DISCUSSION PAPER

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Centralized Dry Storage of Nuclear Fuel

Lessons for U.S. Policy from Industry Experience and Fukushima

By Frank C. Graves, Mariko R. Geronimo, and Glen A. Graves

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Abstract

The Fukushima nuclear event of March 2011 dramatically revealed the potential risks of holding significant spent nuclear fuel at wet pools requiring continuous water circulation to maintain safe cooling. The housings for four spent fuel pools were badly damaged, and all pools lost cooling and nearly suffered fuel exposure. These conditions had the potential to result in catastrophic radiation release, rivaling or exceeding safety concerns over the nuclear reactors themselves. In contrast, the nine casks of spent fuel in dry storage at the Fukushima site hit by the same earthquake and tsunami experienced no material damage and posed no safety concerns.

It is unlikely that any U.S. reactors face a comparable environmental threat, but due to the inability to implement a timely spent fuel disposal program at Yucca Mountain, all of the commercial nuclear plants in the U.S. have spent fuel pools that are filled with roughly five reactor cores of spent fuel, and most have also had to build on-site dry storage facilities (Independent Spent Fuel Storage Installations or ISFSIs) for handling fuel discharges in excess of pool capacities.

A better means of handling this spent fuel, with regard to both costs and safety, would be for the federal government to restart a spent fuel handling program at one or a few centralized, interim dry storage facilities. This idea was recently endorsed in a January 2012 report by the Blue Ribbon Commission on America's Nuclear Future, but no studies to date have assessed what size and pace of program might address today's needs.

This paper presents several assessments of how a new program could be designed to address alternative priorities for improved spent fuel handling, including priority for shut-down plants, avoiding new at-reactor storage site developments, returning existing ISFSIs, and "de-densification" of fuel in wet pools. We find that a program beginning in 2020 with a removal capacity of 6,000 metric tons of uranium (MTU) per year for 10 years and a 3,000 MTU per year pace thereafter would be able to accommodate all of these goals — allowing full decommissioning of sites awaiting fuel removal, retiring all private ISFSIs by 2030, and achieving approximately a 10% reduction in average wet pool density. By contrast, delaying a new federal program by 10 years would cost the industry about $1.6 billion in increased at-reactor storage costs and represent a failure to respond in a timely fashion to some of the important lessons from Fukushima.

Introduction

The Fukushima nuclear accident following the Tōhoku earthquake and tsunami of March 2011 caused widespread public and political concern about the safety of U.S. nuclear facilities, including spent fuel management. While there is no evidence that any U.S. reactors are exposed to environmental threats as extreme as those that struck Japan, several U.S. commercial reactors are located near major metropolitan areas, and most have substantial quantities of spent nuclear fuel in on-site pools that might be vulnerable to loss of cooling.

At the same time, the U.S. government is financially liable for paying nuclear plant owners for their costs of expanded on-site fuel storage facilities, to the extent that the maintenance or expansion of those facilities could have been avoided had a permanent repository for spent nuclear fuel, e.g., the Yucca Mountain Nuclear Waste Repository (Yucca Mountain), been built and in-service in 1998. These liability costs are accumulating on the order of $250 to $350 million per year,[1] as the U.S. Department of Energy (DOE) continues to default on its obligations to remove spent fuel from reactor sites. In addition, litigating those liabilities have added substantially to that expense.

In lieu of shipping to Yucca Mountain, most nuclear plant owners have expanded their at-reactor pool capacities, filled their pools to at or near capacity, and moved "overflow" fuel to on-site dry storage. While this approach has been acceptable thus far, and closely monitored for safety by the plant owners and regulators such as the U.S. Nuclear Regulatory Commission (NRC), a permanent, industry-wide storage solution is long overdue. The Fukushima event provides the motivation and insights into how to conduct a future U.S. nuclear waste management program.

A system of dry storage for spent fuel at one or a few large, federal facilities would offer a number of engineering and economic advantages over the current practice of holding spent fuel at individual reactor sites. The lack of a repository like Yucca Mountain has forced the industry to develop considerable expertise in dry storage cask design, fuel handling, and site monitoring. Building on this operational experience and strong safety record, a federal program could circumvent some of the political and engineering obstacles that paralyzed the Yucca Mountain project. A DOE-run program to transfer title of the spent fuel to the federal government would also address the government's ongoing liability problems. Finally, centralized dry storage preserves longer-term policy and engineering optionality, by serving as interim storage for some future permanent repository or as recycling locations for a closed fuel-cycle industry of the future.

Furthermore, the program could be designed to support several different economic and engineering objectives, including facilitating full decommissioning of shut-down sites, avoiding the construction or expansion of privately owned, plant-specific Independent Spent Fuel Storage Installations (ISFSIs), or accelerating fuel removal from at-reactor pools ("pool de-densification").

The events at Fukushima reveal the potential value of de-densification and dry storage. By reducing fuel in the wet pools needed for initial cooling, a facility might gain a few days of additional time to prevent fuel damage and the potential release of radiation in the event of a loss of power to circulating cooling water. The fuel moved to dry storage at the federal facilities would also have safety advantages. At Fukushima, there were nine casks of spent fuel in dry storage, and none of them were damaged by the earthquake or tsunami. In sharp contrast, the spent fuel pools for units 1 through 4 all suffered structural damage and loss of cooling, which may have contributed to the release of material quantities of radiation.

Reliance on centralized interim dry storage facilities would require a fuel removal program to pick up and transport fuel from individual plant sites, similar to what was originally envisioned for deliveries to Yucca Mountain.[2] Had Yucca Mountain been built on schedule, the DOE's original spent fuel removal program would have been timed and sized to preempt the need for at-reactor storage expansions. Since this did not occur, there is now a much different and greater backlog of spent fuel requiring a storage solution. The federal fuel

removal program needs to be redesigned in light of today's waste inventories as well as heightened concerns about safety and the debate over renewed nuclear development. The appropriate design of such a program depends on (at least) two related issues:

(1) determining what size and pace the overall program should have, and

(2) deciding what fuel to pick up first.

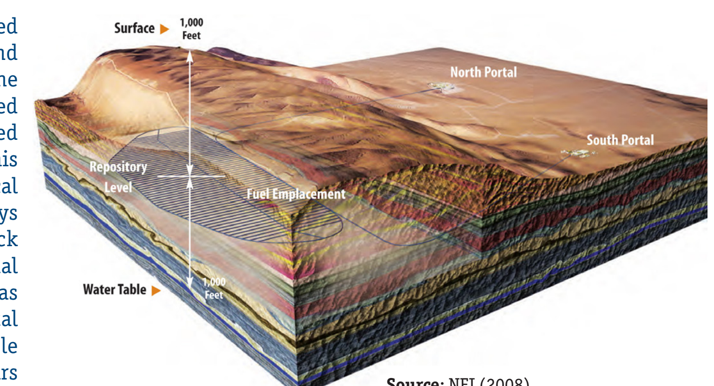
Again, lessons from the failed Yucca Mountain program can be brought to bear on these issues. The new program would be best designed by first laying out specific program goals — for instance, prioritizing full decommissioning of shut-down sites and/or setting fuel density targets for at-reactor storage pools — and then allowing nuclear owners to negotiate and exchange fuel pickup rights based on site-specific needs for fuel removal.

This paper addresses questions about the desirable size, design, and priorities of a new fuel removal program, drawing on our extensive involvement in assessing the impacts of the failure to develop Yucca Mountain. We present several long-term projections of how much spent fuel of different types will need to be removed over the next 40 years, including how those needs will grow if there is continued delay in pursuing a federal waste management program. A key finding is that a program that is able to start taking deliveries in 2020 has lower costs and much quicker centralization of the spent fuel than one beginning 10 years later. That is, starting a new program sooner rather than later serves many public policy objectives.

Yucca Mountain

The Nuclear Waste Policy Act of 1982 (NWPA) called for development of a permanent geologic repository for disposal of nuclear spent fuel. By 1987, a site to be located 1,000 feet under Yucca Mountain, Nevada, became the prime repository candidate. This site is about 100 miles northwest of Las Vegas, at the northern end of a desert area previously used for testing nuclear weapons. The site was designed to hold approximately 65,000 MTUs of spent nuclear fuel, after which the repository would be sealed and monitored for safety.

Initial engineering studies were conducted in the 1980s, and onsite ground and thermal testing of the site began in the mid-1990s. The site was formally approved and authorized as the DOE's recommended repository location in 2002, but by this time a number of engineering and political challenges had created significant delays in its development. One critical setback occurred when a panel at the National Academy of Sciences opined that it was necessary for the U.S. Environmental Protection Agency to consider possible radiation releases up to 1,000,000 years in the future — a horizon far beyond the 10,000 year outlook that had previously been applied. In 2008 the DOE submitted a license application to the NRC to begin construction, but by 2010 the Administration had declared the project "dead," prompting an extensive review of U.S. storage policy by the Blue Ribbon Commission.



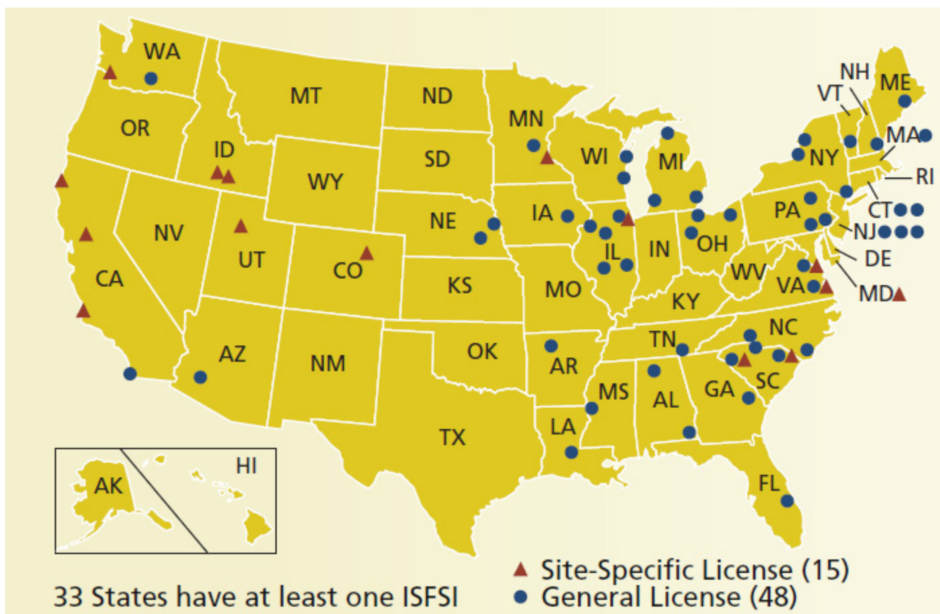
Source: NEI (2008).

Cost estimates for the Yucca mountain project varied, but early estimates (1984) for a first repository were about $3.2 to $5.7 billion for evaluation and development and $1 to $2 billion for construction. To date, the DOE has spent about $10.8 billion on the project. Funding for the program was established under the NWPA through a 1 mill (0.1¢) per kilowatt-hour fee on all nuclear power generation. This fee collects about $800 million per year, and is still in place today. If those monies could be applied to the alternative proposed in this paper (i.e., to federal centralized dry storage), the annual collections would more than cover the likely costs of the program.

SECTION 1 CURRENT SPENT NUCLEAR FUEL STORAGE PRACTICES

Today, 55 out of 75 commercial reactor sites in the United States have licensed and built on-site dry storage facilities, or ISFSIs, to house a portion of their spent nuclear fuel from prior years of operation. Of the remaining 20 sites, 9 are currently pursuing ISFSI licensing (so presumably have plans to build ISFSIs in the near future), and 11 have not yet announced plans to pursue ISFSI licenses.[3] **Figure 1** shows the locations of ISFSIs currently licensed.

Figure 1 Locations of At-Reactor Dry Storage Facilities (ISFSIs)



Source: U.S. NRC (2011).

Note: Locations are as of June 2011. NRC issues two types of ISFSI licenses: site-specific and general. The count of 55 reactor sites with ISFSIs excludes 4 site-specific licenses at non-commercial reactor sites (DOE TMI Storage, DOE Idaho Spent Fuel Facility, Private Fuel Storage, and GE Morris) and 4 site-specific licenses at sites that also carry general licenses (Surry, Robinson, Oconee, and North Anna).

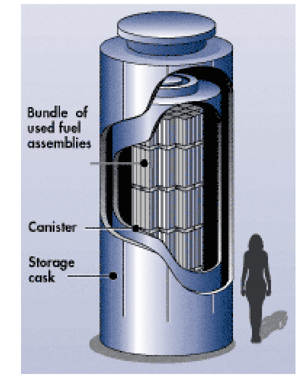
ISFSIs are essentially large, concrete pads at geologically approved sites, loaded with spent fuel sealed in large steel canisters within concrete casks that are around 16 feet high and 8 feet in diameter and weigh about 150 tons.[4] A number of cask designs have been approved by the NRC,[5] all extensively tested for durability under extreme stress conditions (impact/drop testing, fire, water, submersion). In addition to being extremely durable, dry casks feature passive air-cooling, and as a result, generally require less maintenance and supervision than fuel stored in at-reactor wet pools.

ISFSIs serve to expand fuel storage capacity at operating reactors,[6] which all have wet pools for holding and cooling fuel for at least a few years after it has been removed from the reactor core. For most operating reactors in the U.S., these pools hold decades of fuel. They are mostly being used at or near their full capacities, and their total content is often several times the amount of fuel in the reactor core.

Figure 2 shows an illustration of ISFSI design, compared to fuel storage in at-reactor fuel pools. An ISFSI is a compact site, typically a few acres in total area, of which the concrete pad for holding and monitoring the storage casks is often about half the size of a football field, with up to a few dozen casks.

Figure 2 Examples of Spent Nuclear Fuel Storage

Schematic of Dry Cask Storage

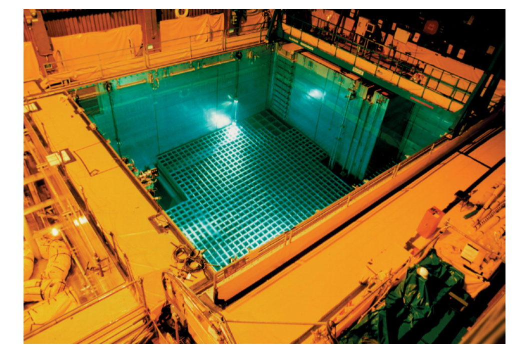


Source: www.nrc.gov

Dry Cask Storage (ISFSI) at Diablo Canyon Nuclear Station

Source: www.nrc.gov

Example of Spent Fuel Pool at a Nuclear Plant



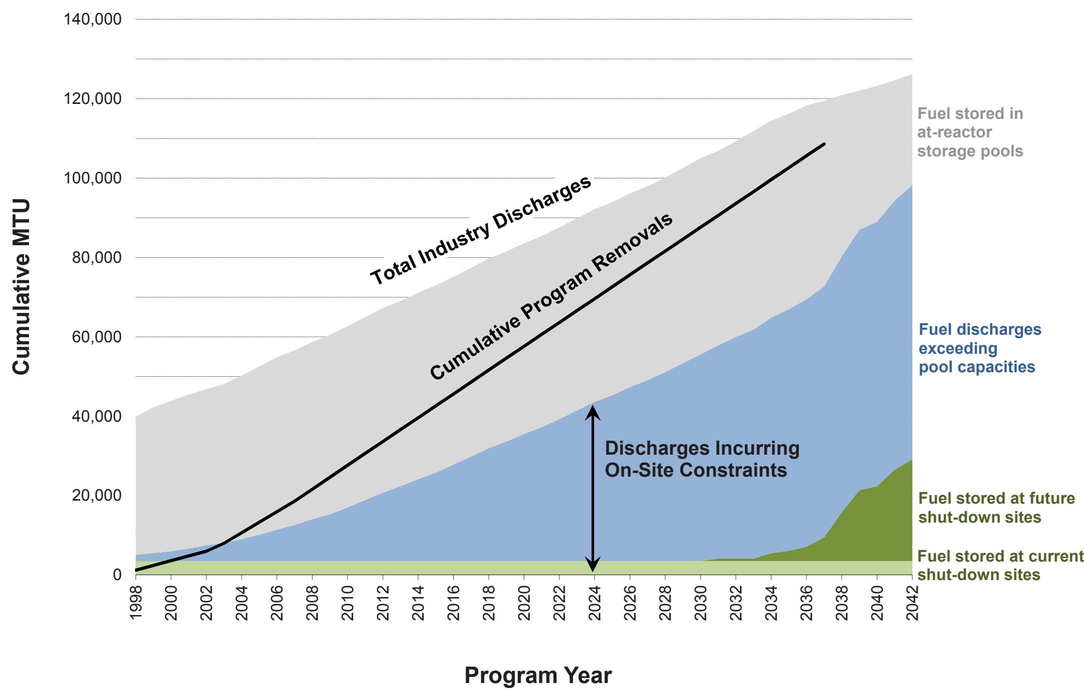
Source: www.nrc.gov

A typical spent fuel pool, by comparison, is about 36 to 49 feet (11 to 14 meters) deep and 26 to 33 feet (8 to 10 meters) across in its surface dimension. The spent fuel assemblies are about 14 feet tall, so they are usually about 23 to 28 feet (7 to 9 meters) below the water surface, and the average water temperature is about 40 degrees Celsius, a temperature that is maintained when water from the spent fuel pool is circulated past cooling radiators outside of the pool. All operating reactors have adjacent wet pools of this type, because spent fuel representing about one-third of the fuel in a reactor is discharged approximately every 18 months and replaced with new fuel. After removal from the reactor, fuel must be cooled for three to five years before it can be handled in any other way. In practice, spent fuel often accumulates in a pool for a much longer time. If the active circulation of cooling water is lost (i.e., for example due to a power failure or damage to the pumps, like what happened at Fukushima) the pool water will heat up and potentially boil off, creating a risk of radiation release due to exposed fuel rods.

Figure 3 shows an illustration of the original fuel program's likely fuel handling capacity in comparison to needs over the period from 1998 to 2042. The graph depicts the cumulative industry-wide spent fuel discharges in the color-shaded areas, and the total removal capability of the intended DOE program as the black line sloping steadily up to the upper right. When the program would have begun in 1998, there would have already been about 40,000 metric tons of uranium (MTUs), with about 4,400 MTU of this stored at shut-down sites and a small amount (1,600 MTU) in excess of existing pool storage capacities at the time (i.e., already moved to plant-specific ISFSIs). The majority of the remaining spent fuel would have been (and was, in 1998) in the at-reactor fuel pools. Annual discharges from reactors to storage pools were increasing at around 2,000 MTU per year (the slope of the top of the shaded area in the figure), but only a small portion of this (the blue area) would have been occurring at reactors facing pool capacity constraints. That is, most plants would have still had unused pool capacity, as shown in the grey shaded area.

The DOE fuel removal program was designed to ramp up over a 10 year period to a steady-state fuel acceptance rate of 3,000 MTU per year by 2008 — a pace that would have been sufficient to work off the backlog of stored fuel exceeding pool capacities by 2004 and, thereafter, to more than keep up with continuing discharges.[7,8] This is seen by the fact that the black line of program removal capacity (with a slope of 3,000 MTU per year after 2007) stays above blue and green shaded areas (of discharges exceeding 1998 wet pool capacities) and also covers some of the grey shaded area (removing some fuel from pools that were not full). Thus, had DOE been able to honor its contracts with the plants and begin removal in 1998, most reactor sites would have had removal schedules sufficient to avoid any spent fuel pool "overflow," and they would not have had to build additional on-site ISFSIs to accommodate their cumulative spent fuel.[9] In addition, the volume of fuel stored in at-reactor pools (grey area in figure) would have been gradually reduced to about 26% below current levels by 2012 and to 44% below by 2020, allowing operators to store less fuel in their pools in a less dense fashion.

Figure 3 DOE's Original Program for Spent Fuel Removal and Storage



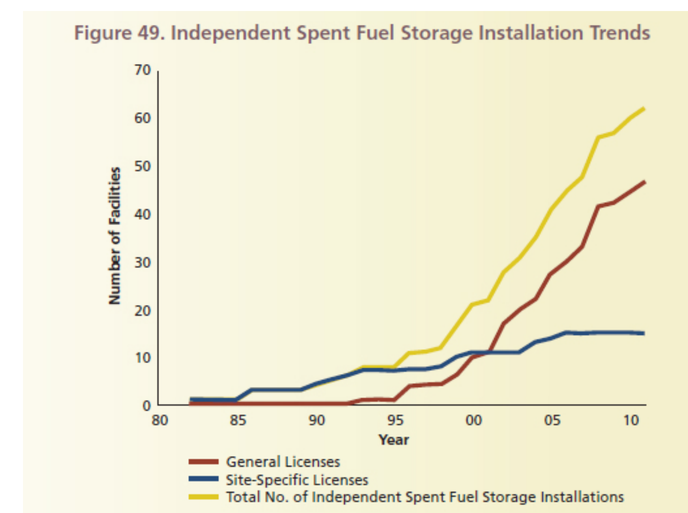
Source: *The Brattle Group* analysis of industry license, discharge, and pool capacity data. Cumulative program removals reflect a DOE transportation rate that ramps up to 3,000 MTU per year, based on the rate used in DOE (1987) and United States Court of Appeals for the Federal Circuit (2008).

Due to the demise of Yucca Mountain, the DOE to date has not removed any fuel from reactor sites under the obligations of the spent fuel program, resulting in the continued accumulation of spent fuel at individual commercial sites. In response, nuclear plant owners have been forced to expand their at-reactor capacities, either by increasing pool capacity (with more closely spaced storage racks, not larger pool dimensions) and/or by building ISFSIs. The latter typically costs about $40 million to build, around $0.8 to $1.0 million per cask, and then a few million dollars per year to monitor and maintain. Since 1998, nuclear owners have collectively spent about $3 billion building ISFSIs and cask systems at nearly every reactor site. Going forward, owners and utility ratepayers will continue to spend roughly $200 million per year on ISFSI operations and maintenance (O&M). As explained further in this paper, some of these ongoing costs could be avoided with a few centralized interim facilities if a new federal program begins soon.

If there is a silver lining to these on-site solutions and increased costs borne by most plants, it is that the experience gained in developing private ISFSIs will help improve the efficiency and effectiveness of a new federal spent fuel program. Several storage canister types and cask designs have been vetted and approved by the NRC. ISFSI development has also resolved a number of technical obstacles to spent fuel management, including accommodating non-standardized fuel such as failed fuel and Greater-Than-Class-C waste. So far, nuclear owners have transported over 1,400 casks from at-reactor pools to ISFSIs, each usually holding about 10 to 12 MTUs of spent fuel. In aggregate, this is equivalent to about 25% of the total U.S. commercial spent nuclear fuel discharged to date.[10] Since the mid-1990s (after it became clear that nuclear owners could not expect timely fuel removal under the DOE program), ISFSIs have been built at a rate averaging three new facilities per year, as shown in **Figure 4**. This experience in the planning, engineering, and operational aspects of dry storage gives the industry a stepping-stone to larger-scale dry storage.

Figure 4 U.S. ISFSI Development and Current Inventory

Cumulative Number of ISFSIs Developed (1980 - 2010)



Source: U.S. NRC (2010).

Spent Fuel Inventory as of January 2011
(values are approximate)

Pool Inventory	49,100 MTU
Dry Storage Inventory	16,100 MTU (1,400 casks)
Total	**65,200**

Source: NEI (2011).

Section 2 SPENT FUEL SAFETY

Even prior to the Fukushima disaster, the question of spent fuel pool safety had been periodically analyzed and debated in the United States. A 2001 NRC report found that there was a low level of public risk at decommissioning plants, due primarily to the low likelihood of pool accidents.[11] A 2003 study by Robert Alvarez, et al did not address the likelihood of accidents occurring but instead focused on pool safety under assumed adverse conditions — partly in response to the industry's accumulation of much larger quantities of spent fuel in pools absent a federal fuel pick up program.[12] This study evaluated several scenarios for loss of spent fuel pool water, including a water boil-off scenario.

When pool cooling systems fail, the internal energy of the stored fuel elements (perhaps 1,000 to 4,000 watts per MTU, depending on how old and cool the fuel is) starts to heat the water, eventually causing it to boil. Depending on the amount and level of radioactivity of the spent fuel in the pool, water in the pool can boil down to the top of fuel rods in just a few days.[13] Once exposed, fuel rods in pools can ignite, melt, and possibly even consolidate, releasing fission materials and creating very dangerous conditions that cannot be easily mitigated. One of the study's primary recommendations (based solely on improving conditional safety considerations) was to remove all spent fuel older than five years from pools and move it to dry storage.[14]

On March 11, 2011, the Fukushima nuclear disaster was a stark demonstration of the importance of these pool safety concerns. During the event, pool cooling systems failed, leading to a partial "boil-off" of water in the pools. (See description of the Fukushima events and resulting safety and economic consequences below.) Based on the event timeline to cooling water restoration at the pools, many experts suspected that pool fuel rod exposure occurred or nearly occurred at Fukushima,[15] placing the situation perilously close to a "worst case" outcome of a very large release of radiation into the atmosphere. Recent studies of the pools seem to indicate that they did not lose enough water for a long enough time for any significant fuel exposure or damage,[16] but there is no question that an extremely dangerous situation prevailed, and that during the event, the status of these pools drew at least as much concern from industry experts as the status of the reactor cores.

Importantly for the current policy focus of this paper, the Fukushima plant had a small amount of fuel in dry storage — approximately 408 assemblies in 9 canisters, <u>all</u> of which survived the event intact, despite being exposed to extraordinary and unprecedented conditions caused by the earthquake and tsunami.[17]

If pool water boil-off were to occur, the degree of public safety risk would be related to the amount of radioactive material in the pool that could be released into the atmosphere. Iodine-131 and Cesium-137 are only two of many such radionuclides, but they are typically the majority of the released radioactive material.

The Events and Current Status at Fukushima (June 2012)

The Fukushima Daiichi nuclear plant is located on the eastern shore of Japan about 160 miles northeast of Tokyo. It is a six-unit facility with a combined power rating of 4,696 MW. On the afternoon of Friday, March 11, 2011 — when the magnitude 9.0 Tōhoku earthquake occurred — units 1, 2, and 3 were operating while units 4, 5, and 6 were offline for maintenance and refueling. The earthquake was so strong that it shifted the Honshu Island of Japan about 2.5 meters to the east and dropped the elevation of the local coastline about a half meter.[i]

All 11 reactors operating in the region shut down automatically within seconds of the quake, and their emergency diesel generators started up. The facilities were able to withstand the earthquake, even though it exceeded the Daiichi plant's ground acceleration design tolerances by about 20%. However they could not withstand the series of tsunami waves that struck approximately 41 minutes later. The plant had been built to tolerate 5.7 meter waves based on modeling of a 1960 Chilean tsunami, but the biggest wave hitting the site was 15 meters high. The tsunami flooded an area of 560 square kilometers, killing approximately 19,000 people and destroying over a million buildings. At the reactors, the main consequence was loss of external power, flooding of the backup generators, and destruction of the batteries for units 1 and 2, resulting in loss of instrumentation, controls and lighting, and, most critically, the loss of cooling water circulation.

Over the first few days after the tsunami struck, most of the attention and concern was on the reactor pressure vessels. All three experienced significant loss (or boil-off) of water and had significant core meltdowns (now known to be 100% of unit 1, 57% and 53% respectively for units 2 and 3), and all apparently released hydrogen into adjacent buildings, resulting in three dramatic explosions on days 2 through 4. Surprisingly, the shut-down unit 4 also experienced a hydrogen explosion on Tuesday, March 15, believed to be due to hydrogen that came from unit 3. The main concern at unit 4 was a loss of coolant at its fuel pool, which was holding 1,331 used fuel assemblies plus a recently discharged full core of 548 assemblies — considerably more and newer fuel than any of the other spent fuel pools. As a result, it had high heat content (estimated to be between 2.25 and 3 MW) and was boiling about 100 m^3 of water per day, absent replacement cooling. The fuel ponds at units 1 through 3 also needed replacement water, which was provided first unsuccessfully by fire hoses and helicopter, but then successfully via a replacement pump. Fortunately, and contrary to fears at the time, subsequent analysis indicates that the fuel assemblies in the storage ponds probably remained covered in water and appear to be intact.[ii]

Radiation releases from the site were primarily Iodine-131 and Cesium-137, thankfully largely drifting to the east into the ocean and into a sparsely populated region to the northwest of the plant.[iii] More than 100,000 people were evacuated from a few thousand square kilometers within 20 to 30 km of the reactors, mostly within three days. Total radiation release was about 15% of the Chernobyl release, but there are currently no known deaths from radiation exposure — even to the site workers. Almost 200,000 regional residents were screened in late May 2011, and only 102 showed trace levels of radiation and none showed harmful health effects at that time. Some residents will be able to return to their homes in the evacuation zones in 2012, however much of the area adjacent to the plant and beyond to the northwest will remain uninhabitable for a long time.[iv] Longer run health effects are very complex to assess, but a recent study using a linear, no-threshold dose response model found that world-wide additional mortality over the next 50 years due to estimated Fukushima radiation could be from 15 to 1,100 lives, with the vast majority of this occurring in Japan.[v]

TEPCo declared the four units to be in "cold shut-down" on December 16, 2011, though the stability of the site has been disputed by some observers. In particular, there is residual concern that the spent fuel pool at unit 4 is sufficiently damaged as to make it structurally unsound or unstable, especially if there are additional earthquakes.[vi] Thus, the spent fuel inventory risks remain serious though increasingly under control.

TEPCo estimates it will remove fuel from the units in 10 to 25 years, and it will demolish the four reactors in 30 to 40 years. It has allocated \$2.5 billion (USD) for cleanup, to which the Japanese government has added \$15 billion. In the past year, TEPCo has paid \$5.4 billion in reparations to businesses and individuals claiming damages, in response to claims from 40% of eligible parties. Japan also shut down its entire fleet of nuclear plants — 54 units normally providing about 30% of total electricity needs — which will cause some regions to have capacity as much as 16% below summer peak demands in 2012 unless they are restarted, replaced, or massive conservation efforts occur. The plants must pass new, strict stress tests in order to be reopened. These tests address the ability to respond to simultaneous natural disasters beyond the plant's design basis, as well contingent failures of backup systems.[vii] So far, two units have passed and are scheduled to restart.

In spite of the great damage sustained by the plants, and the unprecedented chaos and destruction — with loss of power, loss of information, access, and mobility — it is in many respects remarkable and perhaps even commendable that there were no radiation-induced deaths. Part of this is due to luck, both good and bad. Had much of the radioactivity contained in the spent fuel pools been released — a close call — the situation could have been much more serious, both in extent and duration, and perhaps in its death toll. The technical and economic disaster at Fukushima casts a very long shadow into the future. It behooves us to learn its lessons and to plan and act accordingly.

i ESA Observing the Earth website, 2011.
ii ANS Fukushima Committee Report, March 2012.
iii Testimony of John Boice, Jr., May 13, 2011.
iv World Nuclear Association, Fukushima Accident, April 2012.
v Hoeve and Jacobson, 2012.
vi Gailey, April 2012.
vii Boyd, May 2012.

Iodine-131, with a half-life of eight days, is associated with thyroid cancers, especially in children. Its uptake in the thyroid, however, can be significantly blocked by consuming potassium iodide pills. Thus Cesium-137 is often considered the primary radiation concern due to its relative longevity (half-life of about 30 years), its transportability in gaseous plumes, its broad absorption into the human body, and the relatively high volume of Cesium present in spent fuel.

The amount of Cesium-137 in the fuel elements increases steadily through fission in the reactor, so spent fuel tends to be much richer in it than the average fuel in the reactor. A typical U.S. nuclear plant currently stores about five reactor cores in its spent fuel pool. This spent fuel would hold about 10 times the amount of Cesium-137 as the reactor core.[18] This means that the dispersed radiation release from a failed pool could be considerably larger than that from a failed pressure vessel surrounding the core. This affects not just the potential exposure doses, but also the geographic extent of the adjacent area that could become inaccessible or unusable after a catastrophe.

Everything else being equal (as to age, type, burn-up, etc., of fuel), a densely-packed pool holding large quantities of spent fuel is more prone to over-heating from loss of cooling water and correspondingly larger potential releases of radiation than a more sparsely filled pool. Unloading a significant quantity of fuel from pools, and re-packing the remaining fuel less densely, would reduce the volume of radioactive material and should, to some degree, reduce these boil-off and radiation release concerns.

While the precise quantification of incremental safety benefits from "de-densification" and dry storage of spent fuel is a very site-specific and technical issue, there is little doubt about the likely direction of the benefit. Pool de-densification would remove some heat content and increase water-to-fuel ratios, leading to longer boil-off times. A longer boil-off time of even one extra day would strengthen response efforts during an emergency. Moreover, in the event of a boil-off, there would be less fuel in the pool and it could be more widely separated, hence less likely to interact if it separated from the assemblies and clustered in the bottom of the pool.

In the wake of the Fukushima event, the NRC is exploring the issue of pool de-densification, and the Blue Ribbon Commission recently expressed support for an independent study to address it as part of a re-evaluation of pool safety issues, similar to a 2006 report by The National Academies.[19,20] A policy report published by the UK's The Royal Society in late 2011 (and cited by the Blue Ribbon Commission) stressed the importance of minimizing the fuel stored in at-reactor pools and avoiding high-density packing in pools.[21] The report also discussed the benefits of centralized interim storage and safety and security benefits of dry storage systems. If future studies show a positive safety benefit to pool de-densification, then those results could harmonize with a broader policy towards centralized dry storage.

Section 3 SIZE AND PACE OF A FEDERAL DRY STORAGE PROGRAM

Although Yucca Mountain was not developed, the funding for the project did occur and continues today, at roughly $800 million per year from U.S. commercial nuclear plant operators.[22] Access to these funds for a new federal fuel removal program using centralized dry storage facilities would require legislative changes,[23] but with those changes the current funding mechanism would likely be sufficient to cover most or all of the costs of building and managing large-scale federal interim dry storage facilities. A 2009 study by the Electric Power Research Institute (EPRI) estimated the capital cost for a 60,000 MTU site (about 6,000 casks) to be $757 million.[24] A site this size would be able to handle all the spent fuel currently in at-reactor ISFSIs and all the additional spent fuel discharges through 2030. Two of these facilities would be large enough to hold the entire industry's discharges from existing plants, including all fuel currently stored in wet pools and all future discharges through 2050.[25] The capital cost for one of these sites could be covered with a single year's collections under the current funding mechanism — meaning the new program could be pursued without putting any new strain on federal budgets (no new taxes or borrowing).

Once built, there should be considerable operational cost savings from centralization compared to the ISFSI O&M costs being incurred at the numerous private sites. The 2009 EPRI assessment, as well as studies of possible large, private ISFSI sites, estimated the cost of annual steady-state operations to be $3.7 to $8.8 million per year. These annual operating costs are quite close to what are currently being incurred (on average) at each of the 55 private ISFSIs, so switching to a few federal facilities could save more than $200 million per year in at-reactor operating costs. The variable cost of each storage cask, including the canister and concrete overpack, would be about $1 million per cask, totaling about $600 million per year for a program transporting 6,000 MTU per year. Variable transportation costs would be on the order of $28 million per year, using the EPRI assumption of $280,000 per rail shipment and 100 shipments per year (which would imply in this example 6 casks per shipment). Again, all of these annual operating costs could be funded with the assessments being collected already.

In terms of land use, dry storage poses no material or novel problems. For instance, the ISFSI at the shut-down 619 MW Connecticut Yankee plant carries the entire 28-year output of spent fuel discharges from that plant in 43 casks on a pad approximately the size of a hockey rink (about 200 feet by 100 feet, or about 465 square feet per cask).[26] Scaling this up to about 10,000 casks needed to accommodate the entire industry's total spent fuel discharges through 2030 would require 107 acres, equivalent to about 97 football fields — not a large facility or land requirement. Nuclear waste, though heavy, is surprisingly compact compared to the vastly larger waste streams of other energy sources.[27]

The framework for transportation from reactor sites to centralized dry storage would not be materially different from what had been envisioned for Yucca Mountain. Fuel would be loaded into transportation casks and delivered by rail and truck to the storage sites. If all the waste was moved by rail in 10 MTU casks (weighing about 60 tons in their overpack transportation casks), then moving 3,000 MTU per year would entail moving just one 60 MTU (a bit less than the size of two discharges from a typical operating pressurized water reactor or PWR) trainload per week for 50 weeks per year. This would require about a six-car train, so it would impose a very minor logistical and scheduling burden on the United States' rail infrastructure. Even if moving slowly, at 15 mph for an average trip distance of 1,500 miles, transportation would take 100 hours, so only a few such trains would be needed to service the entire industry. Likewise, the fuel handling at each end (loading and unloading) could be done at a rate of a few days per cask, based on experience at decentralized ISFSIs.

While siting one or more federal dry storage facilities would no doubt entail some of the same public debate and protest as affected Yucca Mountain, there are a few locations in the United States that are already experienced in dealing with nuclear waste and might be compatible with expansion to handle spent fuel. One such location is the U.S. DOE Waste Isolation Pilot Plant near Carlsbad, New Mexico.[28] This site has been in use since 1999 for interring transuranic (TRU) wastes from nuclear research facilities in salt caverns. Handling of above-ground spent fuel canisters requires far less engineering complexity than is being applied to these TRU wastes. The surrounding region is a sparsely populated desert and little or no agricultural or alternative use, and the facility already has sophisticated security, waste handling, and monitoring capabilities in place (as well as a large, adjacent uranium enrichment plant).

The government's failure to build a permanent repository ready for service by 1998 means that we now need a faster, larger program in order to "catch up" to the original timeline for fuel removal. As we have demonstrated, however, neither the physical size of the sites nor the logistical burden of transporting the waste should interfere with developing a new and larger program. Indeed, the relevant scale (as shown below) would be about twice the size of the program planned for Yucca Mountain — a size and pace that had already been considered to be achievable based on prior program analyses. In some of its mid-1980s planning documents, the DOE considered a 6,000 MTU per year acceptance rate, assuming deliveries to two repositories instead of one.[29]

Whether a new DOE program could work off the backlog of spent fuel stored on at-reactor ISFSIs in a reasonable timeframe depends primarily on the actual program start date for any reasonable transportation rate. It is more important to start as soon as possible than to wait to conduct a larger program. However, the goal of "avoiding additional at-reactor storage costs" — which shaped much of the original program's design — can no longer be a primary program objective, because those costs, to a large degree, have already been sunk. Today's program requires re-defined objectives that recognize the industry's current situation and concerns. Once these objectives are defined, the program's required transportation rate can then be re-evaluated and sized for compatibility.

Possible New Program Goals

Any new spent fuel removal program should be sized and paced to support goals that:

- *remove all fuel at decommissioned or decommissioning plant sites to allow full completion of decommissioning and restoration at those sites;*
- *avoid major additional capital investments in at-reactor storage, particularly new ISFSI builds or ISFSI expansions;*
- *reduce government liability for operating and maintenance costs at existing ISFSIs; and*
- *possibly, de-densify spent fuel storage pools of their volume and hotter fuels, particularly at any perceived "high risk" sites (perhaps those near urban centers, or at sites more exposed to natural disaster risks).*

In addition, the program should allow plant owners to exchange their fuel pickup rights, so that the economic needs of the plant owners (and DOE's liabilities) can be efficiently prioritized.

For the most part, these goals can be harmonized with one another, particularly if exchanges are encouraged, but there could be tradeoffs in choosing how much of the program to allocate to pool de-densification versus reducing program costs by clearing fuel at existing ISFSIs. The sections below discuss how alternate goals and priorities might affect the pace of a new program design. Each of the major possible priorities is discussed in terms of its implications for program size and timing, and then a balancing of their interests is considered.

Priority for Shut-Down Facilities

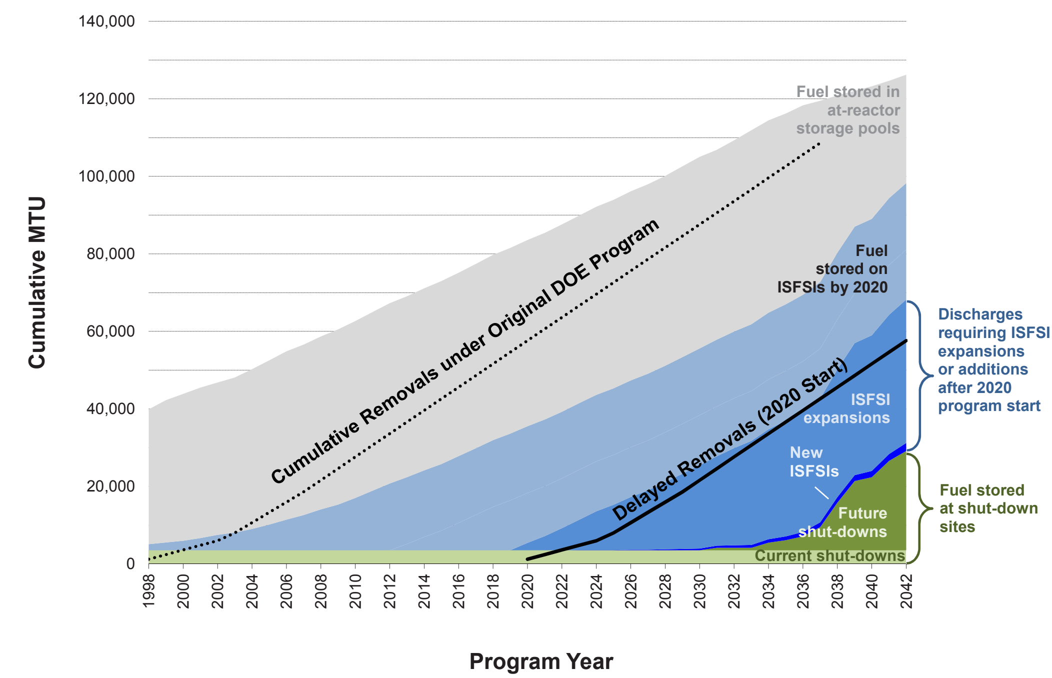
Prioritizing fuel removal at decommissioning plant sites is a relatively easy solution for solving a number of issues relatively quickly. There are currently 14 shut-down commercial sites holding about 3,500 MTUs in total. This fuel could be transported to centralized dry storage in the first 2 to 3 years of the program, assuming it quickly ramped up to a 3,000 MTU per year capacity like the original program plans often assumed. Thus, only the first few years of the new program would have to be dedicated to this goal. Once that fuel was removed, these shut-down sites could be fully decommissioned back to greenfield conditions, thus addressing the broader policy question of how commercial reactors complete their service and retire. The United States litigation at these sites would also have a foreseeable end, once the DOE took title to the fuel. Thereafter, the program capacity would be available to meet other program goals until about 2035, when the next major wave of decommissioning is likely to occur.

Avoid New ISFSI Builds and Expansions

Depending on when the new program starts, there could still be opportunities to avoid some at-reactor capital expenses associated with building new ISFSIs (for the 11 plants that have not yet announced plans to build an ISFSI) or to avoid expanding ISFSIs at existing facilities. A program to start removing fuel by 2020 would be timely enough to avoid these new ISFSIs, but it would need to be in place soon, before plant owners must begin planning and building their own dry storage.

Because there are only a few potential new ISFSIs, it may also be possible to accommodate both this goal and shut-down priority with a program barely faster than the original program's 3,000 MTU per year pace, as shown in **Figure 5**. The figure shows shut-down fuel for the 14 currently decommissioning reactors, as well as future decommissioning reactors (shown in green areas). The small amount of fuel volume shown in dark blue shows additional fuel storage needs at sites currently without an ISFSI, representing the need for a few new ISFSI builds after 2020 absent a fuel pickup program. The fuel volume shown in medium blue labeled "ISFSI expansions" reflects a more extreme version of the "avoid ISFSI expansions" policy since it shows all fuel that will need to be packed and loaded onto existing ISFSIs in the future from 2020 and beyond, including loadings of additional casks onto ISFSIs that may not need platform expansion.[30] With a start date of 2020 and the DOE's original transportation rate, both program goals of "priority for shut-down" and "avoid new ISFSI builds and expansions" would be mostly achievable, as seen by the fact that the dark, upward sloping line for cumulative program removals (beginning in 2020), stays roughly on pace with the sum of spent fuel at shut-down facilities plus incremental discharges needing ISFSI storage.

Figure 5 Priority for Shut-Down and Avoiding ISFSI Additions (Illustrative)

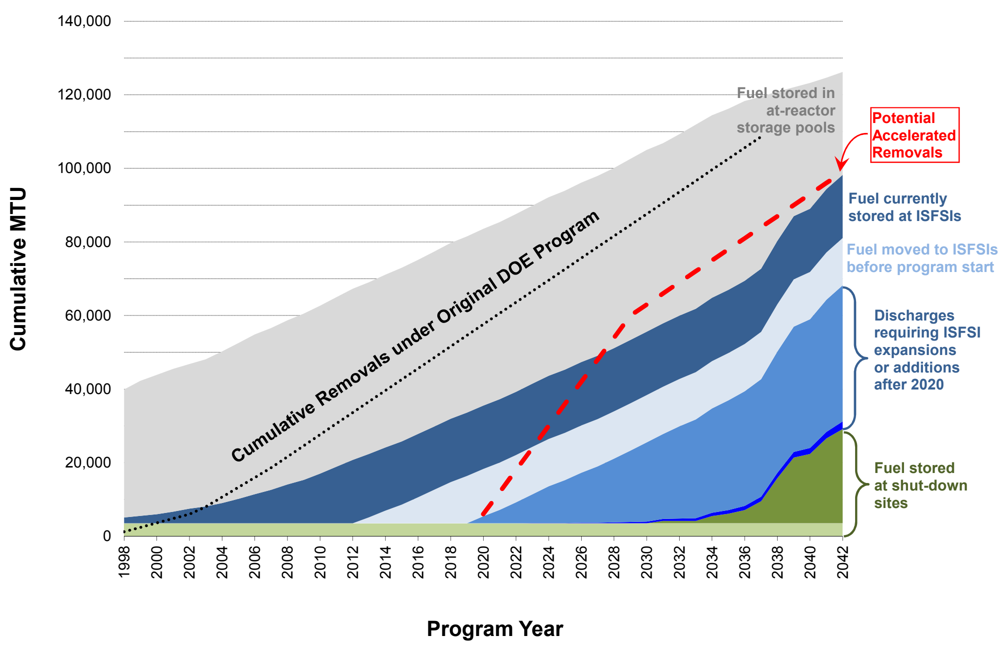


Source: *The Brattle Group* analysis of industry license, discharge, and pool capacity data. Cumulative program removals reflect a DOE transportation rate that ramps up to 3,000 MTU per year, based on DOE (1987) and *Yankee Atomic Electric Co. v. United States* (2008). Delayed removals assume the same transportation rate as the original DOE program.

Reduce At-Reactor ISFSI O&M Costs

There are significant economies of scale to be enjoyed in dry storage O&M expenses, and the DOE could reduce total industry-wide O&M by an order of magnitude or more — eventually saving around $250 to $350 million per year — with centralized facilities. However, to fully achieve this goal the DOE would have to both remove all fuel at existing ISFSIs *and* avoid all new ISFSI builds and expansions. This goal is not achievable without a transportation rate higher than the original program planned. **Figure 6** shows the total volume of fuel requiring dry storage in the blue areas: dark blue is fuel already stored on ISFSIs, while light blue is the incremental quantity added between 2012 and 2020. A new program starting in 2020 with an annual pick-up rate of 6,000 MTU per year for the first 10 years (through 2029) could allow the program to prevent ISFSI expansions and clear fuel from existing ISFSIs, albeit with some delay as the program also works off a 2020 backlog of 36,000 MTU of on-site stored fuel in ISFSIs. After the first 10 years of removing spent fuel at 6,000 MTU per year, the program could be scaled back to 3,000 MTU per year and still keep up with new discharges and fuel removal at future decommissioning sites.

Figure 6 Priority for Shut-Down and All ISFSI Removal (Illustrative)



Source: *The Brattle Group* analysis of industry license, discharge, and pool capacity data. Cumulative program removals reflect a DOE transportation rate that ramps up to 3,000 MTU per year, based on DOE (1987) and *Yankee Atomic Electric Co. v. United States* (2008). Potential accelerated removals assume a 6,000 MTU per year transportation rate through 2029 and 3,000 MTU per year thereafter.

Exchanges for Program Capacity Use

We have described above how the program timing and capacity would need to be sized somewhat differently if various goals and priorities were made preeminent. The key finding is that a new program of 6,000 MTU per year for 10 years, then 3,000 MTU thereafter, could accommodate most economic opportunities to avoid ongoing at-reactor costs and expansions within a decade. Of course, for the first several years of this new program, not all backlogged needs could be met.

However, it should not be necessary for the government to choose who uses the program capacity, or to decide for which of those purposes it would be used. Instead, the program could allocate initial removal rights much like the Standard Contract (now in default) was going to allow, e.g., based on the schedule of past discharges from the reactors to the wet pools. Then, the fuel owners should be allowed to exchange their initial queue position rights (each of which is for a share of the program's capacity, bestowed proportional to each participant's own spent fuel quantities) with each other, via swaps or purchases and sales of rights between themselves and across years when removal is more important to one party than another. Those owners facing a more costly constraint (such as having to build an ISFSI) should be willing to pay more than a party simply interested in drawing down its existing ISFSI, while a shut-down facility capable of decommissioning might be in between. This kind of exchange of economic services and resources is already widely practiced in the industry for a variety of needs, so it would be familiar, easy, and efficient for the participants and the program as a whole to adopt that practice for spent fuel removal prioritization.

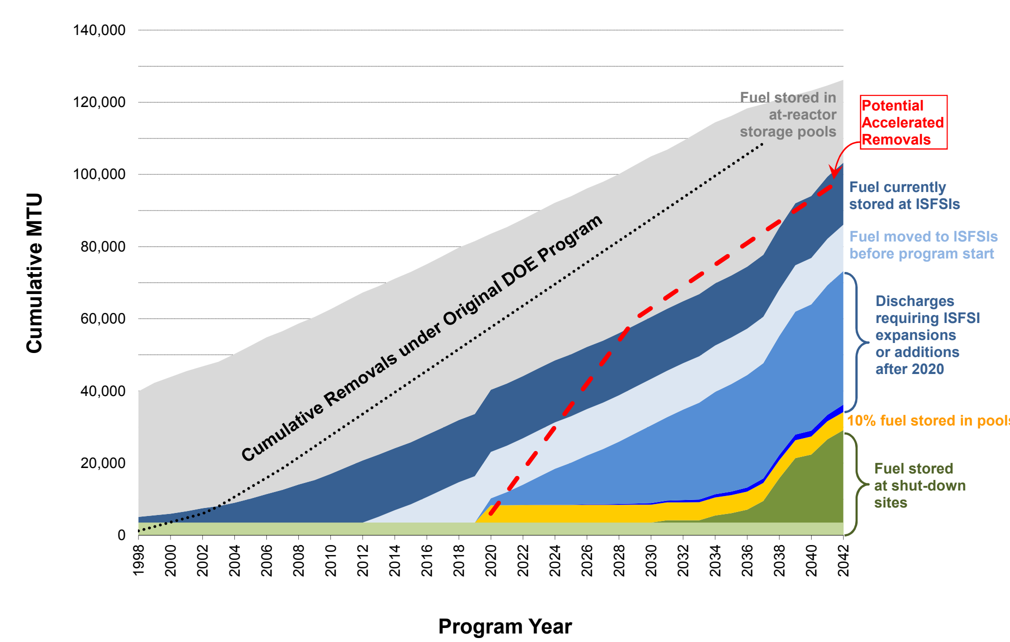
De-Densify Pool Storage Volumes

De-densifying the storage volumes of spent fuel pools in order to reduce pool heat content and radioactivity may be an important new consideration in the design and use of a federal program, at least from the perspective of public concerns and credibility of the nuclear industry's rejuvenation. Procedurally, prioritizing for pool de-densification might be somewhat different in character from goals to facilitate shut-down decommissioning or to avoid new ISFSIs, though it need not be incompatible. Pool de-densification would involve engineering and safety-based scheduling, which might not correspond perfectly with private economic goals to avoid future at-reactor storage costs.

To satisfy these goals, program design for de-densification could involve setting aside some of the early capacity of the program for this purpose, until sufficient de-densification had generally occurred. However, as shown below, this may well leave a considerable amount of the program capacity available to be allocated purely economically. De-densification could also be made into an economically exchangeable priority by making it an obligation subject to some allowable time flexibility with penalties for not achieving it by a certain date.

Figure 7 illustrates a program that includes an immediate goal to reduce pool volumes by 10% (gold area), taking the newer, more radioactive fuel from the pools, combined with the goals of shut-down priority (green areas) and avoiding additions to ISFSIs (blue areas).[31] Removing 10% from each pool would correspond with removing about one to two recent discharges from each pool (about three to six 10 MTU casks), which could be achieved within the first two years of a program having a transportation rate of 6,000 MTU per year. Afterwards, this same transportation rate would be needed for several years to prevent ISFSI expansions or re-densification, as well as to work off the backlog of fuel currently stored on ISFSIs.

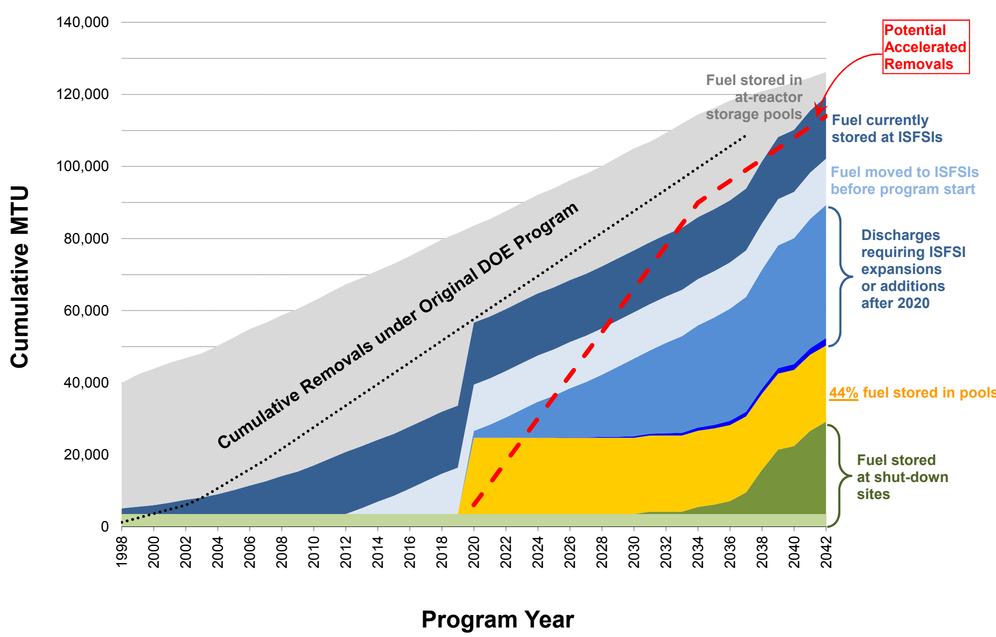
Figure 7 Priority for 10% Reduction in Pool Volumes (Illustrative)



Source: *The Brattle Group* analysis of industry license, discharge, and pool capacity data. Cumulative program removals reflect a DOE transportation rate that ramps up to 3,000 MTU per year, based on DOE (1987) and *Yankee Atomic Electric Co. v. United States* (2008). Potential accelerated removals assume a 6,000 MTU per year transportation rate through 2029 and 3,000 MTU per year thereafter.

More than 10% de-densification could be achieved, but this priority would make shutting down existing ISFSIs more difficult. **Figure 8** shows the program effects of prioritizing pool volume reductions of 44% (about five to seven discharges, or about 17 casks per pool), rather than 10%. This fixed volume reduction is about the same degree of de-densification that would have occurred by 2020 under the DOE's original program, had it transpired on schedule (previously illustrated in Figure 3). However, under this program design fuel currently stored on ISFSIs (dark blue area) would likely remain on-site beyond 2042. A program operating at 6,000 MTU per year for 15 years (instead of 10) would be needed to move all fuel off of existing ISFSIs, achieved by 2035.

Figure 8 Priority for 44% Reduction in Pool Volumes (Illustrative)

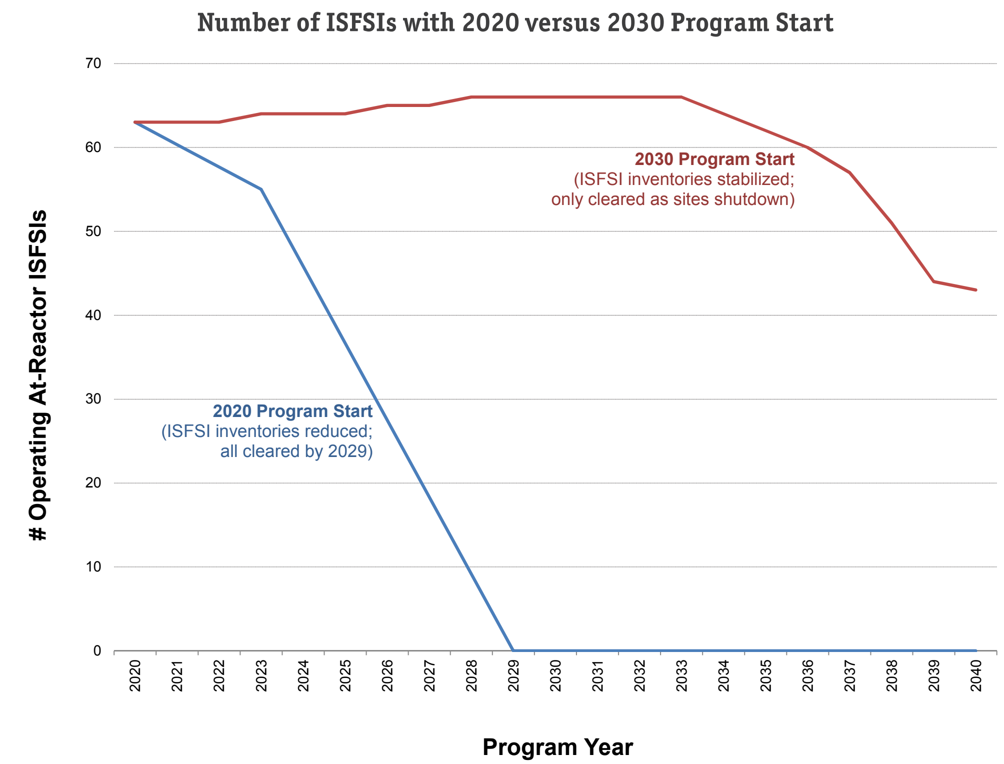


Source: *The Brattle Group* analysis of industry license, discharge, and pool capacity data. Cumulative program removals reflect a DOE transportation rate that ramps up to 3,000 MTU per year, based on DOE (1987) and *Yankee Atomic Electric Co. v. United States* (2008). Delayed removals assume the same transportation rate as the original DOE program, and potential accelerated removals assume a 6,000 MTU per year transportation rate through 2034 and 3,000 MTU per year thereafter.

Program Start Date

All of the above assessments of desirable program size have an assumed start date of 2020. This is arguably ambitious from a political perspective, but it should be quite feasible from an engineering perspective. If the program were delayed another decade (e.g., due to disagreement over new priorities, revised initial allocations, or political agendas), there would be significant adverse consequences for program economics and for public concerns about safe fuel handling and nuclear viability. As demonstrated in **Figure 9**, with a 6,000 MTU per year program starting in 2020, the 63 at-reactor ISFSIs then in existence would decline to zero by 2029, and wet pools could be de-densified by about 10%. In sharp contrast, the same sized program starting in 2030 would have 66 at-reactor ISFSIs to contend with by 2035, and there would still be 43 of them in operation in 2040. Virtually all wet pools would be full through 2040, unless de-densification was made a priority — in which case, more at-reactor ISFSIs would remain. With such a late start, valuable opportunities to reduce costs and improve safety and public confidence in nuclear power would be lost.

Figure 9 Effects of Program Delay



Source: *The Brattle Group* analysis of industry license, discharge, and pool capacity data.

The cumulative annual incremental costs of starting later and maintaining more ISFSIs for longer would be about $4 billion dollars through 2050. Even discounting these costs at a rate of 6% and recognizing the benefit of reduced present value program costs from deferring the expenditures to build the centralized facilities, there would be a net cost of delay of around $1.6 billion to the industry. Perhaps more importantly, this delay in expenditures would further erode public confidence in federal or industry ability to devise durable solutions to foster safer and more economical nuclear power. Opponents of nuclear power may consider this an indirect victory, but they would be compromising their own goals of better waste handling.

Conclusion

While it is not likely that the Fukushima experience is a harbinger of analogous risk for nuclear plants in the United States, the nearly irretrievably catastrophic problems of that accident are an important reminder to look anew at both the safety and economics of spent fuel management in the U.S. This is useful both politically and economically, as the perceived risk from the lack of a long-term solution to nuclear waste management is a barrier to industry development.

The U.S. nuclear fleet is at a critical juncture when most operating plants have wet pools holding several times more spent fuel than was envisioned when the plants were first planned and built. Most have developed ISFSIs sized well below efficient scale (relative to a centralized interim facility) in order to manage the waste they can no longer keep in wet pools. The cost of these site-specific ISFSIs remains a liability for the U.S. government, and these at-reactor dry storage sites are not being used to improve safety by reducing fuel density in the wet pools. Instead, they are being used primarily to accommodate overflow, removing older waste to make room for recent discharges. Thus, there are both safety reasons (reliance on active cooling for densely filled pools) and economic reasons (avoiding continuing at-reactor storage costs) for moving aggressively towards one or a few large federal interim storage facilities.

The size and approach to waste removal prioritization of such a federal program would need to be re-evaluated, as most of the goals and purposes that drove the original intent to build Yucca Mountain have been so badly missed that they have lost relevance. However, it appears feasible to accommodate new goals of closing ISFSIs at shut-down sites, preventing new ISFSIs from being built or expanded, and reducing fuel density from pools to improve their safety, with a program starting by 2020 that is capable of handling about 6,000 MTU per year. Exchangeable queue positions, a feature of the failed Yucca Mountain program, would allow efficient reallocation of this capability (subject to partial constraints for de-densification goals). Given the extensive experience with ISFSI operations over the past decade, this size program should be achievable, and it may even pay for itself from savings in reactor-site O&M costs. Further, it could be funded from existing fees on nuclear generation (subject to legislative authorization), thereby putting no new strain on federal budgets.

Delaying a new program much beyond 2020 would have adverse engineering and economic consequences, as the backlog of unmoved, spent at-reactor fuel would continue to pile up and the costs of maintaining numerous facilities would continue to accumulate as a federal liability. While it is possible to argue about optimal program design, there are clear benefits from starting soon and allowing exchanges to determine the most economical use of the program's capabilities. This is a situation where "the perfect would be the enemy of the good." Improvements in various aspects of spent fuel handling will certainly be made over time, but the knowledge and technology to produce a safe and successful program at a reasonable cost already exist, without any uncertainties in areas that should pose a barrier to action. The U.S. government should find the political will to act soon.

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Endnotes

[1] This is a "steady state" cost estimate of operating and maintaining storage facilities at 14 shut-down sites (about $4 to $9 million per year per site) and 55 dry storage facilities at operating sites (about $4 million per year per site). This cost does not include costs associated with building or loading storage facilities, such as pool re-racking, dry storage planning and engineering, dry storage construction, and loading dry storage facilities.

[2] The DOE signed a "Standard Contract" with each nuclear plant operator following the 1982 Nuclear Waste Policy Act. The Standard Contract imposed a fee of 1 mill (0.1¢) per kWh of nuclear generation, paid into the Nuclear Waste Fund. This fund was to be used to pay for the transportation and irretrievable storage of the fuel at a permanent repository, expected to be at Yucca Mountain in Nevada. See Yucca Mountain sidebar on page 3. For more information on Yucca Mountain and discussion of related policies and activities, see also Wald (2009).

[3] Based on NRC data available at http://www.nrc.gov.

[4] Dimensions depend on specific cask system designs. The casks are also designed to be completely intact through severe natural disasters. For more discussion and technical specifications of cask system designs see Kessler (EPRI, 2010).

[5] For a list of NRC-approved cask designs, see http://www.nrc.gov/waste/spent-fuel-storage/designs.html.

[6] Some shut-down reactor sites have also developed ISFSIs as a cost-effective way to store spent fuel over an uncertain time horizon while awaiting a future government fuel removal program.

[7] The exact pace of the program was not established contractually, but numerous DOE planning documents found that a ramp up to around 3,000 MTU per year within 5 to 10 years of the program's start would have been feasible and desirable. The program removals shown in Figure 3 are based on a ramp up of 1,200 MTU per year for 1998 to 2002, 2,000 MTU per year in 2003, 2,650 MTU per year in 2004 to 2007, and 3,000 MTU per year thereafter, based on a decision by the United States Court of Appeals for the Federal Circuit that for legal remedies plant owners can presume full performance under this schedule. See *Yankee Atomic Electric Co. v. United States* (2008). A 3,000 MTU per year steady-state pace is also consistent with several studies conducted in the mid-1980s and early 1990s on minimizing at-reactor storage costs.

[8] Discharges and future storage requirements are fairly easy to project for decades into the future because of 1) the very high quality of public data on plant operations, and 2) the stability of nuclear plant operations over time, as baseload facilities seek to run on an extremely regular basis.

[9] For a detailed analysis of how the federal program would have avoided additional at-reactor storage see Graves (2009).

[10] NEI (2011). Figures are as of January 2011.

[11] NRC (2001).

[12] Alvarez, et al (2003).

[13] Public estimates of time until boil-off after complete loss of cooling to the top of fuel rods include 1 to 10 days per (Alvarez, 2003) or 100 hours (4 days) per (NRC, 2001).

[14] The DOE's original spent fuel removal program required new fuel discharges to be cooled in pools for at least five year before being transported. Dry storage casks in the U.S. are generally designed with that assumption, although from an engineering perspective it is possible to design casks to accommodate fuel that has only been cooled for less time.

[15] The NRC, for example, publicly expressed the possibility of fuel rod exposure during and after the event.

[16] ANS (March 2012) at page 13 and Appendix G.

[17] BRC (2012), Section 5.5: Safety and Security Considerations for Storage Systems, pages 43-46. See also: http://www.world-nuclear.org/fukushima/fuel_ponds.html.

[18] The estimate of spent fuel volumes in pools is based on the authors' analysis of estimated pool capacities and cumulative reactor discharges, which finds that on average all reactor pools hold about 4.6 reactor cores, Pressurized Water Reactor (PWR) storage pools hold about 5.3 reactor cores, and Boiling Water Reactor (BWR) pools hold about 3.6 reactor cores. This is also consistent with the estimate used in Alvarez (2003), which estimated PWR storage pools in the early 2000s held about 5 reactor cores on average.

[19] Both were discussed at the December 2, 2011 public meeting of the Blue Ribbon Commission. Transcripts and presentations are available at www.brc.gov.

[20] National Academies (2006).

[21] The Royal Society (2011).

[22] Based on the Nuclear Waste Fund fee of 0.1¢ per kWh and Nuclear Energy Institute data on actual annual generation through 2010 of about 800 TWh per year, see http://www.nei.org.

[23] The Blue Ribbon Commission's report addresses these issues in detail. See BRC (2012).

[24] Kessler (EPRI, 2009).The figure includes $67 million for initial planning and licensing, $244.4 million for transportation infrastructure, $175.5 million for site construction, and $270.4 for transportation cask equipment. Note that this study assumed a higher per-cask area requirement of about 600 square feet and a lower number of casks in total (6,000), compared to the example described earlier.

[25] See also Kadak, et al (2010).

[26] Based on information published by Connecticut Yankee after its ISFSI was fully loaded (~2001). Available at: http://www.connyankee.com.

[27] A single 1,000 MW modern supercritical coal plant will burn approximately 2.5 to 3 million tons of bituminous coal per year, leaving about 10%, or 300,000 tons, of that as fly ash and bottom ash, and releasing around 6.5 to 7 million more tons of CO_2. By contrast, the annual spent fuel output of the entire U.S. nuclear fleet (about 101,000 MW, or over 100 times as large as the illustrative coal plant) is only about 2,000 tons of radioactive waste (or about 150 times smaller than the single coal plant's ash alone, by weight).

[28] For more information, see DOE Waste Isolation Pilot Plant at http://www.wipp.energy.gov.

[29] DOE (1985).

[30] For comparison to Figure 3, the blue area in Figure 3 corresponds to the three blue areas combined in Figure 5.

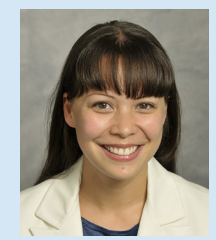
[31] The gold area of de-densification in Figure 7 has been shifted down, out of the upper gray area of fuel that is within wet pools but not facing a pool capacity constraint, hence the small kink in 2020. A similar, larger kink is seen in Figure 8, for the same reason but with greater de-densification.

About the Authors

Frank Graves
Principal

Frank C. Graves is a principal and co-leader of the utility practice area at *The Brattle Group*. He is a specialist in utility systems modeling and risk management, with over 30 years of experience in consulting to the utility industry on planning analyses and regulatory approvals. He has assisted several nuclear utilities with recovery of their spent fuel management costs. He holds an M.S. in Management Science from the MIT Sloan School of Management.

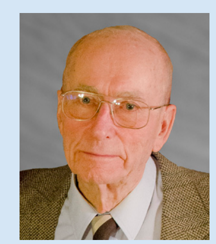
Telephone: +1.617.864.7900 **Email:** Frank.Graves@brattle.com



Mariko Geronimo
Associate

Mariko R. Geronimo is an associate at *The Brattle Group* and has over six years of experience addressing a variety of electricity industry topics in the context of strategic planning, evaluation of market design and performance, and litigation. Ms. Geronimo has also worked extensively in the area of nuclear spent fuel storage, including being the lead analyst managing *Brattle*'s model for projecting the volume and costs of spent fuel at U.S. commercial nuclear plants. She holds a B.S. in Economics and an M.A. in Applied Economics from Northeastern University.

Telephone: +1.617.864.7900 **Email:** Mariko.Geronimo@brattle.com



Glen Graves
Nuclear Physicist

Glen A. Graves is a retired nuclear physicist at the Los Alamos National Laboratory (LANL), where he devoted much of his career to nuclear criticality studies and to the operating and post-shut-down aspects of very high power nuclear propulsion reactors, as well as serving as Assistant for Research in the LANL Director's Office. Dr. Graves also held interim posts as the Head of the Physics Section of the International Atomic Energy Agency (Vienna, Austria) in 1969 and 1970 and as the Acting Director of the National Science Foundation's Office of Energy R&D Policy (Washington, DC) from 1973 through 1977. He has a Ph.D. in Nuclear Physics from Indiana University.