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FROM: DUE: 07/21/03 EDO CONTROL: G20030389
DOC DT: 06/30/03
FINAL REPLY:

Elizabeth H. Sullivan
Andre P. Martecchini
John J. Tuffy
Town of Duxbury, Massachusetts

TO:

Chairman Diaz

FOR SIGNATURE OF : ** PRI ** CRC NO: 03-0434

Chairman Diaz

DESC:

Dry Cask Storage at Pilgrim Nuclear Power Station

ROUTING:

Travers
Paperiello
Kane
Norry
Dean
Burns/Cyr
Miller, RI
Collins, NRR

DATE: 07/09/03

ASSIGNED TO: NMSS

CONTACT: Virgilio

SPECIAL INSTRUCTIONS OR REMARKS:

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EDO --G20030389

Town of Duxbury, Massachusetts

Board of Selectmen
Elizabeth H. Sullivan, Chair
John J. Tuffy, Vice-Chair
Andre P. Martecchini, Clerk

Town Manager
Rocco J. Longo

June 30, 2003

Chairman Nils Diaz
U.S. Nuclear Regulatory Commission
One White Flint North
11555 Rockville Pike
Rockville, Maryland 20852-2738

Re: Dry Cask Storage at Pilgrim Nuclear Power Station

To the Chairman and Commissioners of the U.S. NRC:

As a neighbor to the Pilgrim Nuclear Power Station, the citizens of Duxbury are concerned about potential threats to the Pilgrim Nuclear Power Station – especially its vulnerability to terrorist attack and the catastrophic consequences of a spent fuel pool accident.

Duxbury citizens expressed their concern by approving the following resolution at a Special Town Meeting on May 5, 2003:

> … resolves to request our local, state and federal officials to support, as an interim measure to better protect the health and well being of the citizens of the Town of Duxbury, the placement of all but recently unloaded spent nuclear fuel at the Pilgrim Nuclear Power Station in secured dry cask storage, which is passively safe, hardened, and dispersed and therefore better able to reduce the risk of radioactive release due to attack or accident, and further to require that recently unloaded fuel be placed in a low-density storage pool.

We believe that Yucca Mountain, the proposed federal repository for radioactive fuel rods, will not solve the nuclear spent fuel problem for <u>many</u> years. The Government Accounting Office has stated that Yucca will not open before 2015, and that it could take 30-40 years to ship the nation's current waste. Litigation to prevent Yucca from ever opening is pending. And if and when Yucca does open, it is our understanding that Entergy could decide to delay the shipment of all or some of the spent fuel from Pilgrim by selling or trading its spot on the national shipping schedule.

The risks raised by Pilgrim's spent fuel storage will be increased if their operating license is extended for 20 more years, allowing it to produce substantially more radioactive fuel rods. Entergy officials said to us in public meetings, that in the event the Pilgrim license is extended, dry cask storage technology will be utilized once the spent fuel pool reaches maximum capacity.

For the many years that radioactive spent fuel will remain at Pilgrim, we feel that a safer method of spent fuel storage is required to better protect the citizens of Duxbury, as well as other neighboring communities. Dry cask storage technology is currently available, and is now used at 20 sites in the United States, including some owned by Entergy.

A 1979 study done for the NRC by the Sandia National Laboratory showed that a sudden loss of all the water in a densely-packed pool, even a year after removal from the reactor, would likely heat up to the point where the zircaloy cladding of the rods would burst and catch fire.[1] More recently, NRC's NUREG-1738, 2001 looked at loss of pool water and concluded that a "zirconium fire cannot be dismissed even many years after final reactor shutdown."

A study that appeared in the spring issue of *Science and Global Security*, a publication of Princeton University, concluded that spent fuel pools are particularly vulnerable to terrorist attacks that could generate a pool fire and corresponding contamination of hundreds of square miles around a nuclear plant.[2]

Duxbury's resolution recommends re-equipping spent fuel pools with low-density, open-frame racks and, for longer-term storage, reducing the reliance on the spent fuel pool by utilizing dispersed, hardened, above-ground storage modules.

Until all the spent fuel can be shipped to Yucca Mountain or some other federal repository, we believe dry cask storage will be safer than a densely packed fuel pool for the following reasons.

1. Casks are passive - a pool requires human intervention and operating systems - There is more chance for mechanical or human error.

2. The consequences of a radioactive release from a single dry cask are many times less than a release from the entire spent fuel pool.

3. A fire will result in a densely packed spent fuel pool if cooling water is lost - a low density pool will allow air circulation to keep things cool for awhile giving time to address the problems.

4. Casks, generously spaced apart and protected with earth and gravel berms, will be better protected than those that are closely spaced with no protection which is the current practice at several reactors today. Given the apparent sophistication of terrorist groups, we believe that dispersing and protecting casks is critically important.

We hope that the NRC will give full consideration to the rationale and recommendations contained in our resolution. We would appreciate receiving a response from you regarding our recommendations and your projected action plan.

We also hope that any consideration of extending the license to Pilgrim NPS will require, as one of the key prerequisite requirements, that Pilgrim revert to low-density open-frame racks in its spent fuel pool, and that all but recently removed fuel rods be stored in dispersed, hardened, above-ground dry casks.

We thank you for your attention to this matter, and hope that the NRC will seriously consider the wishes of the citizens of Duxbury in this important public safety issue.

---

[1] Spent Fuel Heat up Following Loss of Water During Storage by Allan S. Benjamin et al. (Sandia National Laboratory, NUREG/CR_0649, SAND77-1371, 1979).

[2] NRC Briefing on The Status of Office of Research (RES) Programs, Performance, And Plans, Rockville, Maryland, Thursday, March 27, 2003, pages 40-44.

Very truly yours,
Selectmen, Town of Duxbury

Elizabeth H. Sullivan
Chairman

Andre P. Martecchini
Selectman

John J. Tuffy
Selectman

Attachments

Article 6, Town of Duxbury Resolution to Decrease Terrorism Risk at Pilgrim Nuclear Power Station - Secured *Dry Cask Storage of Radioactive Fuel - an interim measure to increase Duxbury's safety until Yucca Mountain opens, in 2015 or beyond.*

Article 6, A Safer Way To Store Highly Radioactive Nuclear Fuel At Pilgrim, Rationale prepared for Duxbury Special Town Meeting by Duxbury Nuclear Advisory Committee, May 2003.

Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States, report by Alvarez, Beyea, Janberg, Kang, Lyman, Macfarlane, Thompson, von Hippel.

U.S. NRC Briefing On The Status of Office of Research (RES) Programs, Performance, and Plans, Rockville, Maryland, Thursday, March 27, 2003, pages 40-44.

U.S. NRC: SECY-01-0100, discussion NUREG 1738

March 5, 2003 letter to Dr. Richard Meserve, Chairman, U.S. NRC from Congressman David Price

U.S. NRC, *Locations of Independent Spent Fuel Installations*

U.S. Generating Companies with On-Site Dry Storage Commitments, NEI

Nuclear Waste: *Uncertainties About the Yucca Mountain Repository Project* GAO-02-765T May 23, 2002 Abstract Yucca Mountain Report

TOWN OF DUXBURY, MASSACHUSETTS

OFFICE OF

TOWN CLERK

TELEPHONE
934-1100
ext 150

SPECIAL TOWN MEETING held on May 5,2002 at the T. Waldo Herrick Memorial Gymnasium, Duxbury Middle School, St. George St. at 7:30pm until 11:00pm and recessed to May 6, 2003 at the Duxbury High School Auditorium, St. George St., at 7:30pm and adjourned sine die at 9:10pm.

Article 6-Interium Measure Response to Secured Dry Cask Storage (Non-Binding Resolution)-Moved and seconded that the Town vote to accept the following Resolution:

Resolution to Decrease Terrorism at Pilgrim Nuclear Power Station-Secured Dry Cask Storage of Radioactive Fuel-an interim measure to increase Duxbury's safety until Yucca Mountain opens in 2015 or beyond

Whereas: the citizens of Duxbury recognize that Yucca Mountain, the proposed federal Repository for radioactive fuel rods, will not solve the waste problem for <u>many</u> years;

Whereas: the Government Accounting Office has stated that Yucca will not open before 2015, and that it will take 30-40 years to ship the nation's current waste;

Whereas: litigation to prevent Yucca from ever opening is pending;

Whereas: the Pilgrim Station may decide to delay the shipment of all or some of its rods, exercising its right to sell or trade its spot on the national shipping schedule;

Whereas: the Pilgrim Station is applying to extend its license for another 20 years, allowing it to produce more radioactive fuel rods;

Whereas: the Pilgrim Station must put the radioactive fuel rods in dry casks for eventual shipment to Yucca and therefore can do so now:

Whereas: dry cask storage technology is available---dry casks are now used at 20 sites in the United States;

Whereas: the safety of Duxbury requires a safer storage solution over the next decades than that currently existing.

Therefore: The Town of Duxbury resolves to request the U.S. Nuclear Regulatory Commission to require, and resolves to request, our local, state and federal officials to support, as an interim measure to better protect the health and well being of the citizens of the Town of Duxbury, the placement of all but recently unloaded spent nuclear fuel at the Pilgrim Nuclear Power Station in secured dry cask storage, which is passively safe, hardened, and dispersed and therefore better able to reduce the risk of radioactive release due to attack or accident, and further to require that recently unloaded fuel be placed in a low-density storage pool.
(Citizen's Petition) (Nuclear Advisory Committee)

Motion to move the previous question a 2/3 vote required. Motion declared obtaining the requisite 2/3 vote by moderator.
Motion carried.

A true copy, Attest:

Nancy M. Oates

Nancy M. Oates
Duxbury Town Clerk

ARTICLE 6

A SAFER WAY TO STORE HIGHLY RADIOACTIVE NUCLEAR FUEL AT PILGRIM

Problem

- Human error (accidents) can happen; threat of terrorism is a reality.
- If the radioactive fuel storage pool water is drained - and there are many scenarios by which this can happen (a well placed ball point pen) - there will be a fire and release of high level radioactivity, 10 times worse than Chernobyl.

Solution

Secured dry casks and a low density pool are far safer than a densely packed fuel pool – a safer interim solution until all the rods can be shipped to Yucca or some other federal repository.

Secured Dry Cask Storage is Safer – Why?

1. Casks are passive - a pool is active requiring human intervention, operating systems - many things can go wrong - many targets
2. If there is a problem the consequences of a release from one cask is many times less than a release from the entire pool
3. A densely packed pool will result in fire and release if water is lost - a low density pool will allow air circulation to keep things cool for awhile and time to address the problem.
4. Casks camouflaged with earth and gravel mounds and spaced 60 feet apart (as we suggest) makes more sense post 9-11 than current practice at some reactors and Pilgrim's eventual plan of placing casks 6 feet apart with no camouflage.

What's Wrong with the Opponents Arguments?

Will Yucca Mountain solve the waste problem soon - If we only ask? NO

- Government Accounting Office has stated that Yucca is unlikely to open at 2010. DOE says that it will take 30-40 years to ship the nation's current waste – common sense how much longer than projected has it taken for the Big Dig or any government project to be completed?
- Litigation to prevent Yucca from ever opening is pending; many suits are expected from communities along transportation routes – more delays.
- Pilgrim Station may decide to delay the shipment of all or some of its rods, exercising its right to sell or trade its spot on the national shipping schedule.
- Pilgrim has never stated that they will revert to a safer low density pool as soon as Yucca opens – so we will be left with the same risk.
- Pilgrim Station is applying to extend its license for another 20 years, allowing it to produce more radioactive fuel rods.

Is it unlikely that secured dry cask storage will receive a NRC license? NO

- Dry cask storage is not new technology. It has been used by the industry for about 30 years. At present there are 20 dry cask sites in the US – 15 at sites with nuclear reactors, some owned by Entergy. NEI, the industry lobby, stated that by 2004 about 30 reactors across the nation will move to dry storage. Standard – run of the mill technology - a "routine" licensing situation for the NRC.
- We are asking simply for dry casks licensed and in use today. The only difference is that we want added security measures for those casks - earth and gravel mounds to surround them so that they are not visible "sitting ducks" and spaced further apart - 60 feet instead of 6 feet.

Is it true that our request would require putting the rods in casks twice, once to store on site and again to ship - risking worker and community exposure? NO

- Many casks licensed and used now by the industry are multi-purpose – used for both on-site storage and to transport. Entergy avoids acknowledging this fact.
- Entergy, the nuclear industry and NRC all claim that placing rods in casks is a tested, safe and proven process posing no significant risk.

Is it true that if we get dry casks, the waste might remain permanently? NO

The NRC issues a license for dry cask storage that is valid only for 20 years.

Is cost an important factor? NO

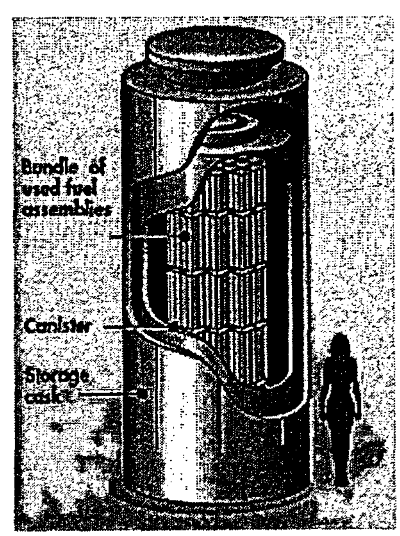
- Pilgrim Station must put the radioactive fuel rods in dry casks for eventual shipment to Yucca anyway and therefore they can do it now – sooner rather than perhaps too late.

- Do we really care about more profits for Entergy Nuclear, the limited liability company that owns Pilgrim or about our community's safety? Public safety is a legitimate cost of doing business.

- Compare the cost of dry cask to the cost of perhaps contaminating an area 3 times the size of Massachusetts.

Typical Dry Cask Storage System

Once the spent fuel has cooled, it is loaded into special canisters. Each canister is designed to hold approximately 2-6 dozen spent fuel assemblies, depending on the type of assembly. Water and air are removed. The canister is filled with inert gas, sealed (welded or bolted shut), and rigorously tested for leaks.



Science and Global Security, 11:1–51, 2003
0892-9882/03 $12.00 + .00
DOI: 10.1080/08929880390214124

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

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

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

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

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

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

INTRODUCTION

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

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

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

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

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

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

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

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

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

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

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

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

In outline, we describe:

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

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

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

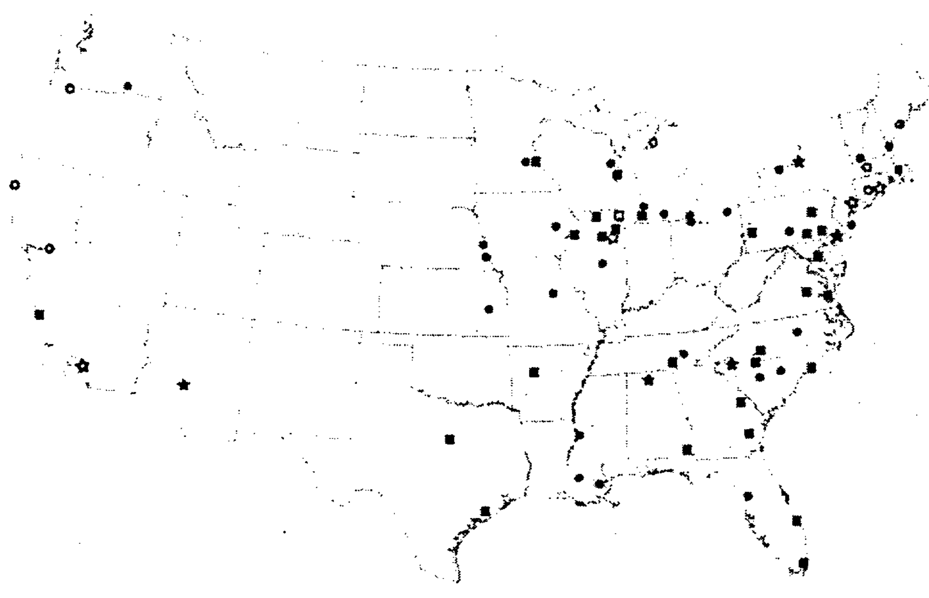

Figure 1: Locations of nuclear power plants in the United States. Circles represent sites with one reactor, squares represent plants with two; and stars represent plants with three. Open symbols represent sites with at least one shutdown reactor. Only the plant in Zion, Illinois has more than one shutdown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

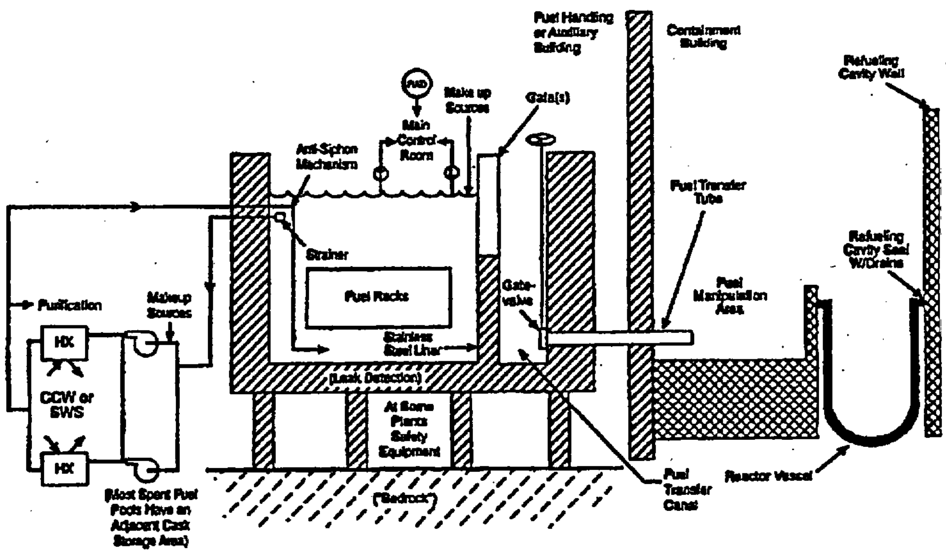

Figure 2a: Layout of spent fuel pool and transfer system for pressurized water reactors (*Source:* NUREG-1275, 1997).

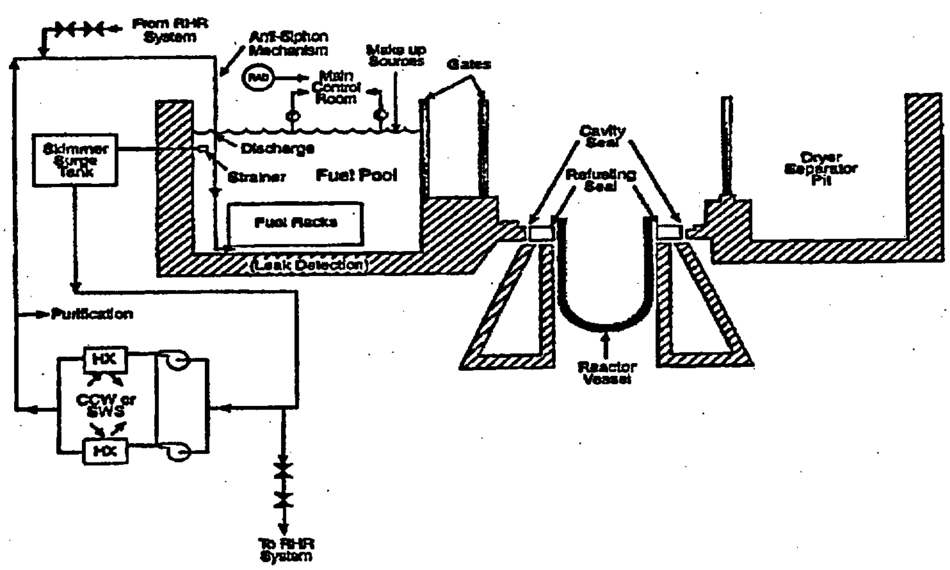

Figure 2b: Layout of spent fuel pool and transfer system for boiling water reactors (*Source:* NUREG-1275, 1997).

THE HAZARD FROM CESIUM-137 RELEASES

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

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

Inventories of Cs-137 in Spent-Fuel Storage Pools

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

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

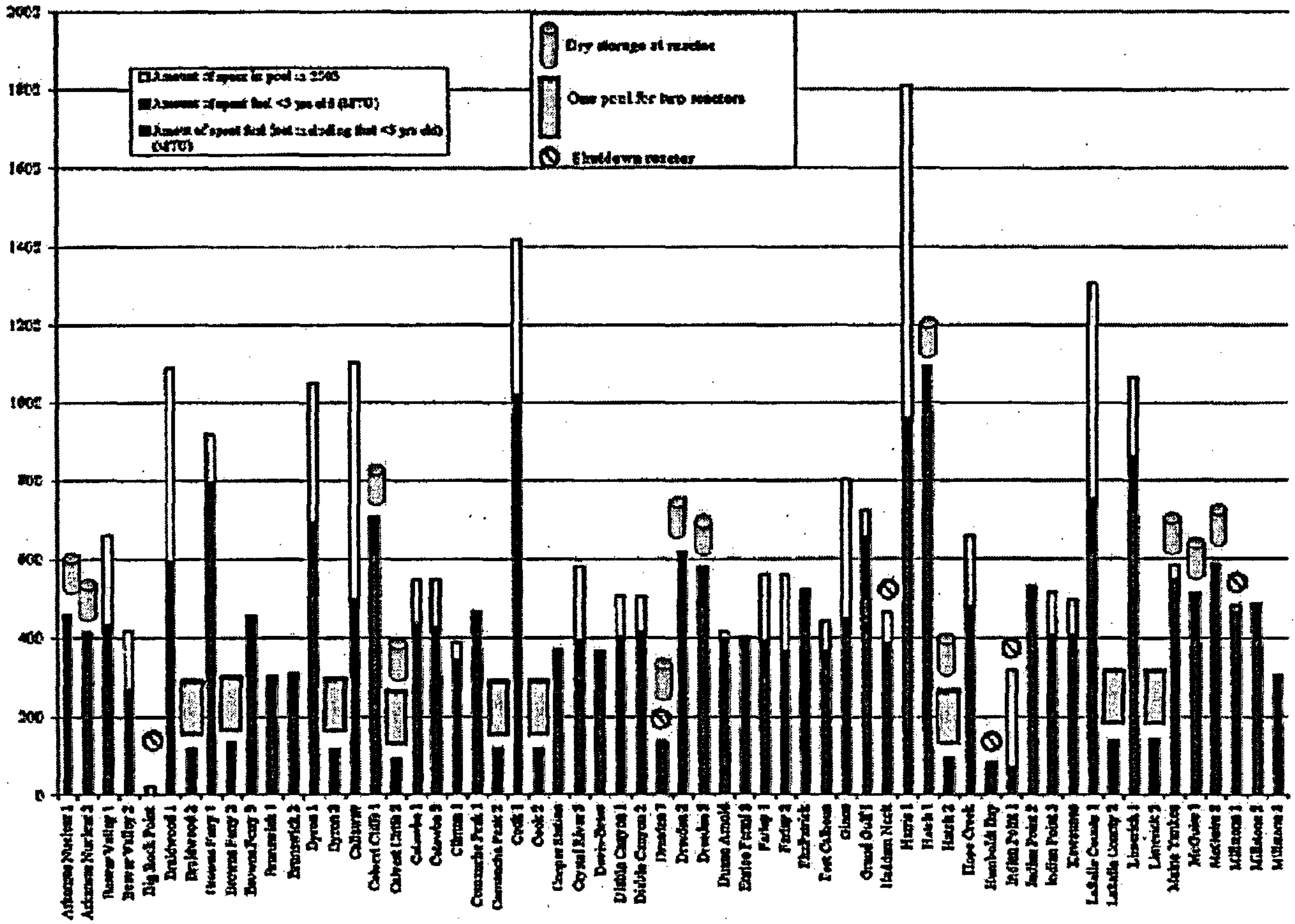

Figure 3: Estimated 2003 spent fuel inventory at each U.S. spent-fuel pool, measured in metric tons of contained uranium. Height of bar indicates total licensed capacity (1998, with some updates). Shading indicates estimated tonnage of spent fuel in pool as of 2003. Dark shading indicates the estimated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

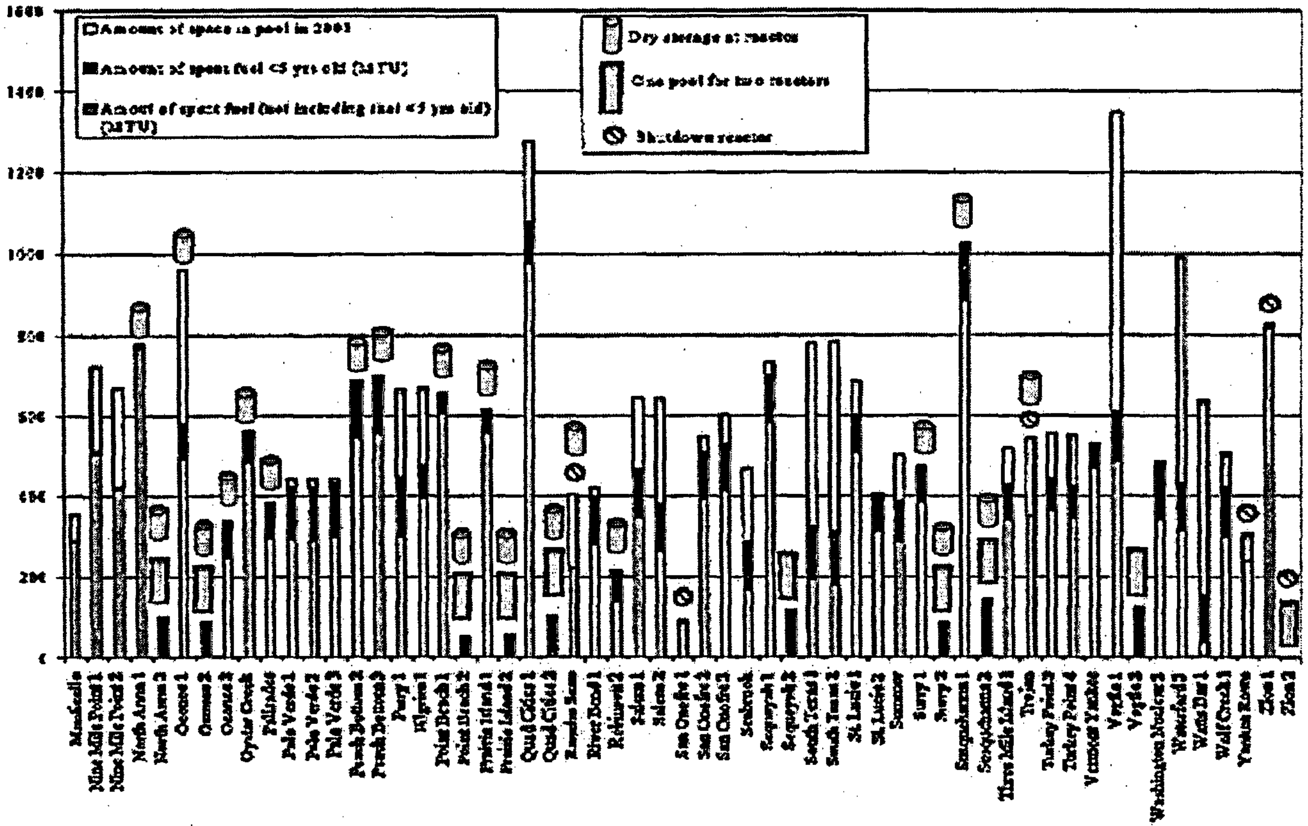

Figure 3: (Continued)

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

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

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

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

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

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

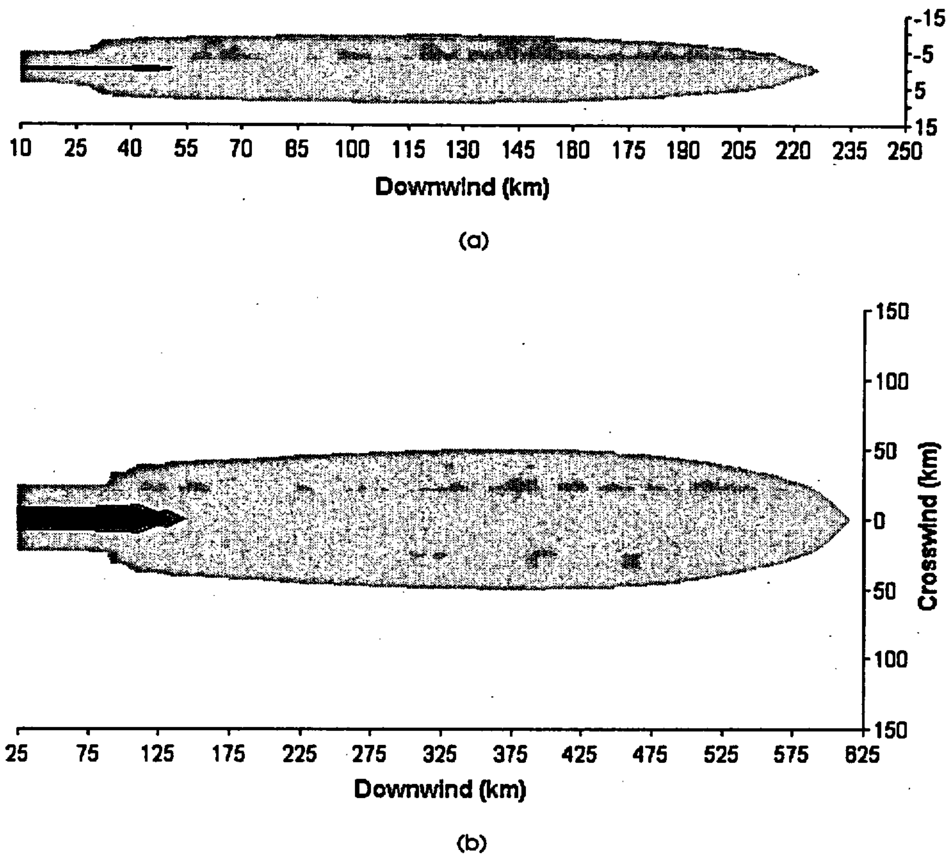

Figure 4: Typical areas contaminated above 100 (shaded) and 1000 (black) Ci/km^2 for release of (a) 3.5 MCi and (b) 35 MCi of ^{137}Cs. The added chance of cancer death for a person living within the shaded area for 10 years is estimated very roughly as between 1 and 10 percent. For someone living within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

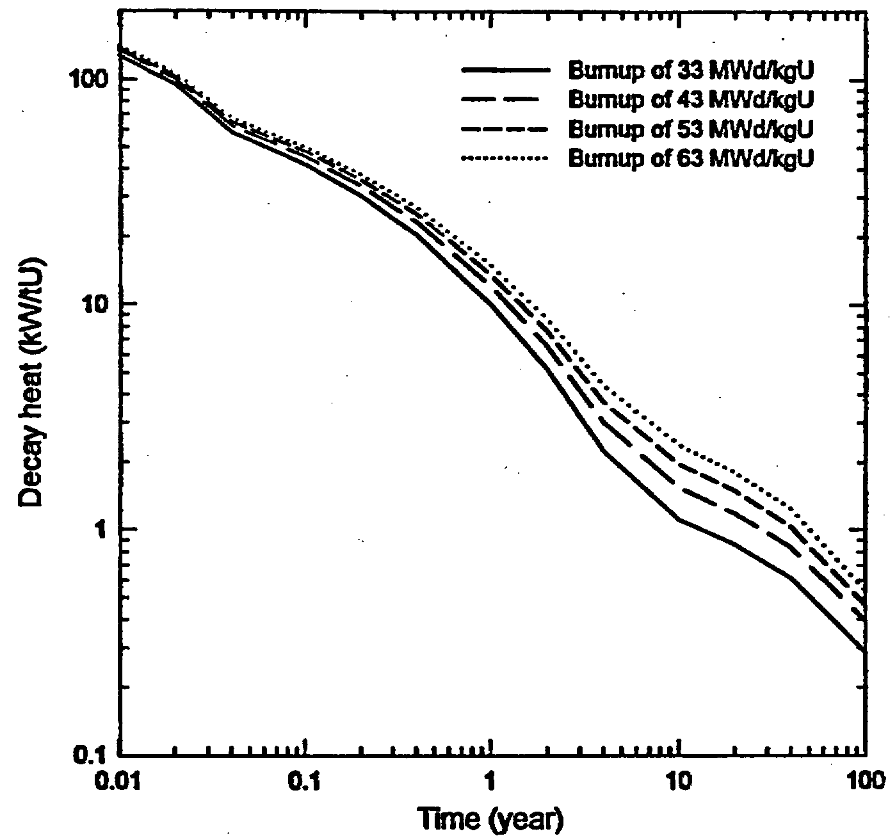

Figure 5: Decay heat as a function of time from 0.01 years (about 4 days) to 100 years for spent-fuel burnups of 33, 43, 53 and 63 MWd/kgU. The lowest burnup was typical for the 1970s. Current burnups are around 50 MWd/kgU (*Source:* authors[38]).

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

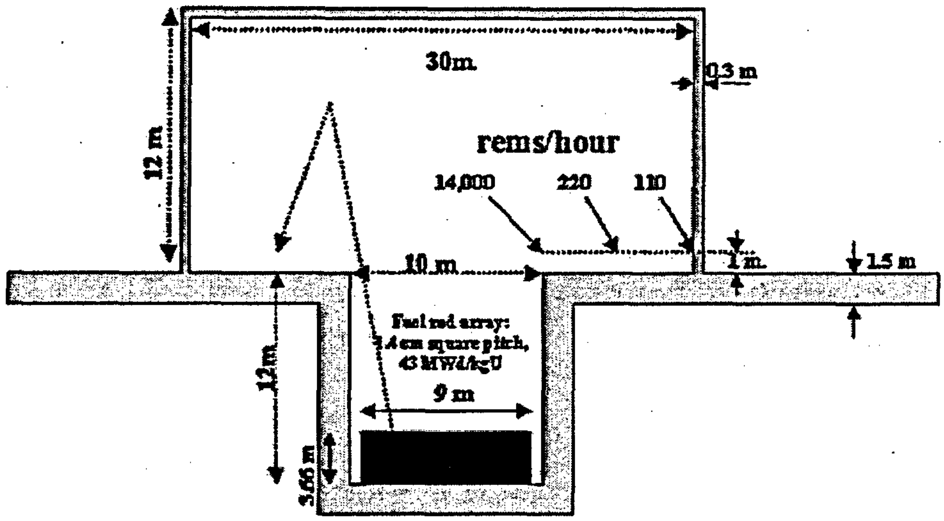

Figure 6: Calculated radiation levels from a drained spent-fuel pool one meter above the level of the floor of a simplified cylindrically-symmetric spent-fuel-pool building. Even out of direct sight of the spent fuel, the radiation dose rates from gamma rays scattered by the air, roof and walls are over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

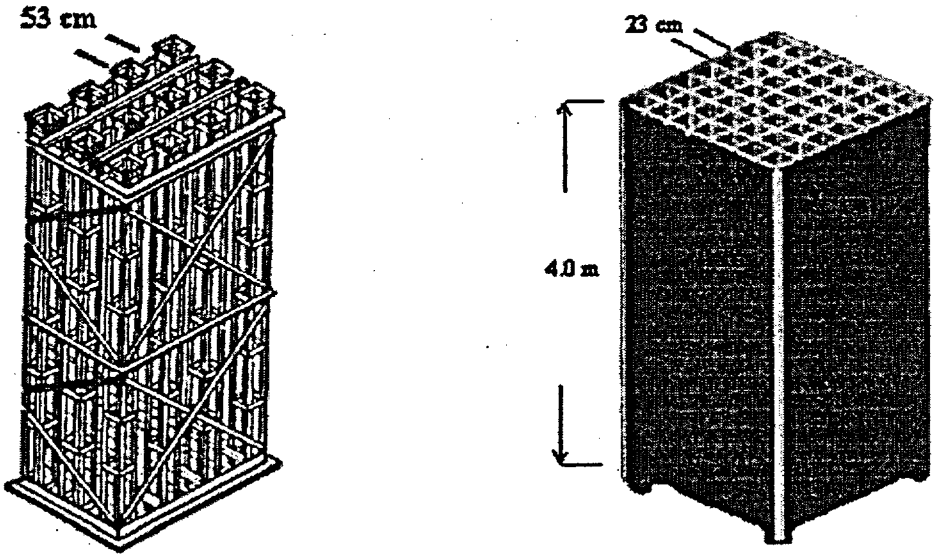

Figure 7: Open and dense-pack PWR spent-fuel racks (*Sources:* Left: NUREG/CR-0649, SAND77-1371, 1979; right: authors).

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) ≈ 3 at the top of the fuel assembly.

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

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

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

Spread of Fires from Hot to Colder Fuel

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

The report notes, however, that its model

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

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

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

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

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

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

Below, we discuss more specifically initiatives to:

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

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

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

Regulatory

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

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

Operational

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

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

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

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

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

Design

Go to Open-Frame Storage

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

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

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

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

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

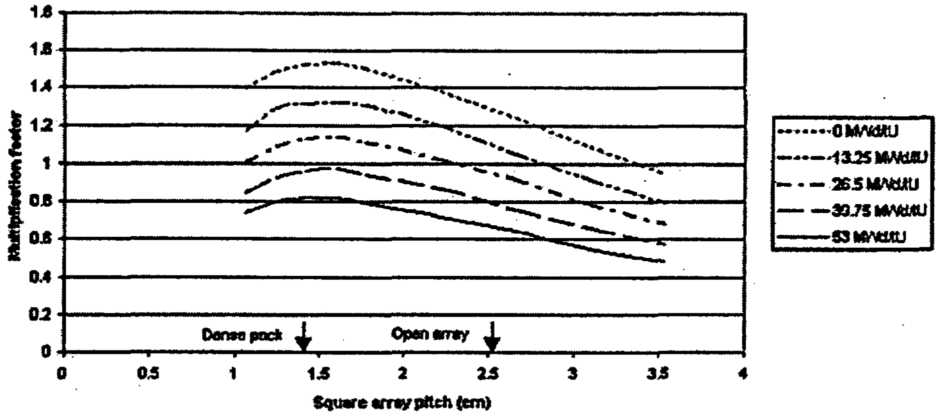

Figure 8: Neutron multiplication as a function of array pitch in an infinite square array of 4.4% enriched fuel rods with a design burnup of 53 MWd/kgU for 0, 25, 50, 75 and 100% irradiation (*Source:* authors).

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

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

Provide for Emergency Ventilation of Spent-Fuel Buildings

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

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

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

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

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

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

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

Install Emergency Water Sprays

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

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

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

Make Preparations for Emergency Repairs of Holes

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

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

Armor Exposed Outside Walls and Bottoms Against Projectiles

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

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

REDUCING THE INVENTORY OF SPENT-FUEL POOLS

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

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

SAFETY OF DRY-CASK STORAGE

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

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

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

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

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

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

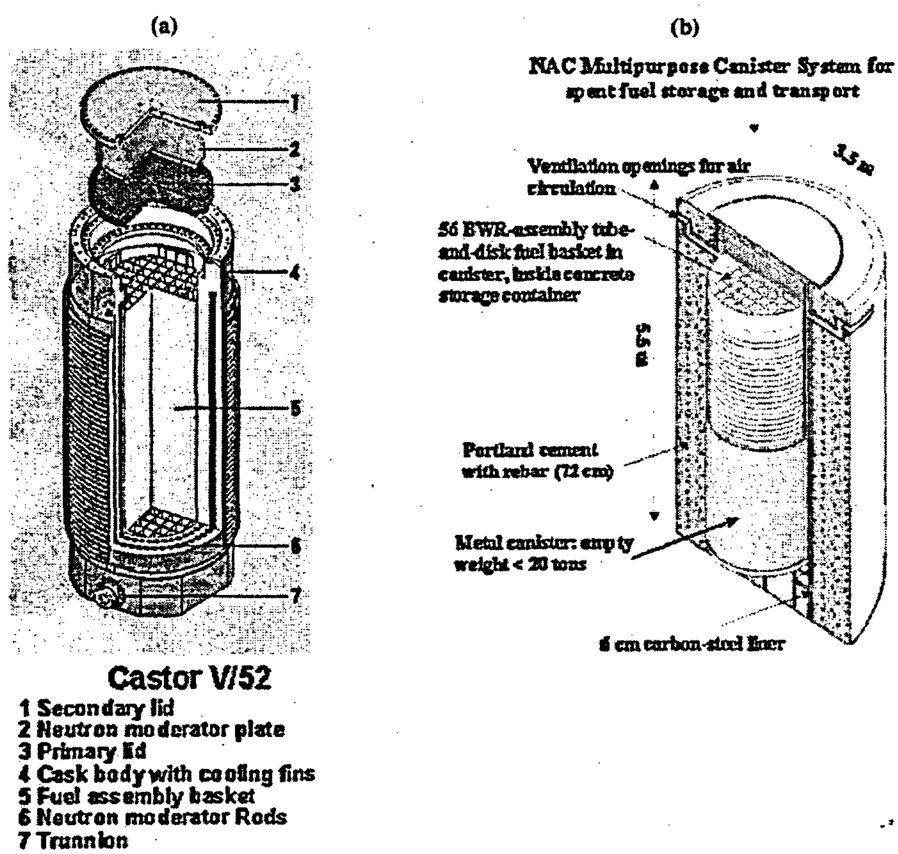

Figure 9: (a) Thick-walled cask[103] and (b) Cask with overpack.[104] (*Sources:* GNB and NAC).

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

Shaped-Charge Missile

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

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

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

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

Turbine Spindle

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

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

Fire

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

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

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

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

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

Cask Availability

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

Dry-Storage Costs

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

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

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

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

Licensing Issues

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

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

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

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

Who Will Pay?

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

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

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

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

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

SUMMARY

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

Improvements

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

Limitations

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

Table 2: Summary of proposals.

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

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

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

ACKNOWLEDGEMENTS

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NOTES AND REFERENCES

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

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

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

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

5. *Ibid.*

6. *Ibid.*

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

55. The gas-diffusion-limited zirconium oxidization rate has been parameterized as $dw^2/dt = K_o\exp(-E_a/RT)$ in the range 920–1155°C, where *w* is the weight gain of the cladding (g/cm²) due to oxidation, K_0 is the rate constant [5.76×10^4 (gm/cm²)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/cm²)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, $L = 4$m 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 ~ 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.)

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

Allan S. Benjamin

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

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

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

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

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

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

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

proposed solution, the competing risks introduced by that solution, and the cost of implementation.

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

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

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

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

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

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

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

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

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

Finally, one must consider the competing risks. The process of removing such a large amount of fuel from the spent-fuel pool and transferring it to the

dry storage casks carries its own set of hazards. During the transfer process, both the probability of an accident and the degree of exposure in the event of a potential terrorist attack are greater than before or after the transfer. The paper suggests that the transfer would take place over a ten-year period. Someone needs to look at the question of vulnerability during that period.

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

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

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

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

NOTE AND REFERENCE

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

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

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THE AUTHORS RESPOND TO ALLAN BENJAMIN'S COMMENTS

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

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

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

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

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

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

Feasibility of totally draining the pool through valves and gates. We make no claim that this is possible. Rather we cite NRC staff concerns that a number of pools could be drained below the top of the spent fuel. This would result in very high radiation levels in the spent-fuel-pool building. Pools should

therefore be equipped with sources of makeup water that can be turned on from a remote location.

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

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

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

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

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

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

UNITED STATES OF AMERICA

NUCLEAR REGULATORY COMMISSION

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BRIEFING ON THE STATUS OF OFFICE

OF RESEARCH (RES) PROGRAMS,

PERFORMANCE, AND PLANS

+ + + + +

ROCKVILLE, MARYLAND

+ + + + +

THURSDAY, MARCH 27, 2003

+ + + + +

The Commission met in open session at 10:00 a.m., at the Nuclear Regulatory Commission, One White Flint North, Rockville, Maryland, the Honorable Richard A. Meserve, Chairman of the Commission, presiding.

<u>COMMISSIONERS PRESENT</u>:

RICHARD A. MESERVE: Chairman of the Commission

GRETA J. DICUS: Member of the Commission

NILS DIAZ: Member of the Commission

EDWARD McGAFFIGAN: Member of the Commission

JEFFREY S. MERRIFIELD: Member of the Commission

remarks yesterday, but --

COMMISSIONER DICUS: My remarks yesterday are on the record.

CHAIRMAN MESERVE: We'll have them incorporated in the record.

COMMISSIONER McGAFFIGAN: Right.

I'm going to talk -- I think you did a valuable thing today, Dr. Thadani, in talking at least initially about the results of your work on the spent fuel pool work. But there's a couple of things that you said that I don't necessarily agree with, and so I'm just going to tell you that.

I want to talk a little bit about the history of 1738 on the record, NUREG 1738, just so the public understands how the Commission -- and I think I'm speaking for the Commission, but if not others can chime in.

The Commission had great skepticism about that document when it was presented to us in January of 2001. I underscore great; very, very large skepticism about that document. We thought it was making bounding assumptions that in many cases were not physical. But staff felt so passionately about putting it out, that we put it out.

Then we held a Commission meeting in February 2001. That Commission meeting transcript, unless something has changed in the last couple of days, is not on our web page. Because when we redid our security review, one of the few documents that did not past muster by the staff for putting back on our web page was the transcript of that meeting.

Now, NUREG 1738 remains on our page web.

ANNETTE VIETTI-COOK: They put it back on. It's back on.

COMMISSIONER McGAFFIGAN: Is it back on? Okay. Well,

I'm glad it's back on. Because the skepticism displayed by the Commission on that day was not on our web page.

Now the skepticism demonstrated by the Nuclear Energy Institute using EPRI and other research was not on the web page. I'm glad it's back on the web page today. It hasn't been for a year.

So then we didn't in the SRM on that meeting say we hate NUREG 1738 because the staff convinced us that we were going to get a paper, and it was ultimately SECY-01-0100 that we did receive, I think in June of 2001 where the staff basically again said, more or less what you said today Dr. Thadani, that we don't really think that it's worth getting a peer review of this paper. We've done enough, it's not resource effective for our purpose, which is do we need to do anything with exemptions of decommissioning reactors. Even though we've made these wildly conservative nonphysical assumptions, we still get the right answers. So please let us not do it. We never voted on that paper. That paper was withdrawn after September 11, correctly. And we never really were given the opportunity as a Commission to say whether we thought that document should be peer reviewed.

I personally, you can tell from my remarks, was going to vote for having that document peer reviewed even before September 11th.

The danger we have with these documents that you all produce where I think your words were "simplified assumptions," "not cost beneficial to expend additional resources for fixing it" -- those are the words I took down -- the problem you have with those papers when you do them is the unintended consequence. That, you know, you are Exhibit A in this Princeton paper that we received on the 29th of January and was briefed to the Congress on the 29th of January and which was allegedly peer reviewed for publication in

this Princeton journal.

Apparently peer review at Princeton means you get somebody like Per Peterson, a distinguished professor at the University of California Berkeley telling you it's not a very good paper and you say "Thank you very much, and we're still going to publish it." And that apparently is what peer review means in the house journals of some of these anti-nuclear activists, which I guess Princeton has become.

We could see that coming. We could see that this document would be misused. And I think it's terribly important. We have all these NUREG CRs and NUREGs, and you guys make these simplifying assumptions, and they get you past the day, and then they come back and haunt us. And so you can't fix all the problems of the past, although I personally think a lot of those documents should simply be withdrawn or, you know, big red marks have to be put at the front "This document does not mean what various people interpret it to mean, misinterpret it to mean." But going forward our analysis has to be more realistic.

And it doesn't just happen here. NUREG 1717 that I think your office is responsible for is another document. I mean, it's hard sometimes in NMSS and material space to tell which office is responsible. But it's another document where it's at least a factor of 40 off in its estimates as to what zirconium sand -- somebody working in the zirconium sand industry would likely get in the way of dose. Because it made a bunch of, you know, simplifying assumptions that are wrong.

But that case, that influences us to do a lot of potentially stupid things in rulemaking, or whatever it is. People sort of carry in their head, oh my God somebody working in the zirconium sand industry can get 4 rem dose when

it's hard to imagine anybody getting more than 100 millirem working in that industry.

So I urge you going forward to do reasonable best estimates sorts of research and to not allow you or your contractors to come up with silly, you know, bounding research because it has a lot of unintended consequences. Okay.

Let me ask you, I'm going to just try to get a couple of other things out in the record about spent fuel pool stuff.

The Academy of Sciences last year in its report to Congress and to the President, and to the nation about terrorism said the following: "The threat of terrorist attacks on spent fuel storage facilities like reactors is highly dependent on design characteristics. Moreover, spent fuel generates orders of magnitude less heat than an operating reactor so that emergency cooling of the fuel in the case of an attack could probably be accomplished using low tech measures that could be implemented without significant exposure of workers to radiation."

Is there anything in our research that would do anything but endorse what the Academy's preliminary judgment was?

DR. THADANI: No, I agree with this. And that's coming out of the result of our analysis.

COMMISSIONER McGAFFIGAN: Okay. I know you're trying to produce your piece of research, but is there any chance that the staff can do a critique of the Alvarez study shortly that gets -- what is happening at the moment, if you read our press clips, is that the authors of that study are merrily going around the country to whatever site, you know, recently it was Diablo Canyon, Indian Point is another one of their favorite sites, saying things that

result from their study that are wrong, but there's nothing that we have out there that says that this study is deeply, deeply flawed and makes assumptions that are wrong, partly using our own studies, unfortunately, that we have to withdraw.

But is there a chance that we can have a hard hitting critique of the Alvarez study anytime soon?

DR. THADANI: A critique can be done. I have to ask Dr. Eltawila. Because the key staff are also engaged in some of the high priority efforts. But we'll have to go through our system -- I'm hesitating on timing because I need to make sure we know what it is that we're not going to deliver to you, basically.

COMMISSIONER McGAFFIGAN: Well, see, I think that part of your answer there demonstrates a tendency in the staff -- I think you can get a hardhitting critique that sort of undermines the study deeply by spending a day on it if you have somebody who knows their stuff. You can then do the perfect critique, on which I don't know how many days you could spend, but it's a large number. And waiting for the perfect critique at day infinity means that we don't play for all those days. If coming up with the one day critique, which I think your staff should be able to do, puts us on the mark and gives our public affairs people and the various regions, gives the Commissioners, gives the senior staff -- you know, they're getting beat up with it. Our staff is getting beat up with this study as they do the annual performance reviews at various reactor sites as part of the reactor oversight process at the moment. And without guidance, they're doing I think a decent job, you know, of fending it off and saying that we don't believe the study.

But I don't know that they're doing it based on guidance. I haven't seen any guidance from you guys that the average branch chief from a

POLICY ISSUE
(Notation Vote)

June 4, 2001

FOR: The Commissioners

FROM: William D. Travers
Executive Director for Operations

SUBJECT: POLICY ISSUES RELATED TO SAFEGUARDS, INSURANCE, AND EMERGENCY PREPAREDNESS REGUI DECOMMISSIONING NUCLEAR POWER PLANTS STORING FUEL IN SPENT FUEL POOLS (WITS 2000

- PURPOSE
- BACKGROUND
- DISCUSSION
- POLICY ISSUES
- EXISTING EXEMPTIONS
- RESOURCES
- COORDINATION
- RECOMMENDATION

PURPOSE:

To present the Commission with policy issues and options related to regulatory decision-making in the areas o emergency preparedness (EP), and safeguards for decommissioning nuclear power plants and to request Comi approval of staff recommendations.

BACKGROUND:

In the early 1990s, the staff initiated an effort to revise the regulatory requirements for decommissioning nucl plants. The decommissioning regulatory improvement effort has focused on revisions to requirements in the ai insurance, EP, and safeguards because existing regulations present a significant burden to decommissioning li without apparent commensurate safety benefits. The technical basis needed to support the decommissioning r improvement effort has been difficult to develop. This has been partly due to an incomplete understanding of t fire risk associated with decommissioning plants.

In March 1999, the NRC staff briefed the Commission about ongoing efforts to improve decommissioning regul staff proposed to consider a risk-informed approach on decommissioning plant issues and to use the risk insigl from this review to guide the Accident Risk at Decommissioning Nuclear Power Plants," NUREG-1738. The stud publicly issued in January 2001. In a December 20, 2000, memorandum forwarding NUREG-1738 to the Comn noted that the study has implications related to previous policy on decommissioning exemptions for insurance, safeguards and so the staff committed to provide a policy options paper for Commission consideration. This pa combined with information regarding previously issued exemptions provided in a separate paper to the Commi that commitment.

DISCUSSION:

As discussed in NUREG-1738, the only postulated scenario at a decommissioning plant that could result in a si offsite radiological release is a beyond-design-basis event commonly referred to as a zirconium fire. An event : resulting in a zirconium fire begins with a substantial loss of water from the spent fuel pool (SFP), uncovering i fuel. Uncovering the spent fuel could result in a heatup to the point where the fuel's zirconium cladding might oxidize in a rapid, exothermic, self-sustaining reaction. The plume from such a zirconium fire could have signif radiological consequences.

In NUREG-1738, the staff concluded that the risk from an SFP zirconium fire at decommissioning plants is very below the Commission's safety goals for operating reactors. The study found that the event sequences most in the zirconium fire risk at decommissioning plants are large (catastrophic) earthquakes and spent fuel cask dro These findings are contingent on the implementation of certain SFP design, operational, and administrative fea assumed by the staff or committed to by the industry that are documented in the study. NUREG-1738 did not compare the risk from nuclear power plant operation to the risk of spent fuel storage at a decommissioning pl However, the likelihood of a large offsite radiological release that could impact public health and safety from a decommissioning plant is considerably lower than the likelihood of such a release from an operating reactor wl initiating events associated with normal and abnormal operations, design basis accidents, and beyond design l accidents.

NUREG-1738 also presented thermal-hydraulic analyses of the stored spent fuel when SFP cooling is lost or th uncovered. The staff found that a generic decay heat level (and, therefore, decay time) beyond which a zircon physically impossible cannot be defined. This is because the geometry of the spent fuel assemblies, the associ cooling flow paths, and the resultant heat transfer rates are not predictable following a major dynamic event (: very severe earthquake), which could rupture and rapidly drain the SFP. As a result, the study concluded that of a zirconium fire cannot be dismissed even many years after final reactor shutdown.

This finding is important because it differs from previous positions on exempting decommissioning plants from insurance, EP, and safeguards requirements as described in SECY-93-127, "Financial Protection Required of Lic Large Nuclear Power Plants During Decommissioning," dated July 13, 1993. The previous position was based o demonstrating by thermal-hydraulic analysis that spent fuel stored in the SFP would air cool sufficiently and nc zirconium fire ignition temperature. The position did not consider blockage or obstructions to natural circulatio through the fuel assemblies since such sequences were considered strictly hypothetical. In NUREG-1738, the s that it is not feasible, without numerous constraints, to define a generic decay heat level beyond which a zirco not physically possible. Stated in this manner, the zirconium fire cannot be considered strictly hypothetical. Hc staff notes that the sequences in which a zirconium fire comes about are very low likelihood sequences. In this sufficiency of previous exemptions that ruled out a zirconium fire based on air cooling calculations assuming n assembly configurations and geometries has been reconsidered. The previous policy established in SECY-93-1: reducing certain insurance, EP, and safeguards requirements at decommissioning plants has been revisited by Potential implications of the finding of NUREG-1738 and the policy recommendation of this paper on previously exemptions at currently decommissioning plants will be provided in a separate paper to the Commission.

The risk from a zirconium fire was examined in NUREG-1738 for a "generic" decommissioning plant. The study the initiating event frequencies (i.e., events that can lead to spent fuel uncovery). The initiating event frequen determined to be very low and dominated by the frequency of severe earthquakes. The frequency of such eve a zirconium fire is less than 3E-6 per year at most decommissioning plant sites. These conclusions apply to decommissioning facilities that have certain design, operational, and administrative characteristics that were a the risk study. Such characteristics are identified in NUREG-1738 as industry decommissioning commitments (staff decommissioning assumptions (SDAs). Zirconium fire probabilities may be higher for facilities that do not staff assumptions or industry commitments, and may be lower for facilities that have different seismic charact likelihood of a zirconium fire at a facility that does not implement all the IDCs and SDAs cannot be determined NUREG-1738. If it were necessary to determine the likelihood of a zirconium fire at such a facility, a plant-spe assessment would be required. The NUREG-1738 study also included zirconium fire consequence assessments. demonstrate that as long as the fuel uncovery frequency is less than 1E-5 per year, the zirconium fire risk is k the Commission's Quantitative Health Objectives (QHOs). In addition, the study developed an approach simila Regulatory Guide (RG) 1.174, "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decision Specific Changes to the Licensing Basis," to assist decommissioning plant regulatory decision making.

In general, the NUREG-1738 risk assessments, insights, and methodologies represent a technically sound basi informing decommissioning plant regulatory decision making. However, there are some limitations and additio considerations in applying the information in NUREG-1738 as noted below:

DAVID PRICE
4TH DISTRICT
NORTH CAROLINA

COMMITTEE ON APPROPRIATIONS
TREASURY, POSTAL SERVICE
AND GENERAL GOVERNMENT

VETERANS' AFFAIRS,
HOUSING AND URBAN DEVELOPMENT
AND INDEPENDENT AGENCIES

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March 5, 2003

Dr. Richard Meserve, Chairman
U.S. Nuclear Regulatory Commission
One White Flint North
11555 Rockville Pike
Rockville, MD 20852-2738

Dear Dr. Meserve:

I am writing to express my continued concerns related to potential terrorist threats to nuclear power plants.

As you are aware from past correspondence, many constituents in my district are particularly concerned with the vulnerability of nuclear plants, and spent fuel pools in particular, to terrorist attack. With regard to spent fuel, you are likely aware of a study slated to appear in the spring issue of *Science and Global Security*, a publication of Princeton University, which concludes that spent fuel pools are particularly vulnerable to terrorist attacks that could generate a pool fire and a corresponding contamination of hundreds of square miles around a nuclear plant. The study recommends the re-equipping of spent fuel pools with low-density, open-frame racks and, for longer term storage, a reduced reliance on spent fuel pools in favor of dispersed, hardened, aboveground storage modules.

I assume that the NRC will give full consideration to the rationale and recommendations provided by this study, and I would appreciate receiving a response from you outlining the agency's evaluation of it.

In addition, I very much appreciated receiving your letter of September 5, 2002, outlining steps taken by the NRC to evaluate and improve security at nuclear power plants. I urge you to continue to periodically provide information of this type to members of Congress and to the public.

Thank you for your time and attention.

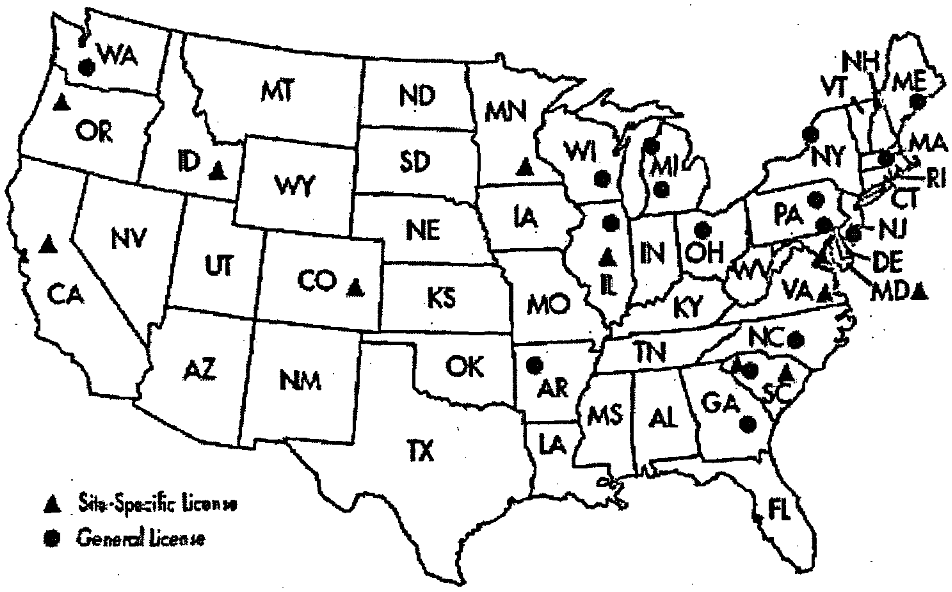
Sincerely,

David Price

DAVID PRICE
Member of Congress

DP:dn

Locations of Independent Spent Fuel Storage Installations



State and Plant	License Type
ARKANSAS Arkansas Nuclear	General ●
CALIFORNIA Rancho Seco	Site-Specific ▲
COLORADO Fort St. Vrain	Site-Specific ▲
GEORGIA Hatch	General ●
IDAHO DOE: TMI-2 Fuel Debris	Site-Specific ▲
ILLINOIS GE Morris Dresden	Site-Specific ▲ General ●
MAINE Maine Yankee	General ●
MARYLAND Calvert Cliffs	Site-Specific ▲
MASSACHUSETTS	

Yankee Rowe	General ●
MICHIGAN	
Palisades	General ●
Big Rock Point	General ●
MINNESOTA	
Prairie Island	Site-Specific ▲
NEW JERSEY	
Oyster Creek	General ●
NEW YORK	
FitzPatrick	General ●
NORTH CAROLINA	
McGuire	General ●
OHIO	
Davis-Besse	General ●
OREGON	
Trojan	Site-Specific ▲
PENNSYLVANIA	
Susquehanna	General ●
Peach Bottom	General ●
SOUTH CAROLINA	
Oconee	General/Site-Specific ● ▲
H.B. Robinson	Site-Specific ▲
VIRGINIA	
Surry	Site-Specific ▲
North Anna	Site-Specific ▲
WASHINGTON	
Columbia Generating Station	General ●
WISCONSIN	
Point Beach	General ●

Data as of March 2003

U.S. GENERATING COMPANIES WITH ON-SITE DRY STORAGE COMMITMENTS

OWNER/OPERATOR	REACTOR	DRY STORAGE TECHNOLOGY	LICENSING METHOD (1)	FACILITY Date (2)
Dominion Generation	Surry 1 & 2	Metal Casks (3)	Site Specific	1986
Progress Energy (CP&L)	H.B. Robinson	NUHOMS-07P	Site Specific	1986
Duke Energy	Oconee 1, 2, & 3	NUHOMS-24P	Site Specific	1990
Public Service Company of Colorado	Fort St. Vrain	Foster Wheeler MVDS	Site Specific	1991
Constellation Nuclear	Calvert Cliffs 1 & 2	NUHOMS-24P	Site Specific	1992
Consumers Energy	Palisades	VSC-24, NUHOMS 32PT	General License	1993
Nucler Management Company (Xcel Energy)	Prairie Island 1 & 2	TN-40	Site Specific	1993
Nuclear Management Company (WEPCO)	Point Beach 1 & 2	VSC-24, NUHOMS 32PT	General License	1995
First Energy	Davis Besse	NUHOMS-24P	General License	1995
Entergy Operations	Arkansas Nuclear One 1 & 2	VSC-24	General License	1996
Dominion Generation	North Anna 1 & 2	TN-32	Site Specific	1998
PP&L	Susquehanna 1 & 2	NUHOMS-52B	General License	1999
Exelon Generation	Dresden 1	Holtec HI-STAR	General License	2000
Exelon Generation	Peach Bottom 2 & 3	TN-68	General License	2000
Southern Nuclear Operating Company	Hatch 1 & 2	Holtec HI-STORM	General License	2000
Duke Energy	McGuire 1& 2	TN-32/ NAC UMS	General License	2001
Portland General Electric	Trojan	Holtec	Site Specific	Planned
Sacramento Municipal Utility District	Rancho Seco	NUHOMS-MP187	Site Specific	2001
Amergen	Oyster Creek	NUHOMS - 61BT	General License	2002
Yankee Atomic Electric Company	Yankee Rowe	NAC MPC	Site Specific	Planned
Energy Northwest	WNP2	Holtec HI-STORM	General License	Planned
Consumers Energy	Big Rock Point	BFS Fuel Solutions	General License	Planned
Arizona Public Service	Palo Verde 1, 2, 3	NAC UMS	General License	Planned
Entergy	Fitzpatrick	Holtec Hi-STORM	General License	2002
Maine Yankee Atomic Power	Maine Yankee (4)	NAC UMS	General License	2001
Connecticut Light & Power	Haddam Neck	NAC MPC	General License	Planned
Vermont Yankee Atomic Power	Vermont Yankee	Holtec HI-STORM	General License	Planned
Tennessee Valley Authority	Sequoyah 1 & 2	Holtec HI-STORM	General License	Planned
Southern California Edison	San Onofre 1, 2 & 3	NUHOMS -24PT	General License	Planned
Pacific Gas & Electric	Diablo Canyon, Humboldt Bay	HI-STORM 100	Site Specific	Planned
Exelon Generation	Dresden 2 & 3	HI-STORM 100	General License	Planned
Entergy	Grand Gulf	HI-STORM 100	General License	Planned
Entergy	River Bend	HI-STORM 100	General License	Planned
Nuclear Management Company	Duane Arnold	NUHOMS - 61BT	General License	Planned
Tennessee Valley Authority	Browns Ferry 1, 2, 3	Holtec HI-STORM	General License	Planned

(1) Site specific licenses are granted in accordance with 10 CFR 72. General licenses refer to the storage of spent fuel in certified casks in accordance with 10 CFR 72 Subpart K.

(2) Facility dates for reactors with site specific licenses earlier than 1996 refer to the date that the license was issued by the NRC. Site specific facility dates in 1998 or later are the dates the utility expects to receive a license from the NRC. For reactors using dry storage with Certificates of Compliance under a general license, the facility date refers to the approximate date that the utility plans to first load fuel into dry storage.

(3) Virginia Power has spent fuel stored in metal casks of various designs.

(4) Maine Yankee loaded GTCC waste into dry storage containers in 2001. Spent fuel loading is expected to begin in 2002

NOTE: Additional utilities are in the process of evaluating dry storage alternatives for implementation in 2001 through 2005. However, no formal announcements have been made regarding selection of a storage technology.

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United States General Accounting Office

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Testimony

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NUCLEAR WASTE

Uncertainties About the Yucca Mountain Repository Project

Statement of (Ms.) Gary Jones, Director, Natural Resources and Environment

GAO
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GAO-02-765T

Mr. Chairman and Members of the Subcommittee:

We are pleased to be here today to discuss the Department of Energy's (DOE) project to develop a nuclear waste repository. As required by law, DOE has been investigating a site at Yucca Mountain, Nevada, to determine its suitability for disposing of highly radioactive wastes in a mined geologic repository. On February 14, 2002, the secretary of energy recommended to the president approval of this site for the development of a nuclear waste repository. The next day, the president recommended approval of the site to the Congress. The president's recommendation began a statutory review process for the approval or disapproval of the site, including action by the state of Nevada, the Congress, DOE, and the Nuclear Regulatory Commission (NRC) within specified time frames. If the site is approved, DOE must apply to NRC for authorization (a license) to construct a repository. If the site is not approved for a license application, or if NRC denies a license to construct a repository, the administration and the Congress will have to consider other options for the long-term management of existing and future nuclear wastes.

Our testimony, which is based on our recent report on the Yucca Mountain Repository Project,[1] addresses (1) DOE's readiness to submit a license application within the statutory time frame, (2) the extent to which DOE can meet its goal of opening a repository at Yucca Mountain in 2010, and (3) the extent to which DOE is managing the project consistent with applicable departmental procedures.

Summary

DOE is not prepared to submit an acceptable license application to NRC within the statutory limits that would take effect if the site is approved. The president's recommendation of the Yucca Mountain site to the Congress triggered specific statutory time frames for the next steps in the repository project. Nevada, which had 60 days from February 15 to disapprove the site, did so on April 8. The Congress now has 90 days (of continuous session) from that date in which to enact legislation overriding the state's disapproval. On May 8, the House of Representatives passed a joint resolution approving the site for a repository. If the Senate also passes this resolution—resulting in final approval of the site—the Nuclear

[1] U.S. General Accounting Office, *Nuclear Waste: Technical, Schedule, and Cost Uncertainties of the Yucca Mountain Repository Project*, GAO-02-191 (Washington, D.C.: Dec. 21, 2001).

Waste Policy Act requires DOE to then submit a license application to NRC within 90 days of the effective date of the legislation. Thus, the process gives DOE about 5 to 8 months from the date of the president's recommendation to submit the license application. However, a September 2001 detailed assessment of the repository program by DOE's managing contractor concluded that DOE would not be ready to submit a license application that would be acceptable to NRC until January 2006. DOE did not accept the contractor's proposed new schedule and directed the contractor to develop a proposal to shorten the time to a license application to December 2004, or about 29 months from now. The contractor has now developed such a proposal, which is under review within DOE. Moreover, while a site recommendation and a license application are separate processes, essentially the same data are needed for both. Waiting until DOE was closer to having the additional information needed to support an acceptable license application would have put DOE in a better position to submit the application within the time frames set out in the law, and to respond to questions and challenges that may emanate from the statutory review process subsequent to the president's recommendation.

DOE is unlikely to achieve its goal of opening a repository at Yucca Mountain by 2010. On the basis of DOE's managing contractor's September 2001 reassessment, sufficient time would not be available for DOE to obtain a license from NRC and construct enough of the repository to open it in 2010. Even under the more recent proposal to submit a license application as early as December 2004, it is questionable whether DOE could open the repository in 2010. A key factor in the future licensing and construction of a repository is whether DOE will be able to obtain the increases in annual funding that would be required to open the repository by 2010. Because of the uncertainty of meeting the 2010 goal, DOE is exploring alternative approaches, such as developing surface facilities for storing waste at the site until sufficient underground disposal facilities can be constructed. Had DOE elected to defer a site recommendation until it was closer to having an acceptable license application, it could have ensured that the site recommendation was based on the approach to developing a repository that it intends to follow. This would have enabled DOE to develop an estimated schedule to design and build the preferred approach and to estimate its cost, including the annual funding requirements, as part of the information on which to make a site recommendation.

DOE currently does not have a reliable estimate of when, and at what cost, a license application can be submitted or a repository can be opened

because DOE stopped using its cost and schedule baselines to manage the site investigation in 1997. DOE needs to reestablish a baseline for the repository program that accounts for the outstanding technical work needed to prepare an acceptable license application and the estimated schedule and cost to achieve this milestone. In conjunction, DOE needs to use the baseline as a tool for managing the program, in accordance with the department's policies and procedures for managing major projects. Therefore, our December 2001 report recommended that the secretary of energy reestablish the baseline through the submission of a license application and follow the department's management requirements, including a formal procedure for changing program milestones. According to DOE, it is currently in the process of establishing a new baseline for the nuclear waste program.

Background

Recognizing the critical need to address the issue of nuclear waste disposal, the Congress enacted the Nuclear Waste Policy Act of 1982 to establish a comprehensive policy and program for the safe, permanent disposal of commercial spent fuel and other highly radioactive wastes in one or more mined geologic repositories. The act created the Office of Civilian Radioactive Waste Management within DOE to manage its nuclear waste program. Amendments to the act in 1987 directed DOE to investigate only the Yucca Mountain site.

The Nuclear Waste Policy Act also set out important and complementary roles for other federal agencies:

- The Environmental Protection Agency (EPA) was required to establish health and safety standards for the disposal of wastes in repositories. EPA issued standards for the Yucca Mountain site in June 2001 that require a high probability of safety for at least 10,000 years.[2]
- NRC is responsible for licensing and regulating repositories to ensure their compliance with EPA's standards. One prerequisite to the secretary's recommendation was obtaining NRC's preliminary comments on the sufficiency of DOE's site investigation for the purpose of a license application. NRC provided these comments on November 13, 2001. If the site is approved, then NRC, upon accepting a license application from

[2] The Energy Policy Act of 1992 required EPA to establish specific health and safety standards for a repository at Yucca Mountain.

DOE, has 3 to 4 years to review the application and decide whether to issue a license to construct, and then to operate, a repository at the site.[3]

- The Nuclear Waste Technical Review Board (the board) reviews the technical and scientific validity of DOE's activities associated with investigating the site and packaging and transporting wastes. The board must report its findings and recommendations to the Congress and the secretary of energy at least twice each year, but DOE is not required to implement these recommendations.

DOE has designated the nuclear waste program, including the site investigation, as a "major" program that is subject to senior management's attention and to its agencywide guidelines for managing such programs and projects. The guidelines require the development of a cost and schedule baseline, a system for managing changes to the baseline, and independent cost and schedule reviews. DOE is using a management contractor to carry out the work on the program. The contractor develops and maintains the baseline, but senior DOE managers must approve significant changes to cost or schedule estimates. In February 2001, DOE hired Bechtel SAIC Company, LLC (Bechtel), to manage the program and required the contractor to reassess the remaining technical work and the estimated schedule and cost to complete this work.

DOE Will Not Be Ready to Submit a License Application within the Statutory Time Frame

DOE is not prepared to submit an acceptable license application to NRC within the statutory limits that would take effect if the site were approved. Specifically, DOE has entered into 293 agreements with NRC to gather and/or analyze additional technical information in preparation for a license application that NRC would accept. DOE is also continuing to address technical issues raised by the board. In September 2001, Bechtel concluded, after reassessing the remaining technical work, that DOE would not be ready to submit an acceptable license application to NRC until January 2006. DOE did not accept the 2006 date. Instead, it directed the contractor to prepare a new plan for submitting a license application to NRC by December 2004. DOE's current plan is that, by the end of September 2002, Bechtel will develop, and DOE will review and approve, a new technical, cost, and schedule baseline for submitting a license application to NRC in December 2004.

[3] The acceptance of a license application is not the same as approving an application. A decision to approve or disapprove any application would be made by NRC following extensive review and testing.

Moreover, while a site recommendation and a license application are separate processes, DOE will need to use essentially the same data for both.[4] Also, the act states that the president's recommendation to the Congress is that he considers the site qualified for an application to NRC for a license. The president's recommendation also triggers an express statutory time frame that requires DOE to submit a license application to NRC within about 5 to 8 months.

DOE Lacks Information for a License Application

The 293 agreements that DOE and NRC have negotiated address areas of study within the program where NRC's staff has determined that DOE needs to collect more scientific data and/or improve its technical assessment of the data. According to NRC, as of March 2002, DOE had satisfactorily completed work on 38 of these agreements and could resolve another 22 agreements by September 30 of this year. These 293 agreements generally relate to uncertainties about three aspects of the long-term performance of the proposed repository: (1) the expected lifetime of engineered barriers, particularly the waste containers; (2) the physical properties of the Yucca Mountain site; and (3) the supporting information for the mathematical models used to evaluate the performance of the planned repository at the site.

The uncertainties related to engineered barriers revolve around the longevity of the waste containers that would be used to isolate the wastes. DOE currently expects that these containers would isolate the wastes from the environment for more than 10,000 years. Minimizing uncertainties about the container materials and the predicted performance of the waste containers over this long time period is especially critical because DOE's estimates of the repository system's performance depend heavily on the waste containers, in addition to the natural features of the site, to meet NRC's licensing regulations and EPA's health and safety standards.

The uncertainties related to the physical characteristics of the site center on how the combination of heat, water, and chemical processes caused by the presence of nuclear waste in the repository would affect the flow of water through the repository.

[4] See *General Guidelines for the Recommendation of Sites for Nuclear Waste Repositories; Yucca Mountain Site Suitability Guidelines* (preamble), 66 *Fed. Reg.* 57298, 57322 (Nov. 14, 2001).

The NRC staff's concerns about DOE's mathematical models for assessing the performance of the repository primarily relate to validating the models; that is, presenting information to provide confidence that the models are valid for their intended use and verifying the information used in the models. Performance assessment is an analytical method that relies on computers to operate mathematical models to assess the performance of the repository against EPA's health and safety standards, NRC's licensing regulations, and DOE's guidelines for determining if the Yucca Mountain site is suitable for a repository. DOE uses the data collected during site characterization activities to model how a repository's natural and engineered features would perform at the site.

According to DOE, the additional technical work surrounding the 293 agreements with NRC's staff is an insignificant addition to the extensive amount of technical work already completed—including some 600 papers cited in one of its recently published reports and a substantial body of published analytic literature. DOE does not expect the results of the additional work to change its current performance assessment of a repository at Yucca Mountain.

From NRC's perspective, however, the agreements provided the basis for it to give DOE its preliminary comments on the sufficiency of DOE's investigation of the Yucca Mountain site for inclusion in a future license application. In a November 13, 2001, letter to the under secretary of energy, the Chairman of the NRC commented that

"[a]lthough significant additional work is needed prior to the submission of a possible license application, we believe that agreements reached between DOE and NRC staff regarding the collection of additional information provide the basis for concluding that development of an acceptable license application is achievable."

The board has also consistently raised issues and concerns over DOE's understanding of the expected lifetime of the waste containers, the significance of the uncertainties involved in the modeling of the scientific data, and the need for an evaluation and comparison of a repository design having a higher temperature with a design having a lower temperature. The board continues to reiterate these concerns in its reports. For example, in its most recent report to the Congress and the secretary of energy, issued on January 24, 2002, the board concluded that, when DOE's technical and scientific work is taken as a whole, the technical basis for DOE's repository performance estimates is "weak to moderate" at this time. The board added that gaps in data and basic understanding cause important uncertainties in the concepts and assumptions on which DOE's

performance estimates are now based; providing the board with limited confidence in current performance estimates generated by DOE performance assessment model.

As recently as May 2001, DOE projected that it could submit a license application to NRC in 2003. It now appears, however, that DOE may not complete all of the additional technical work that it has agreed to do to prepare an acceptable license application until January 2006. In September 2001, Bechtel completed, at DOE's direction, a detailed reassessment in an effort to reestablish a cost and schedule baseline. Bechtel estimated that DOE could complete the outstanding technical work agreed to with NRC and submit a license application in January 2006. This date, according to the contractor, was due to the cumulative effect of funding reductions in recent years that had produced a "...growing bow wave of incomplete work that is being pushed into the future." Moreover, the contractor's report said, the proposed schedule did not include any cost and schedule contingencies. The contractor's estimate was based on guidance from DOE that, in part, directed the contractor to assume annual funding for the nuclear waste program of $410 million in fiscal year 2002, $455 million in fiscal year 2003, and $465 million in fiscal year 2004 and thereafter.[5] DOE did not accept this estimate because, according to program officials, the estimate would extend the date for submitting a license application too far into the future. Instead, DOE accepted only the fiscal year 2002 portion of Bechtel's detailed work plan and directed the contractor to prepare a new plan for submitting a license application to NRC by December 2004. Bechtel has prepared such a plan and the plan is under review by DOE. Although we have not reviewed the entire plan, we note that the plan (1) assumes that the program receives the $525 million in funds requested by the Administration for fiscal year 2003, which would be more than $100 million above the funds provided for fiscal year 2002, and (2) work on 10 of the department's 293 agreements with NRC would not be complete by the target license application date of December 2004.

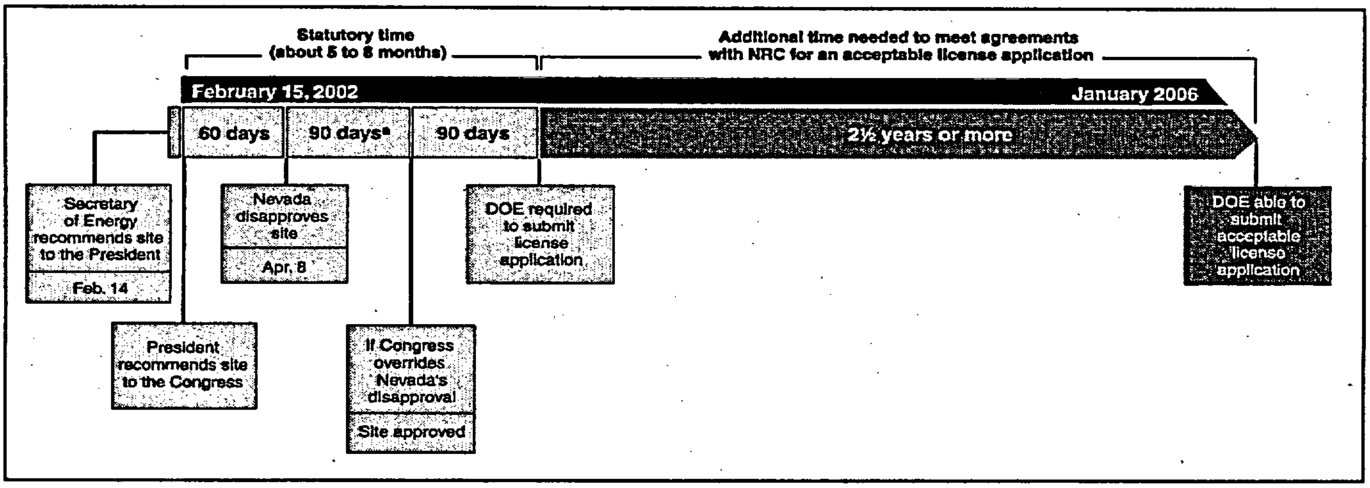
[5] DOE's budget request for fiscal year 2003 is about $527 million, or $72 million more than assumed in Bechtel's reassessment. The preliminary amounts for fiscal years 2004 and 2005 are $538 million and $550 million, respectively.

Essentially the Same Information Is Needed for a Site Recommendation and a License Application

Under the Nuclear Waste Policy Act, DOE's site characterization activities are to provide information necessary to evaluate the Yucca Mountain site's suitability for submitting a license application to NRC for placing a repository at the site. In implementing the act, DOE's guidelines provide that the site will be suitable as a waste repository if the site is likely to meet the radiation protection standards that NRC would use to reach a licensing decision on the proposed repository. Thus, as stated in the preamble (introduction) to DOE's guidelines, DOE expects to use essentially the same data for the site recommendation and the license application.

In addition, the act specifies that, having received a site recommendation from the secretary, the president shall submit a recommendation of the site to the Congress if the president considers the site qualified for a license application. Under the process laid out in the Nuclear Waste Policy Act, once the secretary makes a site recommendation, there is no time limit under which the president must act on the secretary's recommendation. However, when the president recommended, on February 15, that the Congress approve the site, specific statutory time frames were triggered for the next steps in the process. Figure 1 shows the approximate statutory time needed between a site recommendation and submission of a license application and the additional time needed for DOE to meet the conditions for an acceptable license application. The figure assumes that the Congress overrides the state's disapproval of April 8, 2002. As shown in the figure, Nevada had 60 days—until April 16—to disapprove the site. The Congress now has 90 days (of continuous session) from that date in which to enact legislation overriding the state's disapproval. If the Congress overrides the state's disapproval and the site designation takes effect, the next step is for the secretary to submit a license application to NRC within 90 days after the site designation is effective. In total, these statutory time frames provide about 150 to 240 days, or about 5 to 8 months, from the time the president makes a recommendation to DOE's submittal of a license application. On the basis of Bechtel's September 2001 and current program reassessments, however, DOE would not be ready to submit a license application to NRC until January 2006 or December 2004, respectively.

Figure 1: Comparison of Statutory Site Approval Process with DOE's Projected Schedule



[a]Ninety calendar days of continuous session of the Congress.

DOE Is Unlikely to Open a Repository in 2010 As Planned

DOE states that it may be able to open a repository at Yucca Mountain in 2010. The department has based this expectation on submitting an acceptable license application to NRC in 2003, receiving NRC's authorization to construct a repository in 2006, and constructing essential surface and underground facilities by 2010. However, Bechtel, in its September 2001 proposal for reestablishing technical, schedule, and cost baselines for the program, concluded that January 2006 is a more realistic date for submitting a license application. Because DOE objected to this proposed schedule, the contractor has now proposed a plan for submitting the application in December 2004. Because of uncertainty over when DOE may be able to open the repository, the department is exploring alternatives that might still permit it to begin accepting commercial spent fuel in 2010.

Extension of License Application Date Will Likely Postpone 2010 Repository Goal

An extension of the license application date to December 2004 or January 2006 would likely preclude DOE from achieving its long-standing goal of opening a repository in 2010. According to DOE's May 2001 report on the program's estimated cost, after submitting a license application in 2003, DOE estimates that it could receive an authorization to construct the repository in 2006 and complete the construction of enough surface and underground facilities to open the repository in 2010, or 7 years after submitting the license application. This 7-year estimate from submittal of the license application to the initial construction and operation of the

repository assumes that NRC would grant an authorization to construct the facility in 3 years, followed by 4 years of construction. Assuming these same estimates of time, submitting a license application in the December 2004 to January 2006 time frame would extend the opening date for the repository until 2012 or 2013.

Furthermore, opening the repository in 2012 or 2013 may be questionable for several reasons. First, a repository at Yucca Mountain would be a first-of-a-kind facility, meaning that any schedule projections may be optimistic. DOE has deferred its original target date for opening a repository from 1998 to 2003 to 2010. Second, although the Nuclear Waste Policy Act states that NRC has 3 years to decide on a construction license, a fourth year may be added if NRC certifies that it is necessary. Third, the 4-year construction time period that DOE's current schedule allows may be too short. For example, a contractor hired by DOE to independently review the estimated costs and schedule for the nuclear waste program reported that the 4-year construction period was too optimistic and recommended that the construction phase be extended by a year-and-a-half.[6] Bechtel anticipates a 5-year period of construction between the receipt of a construction authorization from NRC and the opening of the repository. A 4-year licensing period followed by 5 years of initial construction could extend the repository opening until about 2014 or 2015.

Finally, these simple projections do not account for any other factors that could adversely affect this 7- to 9-year schedule for licensing, constructing, and opening the repository. Annual appropriations for the program in recent years have been less than $400 million. In contrast, according to DOE, it needs between $750 million and $1.5 billion in annual appropriations during most of the 7- to 9-year licensing and construction period in order to open the repository on that schedule. In its August 2001 report on alternative means for financing and managing the program, DOE stated that unless the program's funding is increased, the budget might become the "determining factor" whether DOE will be able to accept wastes in 2010.[7]

[6] U.S. Department of Energy, *Independent Cost Estimate Review of the Civilian Radioactive Waste Management Program, 2001 Total System Life Cycle Cost (Washington, D.C.:* Jan. 2001).

[7] U.S. Department of Energy, *Alternative Means of Financing and Managing the Civilian Radioactive Waste Management Program*, DOE/RW-0546 (Washington, D.C.: Aug. 2001).

In part, DOE's desire to meet the 2010 goal is linked to the court decisions that DOE—under the Nuclear Waste Policy Act and as implemented by DOE's contracts with owners of commercial spent fuel—is obligated to begin accepting spent fuel from contract holders not later than January 31, 1998, or be held liable for damages. Courts are currently assessing the amount of damages that DOE must pay to holders of spent fuel disposal contracts. Estimates of potential damages for the estimated 12-year delay from 1998 to 2010 range widely from the department's estimate of about $2 billion to $3 billion to the nuclear industry's estimate of at least $50 billion. The damage estimates are based, in part, on the expectation that DOE would begin accepting spent fuel from contract holders in 2010. The actual damages could be higher or lower, depending on when DOE begins accepting spent fuel.

DOE Is Reviewing Alternative Ways to Accept Wastes in 2010

Because of the uncertainty of achieving the 2010 goal for opening the Yucca Mountain repository, DOE is examining alternative approaches that would permit it to meet the goal. For example, in a May 2001 report, DOE examined approaches that might permit it to begin accepting wastes at the repository site in 2010 while spreading out the construction of repository facilities over a longer time period. The report recommended storing wastes on the surface until the capacity to move wastes into the repository has been increased. Relatively modest-sized initial surface facilities to handle wastes could be expanded later to handle larger volumes of waste. Such an approach, according to the report, would permit partial construction and limited waste emplacement in the repository, at lower than earlier estimated annual costs, in advance of the more costly construction of the facility as originally planned. Also, by implementing a modular approach, DOE would be capable of accepting wastes at the repository earlier than if it constructed the repository described in the documents that the secretary used to support a site recommendation.

DOE has also contracted with the National Research Council to provide recommendations on design and operating strategies for developing a geologic repository in stages, which is to include reviewing DOE's modular approach. The council is addressing such issues as the (1) technical, policy, and societal objectives and risks for developing a staged repository; (2) effects of developing a staged repository on the safety and security of the facility and the effects on the cost and public acceptance of such a facility; and (3) strategies for developing a staged system, including the design, construction, operation, and closing of such a facility. In March 2002, the council published an interim report on the study in which it addresses a conceptual framework for a generic repository program. The

Council plans to issue a final report this fall, in which it intends to provide specific suggestions for incorporating additional elements of staged repository development into DOE's repository program.

DOE's Current License Application Milestone Date Is Not Supported by the Program's Baseline

As of December 2001, DOE expected to submit the application to NRC in 2003.[8] This date reflects a delay in the license application milestone date last approved by DOE in March 1997 that targeted March 2002 for submitting a license application. The 2003 date was not formally approved by DOE's senior managers or incorporated into the program's cost and schedule baseline, as required by the management procedures that were in effect for the program. At least three extensions for the license application date have been proposed and used by DOE in program documents, but none of these proposals have been approved as required. As a result, DOE does not have a baseline estimate of the program's schedule and cost—including the late 2004 date in its fiscal year 2003 budget request—that is based on all the work that it expects to complete through the submission of a license application.

DOE's guidance for managing major programs and projects requires, among other things, that senior managers establish a baseline for managing the program or project. The baseline describes the program's mission—in this case, the safe disposal of highly radioactive waste in a geologic repository—and the expected technical requirements, schedule, and cost to complete the program. Procedures for controlling changes to an approved baseline are designed to ensure that program managers consider the expected effects of adding, deleting, or modifying technical work, as well as the effects of unanticipated events, such as funding shortfalls, on the project's mission and baseline. In this way, alternative courses of action can be assessed on the basis of each action's potential effect on the baseline. DOE's procedures for managing the nuclear waste program require that program managers revise the baseline, as appropriate, to reflect any significant changes to the program.

After March 1997, according to DOE officials, they did not always follow these control procedures to account for proposed changes to the program's baseline, including the changes proposed to extend the date for license application. According to these same officials, they stopped

[8] DOE's 2003 budget request states that DOE now expects to submit the license application between October and December 2004.

following the control procedures because the secretary of energy did not approve proposed extensions to the license application milestone. As a result, the official baseline did not accurately reflect the program's cost and schedule to complete the remaining work necessary to submit a license application.

In November 1999, the Yucca Mountain site investigation office proposed extending the license application milestone date by 10 months, from March to December 2002, to compensate for a $57.8 million drop in funding for fiscal year 2000. A proposed extension in the license application milestone required the approval of both the director of the nuclear waste program and the secretary of energy. Neither of these officials approved this proposed change nor was the baseline revised to reflect this change even though the director subsequently began reporting the December 2002 date in quarterly performance reports to the deputy secretary of energy. The site investigation office subsequently proposed two other extensions of the license application milestone, neither of which was approved by the program's director or the secretary of energy or incorporated into the baseline for the program. Nevertheless, DOE began to use the proposed, but unapproved, milestone dates in both internal and external reports and communications, such as in congressional testimony delivered in May 2001.

Because senior managers did not approve these proposed changes for incorporation into the baseline for the program, program managers did not adjust the program's cost and schedule baseline. By not accounting for these and other changes to the program's technical work, milestone dates, and estimated costs in the program's baseline since March 1997, DOE has not had baseline estimates of all of the technical work that it expected to complete through submission of a license application and the estimated schedule and cost to complete this work. This condition includes the cost and schedule information contained in DOE's budget request for fiscal year 2003.

When DOE hired Bechtel to manage the nuclear waste program, one of the contractor's first assignments was to document the remaining technical work that had to be completed to support the submission of a license application to NRC and to estimate the time and cost to complete this work. The contractor's revised, unofficial baseline for the program shows that it will take until January 2006 to complete essential technical work and submit an acceptable license application. Also, DOE had estimated that completing the remaining technical work would add about $1.4 billion to the cumulative cost of the program, bringing the total cost of the Yucca

Mountain project's portion of the nuclear waste program to $5.5 billion.[9] As noted earlier, DOE accepted only the fiscal year 2002 portion of the proposed baseline and then directed the contractor to prepare a plan for submitting a license application to NRC by December 2004. The resulting plan is now under review within DOE.

Because of these management weaknesses, we recommended in our December 2001 report that the secretary of energy reestablish the baseline through the submission of a license application and follow the department's management requirements, including a formal procedure for changing program milestones. According to DOE, it is currently in the process of establishing a new baseline for the nuclear waste program.

Mr. Chairman, this concludes our prepared statement. We would be happy to respond to any questions that you or members of the subcommittee may have.

Contacts and Acknowledgments

For further information about this testimony, please contact me at (202) 512-3841. Dwayne Weigel, Daniel Feehan, Doreen Feldman, Susan Irwin, and Robert Sanchez also made key contributions to this statement.

[9] DOE estimated that the program cost $4.1 billion, on the basis of year-of-expenditure dollars from the program's inception in 1983 through March 2002. The $5.5 billion estimate for the license application is based on year-of-expenditure dollars from 1983 through January 2006.