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Improving Spent-Fuel Storage at Nuclear Reactors

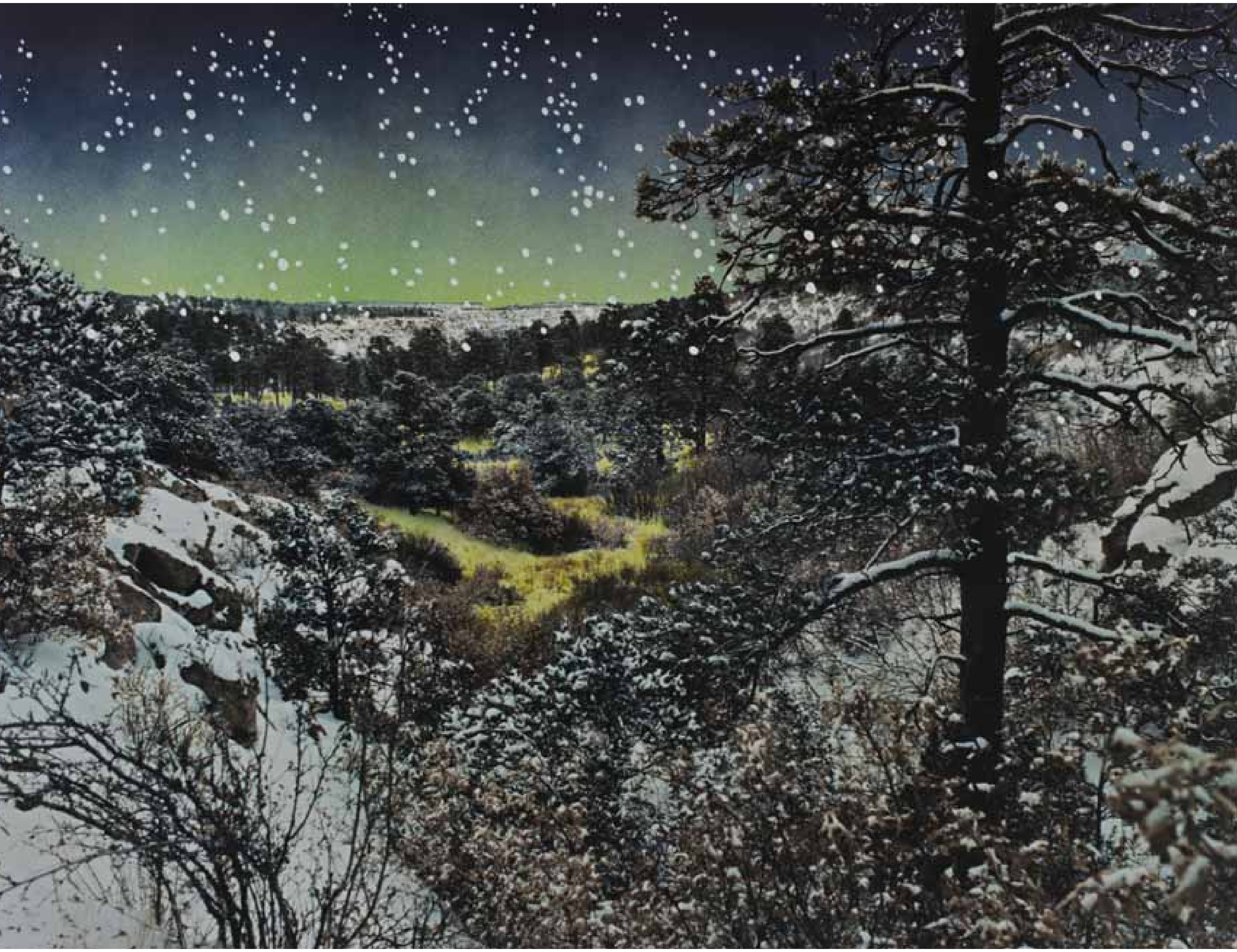
Storing spent radioactive fuel in dry form rather than in increasingly jammed cooling pools is much safer, and can be done with already available funds.

The nuclear disaster in Fukushima, Japan, which began with an earthquake in March 2011 and continues today, is casting a spotlight on nuclear reactors in the United States. At the Dai-Ichi nuclear power plant, at least one of the pools used for storing spent nuclear fuel—indeed, the pool holding the largest amount of spent fuel—has leaked and remains vulnerable. Because U.S. nuclear plants also use cooling pools for storing spent fuel, the U.S. Nuclear Regulatory Commission (NRC) formed a task force to assess what happened at the stricken facility and identify lessons for the U.S. nuclear industry. In a July 2011 report, the NRC placed upgrading the safety of storage pools at reactor stations high on its list of recommendations.

But history and scientific evidence suggest that although useful, improving pool safety will not be enough. Efforts are needed to store more spent fuel in dry form, in structures called casks that are less susceptible to damage from industrial accidents, natural disasters, or even terrorist attacks. Fortunately, money is already available to pay for this step, a situation almost unheard of in today's harsh economic climate. Now it is up to the federal government to develop policies to make this happen, for the safety of the nuclear electric industry and the nation. There is no time to wait. It is estimated that spent-fuel storage pools at U.S. reactors, which are already jammed, will hit maximum capacity by 2015.

History of delay

Since the early days of the nuclear electric industry, the NRC's regulations regarding storage of spent fuel have assumed that the federal government would open in a timely fashion a permanent repository for nuclear wastes. This goal was codified in the Nuclear Waste Policy Act of 1982. Until such a facility became available, the NRC would allow plant operators to store spent fuel on a temporary basis in onsite cooling pools. However, the quest for permanent nuclear waste disposal remains illusory. As a result, nuclear



Patrick Nagatani, *Contaminated Radioactive Sediment, Mortandad Canyon, Los Alamos National Laboratory, New Mexico*, Chromogenic print, 17 x 22 inches, 1990.

Safely securing the spent fuel that is currently in crowded pools at reactors should be a public safety priority of the highest degree.

plant operators are storing spent fuel in cooling pools for longer periods and at higher densities (four to five times higher, on average) than originally intended.

As the owner of the Millstone nuclear reactor in Waterford, Connecticut, observed in a 2001 report, neither the federal government nor utilities anticipated the need to store large amounts of spent fuel at operating sites. "Large-scale commercial reprocessing never materialized in the United States," the utility, Dominion Power, said. "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."

U.S. reactor stations have collectively produced approximately 65,000 metric tons of spent fuel. Roughly three-quarters of the total is currently stored in pools, and the remainder is stored in dry form in casks, an inherently safer form of storage. The spent fuel stored in pools holds between 5 and 10 times more long-lived radioactivity than the reactor cores themselves hold. Because they were intended to be temporary, the pools do not have the same "defense in depth" features that the NRC requires of reactors. Even after it completed its assessment of the Fukushima disaster, the NRC has continued to allow nuclear operators to rely on cooling pools for storing spent fuel. As a result, spent-fuel pools may be destined to remain a fact of life for the indefinite future. But this possible future can and should be avoided, especially given the recent events in Japan.

Lessons from disaster

In the late afternoon of March 11, 2011, a 9.0 magnitude earthquake, followed by a 46-foot-high tsunami, struck the Dai-Ichi nuclear power site in the Fukushima Prefecture of Japan. The destruction was enormous. In a little more than an hour, offsite power was severed, backup diesel generators were rendered inoperable, and the infrastructure of wiring, pipes, and pumps necessary to maintain cooling for the four reactors and the fuel-storage pools was severely damaged.

Almost immediately, the site's personnel became alarmed over the storage pools and shifted the remaining cooling capacity to prevent the overheating of spent fuel at reactor No. 2. However, the emergency batteries that were providing power to cool the reactor cores soon ran out. Fuel rods became exposed and began to melt, while generating large amounts of hydrogen from the rapid oxidation of zirconium contained in the cladding surrounding the nuclear fuel. In a matter of days, venting of hydrogen from overpressurized reactor vessels led to large explosions at reactors 1, 2, and 3, which experienced full meltdown. Reactor 4, which had been shut down for maintenance and its irradiated core transferred to a nearby cooling pool, also experienced an explosion that caused structural damage to the pool and leakage.

On June 18, the Japanese government reported that between March 11 and April 5, approximately 4.3 million curies of radioiodine and 410,000 curies of radiocesium had been released to the atmosphere. A more recent study estimated that almost twice as much radiocesium had been released.

In terms of land contamination, aerial radiological surveillance done by the U.S. Department of Energy between April 6 and April 29 indicated that roughly 175 square kilometers had contamination at levels comparable to those in the exclusionary zone around the reactor ruins at Chernobyl, in the Ukraine region of the former Soviet Union. Other researchers have reported that about 600 square kilometers have been contaminated to levels that at Chernobyl required strict radiation controls. Cesium-137 hot spots were found in soil by a citizens' group in the Tokyo metropolitan area at levels comparable to those in the Chernobyl exclusionary and radiation control zones.

Tokyo Electric Power Company has yet to achieve cold shutdown at the Dai-Ichi site. The Japanese government currently estimates that it may take 30 years to remove and store nuclear and other contaminated material, at an estimated cost of $14 billion. Despite this destruction, spent fuel stored in dry casks at the reactor site was relatively unscathed.

U.S. nuclear portrait

In the United States, 104 commercial nuclear reactors are operating at 65 sites in 31 states. Sixty-nine of them are pressurized-water reactors (PWRs), and 35 are boiling-water reactors (BWRs). Thirty-one of the BWRs are Mark I and Mark II models that are built on the same basic design as those at the Dai-Ichi site. In addition, there are 14 older light-water–cooled reactors in various stages of decommissioning.

These facilities collectively hold in their onsite spent-fuel pools some of the largest concentrations of radioactivity on the planet. 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. Most of them have stainless steel liners. (Basins without steel liners are more susceptible to cracks and corrosion.) At PWRs, pools are partially or fully embedded in the ground, sometimes above tunnels or underground rooms. At BWRs, most pools are housed in reactor buildings several stories above the ground.

Typical 1,000-megawatt PWRs and BWRs have cores that contain about 80 and 155 metric tons of fuel, respectively, and their storage pools contain 400 to 500 metric tons of spent fuel. Nearly 40% of the radioactivity in the spent fuel for both types of reactors is cesium-137, and the pools hold about four to five times more cesium-137 than is contained in the reactor cores. The total amount of cesium-137 stored in all storage pools is roughly 20 times greater than the amount released from all atmospheric nuclear weapons tests combined. 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.

Many U.S. reactors have larger spent-fuel storage pools than found elsewhere. For example, the storage pool at Vermont's Yankee Mark I reactor holds nearly three times the amount of spent fuel that was stored in the pool at the crippled Dai-Ichi reactor No. 4.

Permanent storage déjà vu

In January 2010, the Obama administration canceled long-contested plans to develop a permanent spent-fuel disposal site deep within Yucca Mountain in Nevada. Instead, the administration appointed the Blue Ribbon Commission on America's Nuclear Future to address, once again, the country's efforts to store and dispose of high-level radioactive wastes. The 15-member commission, which will report to the secretary of Energy, includes representatives from industry, government, and academia; it is co-chaired by Brent Scowcroft, a former national security adviser to two presidents, and former congressman Lee Hamilton. The commission's charter made it clear that the Yucca Mountain site was not to be considered and that specific site locations were not to be selected. The commission provided interim recommendations in July 2011 and is expected to issue a final report in early 2012.

The challenge facing the commission is well known. In 1957, the National Academy of Sciences (NAS) warned that the "hazard related to radioactive waste is so great that no element of doubt should be allowed to exist regarding safety." In the same year, the NAS recommended that the federal government establish deep geologic disposal as the best solution to the problem.

For more than two decades, the Atomic Energy Commission (AEC) and its eventual successor, the Department of Energy (DOE), tried and failed to identify one or more sites for geologic disposal that would be acceptable to everyone, including the states where potential sites were located. Congress eventually stepped into the fray in 1982 with the Nuclear Waste Policy Act, which set forth a process for selecting multiple sites at various geographic locations nationwide. Five years later, however, Congress terminated the site selection process, in large part because of opposition by eastern states. Congress amended the law so that Yucca Mountain in Nevada was the only site to be considered. Although Congress set an opening date for January 31, 1998, the project's schedule kept slipping in the face of technical hurdles and fierce state opposition.

This was the situation when the Obama administration halted the controversial process and appointed the Blue Ribbon Commission. In its interim report, the commission recommended a number of amendments to the Nuclear Waste Policy Act. Among them were the following: The law should authorize a new consent-based process for selecting and evaluating sites and licensing consolidated storage and disposal facilities; allow for multiple storage facilities with adequate capacity to be sited, licensed, and constructed, when needed; and establish a new waste management organization to replace the role of the DOE with an independent, government-chartered corporation focused solely on managing spent fuel and high-level radioactive wastes. The act also should have provisions to promote international engagement to support safe and secure waste management. In this regard, Congress may need to provide policy direction and new legislation for implementing some measures aimed at helping other countries manage radioactive wastes in a safe, secure, and proliferation-resistant manner.

Even assuming that Congress promptly adopts the recommendations, however, it will probably take decades before consolidated storage and disposal sites are established. The commission pointed to the record of the Waste Isolation Pilot Project (WIPP), a waste repository developed by the DOE near Carlsbad, New Mexico, for storing transuranic wastes from defense applications. The repository began operation in 1998, 28 years after being proposed by the AEC. Moreover, WIPP faced less difficult (though still substantial) technical challenges. For example, spent fuel from commercial nuclear reactors will be much hotter than transuranic wastes, and this extra heat potentially can corrode waste containers, enhance waste migration, and affect the geological stability of the disposal site.

There is another hurdle as well. Given the inability of the current Congress to agree on routine government funding because of policy disputes, the prospects in a national election year for enacting legislation to reopen the site selection process for the storage and disposal of high-level radioactive waste are dim. These factors underscore the likelihood of the continued onsite storage of spent power reactor fuel for an indefinite period.

Given this situation, the commission concluded: "Clearly, current at-reactor storage practices and safeguards—particularly with regard to the amount of spent fuel allowed to be stored in spent fuel pools—will have to be scrutinized in light of the lessons that emerge from Fukushima. To that end, the Commission is recommending that the National Academy of Sciences conduct a thorough assessment of lessons learned from Fukushima and their implications for conclusions reached in earlier NAS studies on the safety and security of current storage arrangements for spent nuclear fuel and high-level waste in the United States."

Emphasis on pool safety

Until the NAS completes its study, if it agrees to do so, the bulk of current attention is focused on the NRC's analysis of the Fukushima disaster. As in Japan, U.S. spent-fuel pools are not required to have defense-in-depth nuclear safety features. They are not covered by the types of heavy containment structures that cover reactor vessels. Reactor operators are not required have backup power supplies to circulate water in the pools and keep them cool in the event of onsite power failures. Reactor control rooms rarely have instrumentation keeping track of the pools' water levels and chemistry. (In one incident at a U.S. reactor, water levels dropped to a potentially dangerous level after operators simply failed to look into the pool area.) Some reactors may not have the necessary capabilities to restore water to pools when needed. Quite simply, spent-fuel pools at nuclear reactors are not required to have the same level of nuclear safety protection as required for reactors, because the assumption was that they would be used only for short-term storage before the rods were removed for reprocessing or permanent storage.

In its interim report, the NRC task force recognized these shortcomings and recommended that the NRC order reactor operators to:

- ". . . provide sufficient safety-related instrumentation, able to withstand design-basis natural phenomena, to monitor key spent fuel pool parameters (i.e., water level, temperature, and area radiation levels) from the control room."
- ". . . revise their technical specifications to address requirements to have one train of onsite emergency electrical power operable for spent fuel pool makeup and spent fuel pool instrumentation when there is irradiated fuel in the spent fuel pool, regardless of the operational mode of the reactor."
- ". . . have an installed seismically qualified means to spray water into the spent fuel pools, including an easily accessible connection to supply the water (e.g., using a portable pump or pumper truck) at grade outside the building."

Improving pool safety is certainly important. For decades, nuclear safety research has consistently pointed out that severe accidents could occur at spent-fuel pools that would result 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 cause $59 billion in damage, according to a 1997 report for the NRC by Brookhaven National Laboratory.

If the fuel were exposed to air and steam, the zirconium cladding around the fuel would react exothermically, catching fire at about 800 degrees Celsius. Particularly worrisome are the large amounts of cesium-137 in spent-fuel pools, because nearly all of this dangerous isotope would be released into the environment in a fire, according to the NRC. Although it is too early to know the full extent of long-term land contamination from the accident at the Dai-Ichi station, fragmentary evidence has been reported of high cesium-137 levels as far away as metropolitan Tokyo. The NRC also has reported that spent-fuel fragments were found a mile away from the reactor site.

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 New Jersey. During the following decade, the population of this area declined by almost half because of migration to areas of lower contamination.

In addition to risks from accidents or other untoward events caused by either natural events or human error, another threat looms as well. In 2002, the Institute for Policy Studies helped organize a working group to perform an in-

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depth study of the vulnerabilities of spent-fuel reactor pools to terrorist attacks. The group included experts from academia, the nuclear industry, and nonprofit research groups, as well as former federal government officials. The group's report, *Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States*, which I coauthored, was published in 2003 in the peer-reviewed journal *Science and Global Security*. We warned that U.S. spent-fuel pools were vulnerable to acts of terror, and we pointed out that the resulting drainage of a pool might cause a catastrophic radiation fire that could render uninhabitable an area much larger than that affected by the Chernobyl disaster.

Going dry for safety

Our study group recommended that to reduce such safety hazards, all U.S. reactor operators should take steps to store all spent fuel that is more than five years old in dry, hardened storage containers. The casks used in dry storage systems are designed to resist floods, tornadoes, projectiles, fires and other temperature extremes, and other unusual scenarios. A cask typically consists of a sealed metal cylinder that provides leak-tight containment of the spent fuel. Each cylinder is surrounded by additional steel, concrete, or other material to provide radiation shielding to workers and everyone else. Casks can be placed horizontally or set vertically on a concrete pad, with each assembly being exposed to an open channel on at least one side to allow for greater air convection to carry away heat. In hardened dry-cask storage—the safest available design for such systems—the casks are enclosed in a concrete bunker underground.

We also made other recommendations, such as installing emergency spray cooling systems and making advance preparations for repairing holes in spent-fuel pool walls on an emergency basis. The German nuclear industry took these same steps 25 years ago, after several jet crashes and terrorist acts at nonnuclear locations.

The NRC and nuclear industry consultants disputed the paper, and as a result, Congress asked the NAS to sort out the controversy. In 2004, the NAS reported that spent-fuel pools at U.S. reactors were vulnerable to terrorist attack and to catastrophic fires. According to its report: "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 hundreds of miles downwind under appropriate atmospheric conditions."

The NAS panel also concluded that dry-cask storage offered several advantages over pool storage. Dry-cask storage is a passive system that relies on natural air circulation for cooling, rather than requiring water to be continually pumped into cooling pools to replace water lost to evaporation caused by the hot spent fuel. Also, dry-cask storage divides the inventory of spent fuel among a large number of discrete, robust containers, rather than concentrating it in a relatively small number of pools.

The NRC has at least heard the message. In March 2010, the commission's chair, 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 will meet safety and security standards for several centuries. Yet today, only 25% of the spent fuel at U.S. reactors is stored in such systems, and the NRC has not taken strong steps to encourage their use. Nuclear reactor owners use dry casks only when there is no longer enough room to put the waste in spent-fuel pools. Without a shift in NRC policy, reactor pools will still hold enormous amounts of radioactivity, far more than provided for in the original designs, for decades to come.

Money at hand

In our original study, we estimated that the removal of spent fuel older than five years could be accomplished with exist-

John Divola, *Isolated House N34°11.115’W116°08.399’,* Ultrachrome pigmented ink on Museo Silver Rag, 30 x 30 inches, 1995–98.

ing cask technology in 10 years and at a cost of $3 billion to $7 billion. The expense would add a marginal increase of approximately 0.4 to 0.8% to the retail price of nuclear-generated electricity.

In November 2010, the Electric Power Research Institute (EPRI) released its own analysis of the costs associated with our recommendations. The group 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 . . . impacts while providing no safety benefit to the public." EPRI concluded that the cost for the early transfer of spent fuel storage into dry storage would be $3.6 billion—a level near the lower end of our estimates. This increase, EPRI said, would be "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."

EPRI further expressed doubt that the industry would be able to meet demand needs for sufficient numbers of new casks, which the group estimated would require a "three- to four-fold increase in dry storage system fabrication capability." Our study found, however, that two major U.S. manufacturers could increase their combined production capacity within a few years to about 500 casks per year, a level sufficient to meet projected needs.

The EPRI study also argued against our proposal by maintaining that the recommended actions would increase nuclear plant workers' exposures to radiation. Upon further examination, EPRI's estimate would result in a 4% increase in the collective radiation exposure to workers over the next 88 years. This increase in worker doses is not an insurmountable obstacle if there is greater use of remotely operated technologies in the handling of spent fuel assemblies and casks.

Of course, even though our estimates suggest that the added costs of moving to dry-cask storage will not be overly burdensome, individual reactor owners will need to pay them. Here is where the NRC can play a vital role by adopting policies that will allow for the costs of dry, hardened spent-fuel storage to be taken from the electricity rates paid by consumers of nuclear-generated electricity. The Nuclear Waste Policy Act established a user fee to pay 0.1 cent per kilowatt-hour to cover the search for and establishment of a high-level radioactive waste repository, but the law did 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 had been spent of the $25.4 billion collected through user fees, leaving $18.1 billion unspent. This sum could more than pay for the dry, hardened storage of spent reactor fuel older than five years at all reactors. Safely securing the spent fuel that is currently in crowded pools at reactors should be a public safety priority of the highest degree. The cost of fixing the nation's nuclear vulnerabilities may be high, but the price of doing too little is far higher.

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