box 90743
Duke University,
Durham NC 27708

July 5, 2005

DOCKETED
USNRC

July 5, 2005 (4:00pm)

OFFICE OF SECRETARY
RULEMAKINGS AND
ADJUDICATIONS STAFF

To: Annette L. Vietti-Cook
Secretary, U.S. Nuclear Regulatory Commission
Washington, D. C. 20555-0001
ATTN: Rulemakings and Adjudications Staff

Subject: Public Comment on RIN 3150-AH56
Proposed Design Certification Rule -- AP1000 Design Certification

Ref: Federal Register April 18, 2005 (Volume 70, Number 73)
Proposed Rules. Pages 20062-20080.

The comment below is in response to the opportunity provided for public comment on the proposed rulemaking to amend 10 CFR Part 52 to certify the AP1000 standard plant design, which appeared in the referenced Federal Register notice. I am making these comments as a member of the public, unaffiliated with any organization.

....

COMMENT by Dr. S. G. Sterrett, Assistant Professor, Duke University

In spite of the diligence of the NRC and the responsiveness of the applicant on a large number of design issues, the proposed rule granting design certification to the AP1000 as submitted should not be approved, for the following three reasons:

1. The AP1000 DCD (Design Control Document) referenced in the proposed rule does not meet the requirement of 10 CFR Part 52 that the plant design be complete except for site-specific elements and other specified exemptions.

<u>Example:</u> The applicant did not provide, and the NRC staff did not ask for, evidence showing that the auxiliary systems have been, or, even, that they can be, designed to provide the flows, pressures and temperatures claimed in the design descriptions in the applicant's submittal under the challenging layout constraints set for the AP1000 (i.e., keeping the same building "footprint" as the AP600).

The ability of important components such as large relief valves to operate according to their design parameters is dependent on the layout of the inlet piping and the discharge piping. The applicant's DCD does not indicate that the associated design calculations regarding flows achieved in auxiliary systems have been

Template=SECY-067

SECY-02

performed to substantiate the claims in the DCD. The NRC-authored FSER (NUREG-1793) did not address this aspect of the design, yet it does not fall under any exemption the NRC granted (It does not fall under the "Design Acceptance Criteria" exemption nor is it a site-specific element). Such flows, though they are features of auxiliary reactor systems (e.g., main steam (steam generator) relief valve flow) are inputs to the safety analyses.

Since such design information is crucial to the conclusions of the safety analysis, this information is required per 10 CFR Part 52, under which design certification of the AP1000 is sought (specifically, the requirements in 10 CFR 52.47(b)(2) for content of applications). The tendency among some NRC staff[1] to mistakenly regard this kind of information as "as built" indicates a lack of appreciation of the significance of this design information to plant safety. This is not "as built" versus "as designed" information[2]; it is design work crucial to plant safety and it is part of a complete plant design.

2. The fundamental question of the appropriateness of the process used to derive the AP1000 design from the AP600 design has not been given sufficient attention in the NRC's review.

In its evaluation of the applicant's QA (Quality Assurance) program, the NRC evaluated the QA procedures for conformance to 10CFR50 Appendix B. However, the fundamental question of how the AP1000 design was generated from the AP600 design was not broached. The applicant indicated that "a continuous QA program" was used spanning the AP600 and AP1000 design activities, and the cover sheet of the applicant's DCD identifies "change review" as the basis for the AP1000 DCD.

The change review process was devised to apply to proposed changes to the AP600 design during the AP600 design process. It is inappropriate to apply it to the activity of producing a new plant design from the AP600. The NRC appears to have reviewed the acceptability of the QA procedure governing the generation of the AP1000 DCD for its use *as a change review process.* The NRC never addressed the question of whether

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[1] This issue was raised in a letter to the ACRS ("AP1000 Fluid Systems Design and QA Procedures", July 30, 2003. Letter from Susan G. Sterrett to ACRS Subcommittee on Future Plant Designs.) The ACRS did not disagree with the point, but considered it a staff matter (transcript of meeting of ACRS Subcommittee on Future Plant Designs held at Monroeville, PA on July 17th and 18th, 2003). The letter that the NRC staff subsequently sent to me in response ("Response to Concerns About the AP1000 Design Certification", April 20, 2004. From James E. Lyons, Program Director, New, Research and Test Reactors Program, Division of Regulatory Improvement, Office of Nuclear Reactor Regulation, Nuclear Regulatory Commission, to Susan G. Sterrett, Assistant Professor, Duke University) incorrectly assumed that design calculations showing that the correct flows, temperatures and pressures can be achieved was an exemption covered under the DAC (Design Acceptance Criteria), which it is not. Nor should it be; DAC are only appropriate for piping structural criteria.

[2] Since ITAACS are for "as built" verification, it is inappropriate to appeal to ITAACS to ensure that the system is properly designed; ITAACS are not meant to relieve the designer of the plant of performing crucial system design work.

using this change review process to derive a *new* plant design, the AP1000, *from* the AP600, was appropriate.

I fear that Westinghouse is attempting to invent a loophole to avoid appropriate QA procedures, and the NRC has not challenged them on it. I understand that there are Westinghouse QA procedures for proposing new plant designs, there are Westinghouse QA procedures for uprating operating plants, and there are (less involved) Westinghouse QA procedures for reviews of proposed changes to plant designs. The QA procedures for a new plant design and for uprating operating plants address significant changes to major plant parameters and so require steps not included in a change review; they involve coordination with many other design disciplines and groups at a level beyond those involved in a change review. By (inappropriately) treating the AP1000 as a *revised AP600* rather than as a new plant design or an uprating of an existing plant design, the applicant managed to avoid both the QA requirements for design of new plants and the QA requirements for design of upratings.

Besides this omission by the NRC staff being a regulatory error, the situation is of concern; below are two major problems that could affect plant performance and safety:

--- Because the detailed design of the AP1000 is not yet performed, it is nowhere specified which specific details are inherited from the AP600 but need to be changed for compatibility with other changes made for the AP1000. Westinghouse has stated that the AP600 design details will be used in the AP1000 to the extent possible, and much of the AP1000 design makes reference to AP600 documentation. There is the danger of making the false inference that if a system configuration has not changed between the AP600 and the AP1000, the fluid system performance has not changed either. This is not always true, because a system temperature or pressure in one system can affect fluid system performance in another. If the AP1000 is to be regarded as developed by making design changes to the AP600, the kind of fluid systems review called for is one at least as comprehensive as the kind of review required for an extended power uprating. (The NRC has stated that the AP1000 is not an uprating[3], but, were it treated as an uprated version of the AP600, the AP1000 would be about a 70% uprating, which is much larger than any uprating approved to date.) Even though the systems at issue are auxiliary systems, the situation impacts plant safety, since the conclusions of the safety analysis are dependent upon the auxiliary fluid systems performing as described in the system design descriptions in the AP1000 DCD.

-- The NRC never addressed the question of whether the AP600 reports and documents referenced in the AP1000 DCD were verified *as applicable to* the AP1000. The authors and verifiers of the AP600 reports wrote and verified them *specifically for the AP600*. The general issue of how applicability of AP600 re-

[3] In "Response to Concerns About the AP1000 Design Certification", April 20, 2004. From James E. Lyons, Program Director, New, Research and Test Reactors Program, Division of Regulatory Improvement, Office of Nuclear Reactor Regulation, Nuclear Regulatory Commission, to Susan G. Sterrett, Assistant Professor, Duke University.

ports and documents to the AP1000 was determined is an important QA issue but was not adequately addressed in the NRC's review. If the decision that an AP600 report is to be referenced for the AP1000 is not made by the design group that authored the report, the decision effectively bypassed QA procedures and the very important checks and balances between engineering and management.

3. The accelerated schedule for the AP1000 requested by the applicant led to cutting regulatory corners.

Example (i): The decision by the NRC not to require that Westinghouse build and test a prototype of a major valve used in accident mitigation (the ADS 4th stage squib valve, an explosively-actuated valve), even though no valve of the type and size used in the AP1000 design has ever been built, much less tested, was made under the schedular pressures of the accelerated AP1000 schedule. There was no reason not to require it; the design applicant simply preferred not to expend the time and money involved in building and testing a prototype.

Example (ii): The question of the effect of heat of solar radiation on the performance of the AP 1000 Passive Containment Cooling System (PCS) has not been resolved. The AP1000 safety analysis and the test design of prototype scale models used to validate PCS performance assumed that the temperature of a concrete building in direct sunlight cannot exceed the surrounding air temperature, which is false. The effect is especially marked for plants in southern latitudes. This design issue has not been resolved; it has only been dismissed without a quantitative study.

Further information on this example:

--- The AP1000, unlike operating PWRs, uses the outside air as the ultimate heat sink, and so is fundamentally different from operating PWRs, which use a large body of water as the ultimate heat sink and transfer the heat to the ultimate heat sink via cooling towers. In the AP1000, the PCS is relied upon to transfer heat to the outside air in the event of a design basis accident. The PCS uses the water in the PCS storage tank located at the top of the concrete shield building and relies upon air flow through the air passageways between the steel containment and the surrounding concrete shield building, to cool and depressurize the containment in the event of an accident. Since the heat of solar radiation can cause the temperature of objects to exceed that of the surrounding air, the effect of solar radiation on the temperature of the concrete building is relevant to the accident analyses. The configuration is proprietary and so not available to the public; however, the concrete thickness of the conical roof section of the concrete shield building is stated in the DCD as 18 inches, which is not thick enough to justify dismissing the concern as irrelevant to PCS heat removal capability for all latitudes.

In some climates, there are configurations for which the temperature rise in concrete due to heat of solar radiation occurs not only during a daily cycle, but can cause the temperature to continue to build up day after day. The temperature rise due to solar radiation is dependent on surface properties of the concrete, especially color. Hence the surface properties of the concrete shield building might be relevant to the efficacy of the PCS to remove the heat during an accident. The temperature rise is also dependent upon geographical latitude. Hence geographical latitude ought to be a site parameter, unless it can be shown that the PCS is effective at all geographical latitudes, even when heat of solar radiation is taken into account.

The issue was discussed by the ACRS at its very last meeting on the AP1000[4], but the effect was not quantified. In their letter to the Commissioners[5], the ACRS expressed confidence that the effect was covered by design margins, without performing a quantitative analysis. The basis for this confidence is unclear; without a quantitative analysis or testing, it is not possible to determine for what latitudes, if any, the AP1000 PCS heat removal capability is significantly affected. This letter, too, was written under the tight schedular constraints imposed by the accelerated schedule for AP1000 design certification.

Example (iii): The schedule for AP1000 design certification was further accelerated by granting Final Design Approval (FDA) before the Final Safety Evaluation Report (FSER) was made available to the public. Thus all public input on the NRC's Final Safety Evaluation Report prior to the NRC granting FDA was eliminated.

Respectfully submitted,

Susan G. Sterrett

Susan G. Sterrett
Assistant Professor, Philosophy
Box 90743, Duke University
Durham NC 27708
sterrett@duke.edu

[4] At the July 7th, 2004 full ACRS committee meeting, I presented a memo tabulating the issues I had raised about the AP1000 design certification review that remained unresolved. ("NRC Response to Concerns About AP1000 Design Certification" Memo from Susan G. Sterrett to ACRS Members; John P. Segala, AP1000 Project Manager; and James E. Lyons, Program Director, New, Research and Test Reactors Program. July 8, 2004. [actually presented at July 7th ACRS Full Committee Meeting] 4 pgs.)

[5] "Report on Safety Aspects of the Westinghouse Electric Company Application for Certification of the AP1000 Passive Plant Design", July 20, 2004. From Mario V. Bonaca, Chariman, Advisory Committee on Reactor Safeguards to The Honorable Nils J. Diaz, Chariman, Nuclear Regulatory Commission.

B. L. "Pete" Ivey
Vice President
Nuclear Development Support

Southern Nuclear Operating Company, Inc.
42 Inverness Center Parkway
Post Office Box 1295
Birmingham, Alabama 35242

Tel 205.992.7619
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PR 52
(76FR10269)

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DOCKETED
USNRC

May 12, 2011 (9:10 am)

OFFICE OF SECRETARY
RULEMAKINGS AND
ADJUDICATIONS STAFF

SOUTHERN COMPANY

MAY 0 9 2011

ND-11-0912

ATTN: Rulemakings and Adjudications Staff

Secretary
U.S. Nuclear Regulatory Commission
Document Control Desk
Washington, DC 20555-0001

Southern Nuclear Operating Company
Vogtle Electric Generating Plant Units 3 and 4
Comments on Proposed AP1000 DCD Amendment Rulemaking
Docket ID NRC–2010–0131

Ladies and Gentlemen:

Southern Nuclear Operating Company (SNC), Combined License applicant for Vogtle Electric Generating Plant Units 3 and 4 referencing the Westinghouse AP1000 Design Control Document, has reviewed the notice of proposed rulemaking for 10 CFR Part 52 Appendix D entitled "Design Certification Rule for the AP1000 Design" published in the Federal Register on February 24, 2011 (76 Federal Register 10269). SNC has no comment on the proposed rulemaking, and supports the NRC processes that would allow final rulemaking to proceed.

If there are any questions regarding this letter, please contact Mr. Chuck Pierce at (205) 992-7872.

Respectfully submitted,

SOUTHERN NUCLEAR OPERATING COMPANY

B. L. Ivey

BLI/AGA

Template = SECY-067 **DS 10**

cc: Southern Nuclear Operating Company
Mr. J. H. Miller, III, President and CEO
Mr. J. A. Miller, Executive Vice President, Nuclear Development
Mr. J. T. Gasser, Executive Vice President, Nuclear Operations
Mr. D. H. Jones, Site Vice President, Vogtle 3 & 4
Mr. J. R. Johnson, Vice President, Quality and Compliance
Mr. T. E. Tynan, Vice President - Vogtle
Mr. M. K. Smith, Technical Support Director
Mr. D. M. Lloyd, Vogtle 3 & 4 Project Support Director
Mr. C. R. Pierce, AP1000 Licensing Manager
Mr. M. J. Ajluni, Nuclear Licensing Director
Mr. T. C. Moorer, Manager, Environmental Affairs, Chemistry and Rad. Services
Mr. J. D. Williams, Vogtle 3 & 4 Site Support Manager
Mr. J. T. Davis, Vogtle 3 & 4 Site Licensing Supervisor
Mr. W. A. Sparkman, COL Project Engineer
Ms. A. G. Aughtman, Lead AP1000 Licensing Project Engineer
Document Services RTYPE: GOV0208
File AR.01.02.06

Nuclear Regulatory Commission
Mr. V. M. McCree, Region II Administrator
Mr. F. M. Akstulewicz, Deputy Director Div. of Safety Systems & Risk Assess.
Mr. R. G. Joshi, Lead Project Manager of New Reactors
Ms. T. E. Simms, Project Manager of New Reactors
Mr. B. C. Anderson, Project Manager of New Reactors
Mr. M. M. Comar, Project Manager of New Reactors
Ms. S. Goetz, Project Manager of New Reactors
Mr. J. M. Sebrosky, Project Manager of New Reactors
Mr. D. C. Habib, Project Manager of New Reactors
Ms. D. L. McGovern, Project Manager of New Reactors
Ms. T. L. Spicher, Project Manager of New Reactors
Ms. M. A. Sutton, Environmental Project Manager
Mr. M. D. Notich, Environmental Project Manager
Mr. L. M. Cain, Senior Resident Inspector of VEGP 1 & 2
Mr. J. D. Fuller, Senior Resident Inspector of VEGP 3 & 4

Georgia Power Company
Mr. T. W. Yelverton, Nuclear Development Director
Ms. A. N. Faulk, Nuclear Regulatory Affairs Manager

Oglethorpe Power Corporation
Mr. M. W. Price, Executive Vice President and Chief Operating Officer
Mr. K. T. Haynes, Director of Contracts and Regulatory Oversight

Municipal Electric Authority of Georgia
Mr. J. E. Fuller, Senior Vice President, Chief Financial Officer
Mr. S. M. Jackson, Vice President, Power Supply

Dalton Utilities
Mr. D. Cope, President and Chief Executive Officer

<u>Bechtel Power Corporation</u>
Mr. J. S. Prebula, Project Engineer
Mr. R. W. Prunty, Licensing Engineer

<u>Tetra Tech NUS, Inc.</u>
Ms. K. K. Patterson, Project Manager

<u>Shaw Stone & Webster, Inc.</u>
Mr. B. Davis, Vogtle Project Manager
Mr. J. M. Oddo, Licensing Manager
Mr. E. C. Wenzinger, Licensing Engineer, Vogtle Units 3 & 4

<u>Westinghouse Electric Company, LLC</u>
Mr. S. D. Rupprecht, Vice President, New Plant Product Services
Mr. T. H. Dent, VP, Consortium Project Director Vogtle Units 3 & 4
Mr. R. F. Ziesing, Director, US Licensing, NPP
Mr. S. A. Bradley, Vogtle Project Licensing Manager
Mr. M. A. Melton, Manager, Regulatory Interfaces
Mr. T. J. Ray, Manager, AP1000 COL Licensing Support
Mr. D. A. Lindgren, Principal Engineer, AP1000 Licensing and Customer Interface

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Ms. A. L. Sterdis, TVA
Mr. M. Vidard, EDF
Mr. W. Maher, FP&L
Mr. J. Douet, Entergy
Mr. N. T. Simms, Duke Energy
Mr. G. A. Zinke, NuStart & Entergy
Mr. R. H. Kitchen, PGN
Ms. A. M. Monroe, SCE&G
Mr. T. Miller, DOE/PM

PR-52
(76FR10269)

DOCKETED
USNRC

July 5, 2011 (4:50 pm)

OFFICE OF SECRETARY
RULEMAKINGS AND
ADJUDICATIONS STAFF

62

From:
Sent: Wednesday, May 11, 2011 2:42 PM
To: NRC Allegation
Cc
Subject: Design deficiency in GE ESBWR reactor.

Dear USNRC Engineers,

I studied latest BWR reactor design ESBWR in view of Fukushima incident from the document 'The ESBWR Plant General Description' by GE/Hitachi (183 page document). This design is safer but not foolproof. GE claims that ESBWR emergency cooling systems are totally passive but at most they can be called semi-passive only, as their operation is dependant on DC supply. If DC supply is lost, emergency cooling and depressurization systems will fail miserably and it can be catastrophic in an emergency situation. There is a fair chance of failure of DC supply as safety related battery banks (Class-1E grade batteries) are housed below grade (ground) level in reactor building. Not only battery bank but electrical penetration to primary containment is also below grade level. I understand that battery room doors are water-tight but the doors may get damaged in earthquake/tornado or any other natural disaster and they may not remain water-tight. Water may enter through the doors and it may incapacitate battery banks. No one can guaranty that doors will remain leak tight after a severe natural disaster. Even if we assume that battery room doors will remain leak tight in spite of any natural disaster (hypothetical assumption), then also water may enter into room if doors are open at the time of incident for maintenance/testing/replacement of cells etc. Loss of DC supply is like station blackout in this case. Actually in this design GE has shifted function of EDG (class-III supply) to battery bank (class-I supply) and most of the emergency systems operation (except for isolation condenser & PCC) are dependant on it like operation of explosive squib valves, control circuits etc. Fukushima incident has proved that keeping emergency supply systems (EDG, battery bank etc) on grade level or below grade level is not a prudent design. In view of this I suggest you to please enforce relocation of safety related DC batteries and their related systems above grade level so that they may not get flooded in tsunami/tornado/hurricane/heavy rain or in any other natural disaster. Following is the list of systems whose operation is dependant on DC supply.

1. Reactor depressurization system (DPVs)
2. Gravity driven core cooling system (GDCS)
3. BiMAC core catcher cooling (GDCS deluge valves)
4. Suppression pool equalization line Valves (squib valves)
5. Standby liquid control system (SLCS injection line squib valves)

From above list it is clear that most of the emergency safety function is dependant on DC supply and there is no diverse way of above system operation if DC supply fails. There is redundancy but no diversity is above safety systems operations. Thus DC supply reliability must be ensured. Relocating the class-1E battery banks to above grade elevation is not a big thing and it can be done easily. Truly speaking, operation of so many safety systems should not be dependant on a single support system (class-1E DC supply in this case). If they are then there should be at least one diverse way of system actuation.

There are some other deficiencies which should be rectified. These are given below.

1. Two CRDs are scramed by one hydraulic control unit (HCU). A single failure of one HCU will affect scram function of two CRDs. It is done for cost saving. It may be acceptable in a conventional system but not in a safety system. Safety should not be compromised for the cost otherwise it will be very costly.

2. Control room should also be located at sufficient height from the ground to prevent its flooding during tsunami/tornado/hurricane/heavy rain etc. It does not seem to be located at a safe elevation.

GE may still claim that this design is safe but please remember that before 11/3/11, Japanese were also saying the same.

Above rationale about location of class-1E grade battery bank is applicable for AP-1000 reactor also.

In view of this I request you to please implement lessons learned from Fukushima incident and enforce required modifications to make nuclear power safer and make a severe incident to happen 'Never again'.

Thank you.

Rulemaking Comments **PR 52 (76FR10269)** 63

From: John Runkle [jrunkle@pricecreek.com]
Sent: Tuesday, May 24, 2011 11:23 AM
To: Rulemaking Comments
Subject: DOCKET ID NRC-2010-0131
Attachments: additonal comments w atts 1-4.pdf

Attached please find the ADDITIONAL COMMENTS SUPPORTING THE PETITION BY THE AP1000 OVERSIGHT GROUP ET AL. TO SUSPEND AP1000 DESIGN CERTIFICATION RULEMAKING PENDING EVALUATION OF FUKUSHIMA ACCIDENT IMPLICATIONS ON DESIGN AND OPERATIONAL PROCEDURES AND REQUEST FOR EXPEDITED CONSIDERATION, including four attachments.

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ADJUDICATIONS STAFF

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UNITED STATES OF AMERICA
U.S. NUCLEAR REGULATORY COMMISSION
BEFORE THE COMMISSION

In the Matter of	)	
AP1000 Design Certification Amendment	)	NRC-2010-0131
10 CFR Part 52	)	RIN 3150-A18

ADDITIONAL COMMENTS SUPPORTING THE PETITION
BY THE AP1000 OVERSIGHT GROUP ET AL.
TO SUSPEND AP1000 DESIGN CERTIFICATION RULEMAKING
PENDING EVALUATION OF FUKUSHIMA ACCIDENT IMPLICATIONS
ON DESIGN AND OPERATIONAL PROCEDURES
AND REQUEST FOR EXPEDITED CONSIDERATION

NOW COME the AP1000 Oversight Group et al. with additional comments supporting their Petition to Suspend AP1000 Design Certification Rulemaking Pending Evaluation of Fukushima Accident Implications on Design and Operational Procedures and Request for Expedited Consideration (the "Petition") filed with the Commission on April 6, 2011, and in the rulemaking, Docket ID NRC-2010-0131, on the certification of the AP1000 reactor design and operational procedures. The public comment period on the AP1000 design certification rulemaking closed on May 10, 2011, although in its May 10, 2011 memorandum, the Commission through Ms. Annette L. Vietti-Cook, Secretary, stated "Comments received after May 10, 2011 will be considered if it is practical to do so, but assurance of consideration of comments received after that date cannot be given." Given the potentially substantial delays in the NRC review of the AP1000 design and operational procedures, the comment period is essentially still open for comments.

In the rulemaking docket, the AP1000 Oversight Group, Friends of the Earth and many members of the public submitted substantive comments – many of which point out the potential flaws with the AP1000 design and operational procedures, some of which were highlighted by the preliminary lessons learned from Fukushima. Subsequent to the comment period, Congressman Markey (D-MA) released his report, "Fukushima Fallout: Regulatory Loopholes at U.S. Nuclear Plants,"[1] which pointed out issues with emergency diesel generators, hydrogen explosions, and seismic safety. As noted in the Petition and emphasized in the Markey report, the spent fuel pools, such as those proposed for the AP1000 reactors, are fundamentally flawed because of high-density stacking, the lack of emergency power and cooling systems, and the lack of adequate containment of the spent fuel pools. Congressman Markey points out the likely cause of these problems and concludes

> However, an examination of NRC regulations demonstrates that flawed assumptions and under-estimation of safety risks are currently an inherent part of the NRC regulatory program, due to a long history of decisions made by prior Commissions or by the NRC staff ***that have all too often acquiesced to industry requests for a weakening of safety standards***. Coupled with reports that the near-term inspections being conducted at United States nuclear power plants may be limited in scope2 and subject to restrictions on public disclosure, it would be unwise to move forward with any pending licensing actions before the NRC fully completes its review and upgrades of its safety requirements.

(emphasis added). This history of weakening safety standards at the behest of Westinghouse-Toshiba has led to many of the flaws in the AP1000 design and operation procedures; NRC staff decisions are being made for financial considerations rather than to protect public safety.

Subsequent to the closing of the comment period, there has been considerable

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[1] Markey, "Fukushima Fallout: Regulatory Loopholes at U.S. Nuclear Plants," March 12, 2011 (ATTACHMENT 1), also available at http://markey.house.gov/docs/05-12-11reportfinalsmall.pdf

new evidence of flaws in the AP1000 reactor design, with serious questions asked of Westinghouse-Toshiba about the methods it used to calculate structural loads in the reactor shield building.[2] It is apparent from these reports that the analysis by Dr. Ma 2 providing the basis for his Non-Concurrence (discussed in detail in the Petition) conclusively demonstrates the calculations by Westinghouse-Toshiba on structural integrity are inadequate and do not meet NRC standards or even the American Concrete Institute requirements. However, it is also apparent that even after another round of calculations, real-world testing of the Westinghouse-Toshiba design continues to be lacking. Contrary to Westinghouse-Toshiba's position, the issues raised by Dr. Ma and others are not simply matters of "interpretation" but rather integral to the AP1000 design and its lack of protection of public safety.

The NRC continues to require Westinghouse-Toshiba to provide additional information on the shield building issue, as well as other issues that may arise during the NRC's review of the AP1000 reactor. As stated by Chairman Jackzo on May 20, 2011, 3 review has "resulted in the uncovering of additional technical issues."[3] To us, this means the design needs to go back to the drawing board for fundamental changes in the design and operational procedures. Westinghouse-Toshiba needs to provide real-world testing and not just calculations on its shield building design. After this is fully reviewed by the

[2] Platts, "US NRC Asks New Questions About Westinghouse Reactor Design," May, 17, 2011 (ATTACHMENT 2). New York TIMES, Regulators Find Design Flaws in New Reactor," May 20, 2011 (ATTACHMENT 3). To date, the correspondence between Westinghouse-Toshiba and the NRC has not been entered in the ADAMS system; the present comments will be supplemented if necessary.

[3] "NRC Chairman Gregory B. Jaczko's Statement on AP1000 Review Issues," No. 11087, May 20, 2011 (ATTACHMENT 4).

NRC staff, the Commission should reopen the rulemaking on the "final" design for supplemental public comments prior to any decisions about certifying the AP1000 3
reactors. A major part of the review will be by necessity a reexamination of the entire AP1000 reactor in light of the lessons learned from Fukushima concerning spent fuel 4
pools, back up power, containment integrity and redundant cooling systems.

THEREFORE, the Petitioners renew their request for the suspension of the AP1000 design certification rulemaking until the flaws with the AP1000 reactor design and operational procedures are fully reviewed and safely resolved in light of the public comments and the implications of the Fukushima accident.

Respectfully submitted, this the 24th day of May 2011.

FOR THE PETITIONERS:

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FUKUSHIMA FALLOUT

REGULATORY LOOPHOLES AT U.S. NUCLEAR PLANTS

Prepared by the staff of Congressman Edward J. Markey (D-MA)
May 12, 2011

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Executive Summary

In the wake of the Fukushima Daiichi meltdown in Japan, the Nuclear Regulatory Commission (NRC) established[1] an agency task force to conduct a review of the lessons that can be learned from the Tohoku earthquake and the tragic, ongoing events at the Fukushima nuclear power plant that have followed. The task force's stated goal is to "Evaluate currently available technical and operational information from the events that have occurred at the Fukushima Daiichi nuclear complex in Japan to identify potential or preliminary near term/immediate operational or regulatory issues affecting domestic operating reactors of all designs, including their spent fuel pools, in areas such as protection against earthquake, tsunami, flooding, hurricanes; station blackout and a degraded ability to restore power; severe accident mitigation; emergency preparedness; and combustible gas control."

However, an examination of NRC regulations demonstrates that flawed assumptions and under-estimation of safety risks are currently an inherent part of the NRC regulatory program, due to a long history of decisions made by prior Commissions or by the NRC staff that have all too often acquiesced to industry requests for a weakening of safety standards. Coupled with reports that the near-term inspections being conducted at United States nuclear power plants may be limited in scope[2] and subject to restrictions on public disclosure, it would be unwise to move forward with any pending licensing actions before the NRC fully completes its review and upgrades of its safety requirements.

The NRC's stated commitment to learn from the recent Japanese disaster is undermined both by its post-Fukushima approvals of license extension applications for Vermont Yankee Nuclear Power Plant in Vermont and Palo Verde Nuclear Generating Station Units 1, 2, and 3[3] in Arizona and by its apparent failure to fully explore all the vulnerabilities the Fukushima meltdown has revealed.

This report represents a partial summary of regulatory inadequacies, practices and decisions that impair effective nuclear safety oversight, some of which have occurred in the wake of the Japanese meltdown. Key findings include:

- The failure of the emergency diesel generators following the loss of off-site electricity led to the meltdowns at the Fukushima reactors. Despite decades of reported problems and NRC warnings, a review of NRC documents conducted by the staff of Congressman Edward J. Markey indicates that there have been recurrent and prolonged malfunctions of emergency diesel generators at nuclear power plants in the U.S. In the past eight years there have been at least 69 reports of emergency diesel generator inoperability at 33 nuclear power plants. A total of 48 reactors were affected including 19 failures lasting over two weeks and 6 that lasted longer than a month.

[1] http://www.nrc.gov/reading-rm/doc-collections/news/2011/11-055.pdf
[2] http://markey.house.gov/docs/4.15.11.nrc.pdf
[3] http://www.nrc.gov/reactors/operating/licensing/renewal/applications/palo-verde.html

- There never have been any requirements in the U.S. for spent fuel pools to include technologies to prevent the same kind of hydrogen explosions that reportedly occurred at spent nuclear fuel pools in Fukushima. Alarmingly, NRC's regulations do not require emergency diesel generators to be operational at times when there is no fuel in the reactor core, even though this could leave spent nuclear fuel pools without any backup cooling systems in the event of a loss of external electricity to the power plant. Finally, NRC has not required its licensees to reduce the amount of nuclear fuel stored in its spent nuclear fuel pools by moving it to dry cask storage, a safer means of storage that would reduce the risk of fire and radiation release in the event of an accident.

- NRC has removed its regulatory requirements for reactor containments to include technologies to prevent hydrogen explosions, even as NRC officials repeatedly and inaccurately asserted that such technologies were absent in Japan but are required in the U.S.

- The NRC has not factored modern geologic information into seismic safety requirements for nuclear power plants, and has not incorporated its technical staff's recommendation to do so even though the new information indicates a much higher probability of core damage caused by an earthquake than previously believed. In fact, the NRC has continued to process applications for license extensions for many nuclear reactors, including Pilgrim (which is approximately 38 miles from Boston) and Indian Point (which is approximately 25 miles from New York City), even in the absence of upgraded seismic safety requirements.

- NRC's post-Fukushima inspections in the U.S. appear to be limited in scope, and its U.S. nuclear reactor inspection reports will likely exclude vulnerabilities from both the NRC and the public due to limitations imposed by the NRC.

Introduction

Four days before the Tohoku earthquake Rep. Markey wrote to the Nuclear Regulatory Commission (NRC) to urge it to postpone action on the pending NRC approval of the AP 1000, a new nuclear power plant design[4]. One of the NRC's most senior scientists had warned that the containment structure for this reactor design would not be able to withstand a strong earthquake, because 60% of it is made of a material that is so brittle it could shatter like a "glass cup" under sufficient stress.[5] As the non-concurring scientist noted, Brookhaven National Lab scientists found that Westinghouse appeared to have used an inappropriate "pushover" earthquake model that may have ignored the actual back-and-forth forces that occur in an actual earthquake, and instead assumed that such forces would only be imposed in a single direction.[6]

It is not just the designs for new nuclear power plants that raise serious concerns regarding the ability of domestic nuclear power plants to maintain safe operations and safe shut-down even in the face of a beyond design-basis event or near-concurrent series of events. The Fukushima Daiichi meltdown was initiated by the combination of an earthquake and tsunami, but it was the prolonged loss of external electricity coupled with the failure of the emergency backup diesel generators that ultimately prevented the safe shut-down of these nuclear reactors and led to the subsequent core meltdowns, spent fuel pool damage and radiation release.

Like all nuclear reactors, including those in the United States, the Fukushima Daiichi nuclear power plant needed electricity to run the plant's cooling systems, which prevent the reactors from melting down. The cooling systems also keep the spent nuclear fuel from overheating or releasing radiation. To deal with potential loss of electrical power to the plant, Fukushima Daiichi, like American nuclear power plants, had diesel-powered backup generators. But the water from the tsunami went right past the sea walls at Fukushima, swamping the generators. The water also flooded the electrical control rooms at the plant, preventing backup generators from being hooked up.

Without electricity to pump in fresh coolant to the reactor cores and their spent fuel pools, they overheated, resulting in hydrogen explosions (including suspected hydrogen explosions at spent nuclear fuel pools which have not previously been experienced or contemplated), partial core meltdowns, and continuing radiation release. Spent nuclear fuel rods are also leaking radiation into the water that is being used to cool them, which itself is leaking into other areas of the power plants and into the surrounding area. With no way to circulate water through the reactors or their spent fuel pools mechanically, the Japanese were forced to take the extraordinary step of attempting to flood them with seawater using helicopters and water

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[4] http://markey.house.gov/docs/3-7-11.ejmtonrc.pdf

[5] The dissenting Non-Concurrence is available under Accession Number ML103370648 within the NRC Agencywide Documents Access and Management System (http://www.nrc.gov/reading-rm/adams/web-based.html).

[6] R. Morante, M. Miranda, J. Nie. Technical Evaluation: AP1000 Shield Building Design Report, Revision 2. Dated 5/30/2010. Submitted as part of Dr. Ma's rebuttal to the staff response to the Non-Concurrence statement. Accession Number ML103370648 within the Agencywide Documents Access and Management System (http://www.nrc.gov/reading-rm/adams/web-based.html).

cannons, placing emergency responders in harm's way as they were undoubtedly exposed to dangerous radiation levels.

Once emergency responders began to utilize ocean water to flood the reactor vessels and spent fuel pools, the heat from the nuclear fuel rods caused the water to boil off, leaving a crust of salt that filled the reactor vessels and coated the fuel, making efficient cooling all but impossible. While the Japanese have since procured sufficient stores of fresh water in an attempt to mitigate the salt build-up, these and other efforts to cool the reactors have been delayed by the discovery of high levels of radioactive water that are reported to contain short-lived fission byproducts in the basements of Units 1-3, which caused two workers to receive serious radiation burns to their legs and again raised concerns that the reactor vessels may be more severely damaged than they were previously believed to be.[7] On April 4, the Tokyo Electric Power Company began dumping more than 11,000 tons of radioactive water, about 100 times more radioactive than Japan's legal limit, from the Fukushima Daiichi nuclear plant into the Pacific Ocean[8]. Workers also resorted to using shredded newspaper, sawdust, and a material used in diapers[9], in attempts to stop a leak of seven tons an hour of even more highly radioactive water escaping from a pit near the reactor into the ocean[10].

The radiation released from the Daiichi reactors has already caused considerable damage. The Department of Energy has projected what the dose could be to people living around the plant up to about 50 miles away over the first year of the nuclear disaster based on aerial radiation survey data[11]. People are expected to be exposed to about 2,000 millirems in the first year in a swath of land extending about 30 miles to the northwest of Fukushima Daiichi. The exposure estimate assumes that people did not evacuate and do not heed advice to shelter indoors throughout the year. The Japanese government has evacuated people out to 19 miles, and advised evacuation in selected places beyond that distance because of high localized fallout. Thousands of farmers have had to dump tons of produce and millions of gallons of dairy across a swath of north-central Japan where the government has determined radiation makes the food unsafe.[12] Residents in Tokyo, about 150 miles from the Fukushima reactors, were warned temporarily not to allow infants to drink tap water because it contained unsafe levels of radioactive iodine. On April 2, seawater leaking from a crack near unit 2[13] had levels of radioactive iodine-131 that were 7.5 million times Japan's legal limit, and radioactive cesium-134 at a concentration 2 million times that was allowed[14]. As seawater used to cool the reactor was released back to the ocean, radioactive iodine in the ocean 30 miles from Fukushima Daiichi spiked to 2800 times the legal limit on April 7th, while radioactive cesium-134 levels were at 1100 times the legal limit, and cesium-137 at 760 times the limit[15]. Radioactive cesium-134 remained at twice the legal limit at the same sampling location on May 6, 2011[16]. Thousands of miles away, radioactive

[7] http://www.nytimes.com/2011/03/30/world/asia/30japan.html
[8] http://www.nytimes.com/2011/04/05/world/asia/05japan.html
[9] http://english.kyodonews.jp/news/2011/04/82882.html
[10] http://www.nytimes.com/2011/04/05/world/asia/05japan.html
[11] http://news.sciencemag.org/scienceinsider/2011/04/a-map-of-fukushimas-radiation.html
[12] http://www.nytimes.com/2011/03/30/world/asia/30farmers.html?pagewanted=1
[13] http://www.tepco.co.jp/en/press/corp-com/release/betu11_e/images/110405e31.pdf
[14] http://www.tepco.co.jp/en/press/corp-com/release/11040506-e.html
[15] http://www.tepco.co.jp/en/press/corp-com/release/11040815-e.html
[16] http://www.tepco.co.jp/en/press/corp-com/release/11050707-e.html

iodine from Japan has been found in Boston rainwater, although at levels far lower than those that would pose a threat to human health.[17]

While radioactive iodine rapidly decays, with a half life of 8 days, other radioactive elements being released are longer-lasting. The three plutonium isotopes found in Japanese soil samples have environmental half-lives of 87 - 24,000 years. Cesium-134 has a half-life of 2 years, and cesium-137 a half-life of 30 years. Cesium is also absorbed by marine organisms. As of April 28, radioactive cesium has been detected in 41 species off the coast of Japan[18]. In the Pacific sandlance, radioactive cesium has been found at levels as high as 14,400 Bequerels per kilogram, about 29 times the legal limit. The Pacific sandlance is eaten by many in Japan, and additionally serves as food for other fish, and cesium tends to bio-magnify, becoming increasingly concentrated as it moves up the food chain[19]. The Pacific sandlance is eaten by many migratory species, including other fish (salmon, bluefin tuna, skates, cod), seabirds (murres, auklets), and marine mammals (minke whales, seals). When present in a person or other animals, plutonium and cesium continue, for years or even decades, to expose surrounding tissue to radiation that can lead to cancer.

In recognition of the high levels of radiation emitted, on April 12, Japanese authorities raised their assessment of the Fukushima Daiichi nuclear meltdown to a Level 7 "Major Accident"[20]. According to the International Nuclear and Radiological Event Scale of the International Atomic Energy Agency, level 7 means "A major release of radioactive material with widespread health and environmental effects requiring implementation of planned and extended countermeasures". Only once before, during the Chernobyl meltdown of 1986, has there been such a severe nuclear disaster[21] that rated this highest possible classification.

It is clear that the environmental consequences of Fukushima will be broad, severe, long-lasting, not previously contemplated by nuclear regulators in any country, and significant. Yet these consequences were not even fully understood, let alone factored into any of the Commission's post-Fukushima decisions to grant license extensions for four nuclear reactors by way of a revised or supplemental Environmental Impact Statement or by way of new safety requirements[22].

In stark contrast to steps taken by other countries to cancel, postpone or otherwise re-assess nuclear reactor safety in the wake of the events in Japan (see Table 1 for a summary of other countries' announcements), the NRC has continued to process applications for new licenses and licenses extensions even before it has completed its reviews of U.S. nuclear safety. As Martin J. Virgilio, NRC's Deputy Executive Director for Reactor and Preparedness Program, stated on April 6 before the House Energy & Commerce Committee "We have been closely monitoring the activities in Japan and reviewing all currently available information. Review of this information combined with our ongoing inspection, licensing and oversight allows us to say

[17] http://www.wbur.org/2011/03/28/japan-radiation
[18] http://www.jfa.maff.go.jp/e/q_a/
[19] http://www.ncbi.nlm.nih.gov/pubmed/12527234
[20] http://www.iaea.org/newscenter/news/2011/fukushima120411.html
[21] http://www.nytimes.com/2011/04/12/world/asia/12japan.html?_r=4
[22] The NRC granted license extension to Vermont Yankee on March 21, 2011, and to Palo Verde Units 1, 2, and 3 on April 21, 2011. http://www.nrc.gov/reactors/operating/licensing/renewal/applications.html

with confidence that the U.S. plants continue to operate safely." And at a May 4 House Energy & Commerce Committee Hearing, NRC Chairman Greg Jaczko said "As early as late summer, the commission may conduct the first mandatory hearings on new reactor licenses since the 1970s."

This report provides a summary of some of the most egregious failings of previously adopted NRC safety regulations to protect against the vulnerabilities exposed by the Japanese melt-down, as well as the limitations in the steps NRC has taken to date to explore these vulnerabilities in the U.S.

Emergency Diesel Generators: Decades of Reliability and Maintenance Problems

It is not just earthquakes that can lead to the loss of the external electricity supply at nuclear power plants. In the U.S., such outages have also been caused by squirrels[23] and hot weather,[24]and have also occurred at nuclear power plants. In 1990, a fuel truck accidentally backed into a power line at the Vogtle nuclear power plant, knocking out electricity; as with the Fukushima nuclear power plants, it turned out that the plant's emergency diesel generation was also disabled.[25]

In the U.S., nuclear power plants are required to have emergency diesel generators with sufficient fuel to last 7 days, and battery capacity that can further run for 4-8 hours (depending on the reactor) in the event the diesel generators fail. While emergency diesel generators in the U.S. are required to be better protected than in Japan (they are typically required to be in hardened locations that are not vulnerable to tsunamis), an examination of NRC documents nevertheless indicates significant and prolonged problems associated with their operation.

On January 25, 1989, the NRC issued an information notice[26] "to alert addressees to events involving breaks or cracking of small-diameter tubing which can render emergency diesel generators (EDGs) inoperable." On August 6, 2007, NRC issued an Information Notice entitled "Recurring Events Involving Emergency Diesel Generator Operability[27]," which describes some failures of emergency diesel generators that took weeks to resolve and referenced the 1989 notice. However, the document also stated that "no specific action or written response" was required.

A review of NRC documents indicates that here have been recurrent prolonged malfunctions of emergency diesel generators at nuclear power plants in the U.S. (see Table 2). In the past eight years there have been at least 69 reports of emergency diesel generator inoperability at 33 nuclear power plants. A total of 48 reactors were affected, including 19 failures lasting over two weeks and 6 that lasted longer than a month.

A weeks-long failure of the emergency diesel generators leaves these nuclear power plants with only 4-8 hours' worth of secondary emergency battery-powered generation in the event of a loss of offsite electricity. And even these minimal requirements do not apparently apply to spent nuclear fuel pools at nuclear reactors whose cores have been emptied of fuel assemblies. It is clear that the NRC has historically done little to address long-standing and serious problems associated with licensee maintenance of emergency diesel generators that leaves reactors vulnerable to a loss of offsite power.

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23 http://www.usatoday.com/news/nation/2007-03-11-suicide-squirrels_N.htm
24 http://www.cbsnews.com/stories/2006/07/26/national/main1836674.shtml
25 http://www.nrc.gov/reading-rm/doc-collections/gen-comm/info-notices/1990/in90025s1.html
26 http://www.nrc.gov/reading-rm/doc-collections/gen-comm/info-notices/1989/in89007.html
27 http://pbadupws.nrc.gov/docs/ML0717/ML071760544.pdf

Spent Nuclear Fuel: Regulatory Loopholes

Background:

All U.S. nuclear plants store most of their highly radioactive spent nuclear fuel under water in pools, as was the practice at Fukushima Daiichi. Thirty-two General Electric Boiling Water Reactors locate their spent fuel storage pools on top of the reactor cores, as at Fukushima[28]. In Pressurized Water Reactors, spent fuel storage is typically "below grade," meaning below ground level[29]. The water in these pools, which is cooled via circulation using pumps that require electricity, keeps the spent fuel rods from igniting, burning off their zirconium cladding, and releasing the vast quantities of radiation they contain.

The NRC has granted many reactor licensees permission to increase the amount of spent fuel that can be stored in these pools.[30] Spent nuclear fuel pools in this country are filled nearly to overflowing in some cases – for example, the NRC gave the Pilgrim nuclear power plant permission to pack almost 4,000 spent fuel assemblies (up from the 2,320 the NRC had previously allowed and the 880 the reactor was originally designed to hold[31]) into its spent nuclear fuel pool, which, like the Fukushima Daiichi reactors', is located on top of the unit[32]. The tight packing of fuel rods at Pilgrim and many other spent fuel pools would make it more difficult to keep the rods cool, and increase the risk of radiation release, if cooling is lost or a spent fuel pool is damaged.

According to the Nuclear Energy Institute, there was 65,193 metric tons of spent fuel stored at nuclear plant sites across America in December 2010. Of this amount, 49,620 metric tons resided in spent fuel pools while 15,573 metric tons had been transferred to dry cask storage. By comparison, the reactor core of a large nuclear power reactor contains around 200 metric tons of irradiated fuel. There's more than twice as much irradiated fuel in America's spent fuel pools as in the reactor cores of all the nation's operating reactors.

In Fukushima, the spent nuclear fuel pool associated with the unit 4 reactor was particularly troublesome as the loss of electricity needed to power the cooling system caused the water in the spent fuel pools to heat up. Unit 4's spent fuel pool contained larger than normal quantities of fuel, because the reactor core for that unit was undergoing refueling at the time of the earthquake and all of the fuel had been off-loaded into the spent nuclear fuel pool. There has been speculation that the water in the spent fuel pool completely boiled off[33] and that there was a subsequent fire, that there may have been a hydrogen explosion in that pool (something that had

[28] http://www.ucsusa.org/nuclear_power/reactor-map/embedded-flash-map.html
[29] http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0933/sec3/082r3.html
[30] http://www.nrc.gov/waste/spent-fuel-storage/pools.html
[31] Safety Evaluation By The Office Of Nuclear Reactor Regulation Supporting Amendment No. 33 To Facility Operating License No. DPR-35 Boston Edison Company Pilgrim Nuclear Power Station, Unit No. 1 Docket No. 50-293
[32] http://www.gpo.gov/fdsys/pkg/FR-1994-06-21/html/94-15024.htm
[33] http://www.nytimes.com/2011/03/17/world/asia/17nuclear.html

never before been contemplated for spent fuel pools)[34], and that the structure of the pool itself may have been damaged by either the earthquake or the explosion (because water that is being sprayed into the pool is evidently disappearing faster than it should if it were merely being boiled off)[35].

Storing spent nuclear fuel in pools is not as safe as storing it in dry cask storage. Moving fuel into dry cask storage means fewer spent fuel rods remain in the pools, giving workers more time to cope with a loss of cooling power or loss of water from the pool, because fewer rods means less heat generated by the radioactive materials and thus a longer time for the water to heat up and boil away. Less fuel in the pool also allows for more water flow and better cooling for each fuel rod, and, even in the event of a loss of cooling function or water, less fuel also means a lower probability of a spent fuel fire and radiation release.

The safety benefits of dry cask storage were also noted in 2006, when the National Academy of Sciences issued a report[36] that described the following comparative advantages of dry cask storage over spent fuel pools:

- "Less spent fuel is at risk in an accident or attack on a dry storage cask than on a spent fuel pool."
- "The potential consequences of an accident or terrorist attack on a dry cask storage facility are lower than those for a spent fuel pool."
- "The recovery from an attack on a dry cask would be much easier than the recovery from an attack on a spent fuel pool."

Then-NRC-Commissioner and now-Chairman Greg Jaczko has also articulated this view, stating in 2008 that "the most clear-cut example of an area where additional safety margins can be gained involves additional efforts to move spent nuclear fuel from pools to dry cask storage." He went on to call for a rulemaking, stating that "in an effort to be ever vigilant about the safety of spent fuel, I believe the NRC should develop new regulations which require spent fuel be moved to dry cask storage after it has been allowed to cool for five years."[37]

Despite this call for added safety measures to be implemented, no steps have been taken by the NRC to do so.

Earthquakes and Spent Fuel Pool Integrity

The Fukushima Daiichi power remains in peril from further aftershocks, and is months from being fully under control. The fragility of the situation was highlighted when Fukushima Prefecture experienced a major aftershock of magnitude 7.0 on April 11. The aftershock forced the temporary evacuation of workers, and loss of power and water injection to units 1, 2, and 3

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[34] http://www.iaea.org/press/?p=1248
[35] http://www.latimes.com/news/nationworld/world/la-fg-japan-quake-wrapup-20110318,0,2262753.story
[36] http://www.nap.edu/catalog.php?record_id=11263 National Research Council. 2006. "Safety and Security of Commercial Spent Nuclear Fuel Storage: Public Report. P. 68-70.
[37] http://www.nrc.gov/reading-rm/doc-collections/commission/speeches/2008/s-08-023.html

for 50 minutes[38] With visible structural damage to the unit 4 spent fuel pool, which lacked a roof as of March 17 following fires in the pool on March14th and 15th, there remain concerns that additional earthquakes or aftershocks could result in further damage to the spent fuel pools.[39] In California, earthquakes have also caused heavy water losses from sloshing at spent fuel storage pools there, partly because the pools are located high in reactor buildings as they are at Fukushima[40].

Concerns have about spent fuel integrity have previously been raised in the United States, focusing primarily on the threat that terrorists could pose to spent fuel storage. In June 2006, the NRC lost a Ninth Circuit Court case to the San Luis Obispo Mothers for Peace, which had sued to require consideration of the environmental impacts of a terrorist attack on the Diablo canyon nuclear power plant spent fuel storage facility. Instead of requiring these assessments to be performed nationwide, the NRC chose instead to abide by it only within the Ninth Circuit Court, which excludes the Central and Eastern states where most nuclear facilities are found. In June 2006, the Commonwealth of Massachusetts' Attorney General sent the NRC a petition to amend its regulations to require Environmental Impact Statements for *all* nuclear power plant licensing decisions to consider the vulnerabilities of spent fuel storage pools nationwide, and sent a second petition on May 2, 2011 to suspend NRC's evaluation of the relicensing application for the Pilgrim nuclear power plant until the NRC has considered the spent fuel storage safety issues raised by Fukushima[41]. The NRC has not taken either requested action.

Spent Nuclear Fuel Pools Contain No Protections from Hydrogen Explosions

Hydrogen can be produced in several ways during a nuclear reactor accident. One likely scenario at Fukushima is that under extreme heat, as the cooling systems lost power and fuel rods overheated, the zirconium cladding around the fuel rods reacted with water. This metal-water reaction gives off oxygen, and hydrogen, which is flammable. If the hydrogen is not removed, its build-up can lead to explosions that can further damage the reactor buildings and cause further radiation releases.

Protections against hydrogen explosions in the U.S. began when there was a hydrogen explosion, and threats of much greater explosions due to hydrogen buildup, during the 1979 Three Mile Island accident[42]. In 1981, NRC issued rules requiring nuclear power reactors to monitor hydrogen levels in the containment structure, and to have hydrogen recombiners (which act to combine hydrogen and oxygen to produce water before an explosion occurs) and/or vents (different reactor designs require different hydrogen mitigation technologies) to prevent hydrogen buildup,[43] although these rules are not themselves adequately enforced or implemented.

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[38] http://www.jaif.or.jp/english/news_images/pdf/ENGNEWS01_1302521667P.pdf
[39] http://www.iaea.org/newscenter/news/2011/tsunamiupdate01.html
[40] http://www.nytimes.com/2011/03/18/world/asia/18spent.html
[41] http://www.mass.gov/?pageID=cagopressrelease&L=1&L0=Home&sid=Cago&b=pressrelease&f=2011_05_02_pilgrim_nrc&csid=Cago
[42] http://www.threemileisland.org/downloads/188.pdf
[43] http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0737/final/sr0737.pdf

However, there are no requirements whatsoever for hydrogen mitigation technologies to be included at spent nuclear fuel pools[44], presumably because hydrogen explosions were never previously contemplated for these facilities. On March 15[45], an explosion at the Unit 4 spent fuel pool is thought to have occurred, clearly illustrating this particular spent nuclear fuel vulnerability.

There is No Regulatory Requirement for Some Spent Nuclear Fuel Pools to Have Emergency Power Capability

As has been previously noted, the loss of cooling function which was caused by the loss of external electricity and subsequent failure of all the emergency diesel generators and batteries at Fukushima led to both the core meltdowns and the radiation releases (and fires and potential hydrogen explosions) at the Fukushima nuclear power plant.

A review of the NRC's Standard Technical Specifications for nuclear power plants[46] indicates that spent fuel pools at nuclear reactors whose cores do not contain nuclear fuel (for example, because they were in the process of being refueled) do NOT require the presence of operable secondary emergency generation capacity. Thus, the circumstances that led to Japan's Unit 4 fire, potential explosion and radiation release would apparently be in compliance with NRC's requirements.

Additionally, Rep. Markey's staff has learned that licensees often perform maintenance on their emergency diesel generators when the reactors are undergoing refueling outages[47]. For example on November 11, 2009, the Wolf Creek Nuclear Operating Corporation submitted a report to the NRC regarding a loss of external operating power that occurred during a 2009 refueling of the Wolf Creek nuclear power plant in Kansas while one of the emergency diesel generators was also undergoing maintenance.

This regulatory loophole clearly represents an unacceptable risk to the safety of any decommissioned nuclear reactor or any reactor currently undergoing refueling.

[44] Response of Mr. Martin J. Virgilio, NRC's Deputy Executive Director for Reactor and Preparedness Programs, to questions from Rep. Markey at an April 6, 2011 hearing of the Oversight and Investigations Subcommittee hearing of the House Energy and Commerce Committee.
[45] http://www.world-nuclear-news.org/RS_Attempts_to_refill_fuel_ponds_1703111.html
[46] See for example "Standard Technical Specifications General Electric Plants, BWR/4" and "Standard Technical Specifications for Westinghouse Plants"
[47] Private communications from an individual working inside an operating nuclear power plant obtained by Rep. Markey's office and discussions with nuclear safety experts.

Hydrogen Explosions: NRC Regulations Are Lacking, and NRC Officials Have Made Misleading Statements Related to their Use

As noted, it is likely that hydrogen was generated at the Fukushima nuclear power plant when the zirconium cladding around the fuel rods reacted with water as they heated up. This metal-water reaction gives off oxygen, and hydrogen, which is flammable, and as the hydrogen concentrations built up the two gases likely then combined and exploded. Hydrogen explosions then blew apart the outer containments of the Units 1 and 3 reactors of the Fukushima Daiichi reactors, Unit 2's reactor containment was also damaged by an explosion (though its source is less clear), and the Unit 4 spent nuclear fuel pool is also likely to have experienced a hydrogen explosion[48].

After the 1979 Three Mile Island accident,[49] which involved a hydrogen explosion, the NRC issued rules requiring nuclear power reactors to monitor hydrogen levels in the containment structure, and to include technologies to mitigate hydrogen build up as it occurred. The NRC rules for hydrogen control differed for various classes of reactor designs. Boiling Water Reactors (BWRs) were required to have vents, which allow hydrogen gas to be purged from the containment. For BWR Mark I and Mark II reactor designs, licensees were also required to pump the primary containment full of the inert gas, nitrogen, instead of air[50]. As a hydrogen explosion will not occur in the absence of oxygen, this "inerting" of the primary containments is a way of preventing them. For BWR Mark III and for Pressurized Water Reactors with smaller containments, a 1985 rule required plants to have the means to control the hydrogen produced if 75% of the fuel cladding reacted with water. The means to accomplish this was not specified; some plants have "igniter systems" that would burn off hydrogen before it could build up, and others have "hydrogen recombiners" that combine hydrogen with oxygen to form water before an explosion occurs.

However, almost immediately after issuing these rules to prevent hydrogen explosions, NRC began to relax them in response to pressure from industry. In 1984, the NRC agreed that "BWR Mark I Owners Group," had demonstrated that Mark I reactors do not need vent and purge systems for hydrogen because they are inerted[51]. Pressurized Water Reactors with large containments were determined in 1989 to not need any hydrogen controls, because NRC decided the size of the containment could contain all of the hydrogen that could possibly be generated.

Finally, in 2003 NRC granted a request made by the Nuclear Energy Institute to eliminate the requirements for hydrogen recombiners and hydrogen and oxygen monitors.
NRC invoked two conflicting arguments to justify "relaxing safety classifications" for hydrogen controls. First, the NRC concluded that hydrogen release poses a minimal risk of causing a radiation release, stating that "this hydrogen release is not risk-significant because the design-basis "loss of cooling accident" hydrogen release does not contribute to the conditional

[48] http://www.jaif.or.jp/english/news_images/pdf/ENGNEWS01_1304997042P.pdf
[49] http://www.threemileisland.org/downloads/188.pdf
[50] http://www.nrc.gov/reading-rm/doc-collections/nuregs/staff/sr0933/sec2/a48r1.html
[51] http://www.nrc.gov/reading-rm/doc-collections/gen-comm/gen-letters/1984/gl84009.html

probability of a large release up to approximately 24 hours after the onset of core damage[52]." Secondly, the NRC concluded that "these systems were ineffective at mitigating hydrogen releases from risk-significant beyond design-basis accidents (DBAs)." As NRC spokesman Eliot Brenner said more plainly on March 31, 2001,[53] "They weren't needed for design basis accidents and they didn't help with severe accidents''. The result of this tortured logic was that NRC has allowed plants to remove a requirement for hydrogen mitigation technologies from their "Technical Specifications." Some reactors may still have these features installed, but they are not required to keep them operational.

Yet despite the absence of these regulatory requirements in the U.S., the NRC has consistently made inaccurate statements that the Fukushima Daiichi reactors did not have hardened vents that could have prevented hydrogen explosions, and that in the U.S, such features were required. For example, at a March 21 hearing at the NRC,[54] Bill Borchardt, Executive Director for Operations for the NRC stated, in response to a question regarding what measures were in place at U.S. reactors to mitigate hydrogen explosions: "Well, the hardened vent, of course -- the U.S. design approach is to protect the containment... So it's at least my belief that you wouldn't have the hydrogen accumulation in the upper levels of the reactor building, which we believe is the cause of the explosions" at Fukushima Daiichi."

These claims were repeated on April 6 at a hearing before the House Energy & Commerce Committee, when Martin J. Virgilio, NRC's Deputy Executive Director for Reactor and Preparedness Program, stated that "The U.S. nuclear industry has implemented a number of equipment upgrades post 9/11 including hardened vents to prevent hydrogen explosions and systems that allow for reactor cooling and blackout conditions..." "One of the most significant features I would say that has been installed on those Mark I containments is what we called a hardened vent, and that allows the release of hydrogen gas that has built up inside the containment to be vented out safely. As we saw in Fukushima, there were a number of explosions which we are assuming related to that hydrogen gas buildup. Had they had the hardened vent or had they used the hardened vent, this would not have been an issue."

According to an April 5 email[55] sent by NRC staff to the staff of Congressman Edward J. Markey, the Fukushima Daiichi reactors did have hardened vents. Moreover, under questioning by Congressman Markey, Mr. Virgilio also acknowledged that the regulatory requirement for the operability of these vents had been removed, that no such requirements had ever been in place for spent nuclear fuel pools, and that many such systems require electricity to operate.

Clearly, the NRC must revisit its decision not to require technologies for the mitigation of the build-up of hydrogen to be installed and operational on both reactor and spent nuclear fuel pool containment.

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[52] http://www.nrc.gov/reactors/operating/licensing/techspecs/techspecs-pdf/447r1frn.pdf
[53] http://green.blogs.nytimes.com/2011/03/31/u-s-dropped-nuclear-rule-meant-to-avert-hydrogen-explosions/
[54] http://www.nrc.gov/reading-rm/doc-collections/commission/tr/2011/20110321.pdf
[55] http://markey.house.gov/docs/4-6-11markey_e-mail_2_-nrc_question_regarding_fukushima_unit_2.pdf

Seismic Safety: NRC Has Not Factored Modern Geologic Information Into Reactor Safety

Background:

The United States has many areas with the potential for strong seismic activity in the coming decades[56]. California has a historical record of 8 earthquakes of magnitude 7.3 or greater since 1700, including earthquakes close to both the Diablo Canyon and San Onofre nuclear power plants.[57] In 1700, the Cascadia subduction zone, which stretches offshore from British Columbia to Northern California, caused a 9.0 earthquake[58]. New research on underwater landslides caused by past Cascadia megaquakes shows that the average time between such events over the past 10,000 years is 240 years. The next earthquake is therefore overdue, and according to research led by University of Oregon geologist Dr. Chris Goldfiner, there is a 37% percent chance of a magnitude-9 quake over the next 50 years[59]. In the Southeast, Charleston, S.C. had a 7.3 earthquake in 1886. The New Madrid seismic zone, which includes southeastern Missouri, northeastern Arkansas, western Tennessee, western Kentucky and southern Illinois, produced a magnitude 7.7 earthquake in Arkansas in 1811[60].

Eight nuclear power reactors are in the seismically active West Coast, approximately 27 are near the New Madrid seismic zone, and 5 are in earthquake-prone South Carolina (see Figure 1).[61] The 2011 report of the Independent Expert Panel on the New Madrid seismic zone notes: "The estimated hazard in the New Madrid region will evolve because of further analysis and better data." NRC's regulations must also continually evolve in response to scientists' understanding of seismic hazard[62].

According to NRC's website, "Today, the NRC utilizes a risk-informed regulatory approach, including insights from probabilistic assessments and traditional deterministic engineering methods to make regulatory decisions about existing plants." Historical data from a reactor's site "is used to determine design basis loads from the area's maximum credible earthquake, with an additional margin included." But in the past 60 years, since the beginning of the commercial nuclear power industry, geologists have learned more about the likelihoods of earthquakes occurring throughout the country. For example, the geologic field of plate tectonics, which explains how the plates of the Earth's crust move against each other, only emerged in the 1960s, after many nuclear power plants had already been sited.[63]

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56 http://earthquake.usgs.gov/hazards/products/graphic2pct50.jpg
57 http://earthquake.usgs.gov/earthquakes/states/10_largest_us.php
58 http://earthquake.usgs.gov/research/structure/crust/cascadia.php
59 http://www.nature.com/news/2010/100531/full/news.2010.270.html
60 http://earthquake.usgs.gov/earthquakes/states/events/1811-1812.php
61 http://earthquake.usgs.gov/hazards/products/conterminous/2008/maps/us/3hzSA.usa.jpg
62 http://earthquake.usgs.gov/aboutus/nepec/reports/NEPEC_NMSZ_expert_panel_report.pdf
63 http://www.ucmp.berkeley.edu/geology/techist.html

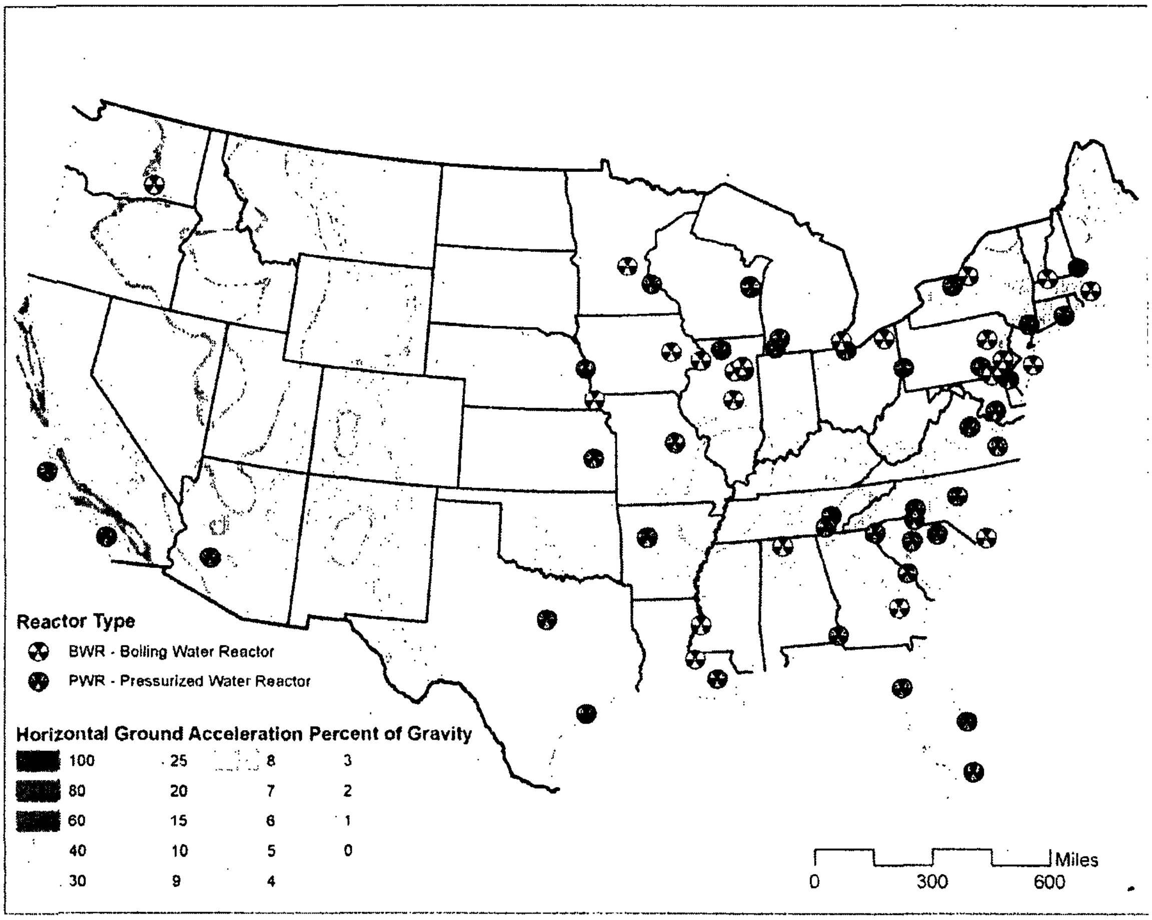

Figure 1: Operating Nuclear Power Plants vs Horizontal Ground Acceleration Percent of Gravity[64]

Case Study: Diablo Canyon

Even when presented with the discovery of previously unknown dangers, the NRC has typically assumed that plants remain safe. An example of this can be seen from the Diablo Canyon Nuclear Power Plant, whose application to be relicensed for another twenty years, until 2044 and 2045 respectively for the two units, is currently pending before the Commission.[65] Located 12 miles from San Luis Obispo, California, the nuclear power plant first became controversial in 1971, when the Hosgri Fault Zone was discovered 3 miles away from Diablo Canyon, requiring PG&E to spend $4.4 billion on re-engineering (double what it had been expected to cost, as the first set of retro-fits were improperly conducted). According to the Southern California Earthquake Data Center, the Hosgri Fault may have been the location for a 7.1-magnitude earthquake that occurred in 1927.[66]

[64] Map constructed by the Congressional Cartography Program, Geography and Map Division, Library of Congress
[65] http://www.nrc.gov/reactors/operating/licensing/renewal/applications/diablo-canyon.html#appls
[66] http://www.data.scec.org/chrono_index/lompoc.html

Despite Diablo Canyon being three miles from an earthquake fault-line, the NRC concluded in 1984 that the probability of an earthquake causing a radiation release at Diablo Canyon, or happening at the same time as a radiation release, has "too low a probability to warrant mandatory consideration".[67] This NRC belief, which has been emphatically refuted by the Japanese meltdowns, has been used by courts to deny requests for additional safety measures to be installed there.[68]

The NRC has also made the surprising conclusion that the Diablo Canyon area was "at most one of moderate seismicity," an assertion based on data drawn from 1950 to 1974[69]. The NRC has thus far accepted Pacific Gas and Electric's argument that the Diablo Canyon Power Plant remains safe despite the 2008 discovery of a new fault called the "Shoreline Fault" about 1 km from Diablo Canyon which extends to the Hosgri Fault, and the NRC has estimated this fault as being capable of leading to a maximum magnitude 6.85 earthquake[70]. According to the NRC, the Diablo Canyon nuclear power plant is rated for a 7.5-magnitude earthquake from the Hosgri fault.[71] Yet the assessment by the Southern California Earthquake Center is that there is a 46% probability of California having an earthquake of magnitude 7.5 or greater in the next 30 years, and this assessment is based on conservative analysis that excludes the possibility of an earthquake in the Cascadia subduction zone that could be even more catastrophic[72].

Following calls for a halt to the NRC's consideration of the license extension application for Diablo Canyon[73] in the wake of the Japanese meltdown, on April 11, Pacific Gas and Electric (PG&E) issued a press release indicating that it had requested a delay in its approval until the accelerated completion of new 3-dimensional seismic studies,[74] and issued a press release indicating that it had requested a delay in its approval until such studies were completed[75].

However, this appears to be a hollow commitment. What PG&E actually requested was for the NRC to "delay the final processing of the license renewal application such that the renewed operating licenses, if approved, would not be issued until after PG&E has completed the 3-D seismic studies and submitted a report to the NRC addressing the results of those studies[76]."

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[67] NRC Decision CLI-84-12. "In the Matter of Pacific Gas and Electric Company (Diablo Canyon Nuclear Power Plant Units 1 and 2." Docket Nos. 50-275 OL, 50-323 OL.

[68] San Luis Obispo Mothers for Peace v. Nuclear Regulatory Commission. http://www.elawreview.org/summaries/environmental_quality/nepa/san_luis_obispo_mothers_for_pe.html

[69] Nuclear Regulatory Commission Document CLI-84-12, In the Matter of Pacific Gas and Electric Company (Diablo Canyon Nuclear Power Plant Units 1 and 2). p. 8.

[70] Research Information Letter 09-001: Preliminary Deterministic Analysis of Seismic Hazard at Diablo Canyon Nuclear Power Plant from Newly Identified "Shoreline Fault", p. 8. Available in ADAMS (http://www.nrc.gov/reading-rm/adams/web-based.html), by entering ML090330523.

[71] NRC. Safety Evaluation Report With Open Items Related to the License Renewal of Diablo Canyon Nuclear Power Plant, Units 1 and 2, Docket Nos. 50-275 and 50-323. January 2011. Available in ADAMS (http://www.nrc.gov/reading-rm/adams/web-based.html), by entering ML110100796

[72] http://www.scec.org/core/public/sceccontext.php/3935/13661

[73] See for example, http://www.scpr.org/news/2011/03/24/congresswoman-wants-diablo-canyon-relicensing-put-/

[74] http://www.pge.com/about/newsroom/newsreleases/20110411/pgampe_commits_to_finishing_3-d_seismic_studies_related_to_diablo_canyon_before_seeking_final_issuance_of_renewed_licenses.shtml

[75] http://www.sanluisobispo.com/2011/04/11/1558606/pge-asks-for-delay-in-license.html

[76] PG&E Letter DCL-11-047. Request for Deferral of Issuance of Diablo Canyon Power Plant Renewed Operating Licenses. April 10, 2011.

Since the NRC has already completed a draft Safety Evaluation Report on the renewal application, the gesture by PG&E appears to be meaningless, since it is not requesting that NRC reevaluate the application based on the results of these forthcoming studies. PG&E simply wants people to feel the "added assurance of the plant's seismic integrity" that they appear certain will emerge from the forthcoming "advanced seismic research".

Seismic Concerns: Not just at West Coast reactor sites

It is not just West Coast nuclear power plants that have long been the subject of seismic examination that require a regulatory review. In 2010, the NRC used 2008 seismic risk data from the U.S. Geological Survey (USGS) and measures of the fragility of each reactor to conclude that the risks of core damage from earthquakes in the Eastern and Central States are greater than previously estimated. But the NRC has not taken steps to use this information in regulation.[77]

Core damage due to earthquake is expected to occur 0.0001 times per year at the Indian Point 3 reactor, according to NRC analysis based on 2008 seismic data from the United States Geological Survey[78]. The NRC is currently reviewing a license extension application for Indian Point[79]. This core damage estimate is 72% higher than the estimate that was based on seismic data from 1989. Indian Point is about 25 miles from New York City. Pilgrim Nuclear Power Station, about 38 miles from Boston and for which there is also an application for a twenty year license extension pending before the Commission[80], is estimated to suffer 0.000069 core damage events per year due to earthquakes. The NRC's risk estimate for Pilgrim is up more than 7 times (763%) from the estimate that was based on 1989 seismic hazard information.

The average number of core damage events for each reactor due to earthquakes, based on 2008 seismic data, is 0.000013 per year, according to an analysis of NRC data performed by MSNBC.[81] Based on 1989 seismic data, by contrast, the expected number of core damage events is 0.0000038. While both of these are small numbers, the estimated risk has more than tripled based on the more current understanding of seismology. The NRC's analysis also notes that it lacks detailed information regarding the physical vulnerability of nuclear power plants to earthquakes for about one third of reactors.

[77] Generic Issue 199 (GI-199): Implications of updated probabilistic seismic hazard estimates in Central and Eastern United States on existing plants: Safety/Risk Assessment. August 2010. Available from NRC at http://www.nrc.gov/reading-rm/adams/web-based.html under accession number ML100270598.

[78] Generic Issue 199 (GI-199): Implications of updated probabilistic seismic hazard estimates in Central and Eastern United States on existing plants: Safety/Risk Assessment. August 2010. Appendix D, Table D-1: Table D-1: Seismic Core-Damage Frequencies Using 2008 USGS Seismic Hazard Curves. This is the value for the "weakest link model". Available by searching for document ML100270756 in ADAMS: http://www.nrc.gov/reading-rm/adams/web-based.html

[79] http://www.nrc.gov/reactors/operating/licensing/renewal/applications.html

[80] http://www.nrc.gov/reactors/operating/licensing/renewal/applications/pilgrim.html

81 http://www.msnbc.msn.com/id/42103936/ns/world_news-asia-pacific/ The MSNBC report used data from NRC document ML100270756, which is available by searching ADAMS: http://www.nrc.gov/reading-rm/adams/web-based.html. The NRC document contains seismic hazard estimates for 96 reactors; the NRC provided MSNBC estimates for the remaining 8 reactors. The data published by MSNBC appear to correspond to the NRC's "weakest link model".

The higher risks to reactors from earthquakes were so clear to the NRC staff who performed this Safety/Risk Assessment that they recommended further action be referred to "the Office of Nuclear Reactor Regulation for regulatory office implementation, and that this office "take further actions to address GI-199 outside the [General Issues Program] (i.e. obtain information and develop methods, as needed, to complete plant-specific value-impact analyses of potential backfits to reduce seismic risk).""[82]

Of course, any core damage event at a U.S. nuclear reactor would be of grave concern, and thus it is important to examine the potential frequency of such disasters caused by earthquakes across the entire fleet of nuclear reactors. Based on the expected number of events per year estimated for each nuclear reactor, we can sum the total number of expected core damage events per year for the nation's fleet as a whole. According to calculations performed by the staff of Congressman Markey, the expected number of core damage events per year, across all the nuclear power plants in the country, is 0.0013.[83]

The threat of a nuclear disaster due to an earthquake is a long-term threat, because nuclear reactors operate for many years. Nuclear power reactors were originally licensed to operate for 40 years. The NRC has issued 20 year extensions to the operating licenses for 19 nuclear reactors since the beginning of 2007[84], and is reviewing applications for 16 more such extensions, including applications for Indian Point and Pilgrim, the nuclear power plants in the central and eastern U.S. the NRC staff deemed to be most at-risk of core damage from earthquakes[85]. If the U.S. continues to have the same set of nuclear power plants over the next twenty years, the expected number of core damage events due to earthquakes is the per-year frequency times twenty, or 0.026, across the entire twenty year interval. This estimated national frequency of reactor core damage due to earthquakes does not factor in the additional hazards due to events that are independent of earthquakes, such as strong storms, wind, fires, operator error, reactor aging issues (for example, failures due to the corrosion of buried pipes that transport both cooling water and fuel to the emergency diesel generators and submerged cables), or terrorism.

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[82] Safety/Risk Assessment Results for Generic Issue 199, "Implications of Updated Probabilistic Seismic Hazard Estimates in Central and Eastern United States on Existing Plants". August 2010.

[83] Staff took the sum of these core damage probabilities for each of the 65 nuclear power plant sites. Many nuclear power plant sites contain more than one nuclear reactor, and staff made the assumption, borne out by the Fukushima Daiichi melt-down, that the reactors that are co-located at a single nuclear power plant site are not independent; rather, they tend to be affected similarly by an earthquake. Additionally, they may impact one another as events unfold (explosions at one unit at Fukushima have been speculated to have damaged other units). For nuclear power plants with multiple reactors, the value chosen was that for the reactor with the highest core damage frequency as estimated by the NRC.

[84] Reactors given license renewals by NRC from 2007 to the present, and the States that host them: Palisades (MI); James A. FitzPatrick (NY); Wolf Creek, Unit 1 (KS); Harris, Unit 1 (NC); Oyster Creek (NJ); Vogtle, Units 1 and 2 (GA); Three Mile Island, Unit 1 (PA); Beaver Valley, Units 1 and 2 (PA); Susquehanna, Units 1 and 2 (PA); Cooper Nuclear Station (NE); Duane Arnold Energy Center (IA); Kewaunee Power Station (WI); Vermont Yankee Nuclear Power Station (VT); Palo Verde, Units 1, 2, and 3 (AZ). http://www.nrc.gov/reactors/operating/licensing/renewal/applications.html

[85] Pilgrim 1, Unit 1 (MA); Indian Point, Units 2 and 3 (NY); Prairie Island, Units 1 and 2; Crystal River, Unit 3 (FL); Hope Creek (NJ); Salem, Units 1 and 2 (NJ); Diablo Canyon, Units 1 and 2 (CA); Columbia Generating Station (WA); Seabrook Station, Unit 1 (NH); Davis-Besse Nuclear Power Station, Unit 1 (OH); South Texas Project, Units 1 and 2 (TX). http://www.nrc.gov/reactors/operating/licensing/renewal/applications.html; http://www.nrc.gov/info-finder/reactor/

Finally, the NRC has also failed to consider the impacts of multiple threats striking simultaneously because the NRC's regulations do not require them to. The Fukushima nuclear power plant was struck not only by the earthquake, but by its direct consequences, including a tsunami, fires, total station blackout due to loss of offsite power and damage to emergency diesel generators, overtaxed emergency responses resources due to crises elsewhere, and the inability to bring equipment to the site because of debris. Even the nuclear industry has recognized this assumption is flawed: "What clearly has shown up in Japan is multiple, stacked events. We've not analyzed for all those things," said Preston D. Swafford, the Tennessee Valley Authority's chief nuclear officer.[86]

86 http://www.nytimes.com/2011/03/27/us/27reactor.html?_r=1

NRC's Post-Fukushima Efforts: Scope Limitations and Secrecy Concerns

On March 23, the NRC voted to require a multi-phase review[87] of U.S. nuclear reactor safety in the wake of the Japanese meltdown. The near-term review portion of these efforts called for the establishment of a task force to:

> "Evaluate currently available technical and operational information from the events that have occurred at the Fukushima Daiichi nuclear complex in Japan to identify potential or preliminary near term/immediate operational or regulatory issues affecting domestic operating reactors of all designs, including their spent fuel pools, in areas such as protection against earthquake, tsunami, flooding, hurricanes; station blackout and a degraded ability to restore power; severe accident mitigation; emergency preparedness; and combustible gas control."

The task force was additionally directed to develop near-term recommendations for regulatory and other changes, and is also required to inform its efforts using stakeholder input. The longer (90 day) review is supposed to include more extensive stakeholder input, and the task force was directed in this phase to "evaluate all technical and policy issues related to the event to identify potential research, generic issues, changes to the reactor oversight process, rulemakings, and adjustments to the regulatory framework that should be conducted by NRC." All of the results of these efforts were supposed to be made public.

The NRC recently initiated inspections at each nuclear power plant in order to assess the operational or regulatory issues that may have arisen as a result of the Fukushima meltdown, and that the reports associated with these inspections are supposed to be submitted by May 13.

According to reports received by Rep. Markey[88], the NRC may be artificially constraining the scope of these investigations and may keep the results of most of these investigations secret. These constraints and limitations include the following:

- The NRC only allowed[89] its inspectors 40 hours in which to perform each inspection for nuclear power plants that contain one nuclear reactor. For nuclear power plants with more than one unit, inspectors are being provided with only 50-60 hours total in which to complete their work. By contrast, the Institute of Nuclear Power Operations (INPO) reportedly spent hundreds of hours performing their inspections.
- The NRC inspectors were initially told to limit their inspections to the adequacy of safety measures needed to respond to Design Basis Events. This meant that inspectors would be assessing licensees' ability to withstand and respond only to events that have already been contemplated and analyzed by the NRC and for which regulatory

[87] Tasking Memorandum – COMBJ-11-0002 – NRC Actions Following The Events In Japan

[88] Private correspondence from an individual working inside an operating nuclear power plant obtained by Rep. Markey's staff

[89] See NRC Temporary Instruction 2515/183 Followup To The Fukushima Daiichi Nuclear Station Fuel Damage Event

requirements have been implemented, but not events such as the ones that occurred in Japan, which were previously believed to be impossible.

- After several NRC inspectors complained that it made no sense to limit the scope of the inspections to Design Basis Events, the guidance was changed to enable inspectors to look beyond them, and explicitly includes an examination of the measures that were implemented following the terrorist attacks of September 11, 2011 (some of which could help mitigate against some of the problems that occurred in Japan); however, they were also explicitly told not to record any of their beyond Design Basis observations or findings in documents that would be made public as part of the Commission's review or public report(s). Instead, these findings would be entered into a private NRC database and kept secret.
- Inspectors were also told not to include matters in their reports that licensees had already identified. Since the INPO inspections were concluded before the NRC inspections began, none of the reportedly dozens of issues that were identified by INPO inspectors and reported to licensees will be included in the NRC inspection reports.

Although four of five NRC Commissioners, in response to questions from Congressman Markey, committed to a full investigation of all vulnerabilities and the public release of all non-security-sensitive findings at a May 4, 2011 hearing of the Energy and Commerce Committee[90], the limitations imposed on NRC's inspectors appear to ensure that the full range of vulnerabilities of U.S. nuclear reactors to events that occurred in Japan will not be performed, or reported to the NRC or the public. The NRC needs to ensure that there is a full investigation of such vulnerabilities, and that all non-security sensitive findings and recommendations are made public.

[90] Private communications from an individual working inside an operating nuclear power plant obtained after the May 4 hearing do not indicate that any changes to these inspections have occurred.

Table 1. National responses to Japanese nuclear disaster

Following the accident at the Fukushima Daiichi nuclear power plant in Japan, many other countries have announced new safety measures with regards to nuclear reactors. China, Venezuela, Switzerland, Italy, Japan, and Taiwan have suspended new reactor development. Germany and Japan announced it would shut down older reactors pending safety review.

[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	NO	NO	NO
[illegible]	NO	YES	YES
[illegible]	NO	NO	NO
[illegible]	YES	YES	YES
[illegible]	NO	NO	NO
[illegible]	NO	YES	YES
[illegible]	YES	YES	YES
[illegible]	NO	NO	NO
[illegible]	NO	NO	YES
[illegible]	NO	NO	NO
[illegible]	NO	NO	NO
[illegible]	NO	YES	NO
[illegible]	NO	YES	NO
[illegible]	NO	NO	YES
[illegible]	NO	YES	NO

[91] http://www.theglobeandmail.com/news/national/after-japan-canadas-nuclear-industry-girds-for-change/article1952403/
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Table 2 – Summary of Emergency Diesel Generator (EDG) Inoperability 2002-2010

To determine cases of EDG inoperability staff used the U.S. NRC Licensee Event Report (LER) Search (https://lersearch.inl.gov). Staff searched between the dates 1/1/2002 and 5/1/2011 using keyword criteria "emergency diesel generators." Current reports are only available up to 3/15/2011. The search yielded 3102 total records. In order to determine which reports related to inoperable EDGs we used a word search for "diesel" and "EDG" in the title of LER record. The number of days inoperable was determined by either direct reporting of days inoperable in the LER record or simple subtraction between the dates when the EDG(s) were cited as inoperable. Inoperability of under 24 hours was rounded up to 1 day.

In the past eight years there have been at least 69 reports of EDG inoperability at 33 nuclear power plants. A total of 48 reactors were affected, including 19 failures lasting over two weeks and 6 that lasted longer than a month.

Power plant	Date	Problem	Days inoperable	Id_number
Wolf Creek	12/6/2010	Technical Specification Required Shutdown due to Inadequate Planning Resulting in Extended Emergency Diesel Generator Inoperability	8	4822010014
Byron 2	11/17/2010	Unit 2 Emergency Diesel Generator Inoperable for Longer than Allowed by Technical Specifications due to Inadequate Work	5	4552011001
Palo Verde 1	9/15/2010	Inoperable Emergency Diesel Generator due to Fuel Oil Transfer Pump Failure	3	5292010002
Brunswick 1 &2	9/13/2010	Emergency Diesel Generator Inoperable for Greater than Technical Specification Completion Time	1	3252010004
Robinson 2	6/24/2010	Emergency Diesel Generator Inoperable due to Inverter Failure	3	2612010005
Turkey Point 3	6/7/2010	Fuel Transfer Pump Failure Renders 3B Emergency Diesel Generator	45	2502010002
Turkey Point 4	5/10/2010	Damaged Speed Sensor Caused the 4A Emergency Diesel Generator to be Inoperable	16.9	25120100003
Robinson 2	4/26/2010	Clearance Error Results in the 'A' Emergency Diesel Generator Becoming Inoperable	8	2612010004
Indian Point 2	3/13/2010	Inoperable Emergency Diesel Generators during Refueling Shutdown due to Inadvertent Isolation of Service Water Cooling Caused by Failure to Properly Verify the In-Service Cooling Header	1	2472010003
Robinson 2	2/22/2010	Emergency Diesel Generator Inoperable in Excess of Technical Specifications Allowed Completion Time	27	2612010001
Wolf Creek	10/22/2009	Loss of both Diesel Generators with all fuel in the Spent Fuel Pool	1	4822009005
Millstone 2	10/7/2009	Two Independent Diesel Generators Rendered Inoperable due to Common Cause	1	3362009003

Brunswick 1 &2	9/20/2009	Technical Specification Required Shutdown Due To Emergency Diesel Generator 4 Inoperability	8	3252009004
Turkey Point 4	8/11/2009	4B Emergency Diesel Generator Inoperable Due to Air-bound Main Fuel Pump	14.3	2512009001
Oyster Creek	8/3/2009	EDG #1 Inoperable due to Failure of its Output Breaker to Close	2	2192009006
Fitzpatrick	7/7/2009	Inoperable Emergency Diesel Generators due to Degraded Voltage Timers	1	3332009007
Robinson 2	4/20/2009	Emergency Diesel Generator Inoperable in Excess of Technical Specifications Allowed Completion Time	3	2612009001
Prairie Island 2	2/16/2009	LER 2-09-01, Clearance Order Renders Opposite train Emergency Diesel Generator Inoperable	2	3062009001
Kewaunee	1/23/2009	Emergency Diesel Generators Inoperable Requiring Notice of Enforcement Discretion	Unreported	3052009001
Palisades	10/9/2008	Emergency Diesel Generator Inoperable in Excess of Technical Specification Requirements	30	2552008007
Hope Creek	4/22/2008	Blown 1E Inverter Main Fuse With One Emergency Diesel Generator Inoperable Causes Loss Of Control Room Emergency Filtration Loss Of Safety Function	1	3542008002
Prairie Island 1	12/21/2007	Technical Specification Required Shutdown due to Both Emergency Diesel Generators Being Inoperable	3	2822007004
Columbia	12/10/2007	Inoperable Diesel Generator due to Inadequate Procedure That Caused Potential Transformer Fuses to Clear during Shut Down of the Diesel	83	3972007005
Comanche Peak 1	11/21/2007	Emergency Diesel Generator Inoperable for Longer Than Allowed by TS due to Paint on Metering Rod	1	4452007001
Prairie Island 2	10/8/2007	Emergency Diesel Generator Inoperable Longer than Allowed by Techincal Specifications Due to Loose Switch	35	3062007002
Cooper Station	9/11/2007	Procedural Guidance Leads to Rendering Second Diesel Generator Inoperable	9	2982007006
Palisades	7/25/2007	Emergency Diesel Generator Inoperable in Excess of Technical Specification Requirements	23	2552007006
Wolf Creek	7/8/2007	Emergency Diesel Generator Out of Service Longer than Technical Specification Allowed Outage Time	4	4822007001
Duane Arnold	4/11/2007	Condition Prohibited by Technical Specifications; 'B' Emergency Diesel Inoperable	60	3312007008
Brunswick 1 &2	4/1/2007	Technical Specification Required Shutdown Due To Emergency Diesel Generator 4 Inoperability	10	3252007002
Fort Calhoun	2/16/2007	Inoperability of a Diesel Generator with an Inoperable Containment Cooling Fan from the Opposite Bus	1	2852007003

Peach Bottom 1 & 2	11/17/2006	Plant Modification Created Diesel Generator Building Carbon Dioxide Suppression Room Flooding Vulnerability	Unreported	2772006004
Brunswick 1 &2	11/2/2006	Operations Prohibited by Technical Specifications due to Inoperable Emergency Diesel Generator 1	15	3252006007
Crystal River 3	11/1/2006	Emergency Diesel Generator in a Condition Prohibited by Technical Specifications due to Mispositioning	28	3022006002
Palo Verde 1,2,3	9/5/2006	Failure of Emergency Diesel Generator to Attain Required Voltage due to a Failed K1 Relay Contactor	18	5302006006
Seabrook	8/31/2006	Plant Shutdown due to Inoperable Emergency Diesel Generators	1	4432006006
Fermi 2	8/17/2006	Emergency Diesel Generators Out of Service due to Undersized Control Power Transformers	1	3412006004
Kewaunee	8/17/2006	Fuel oil leak on Swedgelock fitting renders Emergency Diesel Generator A inoperable	51	3052006009
South Texas	3/25/2006	Standby Diesel Generator Failed Surveillance Test Demonstrating Performance at 110% Load	3	4982006001
Calvert Cliffs 1	3/24/2006	Failure to adequately control design setpoints for feeder breaker supplying EDG support systems	1	3172006001
Prairie Island 2	2/5/2006	Unit 2 Shutdown Required by Technical Specifications due to Inoperable Emergency Diesel Generator	11	3062006001
River Bend	9/9/2005	Operation Prohibited by Technical Specifications due to Diesel Generator Malfunction	23	4582005003
Brunswick 1 &2	8/6/2005	Voluntary Report – Shutdown of Units 1 and 2 Due to Emergency Diesel Generator Operability Concerns	Unreported	3252005006
San Onofre 3	6/26/2005	Emergency Diesel Generator (EDG) 3G003 Declared Inoperable due to Loose Wiring Connection on Emergency Supply Fan	1	3622005001
Cooper Station	6/21/2005	Both Diesel Generators Inoperable in Mode 4 Leads to Condition Prohibited by Technical Specifications	1	2982005003
Prairie Island 2	4/15/2005	Unit 2 Shutdown Required by Technical Specifications due to Inoperable Emergency Diesel Generator	14	3062005002
Crystal River 3	3/25/2005	Emergency Diesel Generator Inoperable due to Fuel Oil Header Check Valves Leaking Past Their Seats	30	3022005002
Perry	2/17/2005	All Emergency Diesel Generators Declared Inoperable due to Degraded Testable Rupture Discs	1	4402005002
Fort Calhoun	10/19/2004	Inoperable Diesel Generator for 28 Days Due to Blown Fuse During Shutdown	29	2852004002
Brunswick 1 &2	8/15/2004	Operation Prohibited by Technical Specifications due to Inoperable Emergency Diesel Generator	47	3252004003

Fermi 2	8/8/2004	Technical Specification Required Shutdown Due to Emergency Diesel Generator Failure	8	3412004001
North Anna 2	5/9/2004	Inoperable Emergency Diesel Generators Due to Shims for Exhaust Support Missing or Not Secured	1	3392004001
Crystal River 3	4/23/2004	Emergency Diesel Generator Inoperable Due To Fuel Oil Header Outlet Check Valve Leaking Past Seat	2	3022004002
Cooper Station	3/28/2004	Failure to Follow Procedure Results in Both Diesel Generators being Inoperable	Unreported	2982004002
Cooper Station	3/23/2004	Both Diesel Generators Inoperable due to Voltage Regulator Design Results in Loss of Safety Function	Unreported	2982006003
Browns Ferry 1,2,3	2/16/2004	Inoperability of Diesel Generator 3D Beyond TS Allowable Outage Time	24	2962004001
Brunswick 1	1/4/2004	Emergency Diesel Generator No. 3 Condition Prohibited by the Technical Specifications	29	32520040010
South Texas 2	12/9/2003	Standby Diesel Generator 22 Failure	Unreported	4992003003
Waterford 3	9/29/2003	Failure of Emergency Diesel Generator A Fuel Oil Line	1	3822003002
Perry	8/20/2003	Unrecognized Diesel Generator Inoperability During Mode Changes	7	4402003003
LaSalle 1&2	4/23/2003	1A and 0 Diesel Generators Inoperable Simultaneously Due to Iinadvertent Partial CO2 Actuation	1	3732003002
Cooper Station	2/28/2003	Inadequate Communication Results in Both Diesel Generators Inoperable Simultaneously	1	2982003001
Kewaunee	2/26/2003	Shutdown Initiated – Diesel Generator Failed Start Test – Unusual Event – Caused by Start Relay Failure	2	3052003002
Columbia	2/16/2003	Failure to Restore Emergency Diesel Generator Within TS Completion Time and Subsequent Plant Shutdown	14	3972003006
Catawba 1 & 2	2/12/2003	Loss of Safety Function Due to Inoperability of the 2B Diesel Generator Upon Loss of Vital Inverter 2EID with the 2A Diesel Generator Inoperable	1	4132003002
Indian Point 2	10/9/2002	Two of Three Emergency Diesel Generators Inoperable Due to Component Failures; a Condition Prohibited by Tech Specs	2	2472002006
Catawba 1	6/24/2002	Technical Specification Noncompliance – Inoperable Diesel Generator Caused by Inadequate Wire Lug Crimping at Closing Spring Motor Disconnect Switch	5	4132002006
Calvert Cliffs 2	1/24/2002	Pump Flexible Drive Gear Wear Causes Emergency Diesel Generator Inoperability	7	3182002001

US NRC ASKS NEW QUESTIONS ABOUT WESTINGHOUSE REACTOR DESIGN

Washington (Platts)--17May2011/357 pm EDT/1957 GMT

The US Nuclear Regulatory Commission on Tuesday said it has asked Westinghouse Electric to explain how methods the company used to calculate structural loads in its new AP1000 reactor shield building meet agency requirements.

During a meeting with Westinghouse officials, NRC branch chief Eileen McKenna said staff reviewing Westinghouse filings on the shield building found the company's calculations were not "fully consistent" with requirements. In some locations in the building, Westinghouse did not add the loads from a possible earthquake to those from day-to-day thermal effects, as the agency staff expected, she said.

The questions come late in the NRC's review of the reactor design, which is expected to be approved this summer and proposed to be built by two groups of US utilities.

NRC completed its safety review of the amended AP1000 reactor design earlier this year, and commissioners have published for comment a proposed final rule that would allow the reactor design to be built by utilities. Some "confirmatory items" such as the load combination, are still to be reviewed, and the commission has not yet approved a final rule, NRC officials said.

Rolf Zeising, director of licensing for Westinghouse, said during the meeting the company believes the design is safe and meets regulatory requirements. The company will "show the adequacy of the approach that we took" during the closed part of the day-long meeting Tuesday, Zeising said.

The question is one of "interpretation" and relates to meeting the requirements of the American Concrete Institute's code for nuclear plant structures, said Michael Corletti, a Westinghouse official. The issue is not expected to lead to a design change, but Westinghouse proposes to update an existing shield building report and make changes to some documents, Corletti said.

The shield building in the AP1000 design protects the reactor containment structure, which in turn houses the reactor vessel.

The AP1000 design could be approved this summer, NRC Chairman Gregory Jaczko said in a speech last week. The two leading US new nuclear developments, Southern Company's two-unit Vogtle site expansion and South Carolina Electric & Gas's two-reactor Summer station project, have chosen to build AP1000s. Four AP1000 reactors are under construction in China.

Westinghouse could show that their methods and calculations are technically sound, and NRC could subsequently accept them, said Mohamed Shams, a branch chief in NRC's Office of New Reactors.

--William Freebairn, william_freebairn@platts.com

May 20, 2011

Regulators Find Design Flaws in New Reactors

By MATTHEW L. WALD

WASHINGTON — In a setback for the only model of nuclear reactor for which ground has been broken in the United States, government regulators have found additional problems with the design of its shield building, a crucial component, the chairman of the Nuclear Regulatory Commission said on Friday.

The chairman, Gregory B. Jaczko, said that computations submitted by Westinghouse, the manufacturer of the new AP1000 reactor, about the building's design appeared to be wrong and "had led to more questions." He said the company had not used a range of possible temperatures for calculating potential seismic stresses on the shield building in the event of an earthquake, for example.

Mr. Jaczko said the commission was asking Westinghouse not only to fix its calculations but also to explain why it submitted flawed information in the first place. Earlier this year the commission staff said it needed additional calculations from Westinghouse to confirm the strength of the AP1000's shield building. The building has not been built; the analysis of its strength and safety is all computer based.

The announcement comes as the commission and the American nuclear industry are facing increased scrutiny as a result of the calamity that began after an earthquake and tsunami damaged the Fukushima Daiichi nuclear plant in Japan in March, leading to releases of radioactive material. Various critics have asked the commission to suspend licensing of new plants, the relicensing of old ones and various other activities until the implications of the Fukushima accident are clearer.

While the commission has said it will evaluate the Japanese accident methodically, it had previously said it did not anticipate that this would cause a delay in approving the AP1000. Now, however, it appears far warier that it will finish this summer.

Westinghouse countered in a statement that the "confirmatory items" that the commission was asking for were not "safety significant." It noted, and the commission agreed, that the company had been the first to identify some of the problems itself. Still, the commission seems to have taken a slightly darker view.

The Southern Company has already dug the foundations and done other preliminary work for two of the AP1000 reactors adjacent to its existing reactors at Plant Vogtle near Augusta, Ga. The Energy Department has promised loan guarantees for that project provided that the Nuclear Regulatory Commission approves the design.

South Carolina Electric and Gas has broken ground for another two, 20 miles northwest of Columbia.

The commission had previously said it expected to approve the AP1000 design this summer. But on Friday a spokesman for the commission, Scott Burnell, said the decision would be delayed for a period of time that he could not specify until Westinghouse submitted a third round of revised calculations.

"They need to be doing the work correctly and completely, and we need to have confidence that that's what they're doing," said one commission official, who said he was not authorized to be quoted by name. "They have additional work they need to do, and a short time to complete it if it's not going to have a significant impact on their schedule."

Southern had been expecting to receive a license to construct and operate the new plant by the end of this year and to have the first reactor on line by mid-2016. On Friday, the company said it still planned to proceed. "We have confidence the AP1000 technology," a company spokesman, Todd Terrell, said.

In addition to the plants in Georgia and South Carolina, ground has also been broken on four AP1000 reactors in China, two at Sanmen and two at Haiyang. Westinghouse, which is owned by Toshiba, is making parts for the Chinese units in factories in the Pittsburgh area.

The AP1000 was in principle designed so it would be faster to build and safer to run than previous models. The letters stand for "advanced passive," with many of its safety features depending on natural forces like gravity and convective cooling rather than pumps and valves, which could be knocked out by electrical failures or floods as they were at Fukushima.

But the design involves a radical departure from those of existing nuclear plants. One change is to put a massive tank of emergency water on the roof so that no pumping is required to deliver it to an overheated reactor. Another is to build a free-standing steel shell around the reactor so that heat can travel through the metal and be passed off to surrounding air.

Existing Westinghouse reactors have a thick concrete dome with a steel liner that forms the reactor's containment shell. In the new design, there is an air gap between the shell and the outer shield building, which is made of steel-reinforced concrete.

The commission has faced some internal dissent about the shield building, and outsiders have complained about the inner shell.

In its statement, Westinghouse said Friday that its reactor was "one of the most studied, reviewed and analyzed nuclear power plant designs in the history of the commercial nuclear power industry." And it said that the value of its passive features was being recognized now "in light of recent events," a reference to Fukushima.

Three other reactor designs are under consideration by the commission, but none of them has any prospect of being built soon. Under a reformed licensing system adopted in the 1990s, the commission is to approve a completed design before substantial work begins on reactor structures.

Beyond the AP1000, opponents of nuclear power are hoping the commission will slow down on other fronts.

"I commend Chairman Jaczko for exercising caution in light of the safety concerns that have been raised about the Westinghouse AP1000 design, and for announcing plans to fully examine outstanding issues regarding structural integrity and resiliency before approving the design," said Representative Edward J. Markey, Democrat of Massachusetts and a longtime Congressional critic of the industry.

He added, "In the wake of the Fukushima meltdown, the N.R.C. also should suspend all of its licensing decisions on new designs, new reactors or relicense applications until it incorporates the lessons of the Japanese catastrophe."

NRC NEWS

U.S. NUCLEAR REGULATORY COMMISSION
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Blog: http://public-blog.nrc-gateway.gov

No. 11-087 May 20, 2011

NRC CHAIRMAN GREGORY B. JACZKO'S STATEMENT ON AP1000 REVIEW ISSUES

The Nuclear Regulatory Commission's efforts to confirm its review of Westinghouse's amended AP1000 reactor design have resulted in the uncovering of additional technical issues. The NRC will always place its commitment to public safety and a transparent process before any other considerations; Westinghouse must resolve the issues before we can consider finalizing NRC certification of the design. The agency will determine what impact this effort may have on the schedule for the AP1000 design amendment and related license application reviews after the staff examines the company's response on these matters.

When the Commission approved issuance of the proposed certification rule earlier this year, the rule language noted the need for what, at the time, were additional calculations to confirm the staff's technical analysis. That work has led to more questions regarding the AP1000's shield building, as well as the peak accident pressures expected within containment. The agency has made it clear to Westinghouse that it must prove to our satisfaction that the company has appropriately and completely documented the adequacy of the design. NRC staff will examine Westinghouse's quality assurance and corrective actions programs as part of an inspection next week, and we expect the company will submit additional information early next month.

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Rulemaking Comments **PR 52 (76FR10269)** 64

DOCKETED
USNRC

June 6, 2011 (2:45 pm)

OFFICE OF SECRETARY
RULEMAKINGS AND
ADJUDICATIONS STAFF

From: tomclements329@cs.com
Sent: Tuesday, May 31, 2011 9:51 AM
To: Rulemaking Comments
Subject: Re: Docket ID NRC-2010-0131, AP1000 Rulemaking

Secretary
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
ATTN: Rulemakings and Adjudications Staff

Re: Docket ID NRC-2010-0131, AP1000 Rulemaking

I submit the following article about an "emergency fuel pool cooling system (EFPCS) developed by Westinghouse" and request that the information in it be considered concerning the design of the AP1000 spent fuel system.

The AP1000 spent fuel pool was requested by Westinghouse to be packed more densely than originally planned. Though technical reasons for this increased density are unclear, the NRC must reanalyze the ability of the AP1000 spent fuel pool to be cooled in case of station blackout. Obviously, Westinghouse has been thinking about the need to upgrade spent fuel pool cooling capacity in case of loss of power and the NRC must review the ability of the Westinghouse "stand-alone emergency fuel pool cooling system" concept to be applied to the AP1000 spent fuel pool

Sincerely,

Tom Clements
Friends of the Earth
Columbia, SC

World Nuclear News

http://www.world-nuclear-news.org/RS-New_system_to_keep_fuel_pools_cool-2605117.html

New system to keep fuel pools cool

26 May 2011

A stand-alone emergency fuel pool cooling system (EFPCS) developed by Westinghouse would be able to keep used fuel cool in emergencies including the loss of all plant power, the company claims.

Developed from the company's existing and patented temporary fuel pool cooling system, the new EFPCS includes a permanent primary cooling loop installed inside the reactor building or spent fuel pool building. The secondary cooling loop is designed as a separate mobile system to be stored off-site, complete with support equipment required to drive the system such as diesel generators, air compressors and switchgear.

The secondary loop would be set up outside the reactor or fuel pool building. As well as reducing the time required for system assembly and startup, this also eliminates any need to enter the reactor building which could be particularly advantageous in emergency situations.

Template = SECY-067 DS 10

According to Westinghouse, its EFPCS is designed primarily as a stand-alone backup system to remove decay heat from spent fuel pools during site emergencies involving a loss of off-site electrical power and on-site emergency diesel power. The system also allows for the addition of make-up water to ensure that safe water levels are maintained in the spent fuel storage pool.

Used nuclear fuel remains hot when it is removed from a nuclear reactor, and is stored underwater in pools at the reactor site until it is cool enough to be transferred for reprocessing or storage and disposal. In normal operation, water circulation keeps the temperature in the spent fuel pool at around 30°C. However, in emergency situations where power is lost and water circulation fails, the water temperature in the pool gradually increases. If the water boils away, the stored fuel rods can become exposed to air leading to the risk of hydrogen formation and radioactive release.

The issue of emergency cooling of used fuel has been thrown into the spotlight following the natural disasters that hit Japan's Fukushima Daiichi nuclear power plant. The pools for reactors 1-4, situated inside the reactor buildings at that particular plant, all lost cooling capacity in the wake of the 11 March earthquake and tsunami, and keeping the fuel pools at all of the Fukushima Daiichi reactors topped up with water has been a priority.

Westinghouse says that the safety design and features of the system take into account a list of plant requirements including seismic requirements, environmental release limits, fuel pool temperature limits, supplemental cooling mode, remote operating interface, independent diesel power and used fuel pool keep-fill system.

During normal plant operations, the EFPCS can be used to provide temporary pool cooling. For example during refuelling outages, the EFPCS could help to reduce fuel movement delays, which are based on the decay heat in the spent fuel pool, as well as improving working conditions on the refuelling floor by reducing pool temperatures.

Nick Liparulo, Westinghouse Nuclear Services senior vice president, said the new product would serve to provide an added layer of safety for nuclear plants around the world. "Recent industry events have placed increased focus on the need to be prepared for every contingency," he noted.

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PR 52
(76FR10269)

DOCKETED
USNRC

June 23, 2011 (4:40 pm)

OFFICE OF SECRETARY
RULEMAKINGS AND
ADJUDICATIONS STAFF

Valery Keramaty
P.O. Box 47, Katonah, NY 10536
June 15, 2011

Nuclear Regulatory Commission
ATTN: Rulemakings and Adjudications Staff
11555 Rockville Pike
Rockville, MD 20852

About the new Westinghouse AP1000 reactor design considered for construction in Georgia, South Carolina and other states:

I request that the NRC put the license application on hold until a thorough review of the Fukushima nuclear disaster has been conducted and weaknesses in the AP1000 design have been reviewed in light of the accident. 1

It is IMMORAL to ask local populations to accept the financial and medical liabilities of a nuclear reactor while receiving inadequate or no compensation. 2

It is ethically irresponsible for the NRC to move forward with licensing or applications for new nuclear facilities until all safety issues (including the medical effects of low levels of radiation downwind and downstream) are satisfactorily addressed. 1 There is now irrefutable evidence of the disastrous effects of low levels of radiation from statistics in places like Chernoble, Iraq, 3 Belarus, and others where depleted uranium or other radioactive products have been distributed. The NRC must face these realities, do what is best for the general public (as it was designed to do; instead of following the lead of the nuclear energy industry), 4 and ensure no facilities are built or licensed that release radioactive material. The NRC must stop the development or licensing of nuclear facilities that cause harm to the families living near them (even when there are no "accidents") through low levels of radioactive substances released as part of normal operations. 1

Westinghouse has not satisfactorily proved that the thin steel containment shell over the reactor would be effective during severe accidents or that the reactor could be properly cooled in conditions similar to those at Fukushima. 5 The NRC must refuse to license nuclear facilities that are unable to protect populations from radiation exposure when there are earthquakes (6.0 and higher on Richter scale) or power outages lasting more than 12 hours. 6

Sincerely,

Valery Keramaty

Valery Keramaty

TEMPLATE = SECY-067

DS 10

66

COMMITTEES

NATURAL RESOURCES
RANKING DEMOCRAT

ENERGY AND COMMERCE

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http://markey.house.gov

March 7, 2011

The Honorable Greg Jaczko
Chairman
Nuclear Regulatory Commission
11555 Rockville Pike
Rockville, MD 20852

Dear Chairman Jaczko:

I write to urge the Commission not to finalize its pending approval of the AP1000 reactor design until serious safety concerns about its shield building have been addressed. These concerns include those raised by one of the Commission's most long-serving staff that there is a risk that an earthquake at, or aircraft impact on, the AP 1000 could result in a catastrophic core meltdown. The danger of terrorist attacks on nuclear power plants, and the importance of their structural resilience, was made very clear on February 24, 2011. A man was arrested in Texas for allegedly planning to blow up nuclear plants using explosive chemicals he purchased online.

The Commission has recently voted to approve the design of the AP 1000. As a result, the NRC's proposed rule for the AP1000 Design Certification Amendment was published in the Federal Register on February 24, 2011. The proposed rule is set to be finalized in the next few months, following a public comment period that ends May 10, 2011 and a 30 day review of public comments. However, the Commission has taken this step toward final approval despite serious safety concerns about the Westinghouse design for the reactor shield building that have been raised by Dr. John Ma. Dr. Ma has been with the NRC since it was created by Congress in 1974. He was the Commission's lead structural reviewer charged with evaluating the design of the reactor shield to determine whether it met NRC safety standards. Dr. Ma has identified potential loopholes, which, if left open, allow designs for unsafe reactors to go forward despite the risk that an earthquake or aircraft impact could result in a catastrophic core meltdown.

While I appreciate the substantive assistance and time spent by your staff in addressing my staff's questions related to the AP 1000 review process, I remain concerned about the safety of the reactor design. I therefore request that the Commission definitively resolve these potential loopholes prior to the finalization of the NRC licensing process.

As you know, the shield building for the AP1000 serves the critical safety function of preventing catastrophic damage to the reactor that could cause fuel melting and radiation releases. The shield building physically protects the highly radioactive core of the nuclear reactor (as well as critical operating equipment) against earthquakes, storms, and airplane strikes. The shield building is intended to ensure safe shutdown following such impacts. As it is designed, the

AP1000 shield building supports a water storage unit on top of it. This water is part of the vital cooling system for the reactor, which is necessary to prevent the sort of overheating that led to core melt at the Three Mile Island reactor in Pennsylvania in 1979.

NRC regulations are intended to ensure that any new reactor design will be able to withstand the dangers of earthquakes, storms, or commercial airplane strikes. The consequences of failure could be severe: According to the report of the 9/11 Commission, Al-Qaeda considered attacking a nuclear power plant as part of its September 11th plot. The Energy Policy Act of 2005 thus included my language that required the NRC to consider the "events of September 11, 2001" and the potential for "suicide attacks" and "air-based threats" in making rules for how reactors will be able to withstand a variety of scenarios related to terrorist attacks. I have long agreed with your 2006 statement that "We should be requiring they design these plants to withstand such attacks.[1]"

On June 12, 2009, NRC issued a rule, 10 CFR 50.150, requiring applicants for new reactors to include an assessment of the ability of the reactor design to withstand the impact of a large, commercial aircraft. The NRC issued its aircraft impact rule after having already issued a final rule certifying the design of the AP1000 on January 27, 2006.[2] In anticipation of the rule change on aircraft impact, Westinghouse amended its design to address aircraft impact, by submitting Revision 16 of its AP1000 design to NRC on May 26, 2007. The NRC is currently considering Revision 18 of the AP1000 design, submitted December 1, 2010[3].

When reviewing the design for the shield building, Dr. John Ma grew concerned that the structure was too brittle and could fail if struck by a natural or manmade catastrophe. He was so concerned by this and other issues that he filed a "Non-Concurrence" statement of dissent[4] on November 4, 2010. Despite the Non-Concurrence, NRC staff issued a positive Advanced Final Safety Evaluation Report (AFSER) on December 28, 2010. The Non-Concurrence accompanied the AFSER throughout a series of approval stages, allowing you and other reviewers to know that these concerns have been raised.

If the NRC approves the AP1000, then it may have widespread use throughout the United States, making questions about its safety of crucial national importance. Among the applications for the construction of 28 new reactors being considered by NRC, the AP1000 would be the design for 7 Combined License applications covering 14 reactors, to be built in Alabama, Florida, North Carolina, South Carolina, and Georgia.[5] The Department of Energy has approved

[1] http://www.nytimes.com/2006/11/09/us/09nuke.html

[2] http://www.nrc.gov/reactors/new-reactors/design-cert/ap1000.html

[3] The current revision is a Design Certification Amendment application that would revise the AP1000 Design Control Document, which is the overall design that NRC certified in 2006.

[4] The Non-Concurrence (NRC Form 757), the response to it by other Division of Engineering staff, and Dr. Ma's rebuttal to this response are all internal NRC documents, Accession Number ML103370648 within the Agencywide Documents Access and Management System (http://www.nrc.gov/reading-rm/adams/web-based.html). The Non-Concurrence Package was published on December 3, 2010.

[5] http://www.nrc.gov/reactors/new-reactors/col.html. The proposed sites include Jackson County, Alabama (Tennessee Valley Authority's Bellefonte site); Levy County, Florida (Progress Energy Florida, Inc.'s site); Homestead, Florida (Florida Power and Light Co.'s Turkey Point site); Wake County, North Carolina (Progress Energy Carolinas, Inc.'s Harris site); Cherokee County, South Carolina (Duke Energy's William States Lee III site);

an application for a loan guarantee of $8.3 billion to Georgia Southern for two proposed AP1000 reactors, conditional on NRC approving the AP1000. Taxpayer dollars should not be spent on 2
unsafe reactors. The Non-Concurrence identifies several potential loopholes. I am asking the Commission to reconsider its approval of the AP1000, in light of these loopholes, the most serious of which I summarize below:

1. The AP 1000 shield building failed tests because it is brittle, and could shatter "like a glass cup"

If a reactor shield is too brittle, it may fail in an earthquake or if struck by an airplane or an automobile or other missile carried by a storm. In fact, Dr. Ma warned that if the AP1000 shield was struck, it could shatter like a "glass cup." The reason for Dr. Ma's statement is that 3
the AP1000 shield building failed, or failed to complete, physical tests designed to evaluate whether the structure has adequate toughness for these sorts of impacts.

In its new design in response to the aircraft impact rule, Westinghouse changed the composition of the shield building from reinforced concrete to a combination of steel and concrete. This "steel-concrete module" is a first-of-its-kind design for nuclear power plants. About 60 percent of the shield building would consist of a module design (module #2) that "failed miserably" in a direct physical test of its toughness. According to the NRC Design Certification Application Review of the AP1000, "test results for out-of-plane shear showed that the modules with **[redacted]** failed in a brittle manner.[6]" A second physical test, of in-plane shear, could not be completed "due to laboratory safety constraints." These shear tests are intended to determine whether the structure will be brittle or "ductile." Ductility enables an object to deform and stretch under force, rather than breaking. Both in-plane and out-of-plane shear would act on the shield building during an earthquake. As you note in comments accompanying your "Yes" vote on the AP1000, the module that would be used for 60 percent of the shield building "was unable to satisfy the experimental protocol developed by Westinghouse and agreed to by the [NRC] staff."

The potential loophole here is that the Commission has apparently accepted Westinghouse's argument that the brittle module design would only be used in regions of the building that are unlikely to encounter high loads. Thus the failing tests were ignored. Instead of 3
relying on the results from the test intended to prove the shield building's design, Westinghouse substituted results from computer simulations that may be a poor approximation of reality.

In his Non-Concurrence, Dr. Ma asks, "How could the [NRC] staff justify using a lower standard, by accepting a brittle structural module for about **[redacted]** of the [steel-concrete] wall for AP1000 shield building, which has more safety functions and greater consequence if the 3
wall collapses, than other types of [reinforced concrete] shield buildings that are required to design to a higher standard of ACI [American Concrete Institute] Code?" Dr. Ma also points to NRC codes stating that the standard to which a design is held must be "commensurate with the

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Fairfield County, South Carolina (South Carolina Electric & Gas' Virgil C. Summer Nuclear Station site); and Burke County, Georgia (Southern Nuclear Operating Co.'s Vogtle site).

[6] Design Certification Application Review – AP1000 Amendment, Chapter 3, page 155. http://www.nrc.gov/reactors/new-reactors/design-cert/amended-ap1000.html

importance of the safety function to be performed".[7] The AP1000 design should not be approved when the material making up 60 percent of the shield building, an essential structural component 3 that is meant to withstand earthquakes, storms, and airplane strikes, has failed a critical physical test showing it to be brittle.

Additionally, the AP1000 shield building design has evidently failed to meet the standards of the American Concrete Institute, despite these being endorsed by NRC[8]. Westinghouse has not complied with the American Concrete Institute (ACI) "Code Requirements for Nuclear Safety-Related Concrete Structures" (ACI-349). . The design fails to 4 meet the Code, because ACI-349 requires the structure to be ductile, would require different spacing between the steel tie-bars, and would not allow substitution of computer models in place of physical tests. Dr. Ma notes that the Safety Evaluation Report "has not provided justifications as to why its acceptance standard, which is lower than that of the ACI Code, is adequate".

To ensure the safety of the AP1000, and any future reactor designs involving steel-concrete composites, I urge you to develop a standard for this novel type of design that would apply both to the AP 1000 and other reactor designs that might seek to use it in the future. The NRC Advisory Committee on Reactor Safeguards notes that "the effort and scope of analysis and assessment required for the shield building in this case suggests that if SC [steel-concrete] composites are to be more widely used in nuclear applications, a consensus code should be developed, as has been done for other types of nuclear construction." You echoed this concern in 5 comments accompanying your "Yes" vote for the AP1000, noting "the lack of a directly acceptable design and construction consensus standard." You write that "it would be advantageous to have such a detailed standard developed independent of any specific design approval. Therefore, I also encourage the [NRC] staff to aid in any effort ... to develop a standard." However, developing such a standard after approving the AP1000 is like planning to comply with building codes to prevent fires after the building has burned down. I ask the Commission to reverse its approval of the AP1000 until such a standard is developed, and then apply this standard to the AP1000 before reconsidering the design.

2. **Weak computer simulations were used to "prove" the reactor shield is "strong enough"**

Westinghouse's assertion that the brittle module is "strong enough" is based on questionable computer simulations in place of the physical tests that it should have done. The computer analysis that Westinghouse did was flawed, because it used off-the-shelf, 6 commercially available codes to evaluate a first-of-its-kind design that could not be expected to be accurately modeled in this manner. The shield building's steel-concrete structure is novel and complex, as is the overall design of the reactor. Given the novelty and complexity of the design, Westinghouse should have developed custom code.

Additionally, Westinghouse relied on a technique known as a static "push-over" simulation. A push-over simulation imagines that an earthquake functions like a finger slowly

[7] Codes and standards: 10 CFR 50.55a(a)(1). http://www.nrc.gov/reading-rm/doc-collections/cfr/part050/part050-0055a.html
[8] Regulatory Guide 1.142 - Safety-Related Concrete Structures for Nuclear Power Plants (Other Than Reactor Vessels and Containments). http://www.nrc.gov/reading-rm/doc-collections/reg-guides/power-reactors/rg/01-142/

pushing a cup until it falls over. Dr. Ma notes that such an analysis is not appropriate, because the shield building would experience several types of forces simultaneously during an earthquake, rather than just one simple "push." In a Technical Evaluation of Westinghouse's modeling work, scientists at Brookhaven National Laboratory agreed, stating that Westinghouse's "models may be inappropriate for static analyses intended to represent cyclic dynamic loading (i.e. earthquake); the effect of load cycling on the effective stress-strain relationship apparently is not considered **[redacted]**.[9]" Westinghouse does not appear to have considered the back-and-forth forces ("cyclic dynamic loading") that occur during an actual earthquake. Instead Westinghouse appears to have fantasized that an earthquake acts like a
constant force in one direction. Had Westinghouse included dynamic cyclic loading, the effective 7
"stress-strain" curve would have had a "backbone" shape; instead, it appeared to be a monotonic curve which is consistent with Westinghouse leaving out the dynamic cyclic loading that occurs in an earthquake. The "static push-over" analysis that Westinghouse did may therefore have been inappropriate because it failed to accounts for the real back-and-forth forces in an earthquake.

Unfortunately, the Technical Evaluation document that details the software's limitations consists mostly of text redacted by NRC staff on Westinghouse's request, but the text that remains is overwhelmingly negative about Westinghouse's simulations. In addition to concerns about how Westinghouse modeled the effects of an earthquake, Westinghouse's results were presented sloppily: There is "no confidence that an appropriate level of quality assurance was implemented in the conduct of the [redacted] analyses." There were "numerous confusing, misleading, or erroneous statements." The concerns raised in this May 30, 2010 Technical Evaluation do not appear to have been addressed by Westinghouse or NRC.

I urge you to require Westinghouse, and other reactor license applicants, to complete and pass physical tests of all materials used in the design, rather than using computer models to substitute for tests that their materials have failed. There should be clear regulations indicating any exceptions where computer analyses are appropriate – and these regulations should require
the use of code that is suitable to the design of the particular reactor under consideration. Where 8
computer models are necessary, the NRC should set standards defining the quality of the models that applicants are required to use, and should conduct independent validations of those models and of the original code. Original code and data should be made available for public review, while accounting for real proprietary and security concerns. As it stands, Westinghouse may be relying on defective models that provide no meaningful assurance of whether the reactor is safe.

3. Earthquake Forces May Have Been Underestimated by Westinghouse

Westinghouse exploited an apparent loophole in how NRC defines earthquake forces.
Westinghouse underestimated the earthquake forces that the reactor would be subjected to 9
through use of a "seismic wave incoherency model to effectively reduce... ground motion"

[9] R. Morante, M. Miranda, J. Nie. Technical Evaluation: AP1000 Shield Building Design Report, Revision 2. Dated 5/30/2010. Submitted as part of Dr. Ma's rebuttal to the staff response to the Non-Concurrence statement. Accession Number ML103370648 within the Agencywide Documents Access and Management System (http://www.nrc.gov/reading-rm/adams/web-based.html).

during an earthquake.[10] It is a "manifestation of mathematical concept that has not been verified and validated by experiments," according to a letter sent by Dr. Ma to your office and mine on November 8, 2010. Indeed, the "interim staff guidance" on incoherency appears to be based on a solitary report of the Electric Power Research Institute, rather than consensus in the peer-reviewed scientific literature. In his letter to my office and to you, Dr. Ma wrote that even assuming these reduced earthquake forces are correct, "the design margin in the shield wall is practically non-existent; the design will be grossly inadequate if the 'correct' and actual earthquake analyses were used." I ask that the Commission require that estimates of seismic forces be drawn from consensus, peer-reviewed scientific literature. Please ensure that Westinghouse re-does its analyses to demonstrate that the AP1000 can withstand real earthquake forces, without minimizing these forces using ill-founded assumptions. 9

I would note that, generally speaking, the NRC staff responses to the Non-Concurrence statements do not dispute the concerns raised by Dr. Ma. Instead, they appear to have acknowledged the flaws associated with Westinghouse's analysis, agreed that addressing the non-concurring staff member's concerns would improve the design, and then shrugged their collective shoulders and chose to abdicate responsibility to further investigate these matters prior to providing a positive Safety Evaluation Report on the shield building of the AP1000 reactor.

In fact, in your January 31 vote to approve the AP 1000 design, you acknowledge that "While it is clear that the use of a ductile material in all areas of the shield building would provide an additional enhancement to safety, I am not convinced that such a design requirement exists..." This is a far cry from a ringing endorsement: you could have said that you are convinced that the design is safe, but you do not go this far. All you say is that there is nothing requiring you to disapprove the design.

There appear to be many unresolved concerns about the AP1000 shield building design, concerns that may justify reversing your vote of approval. Consequently, I ask for your prompt assistance in responding to the following questions.

1. Why did you not require improvements to the AP1000 design to enable it to pass direct physical tests of ductility? Have past reactor shield designs approved by the NRC succeeded in meeting ductility tests that the AP1000 has failed (out-of-plane shear) or has not even completed (in-plane shear)? If so, why is a weaker standard being allowed for the AP1000, which is supposed to be even tougher than past reactor shield designs to meet the aircraft impact rule?

2. There are uncertainties associated with the modeling codes used by the applicant to analyze the accident responses of the highly complex shield building design. Given these uncertainties, are you able to provide me a guarantee that use of brittle modules for about 60 percent of the AP1000 shield building design will not significantly degrade the capability of the wall to resist being hit by a missile propelled by a storm or by an airplane, relative to a design that does not use a brittle module? If so, on what basis, and if not, then why did the Commission vote to approve the design?

[10] Design Certification Application Review - AP1000 Amendment. Chapter 3, page 58. http://www.nrc.gov/reactors/new-reactors/design-cert/amended-ap1000.html

3. There are uncertainties associated with Westinghouse's use of generic computer modeling codes and sloppily presented analyses, the "seismic wave incoherency model," and the static "push-over" analyses of the accident responses of the highly complex shield building design. Given these uncertainties, are you able to provide to me a guarantee that use of brittle modules for the majority of the AP1000 shield building design will not significantly degrade the capability of the shield building to resist an earthquake, relative to a design that does not rely on a brittle module? If so, please explain the basis for such a conclusion. If not, then why did the Commission vote to approve the design?

4. Are you certain that the brittle module is strong enough to withstand the combined stress (in-plane shear, out-of-plane shear, axial force) during a "safe shutdown earthquake"? If so, on what basis did you reach this conclusion? If not, then why did the Commission vote to approve the design?

5. What is the magnitude of earthquake for which the AP1000 would be able to maintain its ability to safely shut down the reactor? Will the NRC require that the AP1000 be able to withstand earthquakes of the magnitudes experienced in all regions of the US, or otherwise limit their deployment to areas in which earthquakes beyond the threshold, "design-basis" magnitude have never been experienced? Why or why not?

6. The shield building design includes two types of steel-concrete modules. Module #2, which failed, has wider spacing of the steel ties that go through the concrete. Module #1 has narrower spacing, which makes it tougher and enabled it to pass the out-of-plane shear test. Instead of accepting Westinghouse's flawed simulations, will the Commission reverse its approval of the AP1000 and instruct Westinghouse to simply replace the brittle module # 2 with a tougher module, such as module #1? If not, why not?

7. Given that there are applications for 14 new reactors using the AP1000 design, will NRC develop a consensus design code for this type of reactor, as has been done for other types of nuclear construction? If yes, will you reverse your approval of the AP1000 design until this code is developed and applied to the AP1000? If not, why not?

8. There are many pages in the Non-Concurrence that have been entirely redacted. For each substantive redaction, please provide me with the legal basis used to justify the redaction in question. If no appropriate basis exists, please ensure that an un-redacted version of the page in question appears in the docket for the AP1000 rule. I also ask that the Non-Concurrence package itself be placed in the docket, since it does not appear to be included among the documents that support the AP1000 rule.[11] The public should be made aware of the existence of the Non-Concurrence when commenting on the proposed design approval.

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[11] The AP1000 documents are available through the Federal e-Rulemaking website at http://www.regulations.gov by searching under Docket ID NRC-2010-0131.

Thank you for your attention to this important matter. Please provide your response no later than March 28. If you have any questions, please have your staff contact Dr. Ilya Fischhoff or Dr. Michal Freedhoff of my staff at 202-225-2836.

Sincerely,

Edward J. Markey

Edward J. Markey