THE GLOBAL CRISIS OF NUCLEAR WASTE

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UNITED STATES

HIGH LEVEL NUCLEAR WASTE IN THE UNITED STATES

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In the 60 years since the start of civil nuclear power production, nuclear power reactors in the United States have generated roughly 30 percent of the total global inventory of spent nuclear fuel (SNF) – by far the largest.[1,2] There are approximately 80,150 metric tons stored at 125 reactor sites, of which 99 remain operational.[3]

The extraordinary hazards of high-level radioactive wastes generated by reactors was described by Johns Hopkins University professor Abel Wolman in January 1959 at the first U.S. congressional inquiry into the subject. “Their toxicity in general terms, both radioactive and chemical, is greater by far than any industrial material with which we have hitherto dealt in this or in any other country” he said. “We dispose of the wastes of almost every industry in the United States by actual conversion into harmless material,” Wolman stressed, “This is the first series of wastes of any industry where that kind of disposal is nonexistent.”

Wolman’s observation still holds true as nations with nuclear power stations attempt to contain some of the world’s largest concentrations of artificial radioactive elements on a time scale that transcends the geologic era defining the presence of human civilization. As of 2012, spent nuclear fuel in the United States was estimated to contain a total of 851,000 PBq (23 billion curies) of radioactivity.[4] Each year about 2,200 metric tons of SNF are generated and is expected to reach a total of about 146,500 mt by 2048 containing more than 1,221,000 PBq (>33 billion curies).

Spent nuclear fuel at U.S. nuclear power sites is made up of more than 244,000 long rectangular assemblies containing tens of millions of fuel rods.[5] The rods, in turn, contain trillions of irradiated uranium pellets, the size of a fingertip. After bombardment with neutrons in the reactor core, about 5 to 6 percent of the pellets are converted to a myriad of radioactive elements with half-lives ranging from seconds to millions of years. Standing within a meter of spent nuclear fuel discharged after one year guarantees a lethal radiation dose in about 20 seconds.[6]

However, after many years of focus on reactor melt-downs, it is becoming apparent that the large accumulation of spent nuclear fuel in U.S. reactor pools poses a far more potentially consequential hazard. This is because the pools are holding several irradiated cores or 3-4 times more spent nuclear fuel than the original designs intended. The pools lack defense-in-depth such as secondary containment and their own back-up power.

Heat from the radioactive decay in spent nuclear fuel is a principal safety concern. A few hours after a full reactor core is offloaded, it can initially give off enough heat from radioactive decay to match the energy capacity of a steel mill furnace. This is hot enough to melt and ignite the fuel’s reactive zirconium cladding and destabilize a geological disposal site it is placed in. By 100 years, decay heat and radioactivity drop substantially but remains dangerous.

The Fukushima accident in March 2011 made it clear that the high heat hazard of spent fuel pools was not an abstract issue. Following the earthquake and tsunami, an explosion destroyed the reactor building of unit 4, exposing the pool containing an entire core-worth of freshly discharged spent nuclear fuel to the open air. By sheer luck, an accidental leak from a water line not actually intended to serve the cooling pool prevented water levels from dropping in the pool and thereby preventing a severe fire of the overheated zirconium cladding.[7]

THE HAZARDS OF SPENT NUCLEAR FUEL STORAGE IN POOLS

For nearly 30 years, NRC 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 ponds much longer, and at higher densities (on average four times higher), than was originally intended.

Decades of nuclear safety research has shown that severe accidents from decay heat can occur if a spent fuel cooling pool loses a significant amount of water. If the fuel assemblies in a pool are exposed to air and steam, their zirconium cladding will react exothermically, after several hours or days catching fire similar to an enormous fireworks sparkler. (Because of its high reactivity to heat, zirconium was at one time used as a filament in camera flash bulbs.)

According to the U.S. Nuclear Regulatory Commission (NRC) 69 radionuclides in spent nuclear fuel pose potentially significant accident consequences
(See list 1).[8]

List 1: the 69 nuclides important to accident consequence studies

241Am, 137mBa, 139Ba, 140Ba, 141Ce, 143Ce, 144Ce, 242Cm, 244Cm, 58Co‡, 60Co‡, 134Cs, 136Cs, 137Cs, 131I, 132I, 133I, 134I, 135I, 85Kr, 85mKr, 87Kr, 88Kr, 140La, 141La, 142La, 99Mo, 95Nb, 97Nb, 97mNb, 147Nd, 239Np, 143Pr, 144Pr, 144mPr, 238Pu, 239Pu, 240Pu, 241Pu, 86Rb, 88Rb, 103mRh, 105Rh, 106Rh, 103Ru, 105Ru, 106Ru, 89Sr, 90Sr, 91Sr, 92Sr, 99mTc, 127Te, 127mTe, 129Te, 129mTe, 131Te, 131mTe, 132Te, 133Xe, 135Xe, 135mXe, 90Y, 91Y, 91mY, 92Y, 93Y, 95Zr, 97Zr

J. A. Rollstin, D. I. Chanin and H.-N. Jow, MELCOR Accident Consequence Code System (MACCS), Nuclear Regulatory Commission, NUREG/CR-4691 Vol.3, 2007

If the fuel were exposed to air and steam, the zirconium cladding would react exothermically, catching fire at about 800-1000 degrees Celsius. Particularly worrisome is the large amount of cesium-137 in spent fuel pools, which contain anywhere from 44 to 84 million curies of this dangerous isotope in U.S. spent fuel ponds. 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.

The damage from a large release of fission products, particularly cesium-137, was demonstrated as a result of the accidents at Chernobyl and Fukushima. The Chernobyl accident forced the permanent resettlement of 100,000 people because of contamination by cesium-137. The total area of this radiation-control zone is huge: more than 1,000 square kilometers, equal to roughly 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.

Following the terrorist attacks of September 11, 2001, my colleagues and I published a paper warning that acts of malice or accidents could cause drainage of spent nuclear fuel pools in the United States, causing spent fuel cladding to catch fire and release catastrophic amounts of long-lived radioactivity—far more than a reactor melt down.[9]

This was followed up by my colleagues, who reported in 2016, if such a fire occurred at the Limerick boiling water reactor near Philadelphia, radioactive fallout could force approximately eight million people to relocate and result in $2 trillion in damages.[10] Other than a major war, there are few, if any, technological mishaps that can hold a candle to the consequences of a major power reactor spent fuel pool fire.

The NRC's 2007 own dispersion model used by emergency responders estimated that within six hours of pool drainage, following a major earthquake at the San Onofre Nuclear Generating Station, spent fuel cladding will catch fire, releasing approximately 86 million curies of radioactive material into the atmosphere. Of that, about 30 percent of the radio-cesium in the spent fuel (roughly 40 million curies) would be released—more than 150 percent of the amount released by all atmospheric nuclear weapons tests. An area within a 10-mile radius—encompassing 314 square-miles of land and offshore waters—could be lethally contaminated.[11]
Naoto Kan, Japan's prime minister when the Fukushima accident occurred, made this point very clear. After being informed about the consequences if the spent fuel in Fukushima Unit 4 pool had caught fire, he later said,

> ***"[W]e would have to evacuate 50 million people. It would have been like losing a major war... I feared decades of upheaval would follow and would mean the end of the State of Japan.[12]"***

Currently, about 70 percent of some 244,000 spent nuclear fuel assemblies in the United States sit in US power reactor cooling pools, with the remaining 30 percent contained in dry storage casks. About a third of the spent fuel in wet storage sits at decades-old boiling water reactors, in pools built several stories above the ground; the remainder is at pressurized water reactors, where the cooling pools are embedded in the ground.

To significantly reduce the probability of such an event, we called for an end of the high-density pool storage of used nuclear fuel and the placement of most spent nuclear fuel in dry, hardened storage containers. This change in fuel storage arrangements could be completed within 10 years, we estimated, at a cost of $3.5 to $7 billion.[13]

In May 2016, for the second time, a National Academy of Science panel refuted the NRC's expressions of confidence in the safety of spent fuel pools. Finding flaws in the agency's technical assumptions, the panel stated that the loss of spent fuel pool cooling at the Fukushima site "should serve as a wake-up call to nuclear plant operators and regulators about the critical importance of having robust and redundant means to measure, maintain, and, when necessary, restore pool cooling." The members also urged the NRC to "ensure that power plant operators take prompt and effective measures to reduce the consequences of loss-of-pool-coolant events in spent fuel pools that could result in propagating zirconium cladding fires."

HIGH BURNUP SPENT NUCLEAR FUEL

Since the 1990's, U.S. reactor operators, were permitted by the U.S. Nuclear Regulatory Commission (NRC) to effectively double the amount of time nuclear fuel can be irradiated in a reactor, by approving an increase in the percentage of uranium-235, the key fissionable material that generates energy. Known as increased "burnup" this practice is described in terms of the amount of electricity in megawatts (MW) produced per day from a metric ton of uranium. US commercial nuclear power plants use uranium fuel that has had the percentage of its key fissionable isotope—uranium 235—increased, or enriched, from what is found in most natural uranium ore deposits. In the early decades of commercial operation, the level of enrichment allowed US nuclear power plants to operate for approximately 12 months between refueling. In recent years, however, US utilities have begun using what is called high-burnup fuel, defined as >45 GWd/t.
High burnup spent nuclear fuel is proving to be an impediment to the safe storage and disposal of spent nuclear fuel. For more than a decade, evidence of the negative impacts on fuel cladding and pellets from high burnup has increased, while resolution of these problems remains elusive.

Research shows the fuel cladding thickness of used fuel is reduced and a hydrogen-based rust forms on the zirconium metal used for the cladding, and this thinning can cause the cladding to become brittle and fail. High burnup fuel temperatures make spent nuclear fuel more vulnerable from handling and transport.

"The technical basis for the spent fuel currently being discharged (high utilization, burnup fuels) is not well established," notes an expert with the National Academy of Engineering in 2012.[14] In May 2016, the Nuclear Waste Technical Review Board, an expert panel that provides scientific oversight for the Energy Department on spent fuel disposal. That panel said there is little to no data to support dry storage and transport for spent fuel with burnups greater than 35 gigawatt days per metric ton of uranium.[15] Over the past 20 years, more than 70 percent of the total inventory of the spent nuclear fuel generated are high burnup.[16] As of 2013, only 8 percent of high burnup spent fuel is stored in dry casks.[17]

A LACK OF PLANNING FOR STORAGE AND DISPOSAL

Recently, a Bloomberg energy finance report suggested that more reactor closures may be on the horizon: "More than half of America's nuclear reactors are bleeding cash, racking up losses totaling about $2.9 billion a year." The accelerated closure of more US reactors could seriously affect a system that lacks necessary planning and logistics for the management of a rapidly growing inventory of wastes. Nearly 20 percent of the nation's spent nuclear fuel is located at closed or soon-to-be closed reactors.[18]

Transporting spent nuclear fuel is further complicated because the storage at reactor sites involves a complicated mix of containers; each spent nuclear fuel canister system has its own unique challenges.

The NRC has licensed 51 different designs for dry cask storage, 13 which are for storage only and not for transport. As many as 11,800 onsite dry storage canisters may have to be reopened or repackaged before transport to either a centralized interim storage facility or to a permanent repository.[19]

The current generation of dry casks was intended for short-term on-site storage— not for direct disposal in a geological repository. None of the dry casks storing spent nuclear fuel is licensed for long-term disposal. The large storage canisters in use at power plants can place a major burden on a geological repository in terms of handling and emplacement of cumbersome packages with high heat loads and high radioactivity.

Indeed, repackaging for disposal may require tens of thousands of smaller canisters, and at an estimated average cost of $50,000 to $87,000 per used fuel assembly, repacking won't be cheap. The estimated cost of managing low-level radioactive waste from removing spent fuel to new canisters is estimated at $9,500 per assembly and could be more than the current cost to load an assembly in any canister.[20]

By the time a centralized interim storage site may be available, there could be a "wave" of reactor shutdowns that could clog transport and impact the schedule for a centralized storage operation. Among the uncertainties identified by DOE include:

• Transportation infrastructures at or near reactor sites are variable and changing;

• Each spent nuclear fuel canister system has unique challenges. For instance, **some dry casks that are licensed for storage only and not for transport.**

• Constraint on decay heat from spent nuclear fuel can impact the timing of shipping.

• The pickup and transportation order of spent fuel has yet to be determined. It has been assumed that the oldest would have priority, leaving sites with fresher and thermally hotter fuel that may be "trapped" at sites for to cool down.[21]

THE ELUSIVE SEARCH FOR GEOLOGICAL DISPOSAL

In 2008, the DOE issued a revised life-cycle cost estimate totalling $113 billion (2016 dollars) for the disposal of 70,000 metric tons of commercial power reactor spent fuel at the Yucca Mountain site.[22] Under current law, spent nuclear fuel more than that amount would have to be disposed in a second disposal site. Under the Nuclear Waste Policy Act, the cost for disposal is to pay by a fee levied on consumer of nuclear powered electricity of one mill ($0.001) per kilowatt-hour. This fee does not cover an estimated cost in the $billions, for predisposal surface storage, transport and repackaging. Efforts to restart the Yucca Mountain licensing process remain stalled.

After cancellation of the Yucca Mountain project in 2010, the U.S. Department of Energy projected that 122,100 Mt of spent nuclear fuel would require 16 years to transport and 50 years for total emplacement in the repository. The repository would be permanently closed after 150 years.[23] Reprocessing of spent nuclear fuel, prior to disposal is not considered viable. The Electric Power Research Institute, a U.S. energy industry organization concludes: "near-term US adoption of spent fuel processing would incur a substantial cost penalty...processing would have to be accompanied by deployment of fast reactor plants. But demonstration fast reactor plants todate has mostly proved expensive and unreliable, which aggravates processing's economic handicap."[24]

The Yucca Mt. repository was chosen, first and foremost, by the U.S. Congress in 1987, to avoid the growing political controversy over siting a disposal site in the eastern United States. The Yucca Mountain site does not meet the basic geological requirements for long term storage established by the International Atomic Energy Agency. Among them are a "stable geochemical or hydro chemical conditions at depth, mainly described by a reducing environment and a composition controlled by equilibrium between water and rock forming minerals; and long term (millions of years) geological stability, in terms of major earth movements and deformation, faulting, seismicity and heat flow"[25] With the distinct possibility of a volcano erupting within the 10,000 year time frame set for isolating the wastes,[26] and the penetration of moisture, Yucca Mountain has neither.

According to the DOE the site requires forced ventilation for at least 100 years to remove decay heat that could impact waste containers and the geology of the site.[27] Maintenance of power and rail and other transport systems to support the repository will be required for about 150 years. After years of claiming that the Yucca Mountain site was dry, DOE conceded that moisture can penetrate and compromise the waste packages.[28] And so, after ~100 years, in a dangerous high temperature environment, of more than 11,000 large titanium drip shields are planned to be emplaced to prevent moisture from corroding the waste packaging.[29] The drip shields would require nearly two thirds of the world's current annual consumption of titanium.[30]

WHAT NEEDS TO BE DONE

The basic approach undertaken in this country is to continue its 60-year quest for geological disposal site and hope for the best. Meanwhile the U.S. lacks a coherent policy for long-term surface storage, which increasingly is very likely. In recognition of major uncertainties, the U.S. Department of Energy has stated that "extended storage, for periods of up to 300 years, is being considered within the U.S."[31] A nuclear industry expert suggests that unless the federal government finds a way to restart efforts to site a repository quickly, the DOE program may never have to take spent fuel from an operating site."[32]

A national policy for the storage and disposal of spent nuclear fuel needs to be fundamentally revamped to address vulnerabilities of spent fuel storage in pools. First and foremost, to protect public safety, high density pool storage of spent nuclear fuel should end.

The U.S. Government Accountability Office, the investigative arm of the U.S. Congress reported in April 2017 that "spent nuclear fuel can pose serious risks to humans and the environment .and is a source of billions of dollars of financial liabilities for the U.S. government. According to the National Research Council and others, if not handled and stored properly, this material can spread contamination and cause long-term health concerns in humans or even death." [33]

Instead of waiting for problems to arise, the NRC and the Energy Department need to develop a transparent and comprehensive road map identifying the key elements of—and especially the unknowns associated with—interim storage, transportation, repackaging, and final disposal of all nuclear fuel, including the high-burnup variety. Otherwise, the United States will remain dependent on leaps of faith in regard to nuclear waste storage—leaps that are setting the stage for large, unfunded radioactive waste "balloon mortgage" payments born by the public in the future.

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