Spent Nuclear Fuel Pools in the U.S.:

Reducing the Deadly Risks of Storage

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Summary

As Japan's nuclear crisis continues, this report details the nature and extent of radioactive spent fuel stored at nuclear reactors across the United States and how it can be made less hazardous.

U.S. reactors have generated about 65,000 metric tons of spent fuel, of which 75 percent is stored in pools, according to Nuclear Energy Institute data. Spent fuel rods give off about 1 million rems (10,00Sv) of radiation per hour at a distance of one foot — enough radiation to kill people in a matter of seconds. There are more than 30 million such rods in U.S. spent fuel pools. No other nation has generated this much radioactivity from either nuclear power or nuclear weapons production.

Nearly 40 percent of the radioactivity in U.S. spent fuel is cesium-137 (4.5 billion curies) — roughly 20 times more than released from all atmospheric nuclear weapons tests. U.S. spent pools hold about 15-30 times more cesium-137 than the Chernobyl accident released. For instance, the pool at the Vermont Yankee reactor, a BWR Mark I, currently holds nearly three times the amount of spent fuel stored at Dai-Ichi's crippled Unit 4 reactor. The Vermont Yankee reactor also holds about seven percent more radioactivity than the combined total in the pools at the four troubled reactors at the Fukushima site.

Even though they contain some of the largest concentrations of radioactivity on the planet, U.S. spent nuclear fuel pools are mostly contained in ordinary industrial structures designed to merely protect them against the elements. Some are made from materials commonly used to house big-box stores and car dealerships.

The United States has 31 boiling water reactors (BWR) with pools elevated several stories above ground, similar to those at the Fukushima Dai-Ichi station. As in Japan, all spent fuel pools at nuclear power plants do *not* have steel-lined, concrete barriers that cover reactor vessels to prevent the escape of radioactivity. They are *not* required to have back-up generators to keep used fuel rods cool, if offsite power is lost. The 69 Pressurized Water (PWR) reactors operating in the U.S. do *not* have elevated pools, and also lack proper containment and several have large cavities beneath them which could exacerbate leakage.

For nearly 30 years, Nuclear Regulatory Commission (NRC) waste-storage requirements have remained contingent on the opening of a permanent waste repository that has yet to materialize. Now that the Obama administration has cancelled plans to build a permanent, deep disposal site at Yucca Mountain in Nevada, spent fuel at the nation's 104 nuclear reactors will continue to accumulate and are likely remain onsite for decades to come.

According to Energy Department data:

- The spent fuel stored at 28 reactor sites have between 200-450 million curies of long-lived radioactivity;

- 19 reactor sites have generated between 100-200 million curies in spent fuel; and,
- 24 reactor sites have generated about 10-100 million curies.

Over the past 30 years, there have been at least 66 incidents at U.S. reactors in which there was a significant loss of spent fuel water. Ten have occurred since the September 11 terrorist attacks, after which the government pledged that it would reinforce nuclear safety measures. Over several decades, significant corrosion has occurred of the barriers that prevent a nuclear chain reaction in a spent fuel pool — some to the point where they can no longer be credited with preventing a nuclear chain reaction. For example, in June 2010, the NRC fined Florida Power and Light $70,000 for failing to report that it had been exceeding its spent fuel pool criticality safety margin for five years at the Turkey Point reactor near Miami. Because of NRC's dependency on the industry self-reporting problems, it failed to find out that there was extensive deterioration of neutron absorbers in the Turkey Point pools and lengthy delays in having them replaced.

There are other strains being placed on crowded spent fuel pools. Systems required to keep pools cool and clean are being overtaxed, as reactor operators generate hotter, more radioactive, and more reactive spent rods. Reactor operators have increased the level of uranium-235, a key fissionable material in nuclear fuel to allow for longer operating periods. This, in turn, can cause the cladding, the protective envelope around a spent fuel rod, to thin and become brittle. It also builds higher pressure from hydrogen and other radioactive gases within the cladding, all of which adds to the risk of failure. The cladding is less than one millimeter thick (thinner than a credit card) and is one of the most important barriers preventing the escape of radioactive materials.

The April 26, 1986 nuclear catastrophe at Chernobyl in Ukraine illustrated the damage cesium-137 can wreak. Nearly 200,000 residents from 187 settlements were permanently evacuated because of contamination by cesium-137. The total area of this radiation-control zone is huge. At more than 6,000 square miles, it is equal to about two-thirds 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.

I co-authored a report in 2003 that explained how a spent fuel pool fire in the United States could render an area uninhabitable that would be as much as 60 times larger than that created by the Chernobyl accident. If this were to happen at one of the Indian Point nuclear reactors located 25 miles from New York City, it could result in as many as 5,600 cancer deaths and $461 billion in damages.

The U.S. government should promptly take steps to reduce these risks by placing all spent nuclear fuel older than five years in dry, hardened storage casks — something Germany did 25 years ago. It would take about 10 years at a cost between $3.5 and $7 billion to accomplish. If the cost were transferred to energy consumers, the expenditure would result in a marginal increase of less than 0.4 cents per kilowatt hour for consumers of nuclear-generated electricity.

Another payment option is available for securing spent nuclear fuel. Money could be allocated from

$18.1 billion in unexpended funds already collected from consumers of nuclear-generated electricity under the Nuclear Waste Policy Act to establish a disposal site for high-level radioactive wastes.

After more than 50 years, the quest for permanent nuclear waste disposal remains illusory.

One thing, however, is clear, whether we like it or not: the largest concentrations of radioactivity on the planet will remain in storage at U.S. reactor sites for the indefinite future. In protecting America from nuclear catastrophe, safely securing the spent fuel by eliminating highly radioactive, crowded pools should be a public safety priority of the highest degree.

With a price tag of as much as $7 billion, the cost of fixing America's nuclear vulnerabilities may sound high, especially given the heated budget debate occurring in Washington. But the price of doing too little is incalculable.

Introduction

As the nuclear crisis at the Dai-Ichi reactors in Japan's Fukushima prefecture continue to unfold, the severe dangers of stored spent nuclear fuel in pools are taking center stage. It is now clear that at least one spent fuel pool lost enough water to expose highly radioactive material, which then led to a hydrogen explosion and a spent fuel fire that destroyed the reactor building of the Unit 4. Radioactive fuel debris was expelled up to a mile away.[1] A second pool at Unit 3 experienced significant damage from a hydrogen explosion from the venting of the reactor vessel (Figures 1, 2, 3 and 4).

In a desperate effort to prevent another explosion and catastrophic fire, lead-shielded helicopters and water cannons dumped thousands of tons of water onto Unit 4's pool.[2] Nearly two months later, the pool remains close to boiling and is still emitting high doses of radiation. Pool water sampling indicates that the spent fuel rods are damaged to the point where uranium fission is taking place.[3] Spent fuel pools at two of the Fukushima Dai-Ichi reactors are exposed to the open sky.

On April 12, the Japanese government announced that the Dai-Ichi nuclear disaster in Fukushi-

Figure 1: Explosion Sequence at Reactor No. 3
March 13, 2011

Source: Associated Press/NTV.

Figure 2: Reactor No. 3 Spent Fuel Pool Area

Source: Air Photo Service Co. Ltd., Japan, March 24, 2011

Figure 3: Hydrogen Explosion at Reactor Fuel Pool No. 4
March 15, 2011

Source: ABC Tv/EPA

Figure 4: Destruction at Reactor No. 4 Pool

Source: Associated Press

ma was as severe as the 1986 Chernobyl accident. According to Japan's Nuclear and Industrial Safety Agency, between March 11 and early April, between 10 and 17 million curies (270,000 – 360,000 TBq) of radioiodine and radiocesium were released to the atmosphere — an average of 417,000 curies per day.[4] The average daily atmospheric release after between April 5 and 25 was estimated at 4,200 curies per day (154 TBq). The radioactivity discharged into the sea from Unit 2 alone was estimated at 127,000 curies (4,700 TBq).[5]

Implications for the United States

This tragic event is casting a spotlight on the spent fuel pools at U.S. nuclear reactors, which store some of the largest concentrations of radioactivity on the planet. For nearly 30 years, Nuclear Regulatory Commission waste-storage requirements have been contingent on the timely opening of a permanent waste repository. This has allowed plant operators to legally store spent fuel in onsite cooling pools much longer, and at higher densities (on average four times higher), than was originally intended. Spent fuel pools were designed to be temporary and to store only a small fraction of what they currently hold.

"Neither the AEC [Atomic Energy Commission, now the Energy Department] nor utilities anticipated the need to store large amounts of spent fuel at operating sites," said a report by Dominion Power, the owner of the Millstone nuclear reactor in Waterford, Connecticut in October 2001. "Large-scale commercial reprocessing never materialized in the United States. As a result, operating nuclear sites were required to cope with ever-increasing amounts of irradiated fuel... This has become a fact of life for nuclear power stations."

The spent fuel stockpiled at U.S. nuclear reactors holds between five and ten times more long-lived radioactivity than the reactor cores themselves. The underlying assumption of the NRC policy allowing for expanded pool storage is that in the near future the government will permanently dispose of it all, as required under the 1982 Nuclear Waste Policy Act. As a result, only 25 percent of the 65,000 metric tons of America's spent fuel is stored in dry casks today.

Without decisive action, the problem will only grow larger and more dangerous. U.S. nuclear reactors generate about 2,000 metric tons of spent fuel each year.

The Obama administration has canceled long-contested plans to develop a permanent, deep disposal site at Yucca Mountain in Nevada. The prospects for establishing a disposal site for spent fuel are increasingly dim. Without decisive action, spent fuel at the nation's nuclear reactors will accumulate and remain onsite for decades to come.

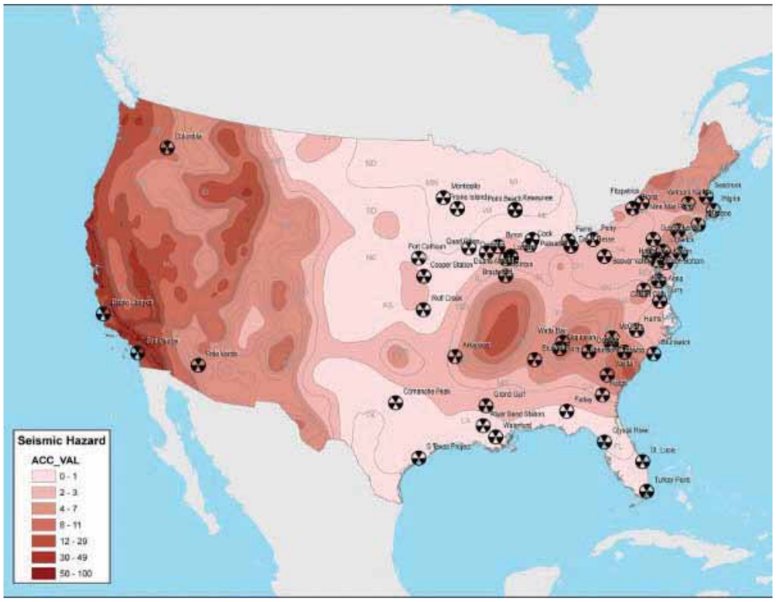
Spent Nuclear Fuel Stored in U.S. Reactors

There are 104 U.S. commercial nuclear reactors operating at 64 sites in 31 states that are holding some of the largest concentrations of radioactivity on the planet in onsite spent fuel pools. The pools, typically rectangular or L-shaped basins about 40 to 50 feet deep, are made of reinforced concrete walls four to five feet thick and stainless steel liners. Basins without steel liners are more susceptible to cracks and corrosion. Most of the spent fuel ponds at boiling water reactors are housed in reactor buildings several stories above ground. Pools at pressurized water reactors are partially or fully embedded in the ground, sometimes above tunnels or underground rooms.

According to estimates provided by the Department of Energy, as of this year this spent fuel contains a total of approximately 12 billion curies of long-lived radioactivity (Table 1).[6] Of the 65,000 metric tons estimated by the Nuclear Energy Institute to be generated by the end of 2010, 75 percent is in pools, while the remainder is in dry storage casks. Several of these reactors are located in earthquake zones (Figure 5).

The Energy Department provided this estimate in 2002 to project the amount of spent fuel that would be placed in a geologic repository — a failed plan predicated on the presumption that such a site would

Figure 5: U.S. Nuclear Power Reactors in Earthquake Zones



Source: Greenpeace

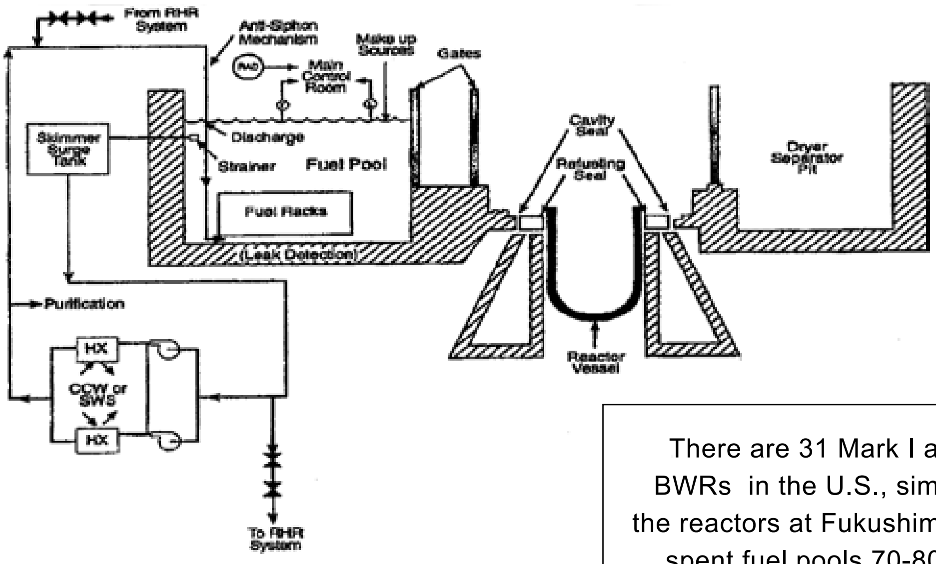
Table 1: Estimated Radioactivity in U.S. Nuclear Reactor Spent Fuel

Isotope	Half Life (years)	Radioactivity (ci)		Isotope	Half Life (years)	Radioactivity (ci)
Hydrogen-3	12.3	10,200,000		Europium-154	8.6	120,000,000
Carbon-14	5,700.0	95,000		Europium-155	4.8	22,000,000
Chlorine-36	30,000.0	750		Actinium-227	2.2	1
Iron-55	2.7	420,000		Thorium-230	75,000.0	18
Colbalt-60	5.3	27,000,000		Protactinium-231	33,000.0	2
Nickel-59	76,000	160,000		Uranium-232	69.0	2,600
Nickel-63	100.0	22,000,000		Uranium-233	69.0	4
Selenium-79	64,000.0	30,000		Uranium-234	250,000.0	84,000
Krypton-85	10.7	150,000,000		Uranium-235	720,000,000.0	1,000
Strontium-90	29.0	3,000,000,000		Uranium-236	23,000,000.0	18,000
Zirconium-93	1,500,000.0	160,000		Uranium-238	4,500,000,000.0	20,000
Niobium-93m	16.0	110,000		Plutonium-241	14.0	3,200,000,000
Niobium-94	24,000.0	56,000		Plutonium-238	88.0	240,000,000
Technetium-99	210,000.0	950,000		Americium-241	430	220,000,000
Rutherium-106	1.0	4,700		Curium-244	18	120,000,000
Palladium-107	6,500,000.0	8,800		Plutonium-240	6,500	36,000,000
Cadmium-133m	14.0	1,500,000		Plutonium-239	24,000	24,000,000
Antimony-125	2.8	3,600,000		Americium-243	7,400.0	1,900,000
Tin-126	1,000,000.0	59,000		Americium-242/242m	140.0	1,600,000
Iodine-129	17,000,000.0	2,400		Curium-242	0.5	1,300,000
Cesium-134	2.1	5,800,000		Curium-243	29.0	1,300,000
Cesium-135	2,300,000.0	36,000		Plutonium-242	380,000.0	140,000
Cesium-137	30.0	4,500,000,000		Neptunium-237	2,100,000.0	30,000
Promethium-147	2.6	18,000,000		Curium-245	8,500.0	29,000
Samarium-151	90	25,000,000		Curium-246	4,800.0	6,300
Total: 12,000,000,000 ci						

Source: DOE/EIS-0250, Appendix A

have ultimately been established by January 1998. The government's estimate of radioactivity in spent fuel is lower than actual amounts at reactors because it does not include other isotopes that have decayed away after 23 years and only includes long-lived radioactivity with half-lives ranging from tens of years to millions of years.

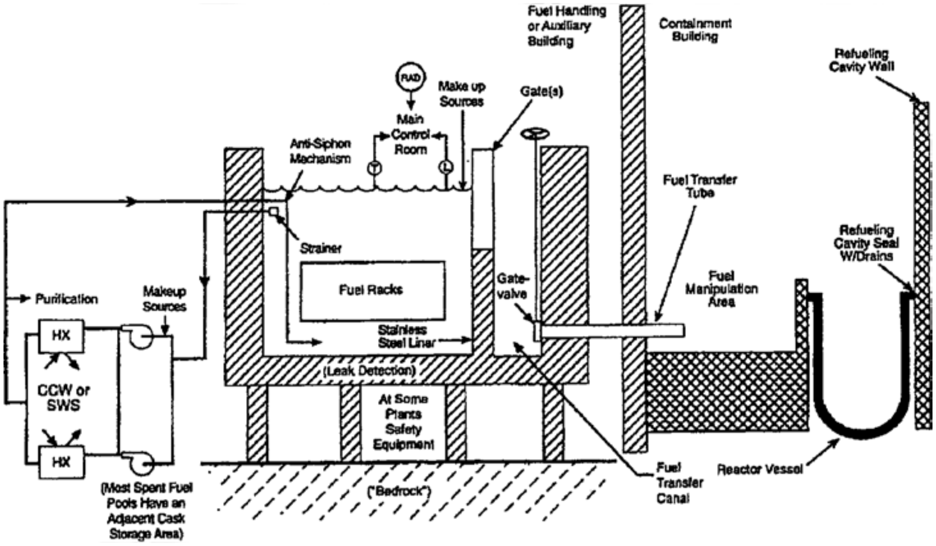
Figure 6: Layout of Spent Fuel Pool and Transfer System for Boiling Water Reactors (BWR)



There are 31 Mark I and II BWRs in the U.S., similar to the reactors at Fukushima, with spent fuel pools 70-80 feet above ground.

Source: U.S. Nuclear Regulatory Commission, NUREG-1275.

Figure 7: Layout for Spent Fuel Pool and Transfer System for Pressurized Water Reactors



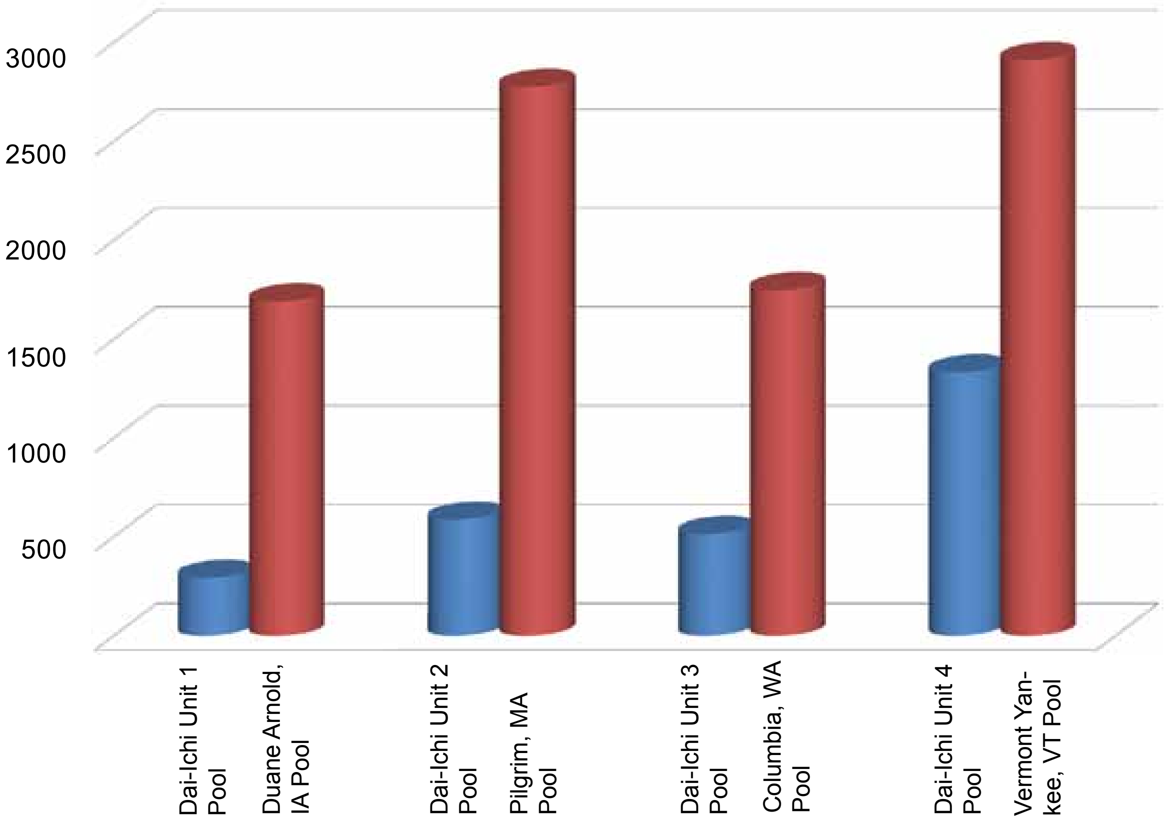
Source: U.S. Nuclear Regulatory Commission, NUREG-1275.

The actual amount of radioactivity in spent fuel at U.S. reactors is higher because of higher "burn-ups" than DOE's estimate and the constant generation of shorter-lived isotopes.[7]

There are 69 pressurized-water reactors (PWRs) and 35 boiling-water reactors (BWRs) across the country. In addition, there are 14 previously operating light-water-cooled power reactors in various stages of decommissioning. As Figure 6 shows, about 50 U.S. nuclear reactors — nearly half of them — are in earthquake zones.

Some of these reactors share spent-fuel pools, so that there are a total of 65 PWR and 35 BWR pools. There are 31 Mark I and II BWRs in the United States that built with same basic design of the Dai-Ichi reactors in Fukushima. They have elevated pools — some 70-80 feet above ground.[8] Figures 6 and 7 show diagrams of "generic" pressurized water reactor (PWR) and boiling water reactors Mark I and II (BWR Mark I and II) spent-fuel pools. Pools at pressurized water reactors — representing about two-thirds of all pools — are partially or fully embedded in the ground, sometimes above tunnels or underground rooms.

Figure 8: Spent Fuel Assemblies in Pools at the Dai-Ichi Nuclear Complex in Fukushima and Indvidual U.S. Boiling Water Reactors



Sources: All Things Nuclear, Union of Concerned Scientists, March 21, 2011; NEI, March 2011; DOE/EIS-0250, Appendix A, Table A-7, Energy NW, March 29, 2011.

Spent fuel pools at nuclear reactors contain a substantially larger inventory of irradiated fuel than the reactors. Typical 1,000-megawatt PWR and BWR reactor cores contain about 80 metric tons and 155 metric tons10 respectively, while their pools typically contain 400 to 500 metric tons.[9] About 40 percent of the total radioactivity in spent fuel (4.5 billion curies) for both designs is from cesium-137. This is about four to five times the amount of cesium-137 in their reactor cores. For example, Vermont's Yankee boiling water Mark I reactor holds nearly three times the amount of spent fuel that was stored in the pool at the crippled Fukushima Dai-Ichi Unit 4 reactor (Figure 8).

Spent fuel at U.S. nuclear reactors contains roughly 20 times more cesium-137 than was released by more than 650 atmospheric nuclear weapons tests throughout the world.[11]

Based on estimates provided by the Energy Department there are:

Figure 9: Spent Fuel Inventories Greater than 200 Million Curies

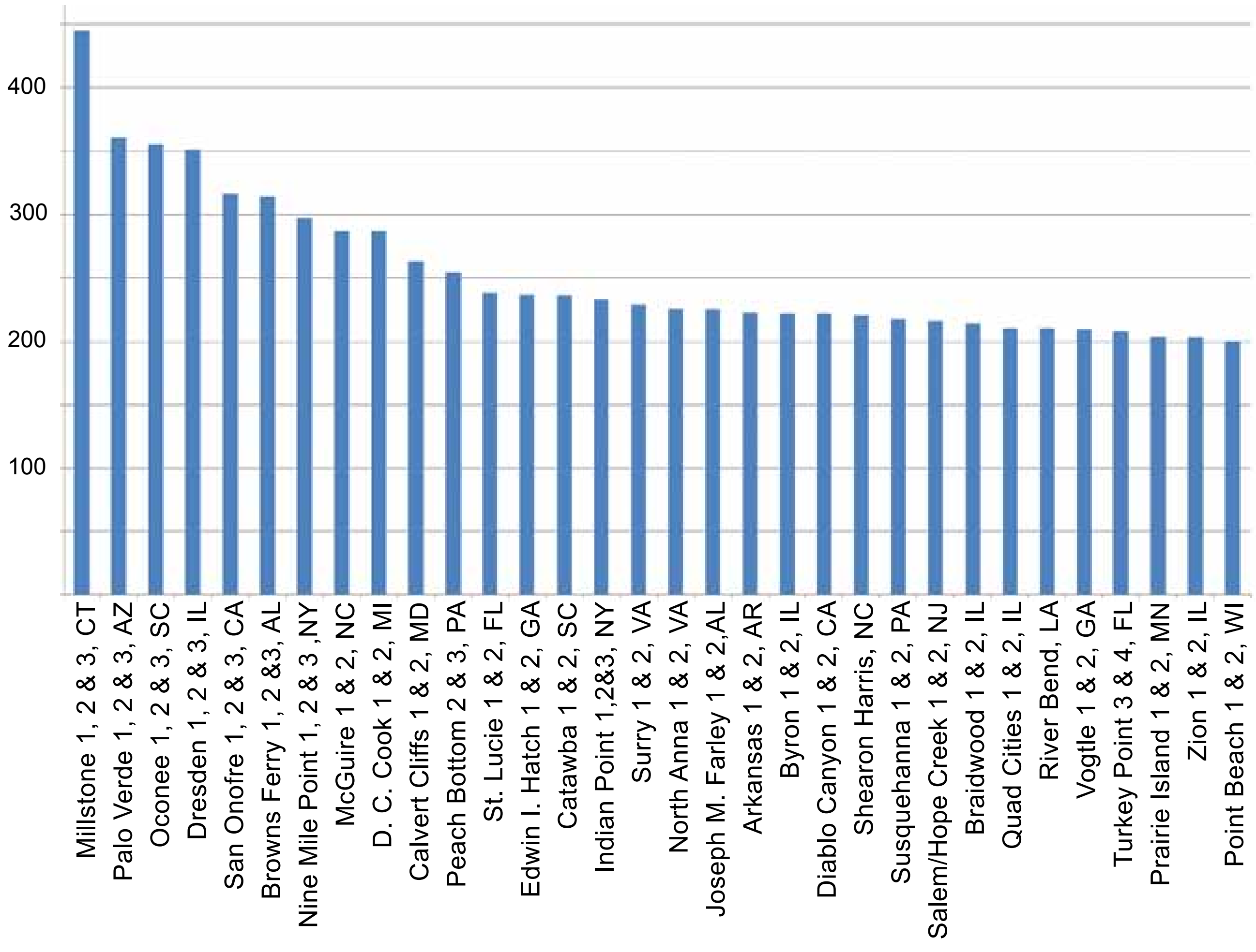
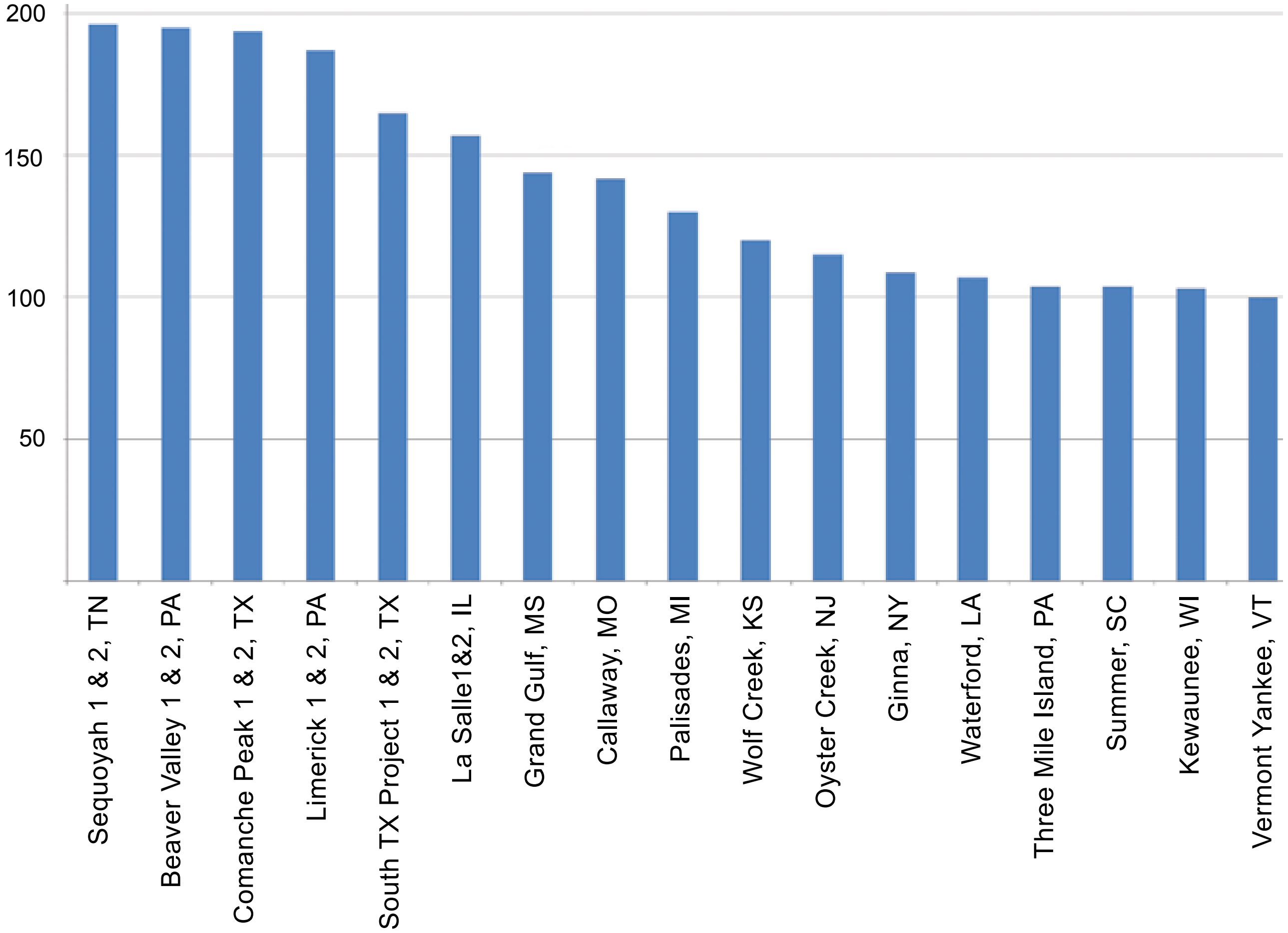


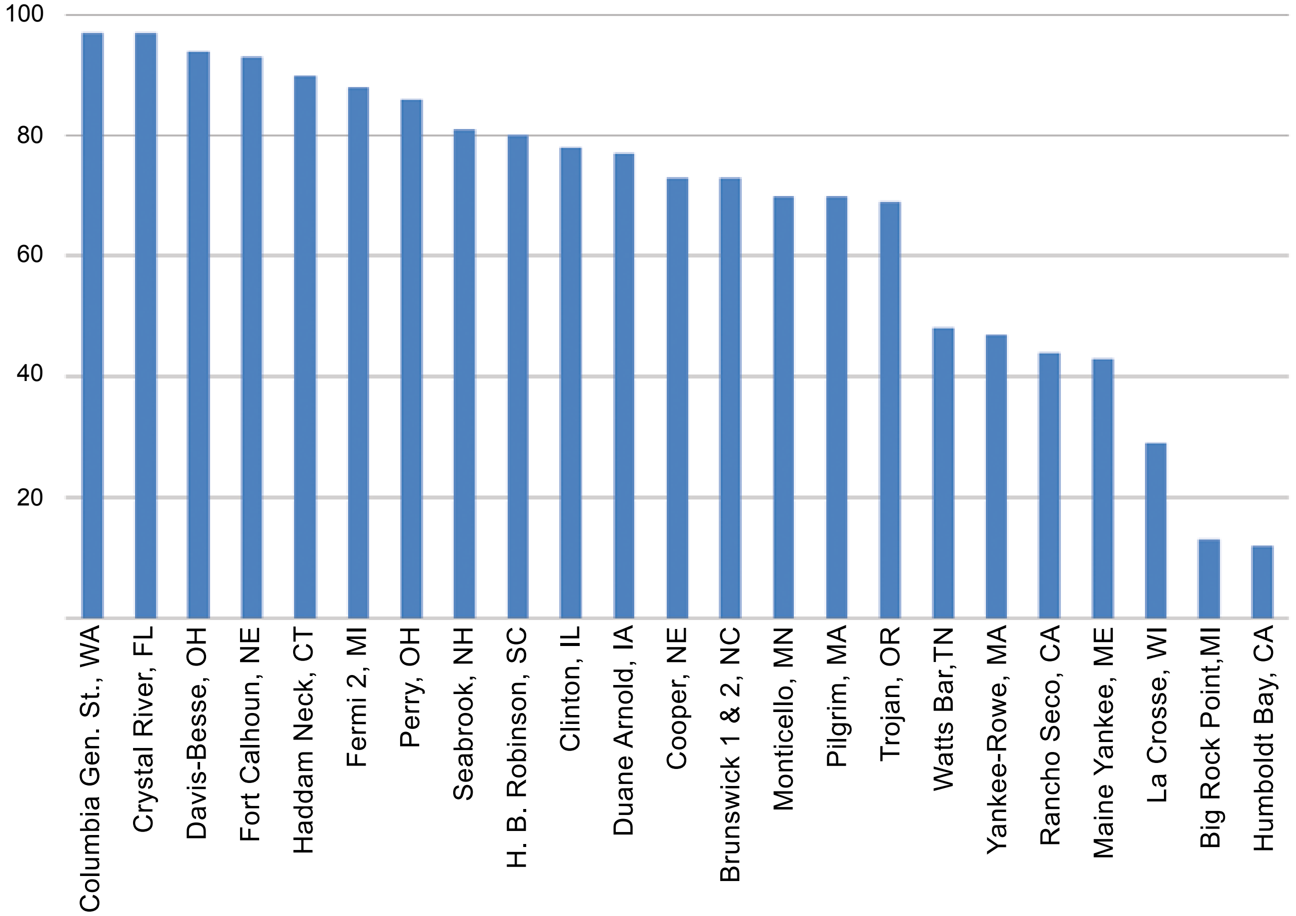
Figure 10: Spent Fuel Inventories Between 100 - 200 million curies



- 28 reactor sites that have generated spent fuel containing about 200-450 million curies of radioactivity (Figure 9);
- 19 reactor sites that have generated spent fuel containing about 10-100 million curies of radioactivity (Figure 10); and
- 24 reactor sites that have generated about 10-100 million curies (Figure 11).

High-density spent fuel pool storage at U.S. nuclear reactors is soon to reach its maximum capacity (Figure 12). The government and the private corporations that own the nation's nuclear reactors have treated the storage of spent fuel as an afterthought for years. They presumed that a safer system for disposal was would be established no later than 1998, as mandated by the 1982 Nuclear Waste Policy Act. Before President Obama terminated the Yucca Mountain disposal project, which was slated to open in 2020, the opening date had slipped by over two decades.

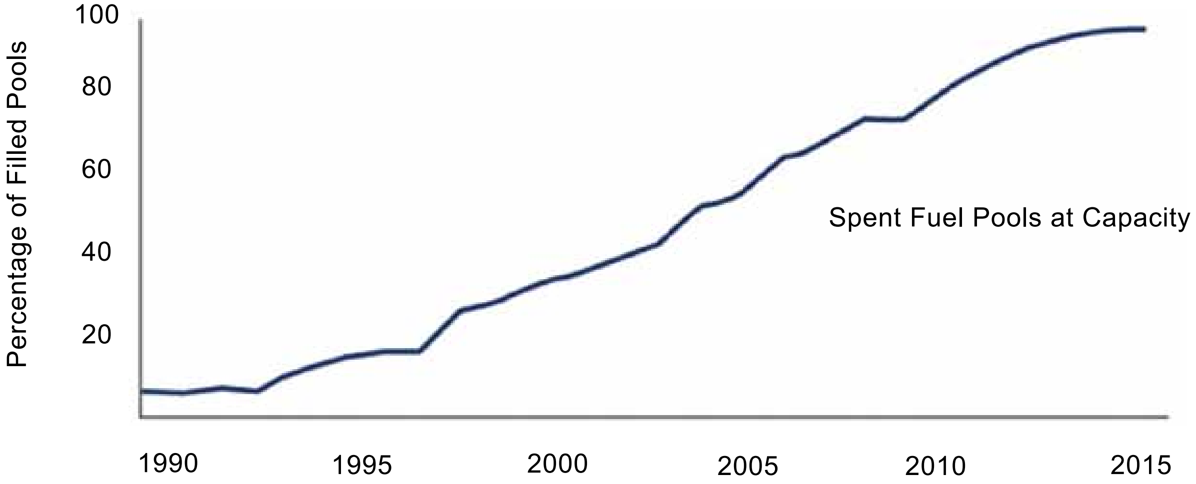
Figure 11: Spent Fuel Inventories Between 10 - 100 million curies



In 1982, after embarrassing failures by the Atomic Energy Commission (the predecessor of the Nuclear Regulatory Commission and the Energy Department) to select a disposal site on its own, Congress enacted the Nuclear Waste Policy Act, which began the selection process for multiple sites throughout the United States. This process was scrapped five years later due to eastern states derailing the selection process. Congress then voted to make Yucca Mountain in Nevada the only site to be considered. Yet Yucca's proposed opening date slipped by more than 20 years as the project encountered major technical hurdles and fierce local and state opposition.

In January 2010, President Barack Obama cancelled plans to build the Yucca Mountain site and formed the Blue Ribbon Commission on America's Nuclear Future. The commission is tasked with rebooting the country's five-decade-plus effort to manage its high-level radioactive waste. It is scheduled to provide interim recommendations by the summer of this year and a final report by January 2012. It is reviewing the

Figure 12: High-Density Spent Fuel Pools at U.S. Nuclear Reactors are Soon to Reach their Maximum Capacity



Source: *Power Magazine*, May 2010. Available on line: http://www.powermag.com/nuclear/The-U-S-Spent-Nuclear-Fuel-Policy-Road-to-Nowhere_2651_p6.html

government's management of the nuclear fuel cycle and is to consider all alternatives for the storage, processing, and disposal of used nuclear fuel, high-level waste, and other hazardous materials derived from nuclear activities. Among the commission's top priorities is to make recommendations regarding U.S. policy for the storage of spent fuel at U.S. nuclear reactors.

In the wake of Japan's unfolding nuclear crisis, the United States needs a new policy that takes into account the likelihood of the indefinite storage of spent fuel at nuclear reactors.

U.S. Regulation of Spent Nuclear Fuel

As in Japan, U.S. spent nuclear fuel pools are not required to have "defense-in-depth" nuclear safety features. They are not under the heavy containment that covers reactor vessels. Reactor operators are not required have back-up power supplies to circulate water in the pools and keep them cool, if there is a loss of off-site power. In the recent past some U.S. reactor control rooms lacked instrumentation keeping track of the pools' water levels. At one reactor, water levels dropped to a potentially dangerous level after operators failed to bother to look into the pool area. Some reactors may not have necessary water restoration capabilities for pools. Quite simply, spent fuel pools at nuclear reactors are not required to have the same level of nuclear safety protection as reactors.

Between 1981 and 1996, the NRC reported that there were at least 56 events that resulted in the loss of spent fuel coolant. Several events lasted for more than 24 hours. The majority of the losses occurred through connective systems involving the transfer of spent fuel from the reactor or to casks. Seven losses occurred from leakage in pool liners. Large losses also occurred though gates and seals connected to the fuel cavity pool in which spent fuel is discharged. Here is how the NRC summed up one such incident in Connecticut: "At Haddam Neck on August 21, 1984, the seal failed, and about 200,000 gal [gallons] of water was drained to the containment building in about 20 min [minutes]."[12]

Since that time, at least 10 instances of spent fuel cooling water losses have occurred. Two involved pool liner leaks.[13]

Reactor operating cycles have been doubled from 12 to 24 months in order to generate more electricity. As a result, more spent fuel with higher radioactivity and thermal heat is being offloaded into ever-more-crowded pools during each refueling outage. This places a strain on pool cooling and cleaning systems making spare pumps and heat exchangers operate for periods far longer than originally intended.

High-density racks in spent fuel pools pose potential criticality safety concerns with aluminum-borate panels that allow spent fuel rods to be more closely packed. Since 1983, several incidents have occurred with these panels in which the neutron-absorbing materials bulged, causing spent fuel assemblies, containing dozens of rods each, to become stuck in submerged storage racks in the pools. This problem could lead to structural failures in the storage racks holding the spent fuel rods in place. According to the NRC: "It was discovered upon investigation that there had been water ingress into the stainless steel sandwich, and the aluminum in the Boral [neutron absorbing material] had reacted chemically with the water to produce hydrogen gas and aluminum oxide. The hydrogen gas pressure had built up to the point where the stainless steel cladding bulged." Blisters were also found to be forming on the panels.[14] This problem remains ongoing.[15] The problem has worsened to the point where degradation of neutron absorbers have reach the point in some reactors where they can no longer be relied on to prevent a criticality. The corrosion, in turn is releasing particles in the water placing an additional strain on pool water cleaning systems.

According to the NRC in May 2010:

> The conservatism/margins in spent fuel pool (SFP) criticality analyses have been decreasing…The new rack designs rely heavily on permanently installed neutron absorbers to maintain criticality requirements. *Unfortunately, virtually every permanently installed neutron absorber, for which a history can be established, has exhibited some degradation. Some have lost a significant portion of their neutron absorbing capability. In some cases, the degradation is so extensive that the permanently installed neutron absorber can no longer be credited in the criticality analysis [emphasis added].*[16]

In January 2010, the NRC reported that neutron absorber material in the spent fuel pool at the Turkey Point Reactor near Miami, Florida had degraded to the point where protection against a chain reaction could not be assured. According to NRC, "this finding was more than minor because the design control attribute that assured fuel assemblies remain subcritical in the spent fuel pool was affected."[17] In effect, the spent fuel pool at Turkey Point had exceeded its criticality safety margin for some five years before the NRC discovered this problem.[18]

Equipment installed to make high-density pools safe actually exacerbates the danger that they will catch on fire, particularly with aged spent fuel. In high-density pools at pressurized water reactors, fuel assemblies are packed about nine to 10.5 inches apart,¬ just slightly wider than the spacing inside a reactor. To compensate for the increased risks of a large-scale accident, such as a runaway nuclear chain reaction, pools have been retrofitted with enhanced water chemistry controls and neutron-absorbing panels between assemblies.

The extra equipment restricts water and air circulation, making the pools more vulnerable to systemic failures. If the equipment collapses or fails, as might occur during a terrorist attack, for example, air and water flow to exposed fuel assemblies would be obstructed, causing a fire, according to the NRC's report. Heat would turn the remaining water into steam, which would interact with the zirconium, making the problem worse by yielding inflammable and explosive hydrogen. As a result, the NRC concluded that "it is not feasible, without numerous constraints, to define a generic decay heat level (and therefore decay time) beyond which a zirconium fire is not physically possible."

Consequences of a Spent Fuel Pool Fire

For the past 30 years, nuclear safety research has consistently pointed out that severe accidents could occur at spent fuel pools resulting in catastrophic consequences. A severe pool fire could render about 188 square miles around the nuclear reactor uninhabitable, cause as many as 28,000 cancer fatalities, and spur $59 billion in damage, according to a 1997 report for the NRC by Brookhaven National Laboratory done for the NRC.

If the fuel were exposed to air and steam, the zirconium cladding would react exothermically, catching fire at about 800 degrees Celsius. Particularly worrisome is the large amount of cesium-137 in spent fuel pools, which contain anywhere from 20 to 50 million curies of this dangerous isotope. With a half-life of 30 years, cesium-137 gives off highly penetrating radiation and is absorbed in the food chain as if it were potassium. As much as 100 percent of a pool's cesium 137 would be released into the environment in a fire, according to the NRC.

While it's too early to know the full extent of long-term land contamination from the accident at the Dai-Ichi station in Fukushima, fragmentary evidence has been reported of high cesium-137 levels offsite. The Nuclear Regulatory Commission also has reported that spent fuel fragments from the explosion the Unit 4 pool were found a mile away.

The damage from a large release of fission products, particularly cesium-137, was demonstrated at Chernobyl. More than 100,000 residents from 187 settlements were permanently evacuated because of contamination by cesium-137. The total area of this radiation-control zone is huge: more than 6,000 square miles, equal to roughly two-thirds the area of the State of New Jersey (Figure 13). During the following decade, the population of this area declined by almost half because of migration to areas of lower contamination.

2003 Study

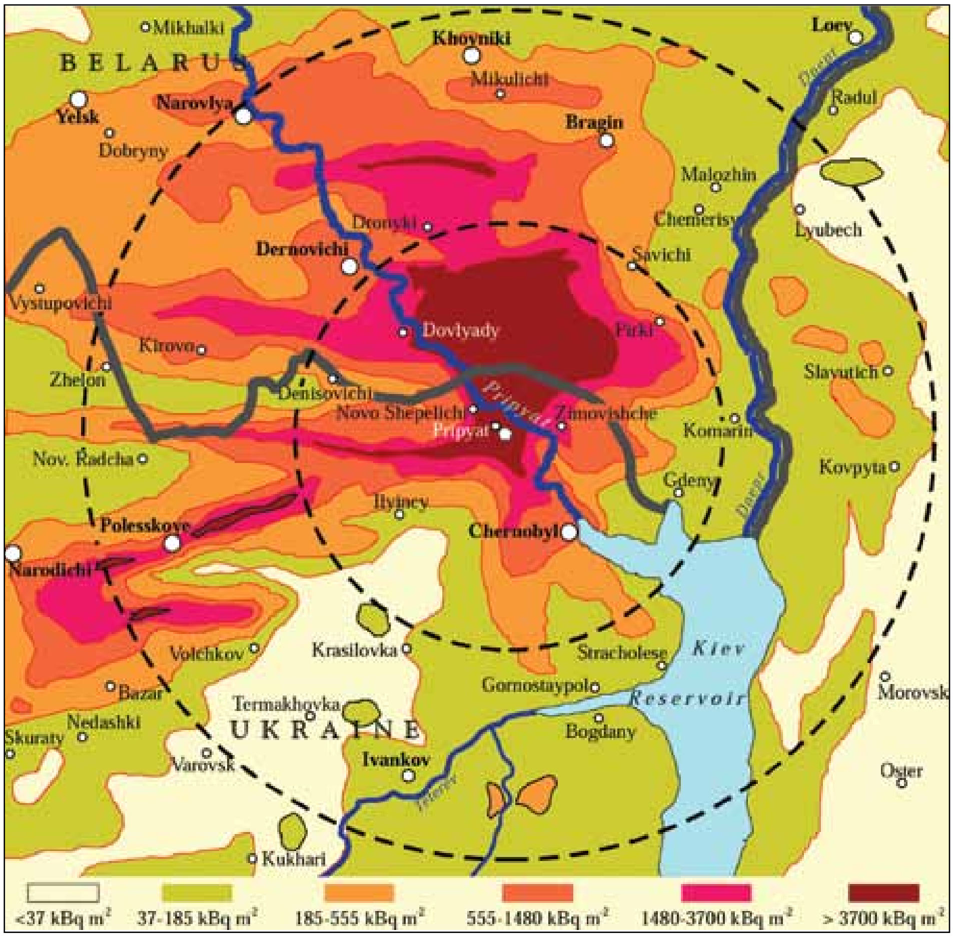
In the summer of 2002, the Institute for Policy Studies helped organize a working group including experts from from academia, the nuclear industry, former government officials, and non-profit research groups to perform in in-depth study of the vulnerabilities of spent power reactor fuel pools to terrorist attacks. By January 2003, our study was completed and accepted for publication in the peer-review journal *Science and Global Security*.[19]

We warned that U.S. spent fuel pools were vulnerable to acts of terror. The drainage of a pool might cause a catastrophic radiation fire, which could render an area uninhabitable much greater than that created by the Chernobyl accident (Figure 14).[20]

In addition to terrorist acts, there are several events could cause a loss of pool water, including leakage, evaporation, siphoning, pumping, aircraft impact, earthquake, the accidental or deliberate drop of a fuel transport cask, reactor failure, or an explosion inside or

Figure 13: Cesium-137 Released by Chernobyl

The distances of 18 miles (permanently evacuated) and 36 miles from the nuclear power plant are indicated.



>15 Ci/km^2: radiation control area:
10,000 km^2
(1/2 area of NJ)

>50 Ci/km^2: >0.7% chance of radiation-caused cancer death from livetime external radiation:
3,100 km^2
(roughly the size of RI)

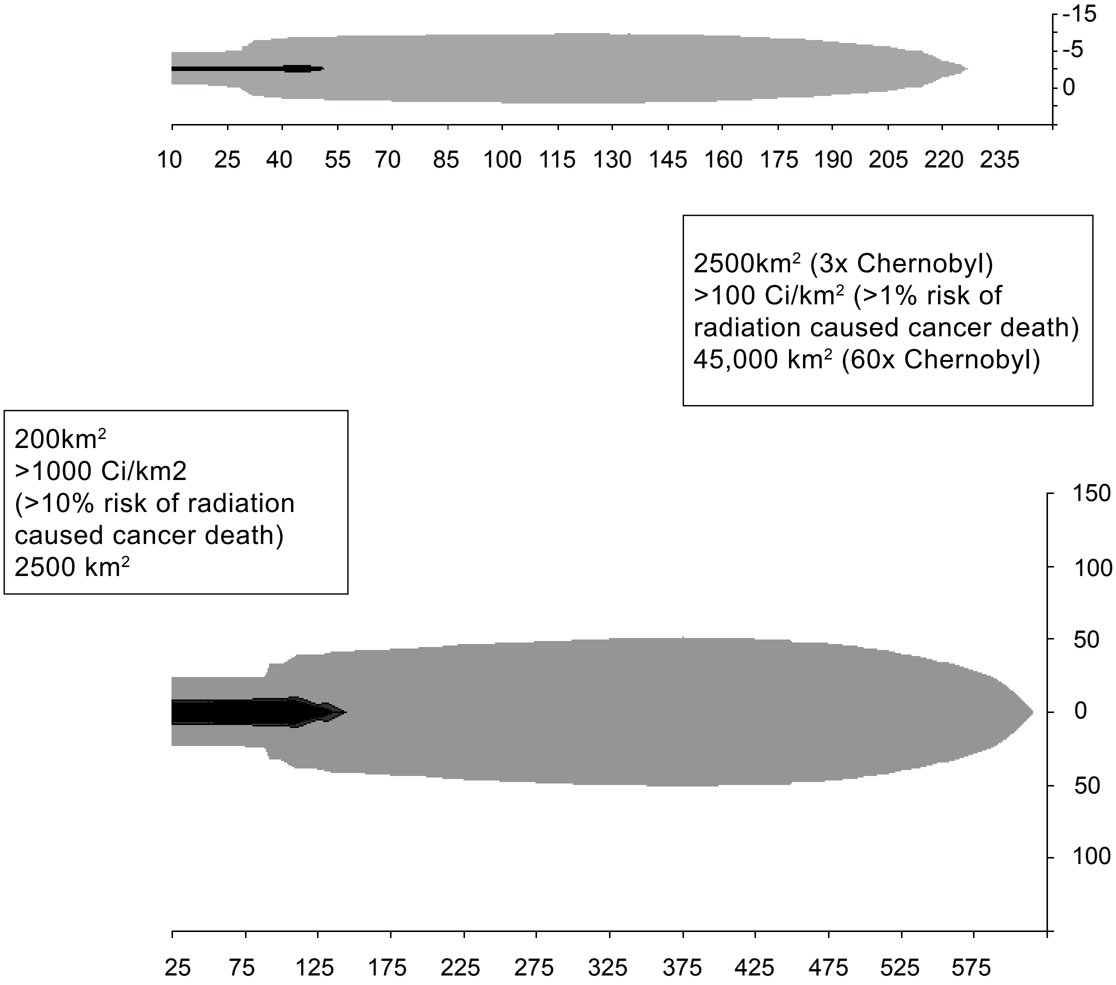
Source: *Exposures and effects of the Chernobyl Accident*, UNSCEAR, 2000. Available at: http://www.unscear.org/docs/reports/2000/Volume%20II_Effects/AnnexJ_pages%20451-566.pdf

outside the pool building. Industry officials maintain that personnel would have sufficient time to provide an alternative cooling system before the spent fuel caught fire. But if the water level dropped to just a few feet above the spent fuel, the radiation doses in the pool building would be lethal — as was demonstrated by the loss of water in at least two spent fuel pools at the Fukushima Dai-Ichi nuclear power station.

The NRC and nuclear industry consultants disputed the paper, which prompted Congress to ask the National Academy of Sciences to sort out this controversy.

In 2004, the Academy reported that U.S. pools were vulnerable to terrorist attack and to catastrophic fires. According the Academy:

Figure 14: MACCS2 Code Prediction for Smoldering Pool Fire Releasing ^{137}Cs into a 10 mph Steady Wind



2500km^2 (3x Chernobyl)
>100 Ci/km^2 (>1% risk of radiation caused cancer death)
45,000 km^2 (60x Chernobyl)

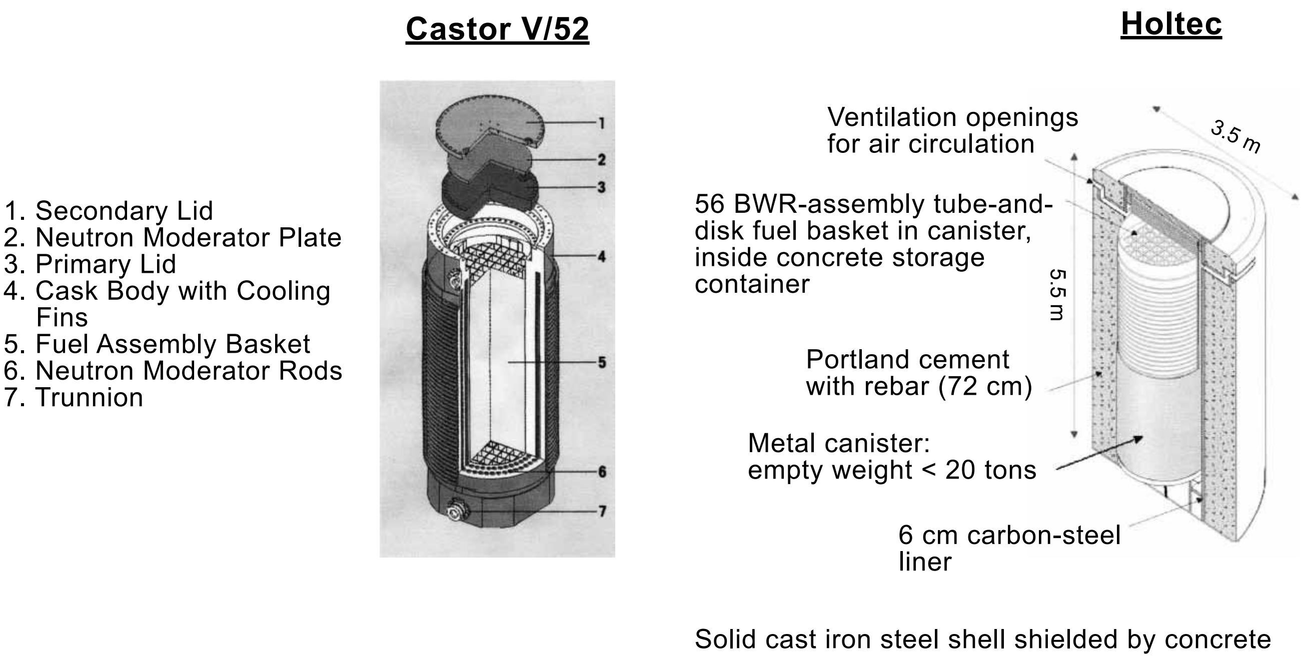
200km^2
>1000 Ci/km2
(>10% risk of radiation caused cancer death)
2500 km^2

Note: Drawings have different scales.

Source: F. von Hippel, presentation to NAS, February 12, 2004.

"A loss-of-pool-coolant event resulting from damage or collapse of the pool could have severe consequences…It is not prudent to dismiss nuclear plants, including spent fuel storage facilities as undesirable targets for terrorists…under some conditions, a terrorist attack that partially or completely drained a spent fuel pool could lead to a propagating zirconium cladding fire and release large quantities of radioactive materials to the environment…Such fires would create thermal plumes that could potentially transport radioactive aerosols hun-

Figure 15: Two Types of Dry Storage Casks



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dreds of miles downwind under appropriate atmospheric conditions."[21]

The NRC's response to this was to attempt to block the release of the Academy's report.

To reduce this hazard we recommended that *all* U.S. spent fuel older than five years should be placed in dry, hardened storage containers, greatly reducing the fire risk if water was drained from reactor cooling pools (Figure 15).

These steps were taken by the German nuclear industry 25 years ago, after several jet crashes and terrorist acts at non-nuclear locations. In March 2010, NRC Chairman Gregory Jaczko told industry officials at an NRC-sponsored conference that spent fuel should be primarily stored in dry, hardened, and air-cooled casks that met safety and security standards for several centuries. Yet today, only 25 percent of the 65,000 metric tons of domestic spent fuel is stored in such casks.

Nuclear reactor owners only resort to using dry casks when they can no longer fill the spent fuel pools. Based on this practice, reactor pools will be still hold enormous amounts of radioactivity, well more than original designs for decades to come.

In this regard, the National Academy panel also agreed that dry casks are safer than pools, but the safety and security of these casks needed improvement.

"Dry cask storage for older, cooler spent fuel has two inherent advantages over pool storage:

> It is a passive system that relies on natural air circulation for cooling; and it divides the inventory of that spent fuel among a large number of discrete, robust containers. These factors make it more difficult to attack a large amount of spent fuel at one time and also reduce the consequences of such attacks."[22]

> "Simple steps …could be taken to reduce the likelihood of releases of radioactive material from dry casks in the event of a terrorist attack. Additional surveillance could be added to dry cask storage...to detect and thwart ground attacks. Certain types of cask systems could be protected against aircraft strikes by partial earthen berms. Such berms also would deflect the blasts from vehicle bombs."[23]

Finally, the Academy panel concluded that inclusion of public input and greater transparency is essential.

> "The…public is an important audience for the work being carried out to assess and mitigate vulnerabilities to spent fuel storage facilities. While it is inappropriate to share all information publicly, more constructive interaction with the public and independent analysts could improve the work being carried out, and also increase confidence in the nuclear Regulatory Commission and industry decisions and actions to reduce the vulnerability of spent fuel storage to terrorist threats"[24]

Dry Storage Costs

We estimated that the removal of spent fuel older than five years could be accomplished with existing cask technology in 10 years at a cost of $3 billion to $7 billion. This would allow for open rack storage of the hottest fuel and could expose at least one side of each assembly to an open channel, allowing for greater air convection, reducing the risks of fuel fires. The expense would add a marginal increase to the retail price of nuclear-generated electricity of between 0.4 to 0.8 percent. The availability of casks could be limiting, but is not insurmountable.

In November 2010, a study by the Electric Power Research Institute released an analysis of the costs associated with our recommendations. "While EPRI agrees that moving spent fuel into dry storage after five years is not justified," the study states, "EPRI's members requested a study be made of the impacts of doing so."[25]

EPRI concluded "that a requirement to move spent fuel older than five years (post reactor operations) from spent fuel pools into dry storage would cause significant economic and worker dose impacts while providing no safety benefit to the public."

EPRI agreed with our lower estimate stating that the cost for the cost for the early transfer of spent fuel storage into dry storage is $3.6 billion. According to the EPRI analysis, "the increase is primarily related to the additional capital costs for new casks and construction costs for the dry storage facilities. The increase in net present value cost is $92-$95 million for a representative two-unit pressurized water reactor; $18-$20 million for a representative single-unit boiling water reactor; and $22-$37 million for a representative single unit new plant."[26]

But the study also found that, "the three-to four-fold increase in dry storage system fabrication capability would require increased NRC inspection and oversight of cask designers, fabricators and dry storage loading operations. In addition, more than 20 nuclear power plant sites would have to load more than 15 dry storage systems annually — representing a two- to four-fold increase in the rate of cask loading — placing pressure on spent fuel pool cranes and other systems during routine operations and outages."

In our 2003 study, we found that:

> "Cask availability could be a rate-limiting step in moving older spent fuel from pools into dry storage at the reactor sites. Currently, U.S. 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."[27]

Besides the increased cost, and additional burdens it placed on reactor owners, the NRC and cask manufacturers, the EPRI study argued against our proposal because it would result in increased occupational exposures. Upon further examination EPRI's estimate would result in a 4 percent increase in the collective radiation exposure to workers over the next 88 years.[28] This increase in worker doses is not insurmountable obstacle if better radiation shielding and administrative controls were implemented.

Achieving this goal cannot occur by individual reactors owners without a federal policy that allows for the costs of expanding dry, hardened spent fuel storage to be taken from the electricity rates paid for by consumers of nuclear generated electricity. The 1982 Nuclear Waste Policy Act (NWPA) established a user fee to pay 0.1 cent per kilowatt hour for the search and establishment of a high-level radioactive waste repository, but does not allow these funds to be used to enhance the safety of onsite spent fuel storage.

As of fiscal year 2010, only $7.3 billion has been spent out of a total of $25.4 billion collected by 2010, leaving $18.1 billion unspent.[29] This large unexpended balance could more than pay for the storage of spent reactor fuel older than five years at all reactors. Safely securing the spent fuel that's currently in crowded pools should be a public safety priority of the highest degree in the U.S. The cost of fixing America's nuclear vulnerabilities may be high, but the price of doing too little is incalculable.

Appendix A: Site Specific Estimates of Radioactvity in U.S. Spent Fuel

Site	State	Reactor Type	Total Assemblies	Metric tons	Radioactive Inventory (Ci)
Arkansas 1 & 2	AR	2 PWRs	2,526	1,109	222,793,200
Beaver Valley 1 & 2	PA	2 PWRs	2,206	1,018	194,569,200
Big Rock Point	MI	BWR	439	58	13,257,800
Braidwood 1 & 2	IL	2 PWRs	2,424	1,029	213,796,800
Browns Ferry 1, 2 & 3	AL	3 BWRs	10,402	1,932	314,140,400
Brunswick 1 & 2	NC	2 BWRs	4,410	896	73,204,800
Byron 1 & 2	IL	2 PWRs	2,515	1,068	221,823,000
Callaway	MO	PWR	1,609	702	141,913,800
Calvert Cliffs 1 & 2	MD	2 PWRs	2,982	1,142	263,012,400
Catawba 1 & 2	SC	2 PWRs	2,677	1,148	236,111,400
Clinton	IL	BWR	2,588	477	78,157,600
Comanche Peak 1 & 2	TX	2 PWRs	2,202	998	194,216,400
Cooper	NE	BWR	2,435	452	73,537,000
Crystal River	FL	PWR	1,102	512	97,196,400
D. C. Cook 1 & 2	MI	PWR	3,253	1,433	286,914,600
Davis-Besse	OH	PWR	1,076	505	94,903,200
Diablo Canyon 1 & 2	CA	2 PWRs	2,512	1,126	221,558,400
Dresden 1, 2 & 3	IL	3 BWRs	11,602	2,146	350,380,400
Duane Arnold	IA	BWR	2,545	467	76,859,000
Edwin I. Hatch 1 & 2	GA	2 BWRs	7,862	1,446	237,432,400
Fermi 2	MI	BWR	2,898	523	87,519,600
Fort Calhoun	NE	PWR	1,054	379	92,962,800
Ginna	NY	PWR	1,234	463	108,838,800
Grand Gulf	MS	BWR	4,771	856	144,084,200
H. B. Robinson	SC	PWR	903	384	79,644,600
Haddam Neck	CT	PWR	1,017	420	89,699,400
Humboldt Bay, CA	CA	BWR	390	29	11,778,000
Indian Point 1, 2 & 3	NY	3 PWRs	2,649	1,164	233,641,800
Joseph M. Farley 1 & 2	AL	2 PWRs	2,555	1,174	225,351,000
Kewaunee	WI	PWR	1,172	451	103,370,400

Site	State	Reactor Type	Total Assemblies	Metric tons	Radioactive Inventory (Ci)
La Crosse	WI	PWR	333	38	29,370,600
La Salle 1 & 2	IL	2 BWRs	5,189	952	156,707,800
Limerick 1 & 2	PA	2 BWRs	6,203	1,143	187,330,600
Maine Yankee	ME	BWR	1,421	536	42,914,200
McGuire 1 & 2	NC	2 PWRs	3,257	1439	287,267,400
Millstone 1, 2 & 3	CT	BWR, 2 PWRs	6,447	1,709	445,230,400
Monticello	MN	BWR	2,324	426	70,184,800
Nine Mile Point 1, 2 & 3	NY	3 BWRs	9,830	1,812	296,866,000
North Anna 1 & 2	VA	2 PWRs	2,571	1184	226,762,200
Oconee 1, 2 & 3	SC	3 PWRs	4,028	1,865	355,269,600
Oyster Creek	NJ	BWR	3,824	699	115,484,800
Palisades	MI	PWR	1,473	585	129,918,600
Palo Verde 1, 2 & 3	AZ	3 PWRs	4,082	1674	360,032,400
Peach Bottom 2 & 3	PA	2 BWRs	8,413	1,554	254,072,600
Perry	OH	BWR	2,470	452	86,160,600
Pilgrim	MA	BWR	2,853	527	69,913,000
Point Beach 1 & 2	WI	2 PWRs	2,270	876	200,214,000
Prairie Island 1 & 2	MN	2 PWRs	2,315	866	204,183,000
Quad Cities 1 & 2	IL	2 BWRs	6,953	1,277	209,980,600
Rancho Seco	CA	PWR	493	228	43,482,600
River Bend	LA	BWR	2,889	531	209,980,600
Salem / Hope Creek 1 & 2	NJ	2 BWRs	7,154	1,659	216,050,800
San Onofre 1, 2 & 3	CA	3 PWRs	3,582	1,423	315,932,400
Seabrook	NH	PWR	918	425	80,967,600
Sequoyah 1 & 2	TN	PWR	2,218	1,023	195,627,600
Shearon Harris	NC	PWR	2,499	750	220,411,800
South TX Project 1 & 2	TX	2 PWRs	1,871	1,012	165,022,200
St. Lucie 1 & 2	FL	2 PWRs	2,701	1,020	238,228,200
Summer	SC	PWR	1,177	526	103,811,400
Surry 1 & 2	VA	2 PWRs	2,604	1,194	229,672,800
Susquehanna 1 & 2	PA	2 BWRs	7,172	1,276	216,594,400
Three Mile Island	PA	PWR	1,180	548	104,076,000
Trojan	OR	PWR	780	359	68,796,000
Turkey Point 3 & 4	FL	2 PWRs	2,355	1,074	207,711,000

Vermont Yankee	VT	BWR	3,299	609	99,629,800
Vogtle 1 & 2	GA	2 PWRs	2,364	1,080	208,504,800
Columbia Generating Station	WA	BWR	3,223	581	97,334,600
Waterford	LA	PWR	1,217	500	107,339,400
Watts Bar	TN	PWR	544	251	47,980,800
Wolf Creek	KS	PWR	1,360	630	119,952,000
Yankee-Rowe	MA	PWR	533	127	47,010,600
Zion 1 & 2	IL	2 PWRs	2,302	1,052	203,036,400
Total			**218,700**	**63,000**	**12,057,685,800**

Source: DOE/EIS-0250, Appendix A, Tables A-7, A-8, A-9, & A-10

Appendix B: Spent Power Reactor Fuel Inventory, December 2010

State	Wet Storage Inventory (MTU)	Dry Storage Inventory (MTU)	Total Spent Fuel Inventory (MTU)
Alabama	2,500	489	2,989
Arizona	1,207	854	2,061
Arkansas	537	722	1,259
California	1,978	867	2,845
Colorado	-	25	25
Connecticut	1,374	613	1,987
Florida	2,723	179	2,902
Georgia	1,972	518	2,490
Idaho	62	81	143
Illinois	7,530	908	8,438
Iowa	313	109	422
Kansas	607	0	607
Louisiana	1,023	184	1,207
Maine	-	542	542
Maryland	533	766	1,299
Massachusetts	514	122	636
Michigan	2,080	456	2,536
Minnesota	635	525	1,160
Mississippi	621	143	764
Missouri	641	0	641
Nebraska	657	181	838
New Hampshire	417	93	510
New Jersey	2,019	455	2,474
New York	3,035	412	3,447
North Carolina	2,947	495	3,442
Ohio	1,031	34	1,065
Oregon	-	345	345
Pennsylvania	4,478	1,370	5,848
South Carolina	2,305	1,587	3,892
Tennessee	1,156	338	1,494

Texas	1,976	0	1,976
Vermont	539	62	601
Virginia	1,002	1,391	2,393
Washington	274	337	611
Wisconsin	934	370	1,304
National Total	**49,620**	**15,573**	**65,193**

Source: Associated Press / Nuclear Energy Institute March. 2011

Less than 25 percent of U.S. reactor spent fuel is in safer dry storage.

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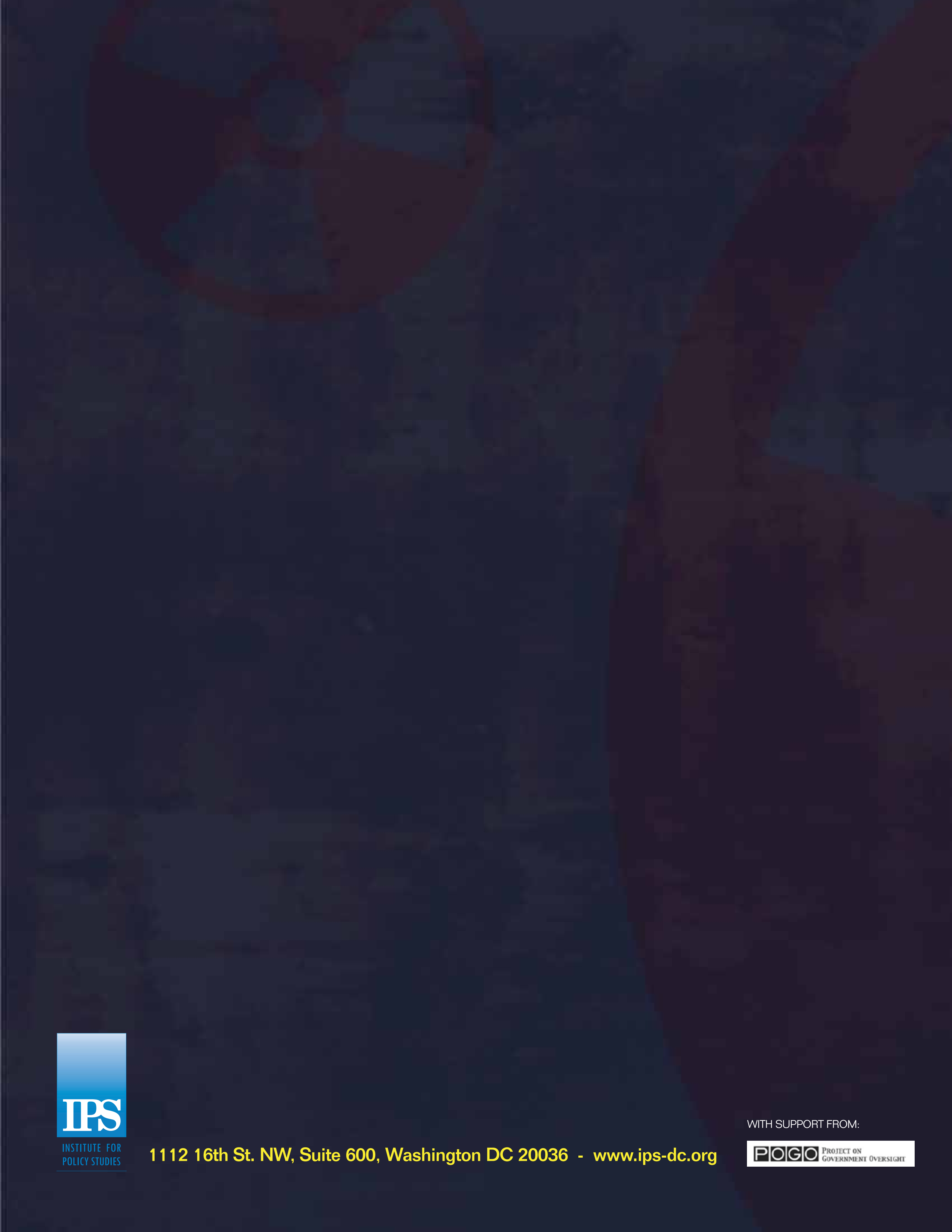

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