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

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

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

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

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

INTRODUCTION

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

No such event has occurred thus far. However, the consequences would be so severe that alternatives to dense-pack storage must be examined—especially

in the context of heightened concerns that terrorists could find nuclear facilities attractive targets.

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

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

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

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

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

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

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

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

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

In outline, we describe:

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

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

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

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

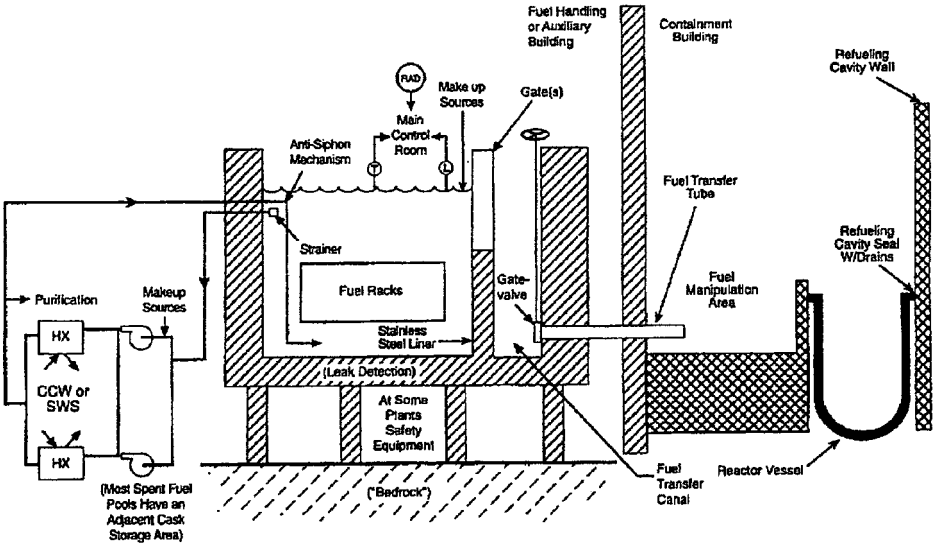


Figure 2a: Layout of spent fuel pool and transfer system for pressurized water reactors (*Source:* NUREG-1275, 1997).

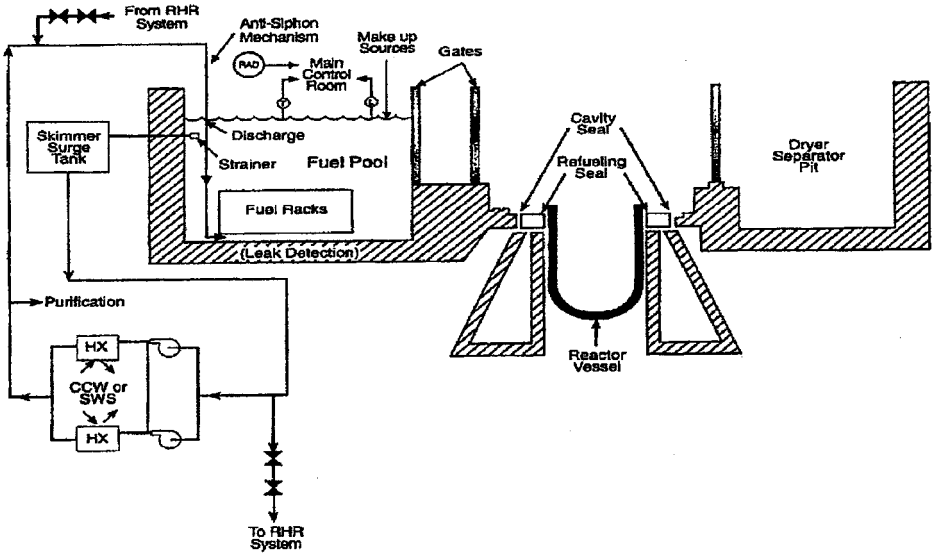


Figure 2b: Layout of spent fuel pool and transfer system for boiling water reactors (*Source:* NUREG-1275, 1997).

THE HAZARD FROM CESIUM-137 RELEASES

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

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

Inventories of Cs-137 in Spent-Fuel Storage Pools

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

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

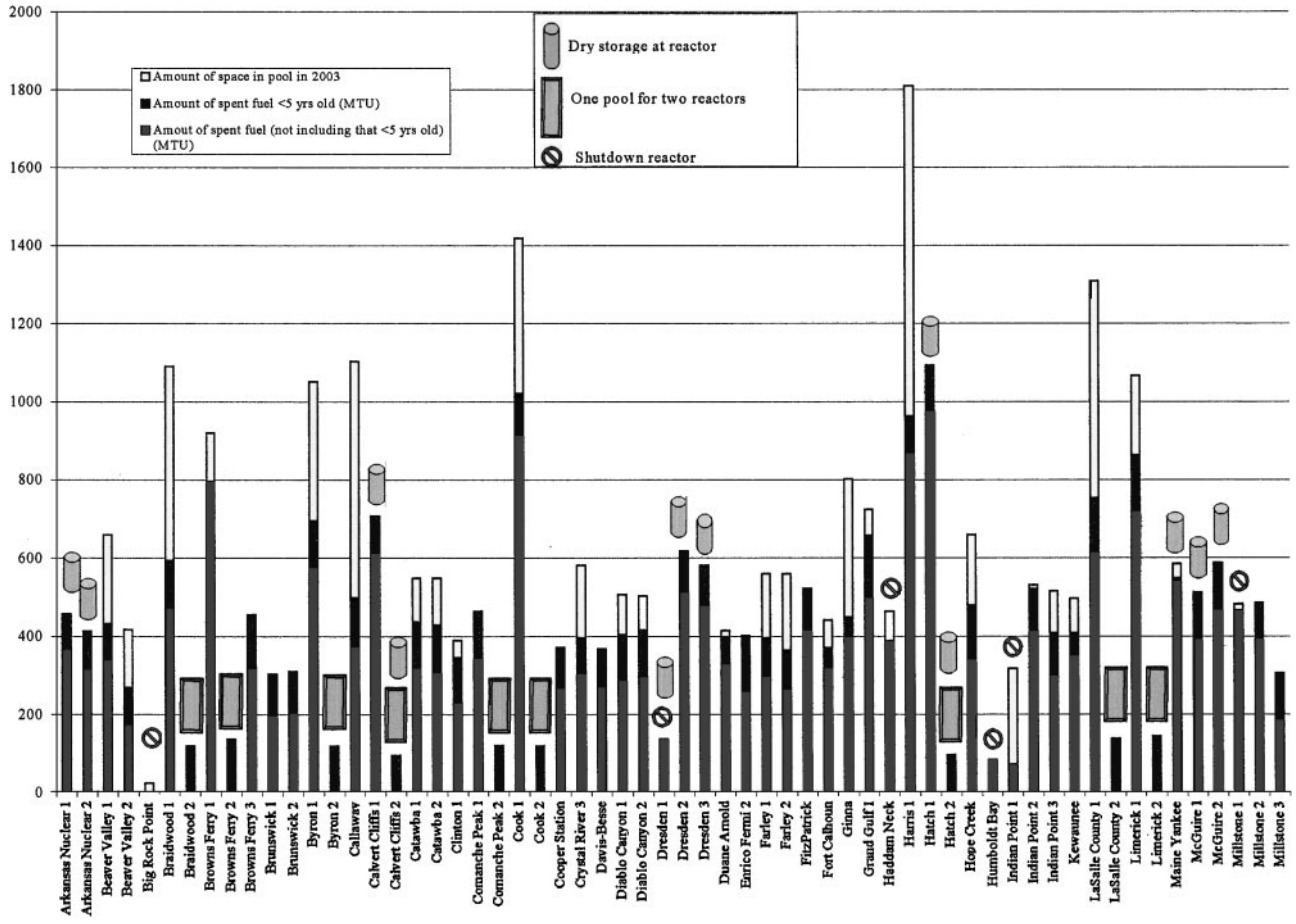


Figure 3: Estimated 2003 spent fuel inventory at each U.S. spent-fuel pool, measured in metric tons of contained uranium. Height of bar indicates total licensed capacity (1998, with some updates). Shading indicates estimated tonnage of spent fuel in pool as of 2003. Dark shading indicates the estimated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

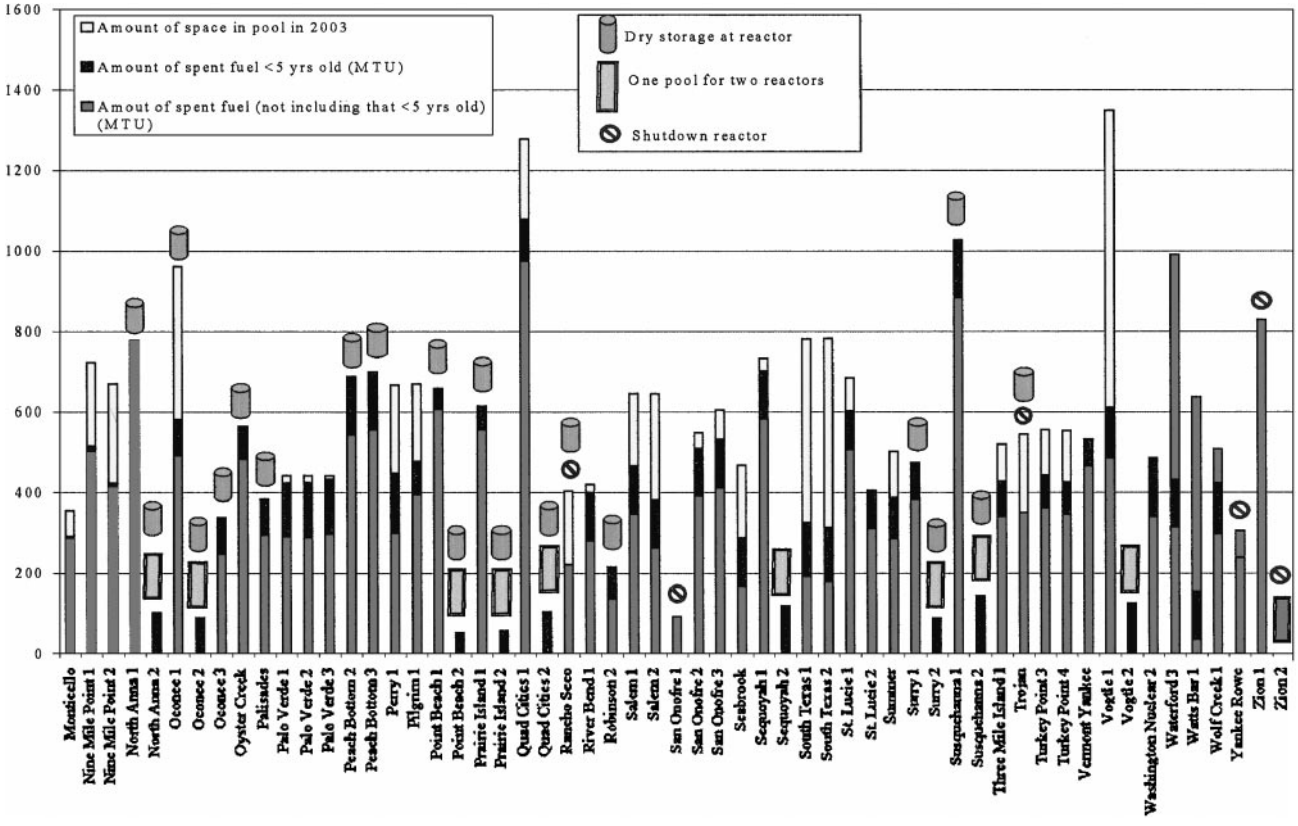


Figure 3: (Continued)

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

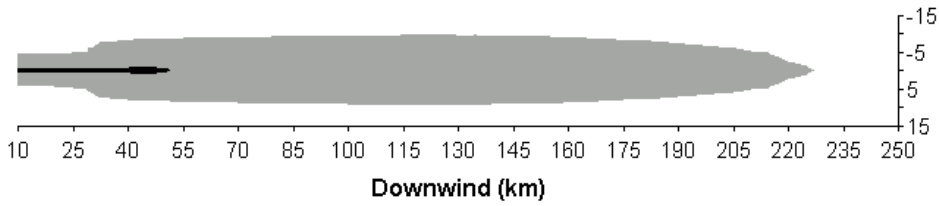
Release	$>$100 Ci/km^2	$>$1000 Ci/km^2
Chernobyl (2 MCi, hot, multi-directional)	$\approx$700	
3.5 MCi (MACCS2)	3,500	200
3.5 MCi (wedge model)	6,000	180
35 MCi (MACCS2)	45,000	2,500
35 MCi (wedge model)	50,000	6,000

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

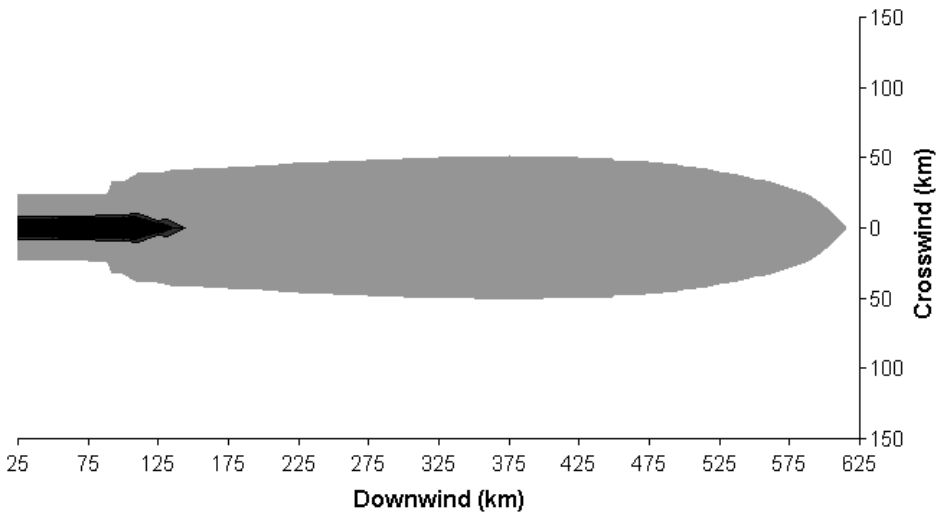
It will be seen in Table 1 that, for the 3.5 MCi release, the area calculated as contaminated above 100 Ci/km^2 are 5–9 times larger than the area contaminated to this level by the 2 MCi release from the Chernobyl accident. The reasons are that, at Chernobyl: 1) much of the Cs-137 was lifted to heights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

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

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



(a)



(b)

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

SCENARIOS FOR A LOSS OF SPENT-FUEL-POOL WATER

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

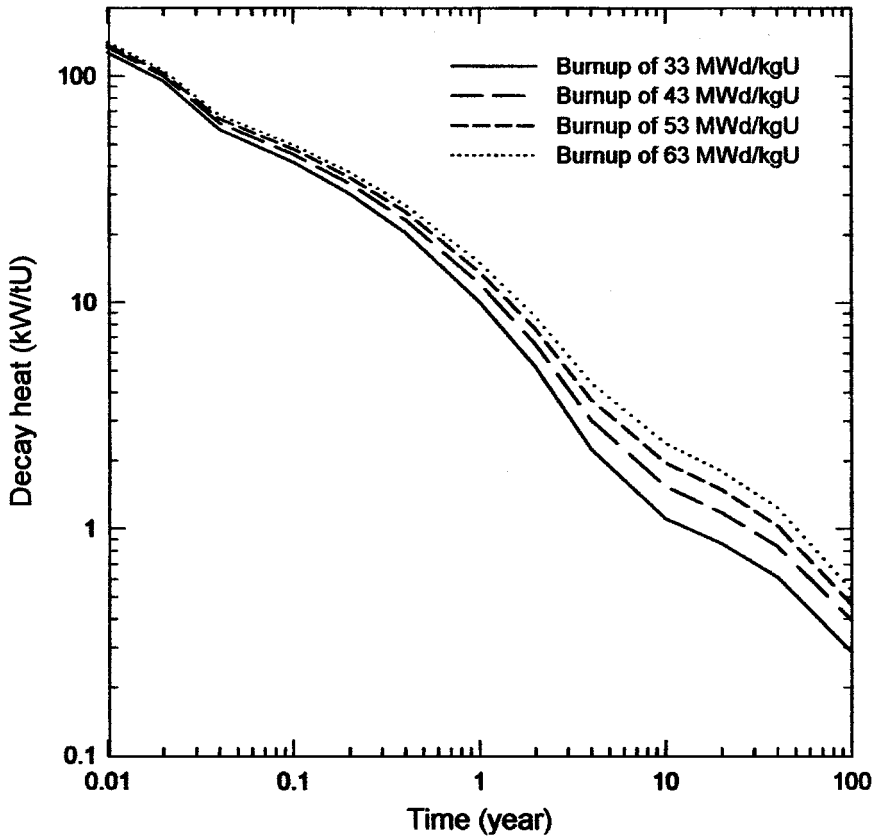


Figure 5: Decay heat as a function of time from 0.01 years (about 4 days) to 100 years for spent-fuel burnups of 33, 43, 53 and 63 MWd/kgU. The lowest burnup was typical for the 1970s. Current burnups are around 50 MWd/kgU (*Source:* authors[38]).

Boil Off

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

In case of a loss of cooling, the time it would take for a spent-fuel pool to boil down to near the top of the spent fuel would be more than 10 days if the most recent spent-fuel discharge had been a year before. If the entire core of a reactor had been unloaded into the spent fuel pool only a few days after shutdown, the time could be as short as a day.[31] Early transfer of spent fuel into

storage pools has become common as reactor operators have reduced shutdown periods. Operators often transfer the entire core to the pool in order to expedite refueling or to facilitate inspection of the internals of the reactor pressure vessel and identification and replacement of fuel rods leaking fission products.[32]

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

Drainage

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

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

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

Fire

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

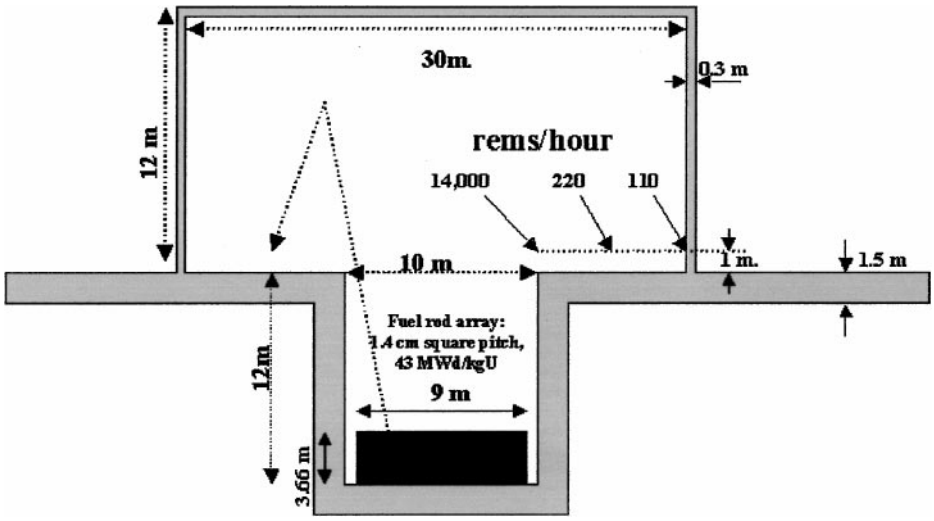


Figure 6: Calculated radiation levels from a drained spent-fuel pool one meter above the level of the floor of a simplified cylindrically-symmetric spent-fuel-pool building. Even out of direct sight of the spent fuel, the radiation dose rates from gamma rays scattered by the air, roof and walls are over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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

"Dense packing"

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

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

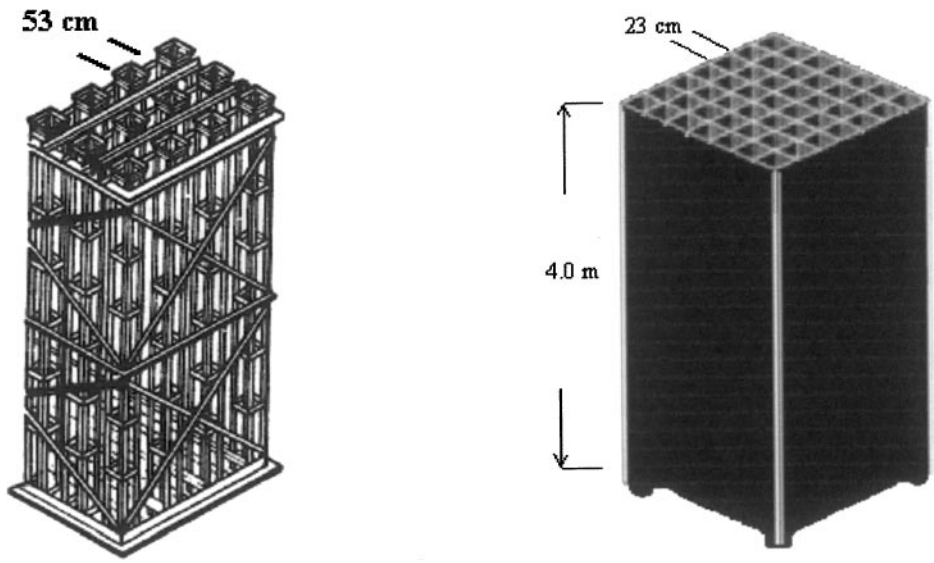


Figure 7: Open and dense-pack PWR spent-fuel racks (*Sources:* Left: NUREG/CR-0649, SAND77-1371, 1979; right: authors).

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

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

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

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

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

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

Thermal Conduction

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

Infrared Radiation

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

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

Steam Cooling

Steam cooling could be effective as long as the water level covers more than about the bottom quarter of the spent fuel. Below that level, the rate of steam generation by the fuel will depend increasingly on the rate of heat transfer

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

Convective Air Cooling

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

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

This is consistent with results obtained by more exact numerical calculations that take into account friction losses in the down-comer and the heating of the air in the building above the spent-fuel pool.[63] The 1979 Sandia study obtained similar results. It also found that, in contrast to the situation with

dense-pack storage, with open-frame storage and a spacing between fuel assemblies of 53 cm (i.e., a density approximately one fifth that of dense-packed fuels), convective air cooling in a well-ventilated spent-fuel storage building (see below) could maintain spent fuel placed into the spent-fuel pool safely below its cladding failure temperature as soon as 5 days after reactor shutdown.[64] These important conclusions should be confirmed experimentally with, for example, electrically heated fuel rods.[65]

Spread of Fires from Hot to Colder Fuel

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

The report notes, however, that its model

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

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

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

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

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

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

Below, we discuss more specifically initiatives to:

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

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

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

Regulatory

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

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

Operational

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

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

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

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

pressure vessel and the first isolation valve on that pipe—or on the isolation valve itself.[76]

Design

Go to Open-Frame Storage

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

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

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

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

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

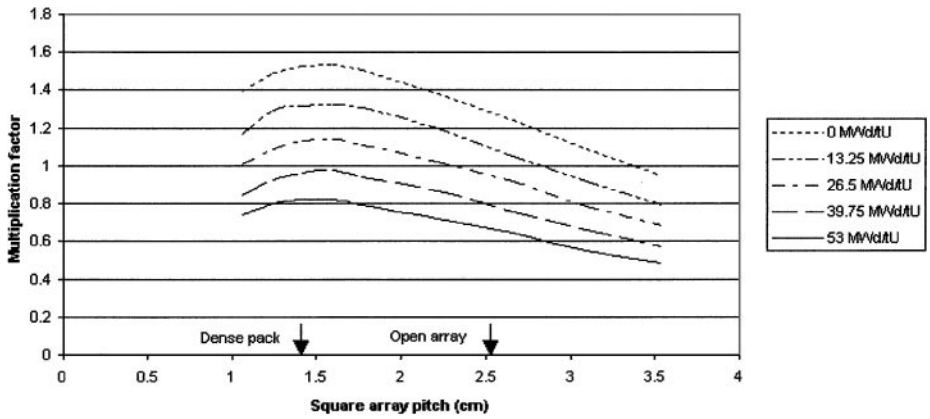


Figure 8: Neutron multiplication as a function of array pitch in an infinite square array of 4.4% enriched fuel rods with a design burnup of 53 MWd/kgU for 0, 25, 50, 75 and 100% irradiation (*Source:* authors).

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

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

Provide for Emergency Ventilation of Spent-Fuel Buildings

The standard forced air exchange rate for a spent-fuel-storage building is two air changes per hour.[81] Consider a building with an air volume V and an air exchange rate of n volumes of external air per hour. If the spent fuel generates heat at a rate P, the air temperature rise will be $\Delta T = 3600P/(nV\rho c_p)$ where ρ is the density of the air entering the building (about 1 kg/m^3) and c_p is the

heat capacity of the air per kg at constant pressure [(about 1000 joules/(kg-°C)]. Therefore, $\Delta T \sim 3.6P/(nV)$. Consider a case where the spent-fuel pool contains 80 tons of freshly-discharged fuel generating 100 kWt/tU of decay heat (i.e., P = 8 MWt) and where V = 10,000 cubic meters (e.g., a building roughly 30 meters square and 10 meters tall). For this case, $\Delta T \sim 2900/n°C$. To bring ΔT down to 100°C would require about 30 air exchanges per hour.

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

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

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

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

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

Install Emergency Water Sprays

The Sandia report also proposed that a sprinkler system be installed.[83] For 80 tons of spent fuel generating 100 kWt/MTU, the amount of water required if it were all evaporated would be about 3 liters per second. Such a flow could easily

be managed in a sprinkler system with modest-sized pipes.[84] The sprinkler system should be designed with an assured supply of water and to be robust and protected from falling debris. It should also be remotely operated, since the radiation level from uncovered fuel would make access to and work in a spent-fuel building difficult to impossible—especially if the building were damaged. The hottest fuel should be stored in areas where spray would be the heaviest, even if the building collapses on top of the pool (e.g., along the sides of the pool). The spray would need to reach all of the spent fuel in the pool, however—especially in scenarios where the spray water accumulated at the bottom of the pool and blocked air flow into the dense-pack racks.

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

Make Preparations for Emergency Repairs of Holes

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

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

Armor Exposed Outside Walls and Bottoms Against Projectiles

The water and fuel in the pool provide an effective shield against penetration of the pool wall and floor from the inside. It should be possible to prevent penetration by shaped charges from the outside with a stand-off wall about 3 meters away that would cause the jet of liquid metal formed by the shaped charge to expand and become much less penetrating before it struck the pool wall. In the case of the turbine shaft, Pennington's analysis for dry casks suggests that it

also might be possible to absorb the shaft's energy with a thick sheet of steel that is supported in a way that allows it to stretch elastically and absorb the projectile's kinetic energy (see below).

REDUCING THE INVENTORY OF SPENT-FUEL POOLS

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

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

SAFETY OF DRY-CASK STORAGE

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

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

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

change under our proposal, it is important to examine the safety of dry-cask storage as we envisage it being used.

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

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

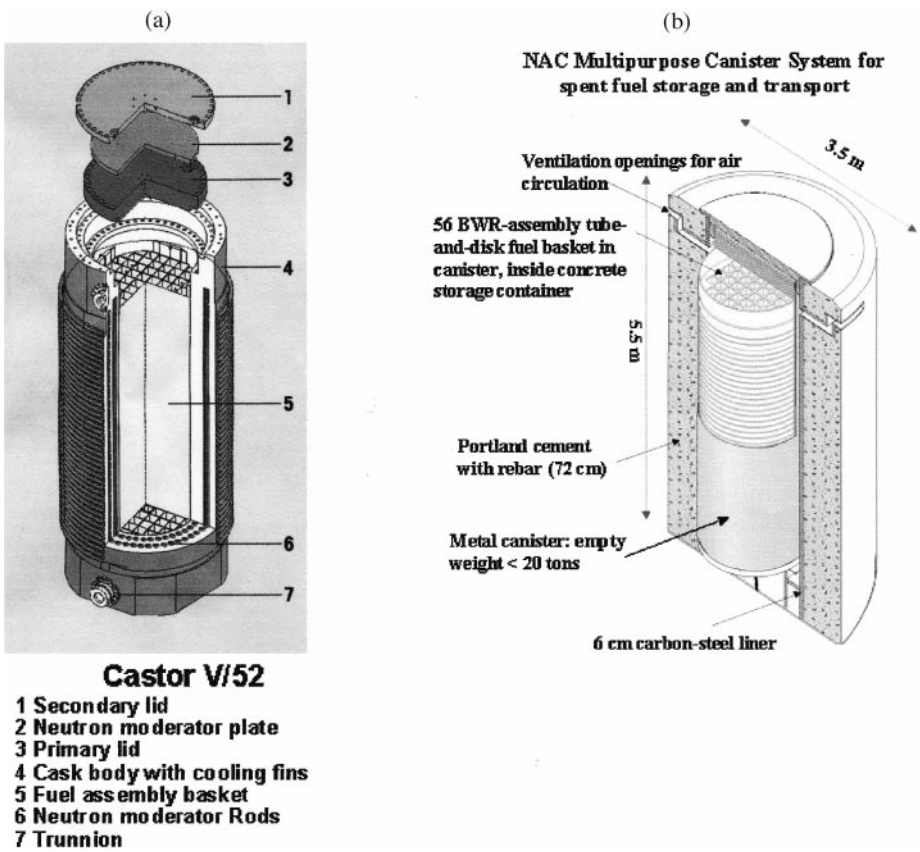


Figure 9: (a) Thick-walled cask[103] and (b) Cask with overpack.[104] (*Sources:* GNB and NAC).

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

Shaped-Charge Missile

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

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

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

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

Turbine Spindle

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

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

Fire

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

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

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

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

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

Cask Availability

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

Dry-Storage Costs

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

equivalent to 30 to 60 percent of the federal charge for the ultimate disposition of the spent fuel (see below).

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

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

Licensing Issues

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

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

Finally, some reactor operators have expressed concern that the NRC does not currently have sufficient manpower to accelerate the process of licensing

on-site dry storage. However, almost all sites will have to license dry storage in the timeframe considered here in any case.

Who Will Pay?

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

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

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

An alternative approach would be to create an additional user fee similar to that which flows into the NWPA fund. A fee of 0.1 cents per nuclear kWh would generate an additional $750 million per year that could in 5 to 10 years

pay the $3.7 to 7 billion cost estimated above to transfer 35,000 tons of spent fuel into dry, hardened, on-site storage. Such a fee would, however, be opposed by the nuclear-plant operators.

SUMMARY

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

Improvements

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

Limitations

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

Table 2: Summary of proposals.

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

Finally, all of our proposals require further detailed analysis and some would involve risk tradeoffs that also would have to be further analyzed. Ideally, these analyses could be embedded in an open process in which both analysts and policy makers can be held accountable. This process would have to be designed

to balance the need for democratic debate with the need to keep from general distribution information that might facilitate nuclear terrorism. We believe that our study shows that such a balance can be achieved.

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NOTES AND REFERENCES

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

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

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

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

5. *Ibid.*

6. *Ibid.*

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

the same as a spent-fuel cask and its kinetic energy at 240 m/sec is about 10 times greater.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

P_L may be approximated as the sum of a loss term due to the constriction of the air passing through the base-plate hole and surface friction within the fuel assembly, $\int_0^L P_L dz = K_0\rho_0(v_0)^2 + \int_0^L f\rho v^2 dz/(2D_H)$. Here $K_0 = 2(1-x)/x$, $x = (A_h/A_f)^2$, A_h is the area of the hole in the base-plate and $A_f = S^2 - 264\ \pi(D/2)^2$ is the cross-sectional area of the air flow inside the box around the fuel assembly. (S = 0.225 m is the inside width of the box and D = 0.0095 m is the outside fuel-rod diameter). For a dense-pack arrangement with a 5 inch [13 cm] hole in the base-plate, $x \approx 0.15$ and $K_0 \approx 11.3$. In the second pressure-loss term, L = 4m is the height of the fuel assembly, f is the friction factor, $D_H = 4\ A_f/P_w$ is the "hydraulic diameter" of the channel, and $P_w = 4S + 264\ \pi D$ is the total perimeter

of all the surfaces in the cross-section (*Users' Manual for the Computer Code SHARP*, pp. 4–7, 4–16). For the fuel assembly in our example, $D_H \approx 0.015$ m. The friction factor may be written as $f = C/(Re)^n$, where $Re = \rho v\ D_H/\mu$ is the Reynolds number, and μ is the viscosity of air (31×10^{-6} pascal-seconds at 600°K). The exponent $n = 1$ for laminar flow ($Re < 2100$), which will be seen to be the case in the fuel assembly. The coefficient $C \sim 100$ within the fuel assembly in the approximation where all rods are treated as interior rods (*ibid.*, p. 4–7, 4–16/17). Thus, $\int_0^L P_L dz = K_0\rho_0(v_0)^2 + \{C\mu/[2(D_H)^2]\} \int_0^L v dz \approx K_0\rho_0(v_0)^2 + 55v_0$ joules/m^3, where we have approximated $\int_0^L v dz \approx 2Lv_0$, where v_0 is the entrance velocity to the air at the base of the fuel assembly. If we add this friction pressure term to the equation at the end of the paragraph above, we get $14.4(v_0)^2 + 55\ v_0 = 20$ joules/m^3 or $v_0 \approx 0.33$ m/sec.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

82. *Ibid.*

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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