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,

Received 9 December 2000; accepted 22 January 2003.

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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.\(^\text{1}\) 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.\(^\text{2}\) 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. 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 ... "

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.

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 ($^{137}\text{Cs}$) 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). 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. Figure 2 shows diagrams of "generic" pressurized-water reactor (PWR) and boiling-water-reactor (BWR) spent-fuel pools. 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.

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).
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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{17}

Inventories of $^{137}$Cs 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\textsuperscript{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 (MWh-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.\textsuperscript{19} If 10--100\% of the $^{137}$Cs in a spent-fuel pool,\textsuperscript{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, 2003.) (Continued)
Table 1: Typical plume areas (km$^2$).

<table>
<thead>
<tr>
<th>Release</th>
<th>&gt;100 Ci/km$^2$</th>
<th>&gt;1000 Ci/km$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chernobyl (2 MCl, hot, multi-directional)</td>
<td>≈700</td>
<td>200</td>
</tr>
<tr>
<td>3.5 MCl (MACCS2)</td>
<td>3,500</td>
<td>180</td>
</tr>
<tr>
<td>3.5 MCl (wedge model)</td>
<td>6,000</td>
<td>180</td>
</tr>
<tr>
<td>35 MCl (MACCS2)</td>
<td>45,000</td>
<td>2,500</td>
</tr>
<tr>
<td>35 MCl (wedge model)</td>
<td>50,000</td>
<td>6,000</td>
</tr>
</tbody>
</table>

be contaminated to greater than 100 Ci/km$^2$ and 180–6000 km$^2$ to a level of greater than 1000 Ci/km$^2$. Table 1 and Figure 4 show typical contaminated areas, calculated using the MACCS2 Gaussian plume dispersion code used by the NRC for fires with 40 MWt thermal power. 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. 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 MCl 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 MCl 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; 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$^2$. In contrast, in the wedge-model calculations for the 3.5 MCl 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. 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 MCl 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. 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.
Reducing U.S. Stored Spent Reactor Fuel Hazards

**Figure 4:** Typical areas contaminated above 100 (shaded) and 1000 (black) Ci/km² 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).

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). 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. 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.  

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. A 1997 NRC report described two incidents of accidental partial drainage as follows:  

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). At the lower radiation level, lethal doses would be incurred within about an hour. Given such dose rates, the NRC staff assumed that further ad hoc interventions would not be possible.

**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
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).
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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 kW/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:

[1]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

Figure 7: Open and dense-pack PWR spent-fuel racks (Sources: Left: NUREG/CR-0649, SAND77-1371, 1979; right: authors).
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 un­
derstand 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 ther­
mal equilibrium at a temperature of $T_0 = \left[\frac{PM}{A\sigma}\right]^{1/4} \cdot K$, 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), $A = 500 \text{ cm}^2$ is the cross-sectional
area of the dense-pack box containing the fuel assembly, and $\sigma = 5.67 \times 10^{-12}
\text{ W cm}^{-2}$ is the Stefan-Boltzman constant. (We assume that the top of the
fuel assembly radiates as a black body, i.e., maximally.) For $P = 1 \text{ kW or 10 kW},
T_0$ 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 $P = 1 \text{ kW/tU}$
(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 cool­
ing 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. 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.

**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/m³, the cross-section of the portion of a dense-pack box that is not obstructed by fuel rods would be about 0.032 m², 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) ~ 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/m³ and that it has an average density of 0.5 kg/m³ 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. 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. 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. These important conclusions should be confirmed experimentally with, for example, electrically heated fuel rods.

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.” 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. 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.

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
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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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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.  

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. 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 $k_{\text{eff}}$ 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. 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. 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. 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. 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 $\Delta T = \frac{3600P}{nV\rho c_p}$ where $\rho$ is the density of the air entering the building (about 1 kg/m$^3$) and $c_p$ is the
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Heat capacity of the air per kg at constant pressure \( (\approx 1000 \text{ joules/(kg}\cdot\text{OC}) \). 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/MTU of decay heat (i.e., \( P = 8 \text{ MWt} \)) and where \( V = 10,000 \text{ cubic meters} \) (e.g., a building roughly 30 meters square and 10 meters tall). For this case, \( \Delta T \sim 2900/\text{OC} \). To bring \( \Delta T \) 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: \( \Delta p = gH(\rho_0 - \rho_i) \) with the sum of the throttling pressure losses at the openings: \( \Delta p_{th} = 0.5\rho_0(v_i/C_D)^2 + 0.5\rho_i(v_o/C_D)^2 \). 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:

\[
A = \frac{P/[C_D\rho_0(2gH)^{1/2}])(T_i(T_o + T_i))/(T_o(\Delta T)^2)]^{1/2}
\]

For \( H = 10 \text{ m}, T_i = 300^\circ\text{K} \) and \( \Delta T = 100^\circ\text{K} \), this equation becomes \( A = 3.6P \text{ m}^2 \) if \( P \) is measured in megawatts. Thus, if \( P = 8 \text{ MWt} \), \( A \) would have to be 30 \text{ 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. 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. 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. 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/cm² 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.

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. 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, 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. 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.

As already noted, to a certain extent this proposal runs counter to the earlier proposal to minimize 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):

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

![Diagram of cask and overpack](image)

**Figure 9:** (a) Thick-walled cask and (b) Cask with overpack. (Sources: GNE 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 $3 \times 3$ 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. Another analysis assumed a $^{137}$Cs release 1000 times larger. 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. 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 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
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.89 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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{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.\textsuperscript{108} This is 0.4–0.8 percent of the average retail price of electricity in 2001.\textsuperscript{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. 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. 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. Furthermore, the use of the fund for interim storage has been blocked by utility lawsuits. 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.

<table>
<thead>
<tr>
<th>Type</th>
<th>Action</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regulation</td>
<td>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.</td>
<td>The NRC currently has no basis for deciding a limit on how much should be spent on strengthening protections against terrorist actions.</td>
</tr>
<tr>
<td></td>
<td>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.</td>
<td>This would apply the NRC’s defense in depth approach for nuclear power plants to spent-fuel pools.</td>
</tr>
<tr>
<td>Operation</td>
<td>Minimize the movement of spent fuel casks over spent-fuel pools.</td>
<td>This has to be balanced with the proposal to remove older fuel from the pools.</td>
</tr>
<tr>
<td></td>
<td>Minimize occasions when the entire core is moved to the pool during refueling outages.</td>
<td>Technically possible with some potential inconvenience to licensees.</td>
</tr>
<tr>
<td></td>
<td>Transfer spent fuel to dry-cask storage 5 years after discharge from the power reactor.</td>
<td>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.</td>
</tr>
<tr>
<td>Design</td>
<td>Return to open-frame storage—perhaps with additional measures of criticality control.</td>
<td>Analysis is required on how to control this air supply if a fire did start.</td>
</tr>
<tr>
<td></td>
<td>Provide for emergency ventilation of spent-fuel buildings.</td>
<td>Water from the sprays could block air circulation in a dense-packed pool or feed a fire under some circumstances.</td>
</tr>
<tr>
<td></td>
<td>Install emergency water sprays.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Make preparation for emergency repair of holes in pool walls and bottom.</td>
<td>Feasibility may vary greatly for different pool designs.</td>
</tr>
<tr>
<td></td>
<td>Armor exposed outside walls and bottoms against projectiles.</td>
<td></td>
</tr>
</tbody>
</table>

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

ACKNOWLEDGEMENTS

The authors would like to thank for their helpful comments and suggestions:
Steve Fetter, Richard Garwin, David Lochbaum, Helmut Hirsch, and a number
of anonymous reviewers.

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 De­
commissioning 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 regu­
lations at decommissioning nuclear power plants storing fuel in spent fuel pools,” (NRC,

Power Station, Unit No. 3)” Docket No. 50-423-LA-3, CLI-02-27, memorandum and order,

5. Ibid.

6. Ibid.


8. NRC’s regulation of Davis-Besse regarding damage to the reactor vessel head

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

Summary of U.S. Generating Company In-Pool Spent Fuel Storage Capabil­
ity Projected Year That Full Core Discharge Capability Is Lost,” June, 2002,

11. In addition, Browns Ferry Unit 1 is nominally operational. However, it is defueled
and not in service.
Reducing U.S. Stored Spent Reactor Fuel Hazards


15. Strontium-90 (28-year half-life) and its decay product, yttrium-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 90Sr is less volatile than 137Cs, especially under the oxidizing conditions typical of a spent fuel pool fire. It and 90Y are not gamma emitters and are therefore a hazard primarily if ingested.


17. Exposures and effects of the Chernobyl accident," Annex J in Sources and Effects of Ionizing Radiation (UN, 2000) http://www.unscear.org/pdf/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).


19. Fission in LEU fuel yields 3.15 Curies of 137Cs per MWt-day of heat released. One Curie is the radioactivity of one gram of radium (3.7 × 10¹⁰ 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 137Cs 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 137Cs might plate out onto cool surfaces in the building.

21. For the “wedge model" the contamination level \( \sigma = \frac{Q(\theta R_d)}{\sqrt{\pi}} \exp(-r/R_d) \) Ci/m² where Q is the size of the release in Curies, \( \theta \) 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" \( R_d = \frac{H v_{w}}{v_{d}} \). 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 \( \theta \). 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

$$\chi = \frac{Q}{2} \left[ \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \exp\left(-\frac{h^2}{2\sigma_z^2}\right) + \sum_{n=1}^{\infty} \left\{ \exp\left(-\frac{(2nH-h)^2}{2\sigma_y^2}\right) + \exp\left(-\frac{(2nH+h)^2}{2\sigma_y^2}\right) \right\} \right].$$

The term $\sum_{n=1}^{\infty} \left\{ \exp\left(-\frac{(2nH-h)^2}{2\sigma_y^2}\right) + \exp\left(-\frac{(2nH+h)^2}{2\sigma_y^2}\right) \right\}$ takes into account multiple reflections of the plume off the top of the mixing layer and the ground. $Q$, $\sigma_y$, and $\sigma_z$ are all functions of downwind distance. $Q$, the number of Curies in the plume, is reduced by deposition. The area deposition concentration is $\nu_df$, where $\nu_d$ 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/sfdatal.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. 15059–15062, 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).


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 masonry 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 1 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 Shut-down 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 rem 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 product. 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 137Cs contamination levels in areas where decontamination would be carried out is from about 2.5 up to 80 Ci/km².


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 m² 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 x 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 m³] 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% SiO₂, 6.5% Al₂O₃, 6.1% CaO, 4.0% H₂O, 2.0% Fe₂O₃, 1.7% Na₂O, 1.5% K₂O, 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 33 MWd/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 x 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).


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.


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 80 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/mathlign/hh/blg.htm, accessed Dec. 10, 2002. A similar dry-cask storage facility was built instead of a storage pool at Ahaus, Germany.


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 x 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, FF/I/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.


51. In recently installed racks, the boron is contained in Boral sheets composed of boron carbide (B₄C) 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 UO₂ 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 dw²/dt = Kₑ.exp(−Eₑ/RT) in the range 920–1155°C, where w is the weight gain of the cladding (g/cm²) due to oxidation, Kₑ is the rate constant [5.76 × 10⁴ (gm/cm²)²/sec], Eₑ 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, Kₑ.exp(−Eₑ/RT) = 1.1 × 10⁻⁵ (gm/cm²)²/sec. The
fuel cladding contains 0.34 gmZr/cm². For full oxidation to ZrO₂ will therefore be about 0.014 (gm/cm²)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).


57. Between 300 and 1200 °K, the longitudinal conductivity of a 0.4-cm radius rod of UO₂ 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 UO₂ falling from 0.076 to 0.03 and for zircalloy rising from 0.13 to 0.25 Watts/(°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 UO₂ 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 T₀, 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) ≈ 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 = -4fαT(dT/dz)(λₗ) where f is the fraction of the area of the fuel assembly between the fuel rods (about 0.6) and (λₗ) = ∬dQ(Cosθ) /λ(θ,φ) 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 Watts/cm³ along the length (L = 400 cm) of the fuel assembly. In this approximation, the temperature profile can be calculated as T = [1000PM/(λₗL)]1/(1/4) + T₀ for z = -L, T(-L) = 600{P[1 + (0.8L/(λₗ))]²}1/4K. For P = 1 kW/tU, T(-L) = 2300 or 1700°C if (λₗ) = 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 Tₘₐₓ at its top and that the water level is at zₘ (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 Pₜₐₜ₈ = PMzₘ/L + Pbb. The heat generation rate of the
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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 $P_\text{bb} / 2300$ grams/sec. When $z$ falls below the bottom of the fuel assembly, $P_\text{bb} \approx P_\text{bb} -$. We approximate $P_\text{bb} = (A/264)\sigma(T_0 + 273)^4$ 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 $T_0 = 200^\circ$C at the point when $T_{\text{max}} = 900^\circ$C, i.e., when the fuel is about to fail. This gives $P_\text{bb} \approx 0.6$ Watts. Assuming perfect heat transfer, the steam will heat to a temperature $T_{\text{max}}$ as it passes through the fuel assembly and absorb approximately $2.1(T_{\text{max}} - 100)$ joules per gram. Therefore, in order to remove the power $P_+$ and maintain the above-water fuel in equilibrium, it is necessary that $P_+ < 2.1(T_{\text{max}} - 100)P_\text{bb} / 2300 \approx 0.3$ Watt/kgU when $T_{\text{max}} = 1200^\circ$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.


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, $\partial(\rho v)/\partial t + \partial(\rho v^2)/\partial z + P_\text{L} = -\partial P/\partial z - \rho g$ where $\rho$ is the air density, $v$ is its velocity, $P$ is the pressure, $P_\text{L}$ 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 $\rho_0(v_1)^2 - \rho_0(v_0)^2 + \int_0^L P_\text{L}dz = P(0) - P(L) - g(0)\rho_0dz$. Assuming that the pressure is constant across the top and bottom of the spent fuel, the air velocity is constant below the spent fuel, the gas velocity is constant in 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 $\rho_1(v_1)^2 + \int_0^L P_\text{L}dz = \rho_0(v_0)^2(T_1/T_0)$. This gives $\rho_1(v_1)^2 + \int_0^L P_\text{L}dz \approx 0.5 \rho_0L = 20$ 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, $\rho_1(v_1)^2 = \rho_0(v_0)^2(T_1/T_0)$, where $T_1 = 1173^\circ$K at the ignition point. We assume that $T_0 = 100^\circ$C = 373 K. We then obtain $3.1(v_0)^2 + \int_0^L P_\text{L}dz = 20$ joules/m$^3$ and $v_0 \approx 2.5$ m/s, if the $P_\text{L}$ term is neglected.

$P_\text{L}$ 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, $\int_0^L P_\text{L}dz = K_0\rho_0(v_0)^2 + \int_0^L f_\text{f} \rho v^2dz/2D_\text{H}$. Here $K_0 = 2(1 - x)/x; x = (A_\text{H}/A_\text{R})^2, A_\text{H}$ is the area of the hole in the base-plate and $A_\text{R} = S^2 - 264 \pi(D/2)^2$ 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, $f_\text{f}$ is the friction factor, $D_\text{H} = 4A_\text{f}/P_\text{w}$ is the "hydraulic diameter" of the channel, and $P_\text{w} = 4S + 264 \pi D$ 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, \( D_H \approx 0.015 \text{ m} \). The friction factor may be written as \( f = C/(Re)^n \), where \( Re = \rho v_D/\mu \) is the Reynolds number, and \( \mu \) is the viscosity of air \((31 \times 10^{-6} \text{ pascal-seconds at } 600^\circ \text{K})\). The exponent \( n \) = 1 for laminar flow \((Re < 2100)\), which will be seen to be the case in the fuel assembly. The coefficient \( C \approx 100 \) within the fuel assembly in the approximation where all rods are treated as interior rods (ibid., p. 4–7, 4–16/17). Thus, \( \int_0^L P_l d\ell = K_0 \rho_0 (v_0)^2 + \left( C \mu / \left( 2(D_H)^2 \right) \right) \int_0^L v d\ell \approx K_0 \rho_0 (v_0)^2 + 55v_0 \text{ joules/m}^3 \), where we have approximated \( \int_0^L v d\ell \approx 2Lv_0 \), 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 \( 14.4(v_0)^2 + 55v_0 = 20 \text{ joules/m}^3 \), or \( v_0 \approx 0.33 \text{ m/sec} \).

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, \( D_H \approx 0.1 \text{ m} \) and the equation above becomes \( 3.1(v_0)^2 + 1.24v_0 = 20 \text{ joules/m}^3 \), or \( v_0 = 2.3 \text{ m/sec} \), which would make it possible to cool a pool filled with fuel generating about 100 KWtU. 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).


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


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 \(^{137}\text{Cs}\) from 400 tons of spent fuel are estimated at $250–1700 billion. We discount these damages to $100–750 billion because the risk would not be completely eliminated by the measures that we propose and their mitigating effect could occur decades after the investment. The 0.6 – 2.4 \times 10^{-6} \text{ probability of a spent-fuel fire per pool-year estimated in Technical Study of Spent Fuel Accident Risk at Decommissioning Nuclear Power Plants (Table 3.1)\right)}$
is equivalent to about 0.6 percent in 30 years for the 103 operating power reactors in
the U.S.
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, 
74. Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear
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 MWh/kg. The Sandia study considered 
fuel with a burnup of only 33 MWh/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: ura-
nium 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 cal-
culated 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 MWh/kgHM, introduction of 
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. Ibid., 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.


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.


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 UO₂ in the ruptured pins would begin to oxidize to U₃O₈, 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 × 10⁶ pascals) without rupturing. The kinetic energy of a 400-kg shaft traveling at a speed of 220 m/sec is about 10⁷ 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 10⁷ 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 GW.

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.


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


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].


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.)
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

Received; accepted.

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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.
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/km$^2$ 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 half-life $^{131}\text{I}$ and 2-year half-life $^{134}\text{Cs}$ in the consequence calculations. Shorter-lived isotopes such as $^{131}\text{I}$ and one-year half-life $^{106}\text{Ru}$ 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 half-life $^{137}\text{Cs}$ 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.
Damages from a Major Release of $^{137}$Cs into the Atmosphere of the United States*

by Jan Beyea, Ed Lyman, Frank von Hippel

We report estimates of costs of evacuation, decontamination, property loss, and cancer deaths due to releases by a spent fuel fire of 3.5 and 35 MCi of $^{137}$Cs into the atmosphere at five U.S. nuclear-power plant sites. The MACCS2 atmospheric-dispersion model is used with median dispersion conditions and azimuthally-averaged radial population densities. Decontamination cost estimates are based primarily on the results of a Sandia study. Our five-site average consequences are $100 billion and 2000 cancer deaths for the 3.5 MCi release, and $400 billion in damages and 6000 cancer deaths for the 35 MCi release. The implications for the cost-benefit analyses in "Reducing the hazards" are discussed.

INTRODUCTION

"Reducing the hazards from Stored Spent Fuel in the United States" (Science & Global Security 11, pp. 1–51), of which we were coauthors, quoted the results of...
a 1997 Brookhaven study,\textsuperscript{1} which estimated the damages from a release of 8–80 Mci of $^{137}$Cs into the atmosphere as $117$–$566$ billion and $54,000$–$143,000$ cancer deaths. "Reducing the hazards" also included (in footnote 29) damage estimates calculated using the "wedge" atmospheric-dispersion model for releases of 3.5 and 35 Mci assuming a uniform population density of 250/km$^2$. In this note, we present the results of a calculation based on real radial population density distributions around five U.S. reactor sites and using the Sandia MACCS2 atmospheric-dispersion model.\textsuperscript{2}

**Population Density**

We have used year-2000 population distributions averaged azimuthally around five sample locations chosen to represent the range of U.S. reactor sites. They are: Catawba, near Rock Hill, South Carolina; Indian Point, on the Hudson River near New York City; LaSalle County near Springfield, IL; Palo Verde, near Phoenix, AZ; and Three Mile Island, near Harrisburg, PA.

Figure 1 shows the cumulative populations within a given radius out to 1600 km from each of these nuclear power plants multiplied by a factor of

![Figure 1: Cumulative population as a function of distance from five U.S. nuclear power plants multiplied by a plume-width factor of 0.038.](image-url)
Table 1: EPA unshielded radiation dose limits for long-term occupation of contaminated land and corresponding derived $^{137}$Cs surface contamination levels.

<table>
<thead>
<tr>
<th>Period</th>
<th>EPA dose limit (rem)</th>
<th>$^{137}$Cs contamination level (Ci/km$^2$)</th>
<th>EPA</th>
<th>MACCS $^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>First year after release</td>
<td>2</td>
<td>44.4</td>
<td>41</td>
<td></td>
</tr>
<tr>
<td>Second year after release</td>
<td>0.5</td>
<td>17.2</td>
<td>14.4</td>
<td></td>
</tr>
<tr>
<td>Cumulative 50-year dose</td>
<td>5</td>
<td>8.2</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

This factor is used so that the figure can be used to convey a sense of the size of the population that might be within a downwind plume, which we have approximated for this purpose as a radial wedge with a 0.24-radian opening angle. We do not include the populations of Canada or Mexico.

Contamination Thresholds for Evacuation

The EPA has proposed allowable radiation-dose limits for unshielded individuals above which relocation would be recommended. These limits are shown in Table 1, along with the corresponding contamination limits calculated by the EPA and in the MACCS$^2$ model.

We have chosen a $^{137}$Cs contamination level of 15 Ci/km$^2$ as our threshold for decontamination. This corresponds approximately to EPA's limit of no more than 0.5 rem unshielded dose in the second year of exposure. This contamination level would give cumulative 50-year doses more than twice the EPA's limit of 5 rem. However, on a threshold of 15 Ci/km$^2$ corresponds to the definition of the zone of "strict radiation control" established within the area contaminated by the Chernobyl accident. According to a recent U.N. study of the consequences of the Chernobyl accident, "within these areas radiation monitoring and preventative measures have been generally successful in maintaining annual effective dose within [0.5 rem/yr]."$^6$ An area approximately equal to that contaminated above 50 Ci/km$^2$ by the Chernobyl accident remains evacuated.$^7$

Decontamination

The most recent and detailed study of the effectiveness and costs of radioactive decontamination was done for Sandia National Laboratories in 1996.$^8$ The study was of the problem of decontamination after plutonium dispersal by a warhead accident but was based mostly on experiments with fission products. Contamination levels were defined as "lightly-contaminated" (requiring a
decontamination factor (DF) of 2–5); “moderately-contaminated” (DF = 5–10); and “heavily contaminated” (DF > 10).

For heavily contaminated areas, the study finds that:

we have been unable to discover any practical method that could reliably achieve successful decontamination short of completely demolishing buildings and disposing of the material in a licensed burial facility.

We assume that, at the edge of heavily contaminated areas there would be a “gray zone” where a few years of radioactive decay will reduce the contamination to a level where decontamination by a factor of eight would make the area habitable again. However, the value of the property is assumed in the MACCS2 model to depreciate at an exponential rate of 20 percent per year so that, after a few years, the average residual value of the property will be less than the cost of decontamination.

Decontamination in the lightly and moderately contaminated areas is described in the Sandia report as involving the following measures:

Lightly-contaminated areas (DF 2–5). “[P]rompt vacuuming of all structural exteriors [and streets, sidewalks and driveways] followed by detergent scrubbing and rinsing. Building interiors would be cleaned by … for example, repeated vacuuming followed by shampooing for carpets … Turf in lawns [and any paved areas that could not be adequately decontaminated by less costly means] would be removed and replaced … Tree foliage would be hosed down, with the wash water collected to prevent runoff, and the trunks would be scrubbed.”

Moderately contaminated areas (DF 5–10). “Roofing would be removed and replaced, all landscape materials, including trees, would be removed, and flooring furniture and personal effects would be removed from the interior.”

The Chernobyl experience suggests, however, that decontamination by a factor of more than three may be unachievable. The U.N. study reports:

The effect of decontamination procedures on external dose was studied … before and after decontamination of the Belarusian village of Kirov. Decontamination procedures included replacing road surfaces, replacing roofs on buildings, and soil removal. The results … suggest that decontamination were most effective for school children and field workers [decontamination factors of 1.5 and 1.3 respectively] but had limited effect on other members of the population. Similar estimates have been obtained with regard to the decontamination of Russian settlements in 1989. The average external dose ratio measured after and before
decontamination was found to range from 0.70 to 0.85 [DF 1.2-1.4] for different settlements.

Nevertheless, we assume that decontamination by up to a factor of eight would be feasible. In our calculations, the boundary between lightly and moderately contaminated areas has been set at a decontamination factor of three and that between moderately and heavily contaminated areas at eight.

Table 2a shows by level of contamination the estimates made in the Sandia report of the per capita costs for decontamination, compensation, and radioactive waste disposal in a mixed-use urban area.13

Compensation costs are based on replacement cost for lost property and 3, 6, and 12 months rental for displaced residents during decontamination of lightly, moderately and heavily contaminated areas, respectively.14 For the residents of condemned properties, it was assumed that the properties would be paid for within a year. During the decontamination period, displaced persons would also receive allowances for “clothing, electronic entertainment items, household articles, and work related tools.” It was assumed compensation would be paid to commercial establishments for their complete stocks and for their average payrolls and net income for 3, 6 or 12 months for lightly, moderately or heavily contaminated areas respectively.

The Sandia study found the costs of disposing of radioactive decontamination wastes to be a significant part of the total cleanup costs. Both on-site and off-site disposal were considered. For on-site disposal, it was assumed that the waste would be containerized, cement stabilized, and emplaced in reinforced-concrete lined trenches buried under 5 meters of cemented broken rock and an 0.61 m thick concrete cap. This resulted in a cost estimate of $318/m³ of waste. This cost would be reduced by approximately a factor of two “for a less protective [on-site] disposal system that just met current requirements.”15 Off-site disposal was assumed to involve truck shipment in steel containers 1000 miles
to a government facility that would accept low-level transuranic waste (recall that this study is for a plutonium contamination accident). The resulting cost estimate was $666/m³ with transportation accounting for slightly over half the cost. The waste-disposal costs shown in Table 2 are for a range of costs from $167 to $666/m³. We have used the bottom of this range in making our own cost estimates.¹⁶

The authors of the Sandia report state that, "[a]lthough in some instances we have chosen parameter values conservatively, the resultant bias is compensated to some unknown extent by the many potential costs that have been omitted from our estimates."¹⁷ Some of the omitted costs discussed in the report are the following:

♦ "If mistakes or deficiencies were found, it is possible that some actions might need to be redone or augmented, at additional expense. We have not attempted to account for those possible additional costs."¹⁸

♦ "Administrative and support costs for the cleanup of Enewetak Atoll were roughly equal to the direct cost of conducting remediation... [A]fter the Chernobyl accident, the Swedish government's cost tabulation for its emergency response programs showed that indirect administration and support were roughly equal to the cost of direct actions... We believe... that it might be reasonable to double the cost estimates provided [here] in order to account for indirect costs."¹⁹

♦ "Decontamination appears to become less effective with the passage of time. Most experiments have been conducted within a few days, or at most a few months of deposition."²⁰

♦ "Possible litigation costs are not addressed... Because of the adverse impact of delays, costs could increase even if lawsuits proved unsuccessful."²¹

♦ "We assumed that properties acquired by the government [for remediation and restoration] would be resold without loss."²²

♦ "The cost estimates... do not include downtown business and commercial districts, heavy industrial areas, or high-rise apartment buildings. Inclusion of these areas would increase costs."²³

The Sandia results don't quite match to the input requirements of the MACCS2 code, which, for example, does not allow for the inclusion of decontamination costs in permanently evacuated areas. We have therefore made the changes shown in Table 2b.
Table 2b: Per capita contamination cost assumptions used in our MACCS2 runs.

<table>
<thead>
<tr>
<th>Decontamination factor</th>
<th>&lt;3</th>
<th>&lt;8</th>
<th>&gt;8&lt;sup&gt;24&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decontamination&lt;sup&gt;25&lt;/sup&gt;</td>
<td>$19,000</td>
<td>$42,000</td>
<td>$0-42,000</td>
</tr>
<tr>
<td>Compensation</td>
<td>$25,000&lt;sup&gt;26&lt;/sup&gt;</td>
<td>$30,000-132,000&lt;sup&gt;27&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Relocation&lt;sup&gt;28&lt;/sup&gt;</td>
<td>0</td>
<td>$3,600</td>
<td>$3,600</td>
</tr>
<tr>
<td>Waste disposal&lt;sup&gt;29&lt;/sup&gt;</td>
<td>$14,000</td>
<td>$15,000</td>
<td>$0-15,000</td>
</tr>
<tr>
<td>Total</td>
<td>$58,000</td>
<td>$85,600</td>
<td>$90,600-135,600</td>
</tr>
</tbody>
</table>

DAMAGE ESTIMATES

Our consequence estimates for the five sites, for 3.5 and 35 MCI<sup>137</sup>Cs releases, are shown in Table 3.

The economic damages averaged over the five sites for the 3.5 and 35 MCI releases are approximately $100 and $400 billion, respectively. For comparison, the cost estimates in “Reducing the hazards,” using the wedge model and assuming a uniform population density of 250/km<sup>2</sup>, were $50 and $700 billion, respectively. The economic damages would largely be incurred within a few hundred km of the reactors. The population density within 400 km of the five sites averages about 80/km<sup>2</sup>.

The five-site average of the estimated number of cancer deaths is 1900-5700, much less than the 50,000-250,000 estimated in “Reducing the hazards” using the wedge model and assuming a uniform population density. The difference is due in large part to the fact that most of the population radiation dose occurs at large distances (small doses to large numbers of people) and the five-site average population density beyond 400 km is approximately 20/km<sup>2</sup>—much less than the 250/km<sup>2</sup> assumed in “Reducing the hazards.” An additional

Table 3: Estimates of economic losses ($billions) and cancer deaths.

<table>
<thead>
<tr>
<th>Site</th>
<th>Release (MCI)</th>
<th>Total costs</th>
<th>Condemned property</th>
<th>Other losses&lt;sup&gt;30&lt;/sup&gt;</th>
<th>Temporary relocation</th>
<th>Decontamination&lt;sup&gt;31&lt;/sup&gt;</th>
<th>Cancer deaths&lt;sup&gt;32&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catawba</td>
<td>3.5</td>
<td>71</td>
<td>10</td>
<td>32</td>
<td>0</td>
<td>29</td>
<td>3,100</td>
</tr>
<tr>
<td></td>
<td>35.0</td>
<td>547</td>
<td>145</td>
<td>192</td>
<td>11</td>
<td>199</td>
<td>7,650</td>
</tr>
<tr>
<td>Indian point</td>
<td>3.5</td>
<td>145</td>
<td>43</td>
<td>85</td>
<td>8</td>
<td>86</td>
<td>1,500</td>
</tr>
<tr>
<td></td>
<td>35.0</td>
<td>461</td>
<td>282</td>
<td>85</td>
<td>8</td>
<td>86</td>
<td>5,600</td>
</tr>
<tr>
<td>LaSalle</td>
<td>3.5</td>
<td>54</td>
<td>2</td>
<td>23</td>
<td>1</td>
<td>27</td>
<td>2,100</td>
</tr>
<tr>
<td></td>
<td>35.0</td>
<td>270</td>
<td>10</td>
<td>121</td>
<td>7</td>
<td>131</td>
<td>6,400</td>
</tr>
<tr>
<td>Palo Verde</td>
<td>3.5</td>
<td>11</td>
<td>1</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>35.0</td>
<td>80</td>
<td>24</td>
<td>26</td>
<td>2</td>
<td>29</td>
<td>2,000</td>
</tr>
<tr>
<td>Three-Mile Island</td>
<td>3.5</td>
<td>171</td>
<td>13</td>
<td>65</td>
<td>6</td>
<td>87</td>
<td>2,300</td>
</tr>
<tr>
<td></td>
<td>35.0</td>
<td>568</td>
<td>278</td>
<td>134</td>
<td>11</td>
<td>144</td>
<td>7,000</td>
</tr>
<tr>
<td>Averages</td>
<td>3.5</td>
<td>91</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1,900</td>
</tr>
<tr>
<td></td>
<td>35.0</td>
<td>385</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5,700</td>
</tr>
</tbody>
</table>
reduction of about a factor of two can be attributed to the fact that a larger fraction of the $^{137}$Cs deposits on the ground close to the reactor in the MACCS2 plume model than in the wedge-model because of the smaller vertical extent of the plume within the first 200 km and correspondingly higher ground-level concentration of the plume. These close-in deposits result in fewer cancers as a result of permanent evacuation and decontamination.

**IMPACT ON THE COST-BENEFIT CALCULATION**

The five-site average of costs, including cancer deaths (valued at $4 million each) for releases of 3.5 and 35 MCI is $100 and $370 billion. The corresponding estimates in “Reducing the hazards” (endnotes 29 and 70) were $250 and $1700 billion. Then we compared the costs of taking spent fuel out of the pool and placing it into dry storage with the potential benefits of subsequently avoiding a spent fuel fire. In so doing, we sought to take into account our assumption that the cost of placing the spent fuel in dry storage would on average be incurred 15 years before the probabilistic benefit of avoiding a spent fuel fire. Discounting the accident costs by an extra 15 years led to the value of $100–$750 billion that was compared with the cost of transferring the spent fuel to dry storage.

To a large extent, however, discounting reflects the assumption that society will be wealthier in the future and that the same expenditures later will therefore be a smaller fraction of this increasing wealth. In the present case, an increasingly wealthy society will also have more to lose from a spent-fuel fire. The two effects work in opposite directions. In this note, therefore, we have not discounted the estimated $100–$400 billion economic damages when comparing with the cost of early partial unloading of the spent fuel pools.

In “Reducing the hazards,” the cost of a spent-fuel fire was compared with the cost of placing into dry casks all of the spent fuel in the pools older than five years (estimated at 35,000 tons in 2010). This cost was estimated as falling in the range $3.5–$7 billion. We then used a mid-range number of $5 billion for our cost-benefit estimate. Dividing this cost by the $100–$400 billion cost of a spent-fuel fire estimated here gives break-even probabilities for a spent-fuel fire occurring during the 30-year period ranging from 1.3 to 5 percent. The corresponding range calculated in “Reducing the hazards” (endnote 70) was 0.7 to 5 percent. In reality, the break-even probability would be somewhat higher, since removal of a fraction of the spent fuel would not entirely eliminate the risk of a spent-fuel fire.

It was noted in “Reducing the hazards” that removing one out of five fuel assemblies could result in each of the fuel assemblies remaining in the pool
Figure 2: Removal of one fifth of the spent-fuel assemblies could result in every fuel assembly having one side exposed to an empty channel.

having one side exposed to an empty channel in the rack (see Figure 2). If further analysis reveals that such a configuration could be convectively air cooled, then only 9,000 tons of the 45,000 tons of spent fuel projected to be stored in U.S. spent-fuel pools in 2010 would have to be removed instead of 35,000 tons. In this case, the extra cost of dry spent-fuel storage would go down by approximately a factor of four and the break-even spent-fuel fire probability would go down correspondingly, although, once again, some correction would be needed to account for the residual probability of a fire. In this configuration, the cesium inventory would not be greatly reduced while it would be reduced by approximately a factor of four if all the spent fuel more than five years old were discharged.

NOTES AND REFERENCES


height of 1000 meters, median (D-type) atmospheric dispersion conditions and a $^{137}$Cs deposition velocity of 0.01 m/sec.

3. The radial population densities were calculated using year-2000 computerized census-tract data available from GeoLytics, (http://www.censuscd.com). According to the Bureau of the Census, “census tracts generally have between 1,500 and 8,000 people” (http://www.census.gov/geo/www/cob/tr_metadata.html).


5. The MACCS2 model calculates the unshielded dose rate from $^{137}$Cs as $[0.032 \text{rem}/(\text{yr} \cdot \text{Ci/km}^2)] \times \exp[-t \ln 2/(30)] \times [\exp(-t \ln 2/0.5) + \exp(-t \ln 2/88.8)] = 0.032[\exp(-1.4t) + \exp(-0.031t)] \text{rem}/(\text{yr}\cdot\text{Ci/km}^2)$ with $t$ measured in years. The 30-year half-life decay factor reflects the radioactive decay of $^{137}$Cs. The second two-exponential factor takes into account that the $^{137}$Cs sinks into the soil—rapidly at first and more slowly later. The ratio of the second-year to the first-year dose is 0.71. The ratio of the dose for the first three months to that of the first year is 0.3.


7. The area within 30 km of Pripyat (the village near the reactor where Chernobyl workers lived) remains evacuated (2800 km$^2$ with a population of 90,000). Some highly contaminated areas outside the 30-km zone with a total population of 3800 were also evacuated. The total area contaminated to greater than 50 Ci/km$^2$ has been estimated at 3100 km$^2$ (Sources and Effects, Annex J) paras. 91–93 and Table 5.


9. The decontamination factor is defined as the ratio of the external gamma dose rate before decontamination to that after.


16. Waste produced as result of decontamination following an hypothetical spent fuel accident will fall into the lowest of the U.S. Nuclear Regulatory Commission's categories of low level radioactive waste, Class A, in which $^{137}$Cs has a concentration less than one Ci/m$^3$ (NRC Regulations, 10 CFR, Part 61.55 --Waste Classification (http://www.nrc.gov/reading-rm/doc-collections/cfr/part061/)) The U.S. Army Corps of Engineers negotiated contracts with Envirosite for disposal of Class A debris at
$320/m^3$ in 1998 and $559/m^3$ in 1997, not including handling or transport (The Disposition Dilemma: Controlling the Release of Solid Materials from Nuclear Regulatory Commission-Licensed Facilities, Washington, DC: National Academy Press, 2002. p. 80, assuming a averaged debris density of 1200 kg/m$^3$). However, the total amount of Class-A waste needing disposal following a spent fuel accident is likely to be of the order of 100-million m$^3$ for a 3.5 MCi release (one million affected persons times 90 m$^3$ per person) which exceeds the annual amount of LLRW currently disposed of in the United States each year by a factor of about one thousand. (About 3 million cubic feet (0.08 million m$^3$) of DOE and commercial LLRW were disposed of per year in 1998 and 1999, Texas Compact Low-Level Radioactive Waste Generation Trends and Management Alternatives Study: Technical Report, Rogers & Associates Engineering Branch URS Corporation, Salt Lake City, 2000, RAE-42774-019-5407-2, Tables 3.1 and 3.4). Consideration would therefore be given to other landfill options. Cost of disposal at Resource Conservation and Recovery Act Subtitle C hazardous waste landfills is typically $90/m^3$, exclusive of waste preparation, handling, and transportation (The Disposition Dilemma, p. 78). Once again, however, the projected capacity for such landfills, both currently and projected to 2013, is only about 1.5 million tons per year (National Capacity Assessment Report: Capacity Planning Pursuant To CERCLA Section 104(C)(9), “Demand for Commercial Hazardous Waste Capacity from Recurrent Landfill Expected to be Generated In State (tons),” at (http://www.epa.gov/epaoswer/hazwaste/tsds/capacity/appa_lf.pdf) (25 March 2004)). Municipal waste (Subtitle D) landfills, would typically charge $25/m^3 (The Disposition Dilemma, p. 78) but the concentration of $^{137}$Cs is likely to exceed by an order of magnitude the 11 pCi/g concentrations associated with expected doses less than one mrem/yr to critical groups that have been discussed as possible consensus standards for disposal without controls (The Disposition Dilemma, pp. 119, 173). For soil with a bulk density of 1.3 g/cm$^3$ removed to a depth of 10 cm, the average $^{137}$Cs concentration would be 115 pCi/g for a surface contamination level of 15 Ci/km$^2$. The contamination levels of other types of debris would generally be higher.

18. Site Restoration, pp. 6-3, 6-4.
19. Site Restoration, p. 6-3. The factor might not be as great in the current case, however, because of economies of scale.
22. Site Restoration, p. 2-5.
23. Site Restoration, p. 6-2.
24. Decontamination by a factor of eight would make regions near the edge of this zone habitable during the few-year period before depreciation reduces the value of the property to the point where decontamination is no longer cost effective. MACCS2 does not include the decontamination costs that Site Restoration estimates would be incurred in areas where structures would be so heavily contaminated that they would have to be condemned.
25. From Site Restoration.
26. MACCS2 allows only one value for all decontaminated areas. We have therefore used the average of the values calculated in Site Restoration for light and medium
contamination. Loss of income for a period of 4.5 months would amount to $13,500. (U.S. per capita income in 2000 was $35,000, Statistical Abstracts of the United States: 2001, U.S. Census Bureau, 2003, Table 646). Site Restoration includes in addition compensation for losses of business inventories, personal property and relocation time beyond 90 days.

27. $30,000 if the property can be decontaminated after a minimal period of depreciation. $132,000 if the property is so heavily contaminated that it must be condemned. The year-2000 average per capita value of U.S. fixed assets was $107,000 and the per capita value of residential land, using the MACCS2 default value of 20% of the value of U.S. housing value in 2001, was $7,000, (Statistical Abstracts of the United States: 2002, U.S. Census Bureau, 2003, Tables 1 and 679). We add six months lost income.

28. 90 days at $40/day in areas where the projected unshielded dose for the first year would exceed 2 rem. The 1989 Manual of protective action guides (p. E-9) estimated $26/day.

29. We have assumed the bottom end of the range given in Site Restoration, i.e., onsite disposal in a facility whose design “just met current requirements.”

30. Heavily contaminated furnishings, business inventory and vehicles. Also depreciation of property when radioactive decay is required in addition to $D_F = 8$ before reoccupation is possible.

31. Including disposal of radioactive decontamination waste at a cost of $167/m³.

32. Assuming an average dose-reduction factor of one third due to shielding by buildings and ground roughness and one cancer death per 2000 whole-body rem population dose.

33. Assuming that safety concerns resulted in spent fuel being placed in dry storage 30 years earlier otherwise.
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

THE NATIONAL ACADEMIES PRESS
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JA564
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ACKNOWLEDGMENTS

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

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

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible 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.
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NOTE TO READERS

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

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

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

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

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

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

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

The highlights of the report are as follows:

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

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

In the Fiscal Year 2004 Energy and Water Development Conference Report, the U.S. Congress asked the National Academies to provide independent scientific and technical advice on the safety and security 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

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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.
EXECUTIVE SUMMARY

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 independent2 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
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
EXECUTIVE SUMMARY

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.
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 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 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 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. 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, 2001a).

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.
INTRODUCTION AND BACKGROUND

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 4).

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).

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 pools 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 gathered.

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5 Committee on Transportation of Radioactive Waste. See http://national-academies.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, 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 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 (0.8 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. 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 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 radionuclides: Ruthenium-106 (with a 372.6-day half-life), cerium-144 (284.4-day half-life), cesium-137 (30.2-year half-life),

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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.
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.
INTRODUCTION AND BACKGROUND

FIGURE 1.2 Decay-heat power for spent fuel (measured in watts per metric ton 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. 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. 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 discharge.

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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. 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 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.

\footnote{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.}

\footnote{There are 103 operating commercial nuclear power reactors in the United States. Many sites have more than one operating reactor.}
INTRODUCTION AND BACKGROUND

TABLE 1.1 provides a listing of the 30 operating Independent Spent Fuel Storage Installations (ISFSIs) 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). 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

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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

<table>
<thead>
<tr>
<th>Name</th>
<th>Location</th>
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<tbody>
<tr>
<td>Palo Verde</td>
<td>Arizona</td>
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<td>Arkansas Nuclear One</td>
<td>Arkansas</td>
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<td>Rancho Seco</td>
<td>California</td>
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<td>San Onofre</td>
<td>California</td>
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<tr>
<td>Diablo Canyon</td>
<td>California</td>
</tr>
<tr>
<td>Fort St. Vrain ¹</td>
<td>Colorado</td>
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<tr>
<td>Edwin L. Hatch</td>
<td>Georgia</td>
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<td>Point Beach</td>
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Notes:

¹The Fort St. Vrain ISFSI stores fuel from a commercial gas-cooled reactor. The facility is operated by the Department of Energy.

²The DOE-INL facility stores fuel from the Three-Mile Island Unit 2 reactor. The facility is operated by the Department of Energy.

³The G.E. Morris ISFSI is a wet storage facility.

Sources: Data from the USNRC (2004).
INTRODUCTION AND BACKGROUND

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-coolant 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 additional 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).
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. 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.

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. 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:

\[
\text{Risk}_{\text{airliner attack}} = \text{Probability}_{\text{airliner attack}} \times \text{Consequences}_{\text{airliner attack}}
\]

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:

\[
\text{Risk}_{\text{total}} = \text{Risk}_{\text{airliner attack}} + \text{Risk}_{\text{truck bomb attack}} + \text{Risk}_{\text{armed assault attack}}
\]

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 injuries, 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. 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.

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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-Qaeda 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. 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.

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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 involving 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. 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

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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_jp_manual.asp.
TERRORIST ATTACKS ON SPENT FUEL STORAGE

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, 2001a) and Alvarez et al. (2003a), on the other hand, describe maximum-credible to worst-case releases.

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 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.

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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. 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 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

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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.
Previous studies on aircraft crash impacts (Droste et al., 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).\(^\text{10}\)
- 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. 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

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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 plants13 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, 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 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:

\[
\text{Reaction in air: } \text{Zr} + \text{O}_2 \rightarrow \text{ZrO}_2 \quad \text{heat released} = 1.2 \times 10^7 \text{ joules/kilogram} \\
\text{Reaction in steam: } \text{Zr} + 2\text{H}_2\text{O} \rightarrow \text{ZrO}_2 + 2\text{H}_2 \quad \text{heat released} = 5.8 \times 10^6 \text{ joules/kilogram}
\]

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 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. In some reactor designs, the spent fuel pools are contained within the reactor building, which is typically constructed of about 2 feet of reinforced concrete (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 tornado-borne 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...

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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.
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
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. 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 light 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 Chernobyl 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 al., 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.\textsuperscript{8}

The committee provides a discussion of the Alvarez et al. (2003a) analysis 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,\textsuperscript{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

\textsuperscript{8} The quote is from a PowerPoint presentation made by Nuclear Regulatory Commission staff to the committee at one of its meetings.

\textsuperscript{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. 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 were designed primarily with safety, not security, in mind. 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. 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 pool-boiling event described above could result in the release of small amounts of radionuclides that are normally present in pool water. 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 lead to additional ventilation.

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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. 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-

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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.
scale 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) 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, 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

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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 3.4: 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. 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.

\^ The global-response model runs took between 10 and 12 days on the personal computers used in the Sandia analyses.
performed by Sandia.\(^\text{19}\)

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. 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.

• 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

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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 had not been 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.
SPENT FUEL POOL STORAGE

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.
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 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. 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 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.
The terms in the second bullet indicate how spent fuel is loaded into the casks. In bare-fuel\textsuperscript{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 $\frac{1}{2}$-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

\textsuperscript{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). 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, 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. 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.

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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.
4.2 EVALUATION OF POTENTIAL RISKS OF DRY CASK STORAGE

Dry casks were designed to ensure safe storage of spent fuel,\(^\text{10}\) 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.\(^\text{11}\)

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.\textsuperscript{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.

\subsection{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.

\textsuperscript{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.
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. 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.

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.\(^\text{15}\)
- 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.\(^\text{16}\) 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. 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>
<thead>
<tr>
<th>Cask design</th>
<th>License holder</th>
<th>Fuel type</th>
<th>Construction</th>
<th>Closure system</th>
<th>Number of casks used</th>
<th>Number of sites</th>
<th>Number of casks on order</th>
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</thead>
<tbody>
<tr>
<td>CASTOR V/21</td>
<td>GNSI (General Bare-fuel, Nuclear Systems, Inc.)</td>
<td>BWR</td>
<td>Ductile cast iron</td>
<td>Primary and secondary lids (44 bolts)</td>
<td>25 loaded (Surry); 0 purchased</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>CASTOR X/33</td>
<td>GNS (Gesellschaft für Nukleare Service mbH)</td>
<td>BWR</td>
<td>Ductile cast iron</td>
<td>Primary and secondary lids (70 cup screws)</td>
<td>1 loaded (Surry); 0 purchased</td>
<td>0</td>
<td>0</td>
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<tr>
<td>NAC S/T</td>
<td>NAC International</td>
<td>PWR</td>
<td>Inner and outer stainless steel shells</td>
<td>One shield lid and two sealing lids, all bolted</td>
<td>2 loaded (Surry); 0 purchased</td>
<td>0</td>
<td>0</td>
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<td>MC-10</td>
<td>Westinghouse</td>
<td>BWR</td>
<td>Carbon steel</td>
<td>Canister lid welded cask lid (48 bolts)</td>
<td>61 loaded (4 sites); 22 purchased</td>
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<td>0</td>
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<tr>
<td>TN-32, TN-40</td>
<td>Transnuclear Inc</td>
<td>BWR</td>
<td>Canister based, dual-purpose</td>
<td>Canister lid, welded cask lid (4 bolts)</td>
<td>24 loaded (Peach Bottom); 7 loaded (Big Rock Point; 0 purchased</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>TN-68</td>
<td>Transnuclear Inc</td>
<td>BWR</td>
<td>Canister based, dual-purpose</td>
<td>Canister lid, welded cask lid (4 bolts)</td>
<td>7 loaded (7 sites); 177 on order</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Fuel Solution</td>
<td>BNFL Fuel Solutions</td>
<td>BWR</td>
<td>Canister based, dual-purpose</td>
<td>Canister lid, welded cask lid (4 bolts)</td>
<td>7 loaded (2 sites); 5 on order</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Storage Cask W-150</td>
<td>Holtec International</td>
<td>BWR</td>
<td>Reinforced concrete and neutron absorb polymer</td>
<td>Canister lid, welded cask lid (4 bolts)</td>
<td>58 loaded (7 sites); 177 on order</td>
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<td>0</td>
</tr>
<tr>
<td>Hi-STORM 100</td>
<td>Holtec International</td>
<td>BWR</td>
<td>Reinforced concrete and neutron absorb polymer</td>
<td>Canister lid, welded cask lid (4 bolts)</td>
<td>7 loaded (2 sites); 5 on order</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Canister Manufacturer</td>
<td>Canister Supplier</td>
<td>Canister Type</td>
<td>PWR/BWR</td>
<td>Reinforced Concrete Details</td>
<td>Storage Details</td>
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<td>VSC-24</td>
<td>BNFL Fuel Solutions</td>
<td>Canister-based, storage-only</td>
<td>PWR</td>
<td>Reinforced concrete with inner steel shell</td>
<td>Canister lid, welded cask lid (6 bolts)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NAC-MPC</td>
<td>NAC International</td>
<td>Canister-based, dual-purpose</td>
<td>PWR</td>
<td>Metal canister surrounded by storage overpack. Storage overpack consists of an inner steel liner 3.5 in. thick, two rebar cages, and concrete</td>
<td>Canister lid, welded cask lid over a shield plug (6 high-strength bolts)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NAC-UMS</td>
<td>NAC International</td>
<td>Canister-based, dual-purpose</td>
<td>PWR, BWR</td>
<td>Metal canister surrounded by storage overpack. Storage overpack consists of inner steel liner 2.5 in. thick, two rebar cages, and concrete</td>
<td>Canister lid, welded cask lid over a shield plug (6 high-strength bolts)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Holtec MPC 24E/EF</td>
<td>Holtec International</td>
<td>Canister-based, dual-purpose</td>
<td>PWR, BWR</td>
<td>Metal canister surrounded by storage overpack. Storage overpack consists of inner and outer steel liners, a double-rebar cage, and concrete</td>
<td>Canister lid, welded cask lid, shield plug plus 48 bolts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NUHOMS 24P, 52B, 61BT, 24PT1, 24PT2, 32PT</td>
<td>Transnuclear Inc.</td>
<td>Canister-based, dual-purpose</td>
<td>PWR, BWR</td>
<td>Horizontal reinforced concrete storage module with shielded canister</td>
<td>Canister lid, welded storage module lid, reinforced concrete</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

58 loaded (3 sites); 4 purchased
Canister lid, welded cask lid over a shield plug (6 high-strength bolts)
21 loaded (Yankee Rowe and CT Yankee); 59 purchased
80 loaded (2 sites); 165 purchased
34 loaded (Trojan); 0 purchased
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 HB.
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. 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 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

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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.
REFERENCES


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REFERENCES


