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Reducing the Danger from Fires in Spent Fuel Pools

Frank N. von Hippel and Michael Schoeppner

Program on Science and Global Security, Princeton University, Princeton, NJ, USA

ABSTRACT

This article reviews the case of the spent fuel fire that almost happened at Fukushima in March 2011, and shows that, had the wind blown the released radioactivity toward Tokyo, 35 million people might have required relocation. It then reviews the findings by the United States Nuclear Regulatory Commission (NRC) in 2013 that the consequences of a loss-of-water event could be drastically reduced if spent fuel were moved to dry storage after 5 years of pool cooling but that the probability of a spent fuel pool fire is too low to make this a requirement. Our atmospheric dispersion and deposition calculations using HYSPLIT for hypothetical releases from the Peach Bottom plant in Pennsylvania find average interdicted areas and populations requiring relocation larger than NRC estimates presented to the National Academy of Sciences (NAS) and support the NAS findings of errors and omissions in the NRC's cost-benefit calculations. Political pressures from industry on the NRC may be biasing its analyses toward regulatory inaction.

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Introduction

It has long been known that the loss of water from a nuclear power plant's spent-fuel pool could have catastrophic results. The dense-packing of pools in the United States also has been a long-term concern because such pools contain several times as much spent fuel as they were originally designed to hold. This makes it more likely that, if there were a loss of coolant, the spent fuel would heat up and catch fire and release huge quantities of cesium-137 into the atmosphere.[1] Cesium-137 is a fission product with a 30-year half-life that emits a high-energy gamma ray when it decays.[2] Cesium-137 is the main radioactive contaminant that has forced the long-term relocation of populations from large areas around the Chernobyl and Fukushima Daiichi nuclear power plants.

Since the early 1980s, the U.S. Nuclear Regulatory Commission (NRC) has repeatedly revisited the question of whether or not to require U.S. nuclear utilities to move older, cooler spent fuel in pools to safer air-cooled dry-cask storage. Each

CONTACT Frank N. von Hippel fvhippel@princeton.edu Program on Science and Global Security, Princeton University, 221 Nassau St., Princeton, NJ 08542, USA.
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time, it has concluded that a loss-of-water incident is so improbable that it would not be worthwhile to require nuclear power plant owners to buy the extra casks.

The discussion intensified after the attacks of 11 September 2001 (9/11) raised the possibility that a terrorist attack on a nuclear power plant could puncture a spent fuel pool. It regained traction after it appeared for a time during the Fukushima accident that a spent fuel fire was occurring. Since 9/11, Congress has twice asked the National Academy of Sciences (NAS) to review the issue. The most recent review, in which one of the authors of this article (FvH) participated, was released in May 2016. This article builds on that review.[3]

After the 2011 Fukushima accident, when the NRC staff revisited the spent fuel fire issue it discovered a dramatic new argument for reducing the amount of spent fuel in pools. In a loss of coolant incident that drained the pool relatively slowly, a hydrogen explosion would be probable in a dense-packed but not in a low-density pool. Because the hydrogen explosion would blow out the walls and roof covering the pool, the staff found that the release of cesium-137 to the atmosphere from a fire in a dense-packed pool would be almost complete and about one hundred times larger than the leakage from a fire in a low-density pool inside an intact reactor building. The release from a high-density pool fire would be so large that, on average, it would require the relocation of the population from an area larger than the State of New Jersey (22,600 km^2). Nevertheless, the staff concluded once more that the probability of a loss of coolant from a spent fuel pool was too low to justify the requirement to shift away from dense packing. This analysis did not, however, include the possibility of terrorism and underestimated by an order of magnitude the cost savings from the reduced accident consequences that would result from low-density racking.

This skewed approach may be due in part to the fact that, in recent decades, U.S. nuclear utilities have been subjecting the NRC to intense political pressure, both directly and indirectly through Congress. While regulators in France and Japan have been forcing their nuclear utilities to make post-Fukushima safety upgrades costing hundreds of millions of dollars per reactor,[4] U.S. utilities have succeeded in investing much less. They are concerned that higher costs would force them to shut down many of their plants, which face tough competition from wind and natural-gas-fueled power plants.

Below, the case of the spent fuel fire that almost happened at Fukushima is reviewed. Then the NRC staff's cost-benefit analysis for a shift to low-density pool storage and the politics of nuclear regulation in the United States are discussed.

The spent fuel pool fire that almost happened in Fukushima

The Great East Japan Earthquake off the northeast coast of Japan occurred on 11 March 2011 at 14:46 Japan Standard Time. Fifty minutes later, a 13-meter-high tsunami hit the Fukushima Daiichi Nuclear Power Plant and flooded the basements of Units 1–4, knocking out their electrical distribution panels and virtually all of their cooling and emergency systems. With the core cooling systems in units 1, 2, and 3 incapacitated, the water in their reactors boiled off, and steam reacted with the hot zirconium alloy (zircaloy) cladding of their fuel to produce hydrogen. The pressures in the reinforced concrete primary containment structures around reactors in units 1 and 3 climbed to the point where the bolts holding down the tops of the containments stretched and allowed hydrogen to leak into the surrounding reactor buildings. A day after the tsunami, a hydrogen explosion blew out the walls and roof of the top floor of reactor building 1. Two days later, a similar explosion occurred in reactor building 3. The core of unit 2 also melted down and its primary containment leaked, but perhaps in another location, and there was no hydrogen explosion.

Fortunately, despite the leakage and the explosions, the primary containments and the surrounding reactor buildings of units 1—3 trapped about 98% of their combined core inventories of radioactive cesium.[5]

Concerns about the possibility of a spent-fuel pool fire

When the earthquake occurred, reactor unit 4 had been down for maintenance for 102 days and all the fuel in the reactor had been unloaded into its spent fuel pool. Four days after the earthquake, however, a hydrogen explosion occurred in the top floor of the reactor building where the spent fuel pool is located.[6]

Initially, nuclear safety experts around the world assumed that most of the water in the spent fuel pool was lost and, as with the cores of units 1 and 3, steam had reacted with the hot zircaloy cladding of the exposed fuel to generate hydrogen, forming an explosive mixture with the air above the pool. The day after the hydrogen explosion, however, Tokyo Electric Power Company (TEPCO), the Japanese utility that owns the plant, sent a helicopter to take video footage of its condition and became convinced by a brief sighting that water still covered the fuel in pool 4.[7] Later, TEPCO concluded that hydrogen had back-flowed into reactor building 4 through an exhaust system shared with unit 3.[8] For more than a week, however, there were doubts at the NRC's Operations Center outside Washington, D.C. that the spent fuel in pool 4 was still covered with water.[9]

In Japan, Prime Minister Naoto Kan asked Shunsuke Kondo, the chairman of Japan's Atomic Energy Commission, about the potential scenarios for the unfolding of events at Fukushima. On 25 March, Kondo reported back that one possible outcome could be a spent-fuel fire.[10] The spent fuel pools were outside the reactor containments and hydrogen explosions had destroyed the walls and roofs surrounding the pools of units 1, 3, and 4. Spent-fuel fires in any of those units therefore would release radioactivity directly into the atmosphere. If a fire in pool 4 released the equivalent of the cesium-137 in one or two spent reactor cores to the atmosphere (it contained the equivalent of 2.4 cores), compulsory relocations might be required out to 110—170 km and voluntary relocations might occur out to 200–250 km. In making these judgments, Kondo used the cesium-137 contamination levels of 1.5 MBq/m^2 (40 Ci/km^2) and 0.56 MBq/m^2 (15 Ci/km^2) that had been used after the Chernobyl accident to define respectively the boundaries of the areas of compulsory relocation and strict radiation control.[11] A decade after the Chernobyl accident, about half of the residents of the latter area had voluntarily relocated.[12] The distance from the Fukushima Daiichi nuclear power plant to central Tokyo is about 225 km.

A near miss

Although there was no spent fuel pool fire at the Fukushima Daiichi Nuclear Power Plant, six weeks after the earthquake, TEPCO learned that the catastrophe had been avoided by a margin smaller than it had realized.

What almost happened in pool 4 can be understood through a combination of TEPCO's reconstruction of events and a scenario published by a group at Sandia National Laboratory a year after the accident.[13]

There were 240 metric tons of uranium (1331 fuel assemblies) in the spent fuel in pool 4 when the earthquake happened on 11 March 2011, including a full core (548 assemblies) that had been removed from the reactor after it was shut down on 30 Nov. 2010. The cesium-137 inventory of the pool was about 900 PBq (24 MCi).[14]

The Sandia group calculated what would have happened had the water in the pool simply been allowed to boil down in the absence of walls or a roof above the hot pool so that water vapor could be carried away by the wind, as from a kettle with the top removed. This is a good match to the actual situation since, as already noted, four days after the earthquake a hydrogen explosion had created a near open-air situation above pool 4.

Spent fuel pool 4 is about 12 m deep and, before the earthquake, was filled with 11.5 m of water, about 7 m above the top of the spent-fuel racks. In the Sandia scenario, the decay heat produced by the spent fuel, about 2 MWt, would raise the temperature of the approximately 1400 m^3 of water in the pool to near boiling in about three days.[16] As the water's temperature approached the boiling point, its evaporation rate would increase until the cooling due to evaporation approximately balanced the heating at about 90°C.[17] After that, the average rate of water loss to evaporation would be about 0.67 m per day. The volume of the pool above the rack was about 120 m^3 per meter of depth. The rate of water loss therefore would correspond to the evaporation of about 80 metric tons of water per day and the level would have dropped to 2 m from the bottom of the pool, uncovering the top half of the stored spent fuel, on 27 March 2011, sixteen days after the earthquake.[18] At that point, a runaway exothermic reaction of steam with the hot exposed zircaloy cladding would have ignited a spent fuel fire.

What actually happened was more complicated:

1. In its reconstruction of the history of the water level in the pool, TEPCO estimated that the pool lost a total of about 1.5 m of water depth as a result of overflow due to the rocking of the pool by the earthquake and later by uneven overpressure from the hydrogen explosion. This would have moved the date when the pool water level would have boiled down to the 2 m level about 2 days earlier, to 25 March.

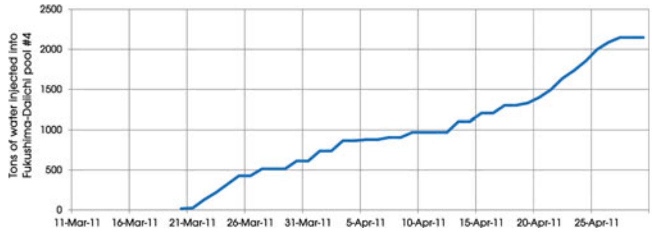

Figure 1. TEPCO estimate of cumulative quantity of water injected into pool 4.[15]

2. Starting on 22 March, water was added to the pool using a cement pump "giraffe." TEPCO's best estimate is that a total of about 1000 tons had been added as of 10 April (Figure 1), equivalent to about 12.5 days of evaporation. About 2 days would be added by the energy required to heat the added water up to the near boiling temperature of the pool.[19] This would increase the time before the 2 m level would have been reached to about 8 April.

But why, if beginning on 22 March, TEPCO was able to deliver water into the pool effectively, did it not pump in enough to refill the pool? The answer appears to be that, before 12 April, when TEPCO hung a measuring instrument and video camera on the boom of the giraffe, it was not able to directly measure the water level in the pool. Instead, it misinterpreted indirect evidence to conclude that it *had* filled up the pool. The indirect evidence was that water was flowing into the pool's overflow "skimmer" tank.[20] Apparently, however, some of the water being delivered by the giraffe was going directly into the skimmer tank.

Fortunately, there was another source of water that kept the spent fuel covered. As a result, on 8 April, the water in the pool was still 2.5 m above the top of the rack (see Figure 2). Thus, the pool contained about 5 more meters or 600 more tons of water than calculated above.

The source of the extra water in the spent fuel pool was leakage from the adjacent reactor well, which had been filled with water to shield the workers from the radiation coming from the open reactor pressure vessel and from the radioactive steel reactor components stored in the dryer-separator pit that is a part of the reactor

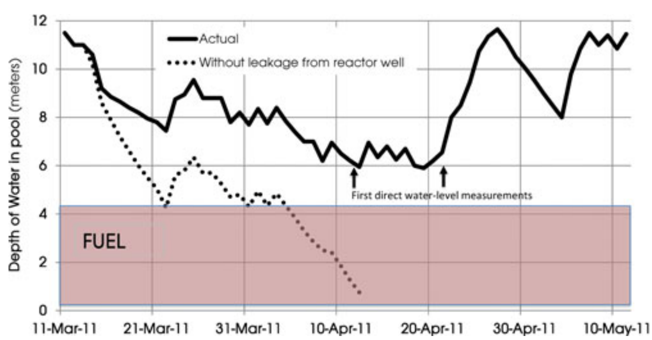

Figure 2. Solid line: TEPCO reconstruction of the history of the water level in pool 4 during the two months after the earthquake.[21] The arrows show the first actual measurements, the first of which was made on 12 April and the second on 22 April. The dotted line below shows an estimate in the National Academy of Sciences report of the amount of water that would have been in the pool in the absence of water leaking into the pool from the adjacent reactor well.[22]

well.[23] The reactor well is separated from the spent fuel pool by a gate. Apparently, as evaporation lowered the level of the spent fuel pool, leakage past the gate kept the water in the reactor well at approximately the same level as in the pool.[24] TEPCO estimated that, as of 12 April, about 600 m^3 of water had flowed from the reactor well into the spent fuel pool.[25] This would have raised the water depth in the pool to approximately the level measured from the giraffe boom on 12 April.

Consequences if a fire had happened

Figure 3 shows the Sandia scenario predictions for the temperatures at the top and bottom of the spent fuel in the absence of added water. The temperature of the underwater portion of the fuel would have been about 90°C. After a length of spent fuel became uncovered, however, it would begin to heat up. In the Sandia calculations, the temperature of the top of the fuel would spike on day 17 after it reached about 1200°C, when a runaway steam-zircaloy reaction would generate both heat and hydrogen. So much of the zircaloy cladding was predicted to be consumed that the Sandia group stopped plotting the temperature of the top of the fuel thereafter. The same thing would happen to the bottom of the fuel a few days later but the zircaloy would be consumed more slowly, perhaps because the pool would be almost empty and steam would be generated at a lower rate resulting in a lower reaction rate with the hot fuel.

Figure 4 shows the estimates of the daily fractional releases of the cesium-137 inventory of spent fuel pool 4 in the Sandia scenario, with the first day of the fire delayed until 9 April by TEPCO's addition of 1000 tons of water. The Sandia calculations predict that virtually the entire inventory of the pool's cesium-137 would have been released into the atmosphere, mostly during the first four days after the uncovering of the top half of the fuel.

To assess the consequences for Japan had this scenario occurred in Fukushima Daiichi pool 4, the dispersion of the cesium-137 released was calculated for historical atmospheric conditions during the spring of 2011. The threshold for relocation

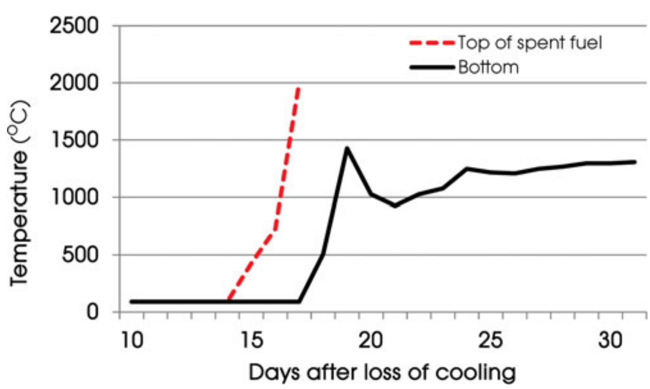

Figure 3. Spent fuel temperatures in a Sandia boil-down scenario for pool 4. After a section of the fuel is uncovered, the local fuel temperature rises, first because of heat from the radioactive decay of the contained fission products and then, above about 1200°C, because of oxidation of the zircaloy cladding by steam, which yields hydrogen. The simulation ends at 32 days because the oxidized fuel and racks are assumed to have crumbled into debris.[26]

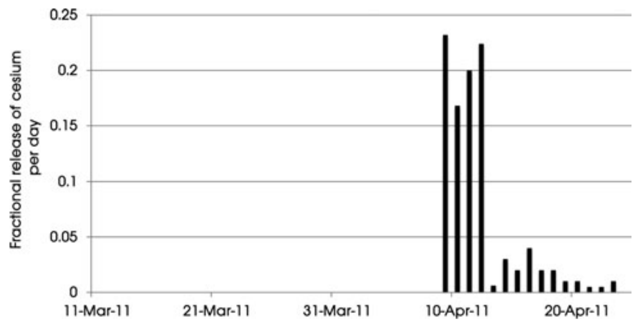

Figure 4. Daily fractional releases of the radioactive cesium in pool 4 to the atmosphere in the Sandia boil-down scenario delayed by TEPCO's addition of 1000 tons of water.[30]

was assumed to be the approximate level that Japan adopted for the Fukushima accident, about 1 MBq/m^2 (27 Ci/km^2).[27]

The atmospheric transport and deposition of cesium-137 from the hypothetical spent fuel pool fire were calculated using the U.S. National Oceanic and Atmospheric Administration's (NOAA's) HYSPLIT model,[28] which uses meteorological data archived in NOAA's Global Data Assimilation System.[29]

Plume trajectories were calculated for releases on each day of March and April 2011. During most of this period, the wind blew eastward to the Pacific Ocean, and a relatively small fraction of the cesium-137 would have been deposited on the land area of Japan, although potentially more in absolute terms than the amount deposited from the actual reactor core meltdowns. Figure 4 shows that, in the absence of leakage into the spent fuel pool from the reactor well, 9 April would have been the day a spent pool fire began to release cesium-137 into the atmosphere. On that and subsequent days, due to mainly eastbound winds, only 5% of the released activity would have been deposited on Japanese land with the remainder going over the Pacific. Had the release begun on 19 March, however, the wind would have carried most of the cesium-137 towards Tokyo. Figure 5 shows from left to right the areas of Japan contaminated to more than 1 MBq/m^2 by the actual accident, which released in the range of 6–20 PBq[31] and by hypothetical 4-day releases of 890 PBq in the proportions shown in Figure 4 beginning on 9 April and 19 March respectively. It should be emphasized that the 19 March case is included as a near-maximum credible case for the consequences of a spent fuel fire at Fukushima. Given that the tsunami occurred on 11 March, a fire could have started on 19 March only if the earthquake had caused a leak in pool 4.[32]

Even a release with mostly eastbound winds would have led to a compulsory relocation of 1.6 million people from an area of 4300 km^2. The compulsory relocation zone shown on the right of Figure 5, with the winds carrying large quantities of radioactivity towards Tokyo, would have extended down the east coast of Japan's Honshu Island to Tokyo. Its area of 31,000 km^2 would have covered about 8% of Japan's land area. Twenty-seven percent of the population of Japan or thirty-five million people live in this zone.

The main parameters determining the level of ground contamination are the winds during and following release and the assumed dry and wet deposition rates.

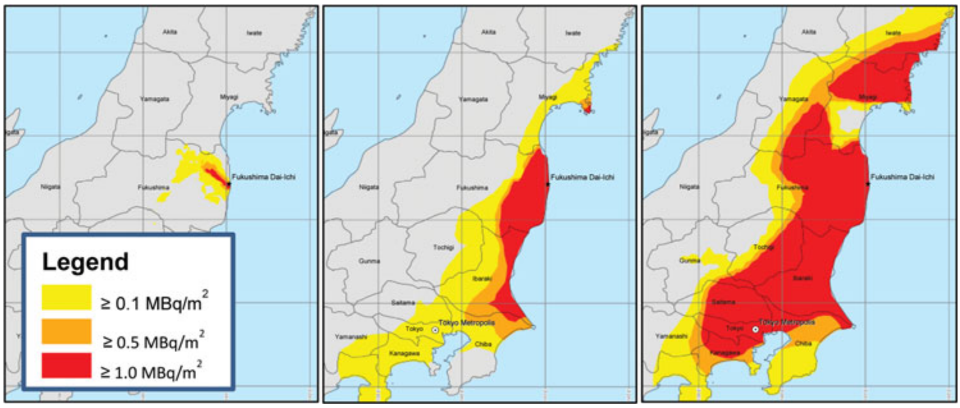

Figure 5. Left: Actual contamination levels after the Fukushima Daiichi accident.[33] Middle: Contamination levels after a hypothetical spent fuel fire in pool 4 starting, as per the scenario in Figure 4, on 9 April 2011 when the wind was blowing mostly to sea. Right: Contamination levels after a hypothetical spent fuel fire in pool 4 starting on 19 March 2011 when the wind was blowing toward Tokyo. This is a scenario that physically could only have occurred had there been a leak in pool 4. The maps show the levels of cesium-137 contamination with the red areas contaminated to above 1 MBq/m^2, which led to compulsory relocation for the actual accident. The orange areas are contaminated to between 0.5 and 1 MBq/m^2. The huge difference in the areas contaminated above 1 MBq/m^2 in the left and right figures is due to the fact that the destruction of the roof and walls surrounding pool 4 by a hydrogen explosion would have allowed the cesium-137 in the pool to be released directly into the atmosphere. In contrast, the primary containments of reactors 1–3 at Fukushima Daiichi released on average only about 2% of their core inventories of cesium-137.

The dry deposition velocity of an aerosol depends on its density and particle size, For a hypothetical spent-fuel fire with a release of about 1090 PBq, the NRC calculated a two-humped particle-size distribution with 74% of the activity centered around an average deposition velocity of about 0.2 cm/s and the remainder with an average deposition velocity of 2.8 cm/s.[34] Sensitivity studies for dry deposition velocities between 0.2 and 2.8 cm/s and with and without wet deposition show that the high contamination areas in this scenario are determined primarily by wet deposition. This is consistent with the fact that, for the actual accident, the high-contamination area to the northwest of the Fukushima Daiichi Nuclear Power Plant appears to have been due to rainout.[35]

Dry and wet deposition with a dry deposition velocity of 0.2 cm/s was calculated for the seven days following the start of the release. According to our calculations, by that time, for the right-hand case in Figure 5, 23% of the cesium-137 would have been deposited on Japan with most of the remainder deposited in the Pacific Ocean.

The U.S. Nuclear Regulatory Commission's considerations of the dangers of high-density racking in spent fuel pools

Congress established the NRC as an independent agency in 1974, when it broke up the U.S. Atomic Energy Commission. The AEC had been weakened politically by many controversies in which it appeared to be overriding legitimate public safety concerns about its projects.

The AEC had hoped to prove that the consequences of a nuclear reactor accident would not be that bad. Its first effort, "Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants," (WASH-740), was published in 1957.[36] Critics highlighted the worst-case accident considered in that report, however, an unrealistic release to the atmosphere of 50% of the fission products in the core of a 500-megawatt (electric) reactor. This accident was estimated to require the long-term relocation of the population from 700 square miles (1800 km^2). An update of WASH-740 was completed in 1964 but its worst-case accident was even worse and the update was only released to the public ten years later as the AEC was being broken up.[37] The NRC inherited a draft of the AEC's third effort, WASH-1400, titled simply "Reactor Safety Study," RSS, in which an attempt was made to systematically calculate the probabilities of nuclear reactor accidents as a function of the seriousness of their consequences.

The NRC published the RSS in 1975. The Executive Summary showed in graphical form, for the foreseeable U.S. fleet of about 100 nuclear power reactors, that the probability of one thousand people being killed by a nuclear power plant accident was two orders of magnitude lower than the probability of the same number of people being killed by a falling airplane or a chlorine gas release and four orders of magnitude lower than the probability of one thousand people being killed in the U.S. by an earthquake or a tornado. With regard to property loss, the RSS found that the probability of an accident costing more than $15 billion ($60 billion in 2015 $) was less than one in 10 million per year. The RSS did not consider spent fuel fires at length but stated, "potential releases are small in comparison to the releases associated with core melt."[38]

Reviewers found the RSS to be deeply flawed, however, starting with the presentation of its results. It made its primary comparisons with other risks on the basis of early "prompt" fatalities from high radiation doses. But most of the deaths from a reactor accident would be delayed cancer deaths. Indeed, there were no prompt high-radiation fatalities among the public from either the Chernobyl or Fukushima accidents while tens of thousands of cancer deaths have been projected from Chernobyl[39] and perhaps a thousand from Fukushima.[40]

With regard to accident probabilities, the uncertainties in the predicted probabilities of high-consequence accidents in the RSS were claimed to be a factor of five. However, independent reviews quickly identified key accident sequences where uncertainties in probabilities had been arbitrarily reduced by orders of magnitude.[41]

Probably most damaging to the credibility of the RSS was a critique by a group organized by the professional society of U.S. physicists, the American Physical Society (APS).[42]

The NRC's new oversight committee in the House of Representatives pressed the Commission to sponsor its own outside review and the NRC appointed a committee of seven including three members from the APS study group, including one of the current authors (FvH).

After the review group confirmed the criticisms of the RSS,[43] the Commissioners issued a policy statement that, on the one hand, declared, "the Commission does not regard as reliable the Reactor Safety Study's numerical estimate of the overall risk of reactor accident" while, on the other, stating that "the Commission supports the extended use of probabilistic risk assessment in regulatory decision making."[44]

The decision to dense-rack U.S. spent fuel pools

In 1981, U.S. nuclear utilities abandoned their plans to reprocess spent fuel to recover plutonium. The economics of reprocessing had been premised on the expectation that plutonium recovered from the spent fuel would be sold at a high price for use in startup fuel for the liquid-sodium-cooled plutonium breeder reactors that the AEC had been promoting. The Carter Administration concluded, however, that breeder reactors would not be able to compete economically with existing water-cooled power reactors.[45] U.S. nuclear utilities came to the same conclusion a few years later.

As a result, until an alternative off-site destination for spent power reactor fuel can be found, U.S. nuclear utilities have mostly been storing their accumulating stocks on their reactor sites.

The nuclear utilities chose the least costly way to provide additional spent fuel storage: dense-packing their storage pools by storing the spent fuel assemblies vertically with very little space between them in racks of individual vertical steel boxes. To prevent the dense-packed fuel from going critical, the walls of the boxes were surfaced with sheets containing neutron-absorbing boron. The closed racks replaced racks with open lattice sides through which air could circulate freely if the pools lost water.

Dense-racking allowed the nuclear utilities to delay for about 20 years the time when their pools would be full. In addition, when it became necessary to remove fuel to dry casks to make space available for newly discharged hot fuel, the oldest fuel in the pool would have cooled for an additional 20 years and each dry cask would be able to hold more fuel assemblies before reaching its temperature limits.[46]

In subsequent decades, however, the safety of dense packing spent fuel pools became a chronic concern for the NRC and the research groups it funds in the Department of Energy's national laboratories:[47]

- In 1984, a Sandia study found that a spent fuel fire might occur in a drained pool.[48]
- In 1987, a Brookhaven National Laboratory study found that such a fire could result in a large release of radioactivity and suggested a number of risk-reduction measures, including returning to low-density racking.[49]
- In 1989, an NRC cost-benefit study concluded, however, that, given the low probability of a spent fuel pool fire, the costs of every one of the risk-reduction measures that had been proposed would exceed its probability-weighted benefits.[50]
- In 2001, an NRC study of safety issues at decommissioned nuclear power reactors concluded, "the possibility of a zirconium fire leading to a large fission product release cannot be ruled out even many years after final shutdown" but

concluded again that "the risk [defined as the product of the probability and the consequences] is low because of the very low likelihood of a zirconium fire."[51]

In 2003, following the terrorist attacks of 11 September 2001, a group of outside researchers, Alvarez *et al.*, reviewed the above reports and others and argued that, given the risk of terrorist attacks and the huge potential consequences of a spent fuel pool fire, the NRC should require that U.S. spent fuel pools be returned to low-density racking. To make that possible, they proposed that spent fuel should be moved into dry-cask storage after five years of pool cooling.[52] The article attracted considerable attention[53] and Congress requested an NAS study. The NAS study recommended more research on the issue but the NRC found even this too critical and delayed clearance of the report of the NAS study for public release for two years, trapping itself in an apparent contradiction between its position that the risk of a spent fuel fire was not significant and its position that the NAS report contained information that would be useful to terrorists.[54]

In 2011, after the Fukushima accident, the NRC established a "Lessons Learned" task force. One of the resulting studies was an examination of a possible requirement that U.S. nuclear utilities remove spent fuel from pools after five years of cooling. The idea differed from the proposal that had been put forward by Alvarez *et al.* in that the NRC would not require the replacement of the high-density closed racks but just the removal of approximately 80% of the fuel that they contained. Convective air cooling of the spent fuel in the racks therefore could not occur unless and until the pool drained so completely that the holes in the bottoms of the racks were uncovered. The NRC staff termed this idea "expedited transfer" and submitted a regulatory analysis of it to the Commissioners in 2013.[55]

That analysis built on an NRC staff study (NUREG-2161) of the consequences of loss-of-water accidents from spent fuel pools of the Fukushima type. The specific scenario considered in NUREG-2161 was a loss of water in one of the pools of the twin boiling water reactors (BWRs) at the Peach Bottom Nuclear Power Plant in Pennsylvania.[56] Despite the experience of Fukushima, the study did not consider the possibility of a simultaneous reactor accident impeding access to the pool. It therefore ruled out an evaporation scenario such as had occurred in pool 4 of Fukushima Daiichi because it would take more than 72 hours for the water level to fall to the top of the fuel and the staff deemed it incredible that a situation could remain uncontrolled for more than three days. The staff therefore considered situations in which an earthquake resulted in leakage from the bottom of the pool, draining it faster than the water could be replenished. It was found that, if the top half of the spent fuel were uncovered and the drainage of the pool were not too fast, a steam-zircaloy reaction would produce substantial amounts of hydrogen. In the case of a dense-packed pool, enough hydrogen could be generated to produce an explosive concentration in the large space over the pool. A hydrogen explosion would blow out the upper walls and roof of the reactor building, as happened at Fukushima, and allow the ingress of air carrying unlimited quantities of oxygen. The resulting spent fuel fire would release a significant fraction of the cesium-137 from the fuel into the atmosphere, a total of up to 900 PBq (24 MCi) in the cases discussed in the study, about the same as the inventory of Fukushima Daiichi pool 4.[57]

For low-density storage, however, NUREG-2161 found that, because a smaller amount of fuel would be exposed to steam,[58] the concentration of hydrogen produced above the pool would be below the threshold required for an explosion and only a small fraction of the cesium-137 inventory would leak from the intact reactor building,[59] up to 11 PBq (0.3 MCi), about 1% as much as calculated for a fire and hydrogen explosion in a high-density pool.[60] Eleven PBq is in the range of the 6–20 PBq (0.16–0.54 MCi) estimated release of cesium-137 from the Fukushima accident and an order of magnitude less than the 85 PBq (2.3 MCi) released by the Chernobyl accident.[61]

When the NRC staff compared the average consequences of releases of about 7 PBq (0.2 MCi) of cesium-137 from a low-density pool and 330 PBq (8.8 MCi) from a high-density pool at the Peach Bottom Nuclear Power Plant, it found that the smaller release would cause the displacement for a year or so of about 120,000 people from an area of about 600 km^2, on the same order as the area made uninhabitable by the Fukushima accident. The larger release would displace an average of 4.1 million individuals from an area of 24,000 km^2, larger than the land area of the state of New Jersey. The calculated population radiation doses would result in an estimated 3,000 and 20,000 cancer deaths respectively.[64]

The NRC's 2013 regulatory cost-benefit analysis

In its 2013 analysis of a possible regulatory requirement for the nuclear utilities to move to low-density storage, the NRC staff estimated the average release of cesium-137 from fires in the four classes of U.S. dense-packed spent fuel pools including all U.S. operating nuclear power reactors and four under construction (Table 1). The pool-weighted average estimated release was 1600 PBq (43 MCi) almost twice as much as the cesium-137 inventory in Fukushima Daiichi spent fuel pool #4, because spent fuel pools in the U.S. contain much more spent fuel than those in Japan.

As in Japan, the magnitudes of the resulting economic losses, population displacements and radiation doses would depend on the overlap between where the winds carried the radioactivity and the distribution of population and infrastructure and where there was "wet" deposition of the airborne radioactivity by rain or snow. The

Table 1. NRC staff base-case estimates of cesium-137 releases and the associated uncertainty ranges for fires in four classes of U.S. dense-packed spent-fuel pools.[62]

Reactor type[63]	Pools	Average Cs-137 inventory (PBq)	Release (%)	Release (PBq)
BWR I & II	31	1950 (1500–2340)	40 (3–90)	781 (44.4–2110)
BWR III and PWRs	49	2510 (2120–2890)	75 (10–90)	1900 (211–2600)
AP-1000s (under const.)	4	1640 (1250–2010)	75 (10–90)	1230 (126–1810)
Units with shared pools	10	3740 (2350–5260)	75 (10–90)	2800 (237–4740)
Pool-weighted averages		**2420 (1910–2930)**	**63 (8–90)**	**1600 (155–2630)**

Table 2. Pool-weighted averages of interdicted areas and displaced populations for fires in U.S. dense-packed spent fuel pools provided by NRC-staff to the NAS committee compared with Chernobyl and Fukushima. The NRC estimates of "interdicted" populations include only inhabitants of areas subject to compulsory relocation. For Chernobyl and Fukushima, voluntary relocations from less contaminated areas approximately doubled the numbers shown.

	Average (range)
Area "interdicted" (km^2)	
NRC calculation: fire in a U.S. high-density pool[67]	31,000 (14,000–48,000)
Chernobyl[68]	3,100
Fukushima[69]	1,100
Population "interdicted" (millions)	
NRC calculation: fire in a U.S. high-density pool[70]	3.5 (1.3–8.8)
Chernobyl[71]	0.116
Fukushima[72]	0.088

NRC staff calculated the consequences for different weather conditions to obtain averages and ranges.[65]

In its regulatory assessment, the NRC staff presented the reduction in accident consequences resulting from shifting to low-density racking only after multiplying the consequences by its estimates of the probabilities of spent fuel fires occurring in pools of each plant type. This was done because it is the probability-weighted benefits that the staff weighs against the costs of the regulatory action under consideration.[66] This mode of presentation, however, also makes NRC regulatory analyses almost impenetrable.

The NAS Committee on Lessons Learned from the Fukushima Nuclear Accident felt it to be important to know the absolute magnitudes of the consequences, especially for large-consequence, low-probability events such as spent fuel fires where probability estimates would necessarily be uncertain and incomplete. The committee therefore requested that the NRC staff provide its estimates of the accident consequences *without* the probability multiplier.

The pool-weighted averages of the staff's estimates of the sizes (and uncertainty ranges) of the interdicted areas and displaced populations for high-density spent pool fires are shown in Table 2.

The NRC staff used the MACCS2 dispersion model program to obtain its estimates. In this article, HYSPLIT has been used to do calculations of the interdicted area and populations for a 1600 PBq release of cesium-137 from the Peach Bottom Nuclear Power Plant over about 32 hours. The release as a function of time was scaled to the release profile for a 1090 PBq release of cesium-137 from the Peach Bottom Nuclear Power Plant in a MACCS2 computer printout released by the NRC as a result of a request by the State of New York.[73] As in the Japan case, the particles carrying the cesium-137 were released from a vertical line source 75 to 125 m above ground level and a dry deposition velocity of 0.2 cm/s was used.

The treatment of dispersion and deposition in HYSPLIT is much more realistic than in MACCS2. Although MACCS2 can simulate various weather conditions, it is based on a straight-line Gaussian plume model and assumes that the weather everywhere is the same as at the source point.[74] It therefore is designed to describe dispersion and deposition near the source. HYSPLIT, by using real historical weather data, takes into account the medium and long-range atmospheric transport phenomena as well as the topography of a region, which are important in calculating contamination levels over the huge areas that would be affected by a large release of cesium-137 from a high-density spent fuel pool fire. For example, even if there is no precipitation at the release point, the air masses that pass it will tend to carry the cesium-137 toward low-pressure areas, which, on the U.S. East Coast, tend to be areas of rainfall.

The relocation ("interdiction") criteria recommended by the U.S. Environmental Protection Administration (EPA) are a dose of 2 rem in the first year and 0.5 rem/yr. in each of the subsequent four years, assuming no radiation shielding by buildings, etc.[75] A cesium-137 contamination level of 1 MBq/m^2 will produce an initial unshielded dose-rate of about 1.74 rem/yr.[76] Taking into account the lifetime of cesium-137 and using the NRC's formula for attenuation of the gamma rays as the cesium-137 sinks into the soil,[77] a contamination level of 1.5 MBq/m^2 would give first-year dose of 2 rem and 0.53 MBq/m^2 would give a dose of 0.5 rem in the second year, bracketing the 1 MBq/m^2 that defined the compulsory evacuation zone in Japan.

The same release time dependence that was used in the NRC's MACCS2 calculations for an accident at the Peach Bottom Nuclear Power Plant was used with real weather data starting on the first day of each month of 2015. The results were averaged over these twelve HYSPLIT runs for the first day of each month in 2015 to take into account seasonal weather variations. Figure 6 shows selected examples of contamination areas. The sizes and locations of the affected areas are strongly dependent on the weather conditions. The examples shown in Figure 6 represent cases with the lowest overall impact (1 January), strong long-range effects (1 April), highest number of people to be relocated (1 July), and the largest interdicted area (1 October).

As of a week after the start of the release, on average 44% of the cesium-137 released in these scenarios had settled on land within 15 degrees latitude and longitude of Peach Bottom. Also, on average, about half of the areas shown as contaminated above 1 MBq/m^2 would not be contaminated above that level in the absence of rainfall.[79]

Table 3 compares the results of the NRC MACCS2 results reported to the NAS Committee and as calculated with HYSPLIT for a number of different interdiction contamination thresholds.

The results in Table 3 show that, for an interdiction contamination level of 1.5 MBq/m^2 (a first year limit on the unshielded dose of 2 rem) the average HYSPLIT results for interdicted areas and population relocation are respectively 2.5 and 4.5 times larger than the numbers provided by the NRC staff to the NAS committee. In the case of the relocated population, part of the explanation for the discrepancy appears to be that the Peach Bottom site is considered by the NRC to be in the 90th percentile in terms of site population density within 50 miles.[80] If our results for displaced population are compared with the 8.8 million at the high end of the range given by the NRC, the discrepancy with regard to interdicted population is reduced to about a factor of 1.7 for an interdiction contamination level of 1.5 MBq/m^2.

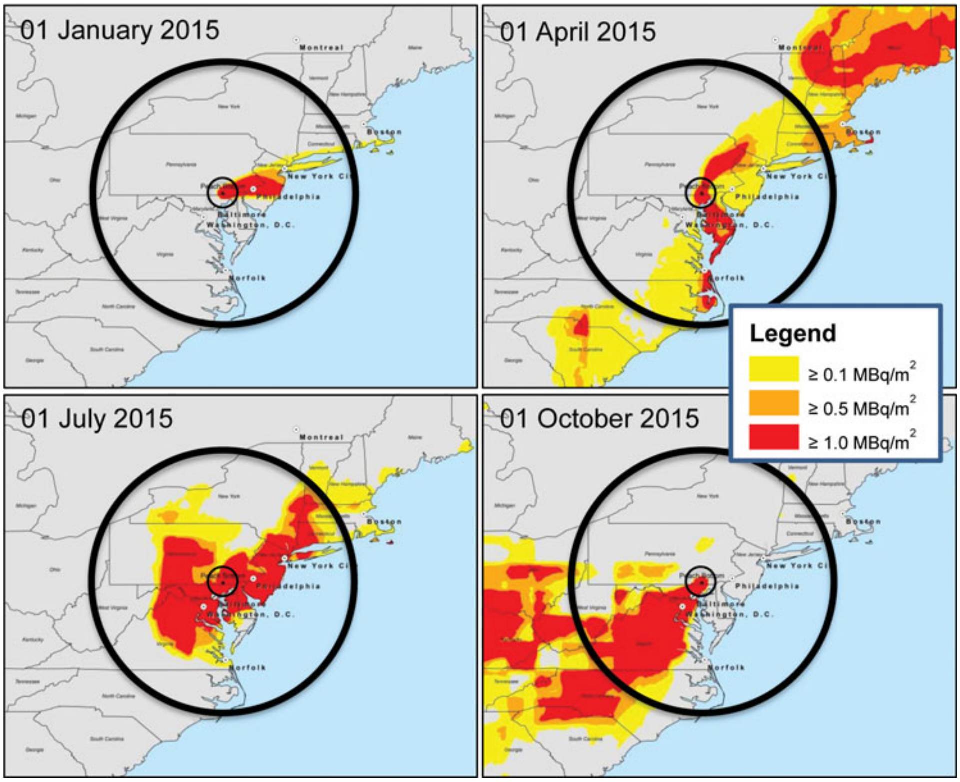

Figure 6. Contamination areas from a hypothetical fire in a high-density spent fuel pool at the Peach Bottom Nuclear Power Plant in Pennsylvania releasing 1600 PBq of cesium-137 on four dates in 2015. NRC cost-benefit analyses do not include the benefits of reduced population relocations and radiation doses beyond 50 miles (80 km) shown by the small circles. The large (540-km or 335-mile) radius circles show the average maximum distance out to which the NRC staff found that long-term relocations would be necessary for a 1090 PBq (29 MCi) release of Cesium-137. The NRC has not released such detailed information for a 1600 PBq release. The wind in this region tends to blow toward the Atlantic Ocean but the site is inland and there are major urban areas along the coast. Densely populated areas therefore would be downwind from Peach Bottom relatively frequently.[78] Square corners in some deposition patterns are artifacts due to the fact that the meteorological data is provided on a 0.5-degree grid.

With regard to the discrepancy in area, as of the date this article went to press no answers had been received from the NRC staff to questions about the interdiction assumptions it made in its regulatory analysis (COMSECY-13-030),[81] but the most likely explanation appears to be a shielding factor inserted into its calculation. The U.S. Environmental Protection Administration's (EPA's) "Protective Action Guide" recommends relocation of the population when, "*in the absence* of shielding from structures or the application of dose reduction techniques," the projected dose exceeds 2 rem in the first year or 0.5 rem in the second year [emphasis added].[82] In the MACCS2 output from the NUREG-2161 study for the Peach Bottom Nuclear Power Plant on which the NRC's regulatory analysis was built, the staff included an average shielding factor of 0.18, resulting in interdiction only for unshielded doses above 11.1 rem in the first year and 2.8 rem annually thereafter instead of 2 rem and 0.5 rem respectively.[83] In other analyses, the staff has used shielding factors of up to

Table 3. Average calculated interdicted areas and relocated populations for a hypothetical 1600 PBq release from the Peach Bottom Nuclear Power Plant. The HYSPLIT calculations have been averaged over the results obtained using weather data for the first of each month of 2015.

	NRC estimate for NAS report	Average of first-of-the-month HYSPLIT calculations for releases in 2015 of 1600 PBq from Peach Bottom for five different interdiction thresholds				
		5 MBq/m^2	2.5 MBq/m^2	1.5 MBq/m^2	1 MBq/m^2	0.5 MBq/m^2
Interdicted Area (km^2)	31,000 (14–48)x10^3	25,000 (3–61)x10^3	50,000 (6–103)x10^3	77,000 (8–187)x10^3	101,000 (11–274)x10^3	156,000 (16–403)x10^3
Relocated Population (millions)	3.5 (1.3–8.8)	6.3 (0.6–9)	11.1 (1–28)	15.3 (2.5–36.5)	18.1 (6.8–40.8)	26.3 (10.7–47.9)

0.33.[84] In the regulatory analysis, the staff may have used different shielding factors for different classes of plants. Also, because of the limitations of the MACCS2 program, the staff combined the first and subsequent year requirements into a single requirement that the dose be less than 4 rem over 5 years.[85] With a shielding factor of 0.18 or 0.33 and the NRC's assumptions concerning weathering, this would correspond to contamination levels of about 5 or 2.5 MBq/m^2 respectively. In that range of contamination levels our calculated average interdiction area is in rough agreement with that provided to the National Academy committee by the NRC. Without the shielding factor, the interdicted area would correspond roughly to our HYSPLIT results obtained for a contamination level of 1 MBq/m^2. For that contamination level, our HYSPLIT calculations without shielding yield an average interdiction area roughly three times larger than the number used by the NRC in its cost-benefit analysis.

The discrepancy would be still larger if the dose from 2-year half-life Cs-134 were taken into account. The NRC staff has not said what ratio of Cs-134/Cs-137 it used in COMSECY-13-0030. In NUREG-2161, however, it assumed a ratio of 0.36.[86] For this contamination ratio, the initial ratio of dose rates is 0.97, the ratio of first year doses is 0.83 and the ratio of 5-year doses is 0.43.[87] For a cesium-137 contamination level of 1 MBq/m^2, the first-year dose therefore would be 2.4 rem with Cs-134 and 1.3 without and the 5-year dose would be 6.6 rem with Cs-134 and 4.6 rem without.

Table 4 shows the pool-weighted averages of the NRC staff's estimates, in a sensitivity test, of the reduced costs of a spent fuel pool fire to the U.S. public in radiation doses (at \$4000/rem or \$400,000/Sv) and property losses if spent fuel pools where shifted from dense-packed to low-density storage. In these calculations, damages were included out to a distance of 1,000 miles. Since the staff estimated that the releases to the atmosphere of cesium-137 from low-density pool fires would be about 1% of the releases from high-density pool fires, the numbers shown in Table 4 are also, to a good approximation, estimates of the average costs from fires in dense-packed pools.

The base case average reduction in damages to the public from a spent fuel pool fire in the U.S. following a shift to low-density pool storage was found in this

Table 4. NRC staff estimates of the average reduction in accident consequences (and uncertainty ranges) for spent fuel pool fires if U.S. spent fuel were transferred to dry-cask storage after five years and the remaining fuel in the pools were stored in a low-density configuration. These numbers also are, to a good approximation, the NRC's estimates of consequences of a fire in a high-density pool because the consequences of a fire in a low-density pool would be negligible in comparison. They were calculated as part of a sensitivity test to determine the impact of including accident consequences out to 1000 miles and valuing reduced population radiation doses at \$4000/rem.[88] In the cost-benefit estimate done for its regulatory analysis, the NRC truncated accident consequences at 50 miles and assumed \$2000/rem.

Reactor type	Pools	Avoided doses	Reduced losses	Total benefits
			(billions of 2012\$)	
BWR I & II	31	\$389 (34–968)	\$140 (20–554)	\$529 (54–1524)
BWR III and PWRs	49	\$443 (110–1153)	\$310 (119–661)	\$754 (229–1815)
AP-1000s (under const.)	4	\$350 (74–980)	\$202 (68–490)	\$552 (142–1471)
Units with shared pools	10	\$574 (118–1612)	\$463 (132–1123)	\$1037 (250–2736)
Pool-weighted averages		**\$435 (84–1133)**	**\$266 (86–668)**	**\$701(170–1802)**

sensitivity case to be about \$700 billion. The staff also estimated, however, that the average probability of such a release would be only about one in 200,000 per reactor-year.[89] As of the end of 2019, the year it was assumed that transfer of spent fuel over 5 years old could be completed, the average remaining licensed life of U.S. reactors would be about 21 years.[90] This would result in an average probability of a spent-fuel fire during the remaining licensed lives of the reactors of about 1/10,000 per reactor or about 1% nationally for the 94 U.S. pools (between 0.14 and 6% taking into account the staff's estimates of the uncertainties in the probabilities). These probabilities would be doubled if, as the NRC is discussing, the licensed lives for U.S. nuclear power plants are increased from 60 to 80 years.[91]

In any case, using the NRC's assumptions, the probability-weighted average benefits per pool from shifting to low-density storage would be roughly \$700 billion divided by 10,000 or about \$70 million per reactor. This is comparable to the staff's estimate of the average cost of about \$50 million per reactor for the nuclear utilities to implement low-density storage.[92]

As noted above, however, the estimated benefits shown in Table 4 are from a "sensitivity case" calculated by the NRC staff. They were not the "benefits" actually used in its regulatory analysis. The NRC's rules for cost-benefit analyses in force in 2013 (and still in 2016 at the time of this writing) reduced the benefits shown in Table 3 about ten-fold. Specifically, the NRC's cost-benefit analysis:

1. Excluded accident consequences beyond 50 miles (∼80 km). This, despite the fact that, for a large release of 1090 PBq (29 MCi) of cesium-137 from the Peach Bottom Nuclear Power Plant in Pennsylvania, the staff found that, on average, 91% of the interdicted area and 84% of the population that would have to be relocated were located more than 50 miles from the plant.[93]
2. Used a value of \$2000/rem for avoided radiation doses that had not been updated since 1995. The NRC staff has estimated that the updated value as of 2015 would be \$5100/rem.[94] In the sensitivity tests whose results are shown in Table 4, \$4000/rem was used.

3. Discounted the benefits to the public of reduced accident consequences by 7% per year after 2019 when expedited transfer was assumed to have been completed. This discounting was designed to take into account the possibility that, if the utilities were not forced to invest in expedited transfer, they could have invested those funds in the stock market with a long-term average annual rate of return in constant dollars of about 7%.[95]

These three assumptions, the first two of which the NRC staff understood to be incorrect (hence the sensitivity tests) reduced the average probability-weighted benefit by a factor of about ten to $6.6 million per pool—significantly less than the estimated $50 million cost per pool of implementing expedited transfer.[96]

In addition, as noted above, the NRC's cost-benefit analysis apparently estimated the sizes of relocated populations based on projected *shielded* doses rather than the unshielded dose recommended by the EPA in its guidance on protective actions for radiological incidents. According to our calculations, this resulted in an underestimate by a factor of approximately three of the areas out of which populations would be relocated if the EPA's guidance or Japan's practice were followed.

The NRC's approach to cost-benefit analysis also underestimated the benefits of expedited transfer in a number of other important ways. Below, the NRC's assumptions concerning compensation payments to the relocated population and businesses are compared with the compensation provided to relocated populations in Japan, and the NRC's omissions from its cost-benefit analyses of indirect losses, psychological impacts and the possibility of nuclear terrorism are discussed.

Compensation payments to relocated population and businesses

Dividing the average of 3.5 million relocated population in Table 2 into the average estimated economic losses of $266 billion shown in Table 4 gives an average economic loss per relocated individual of $76,000.

For comparison, the $57 billion (¥7.07 trillion) in compensation to Fukushima relocatees approved by Japan's government as of mid-2015[97] corresponds to an average of $650,000 per compulsorily relocated individual. (Only 45% of this money was paid directly to compulsory relocatees, however. As of 8 April 2016, approximately 6% had gone to voluntary relocatees and 49% to businesses.[98])

The compensation payments that Japan has been paying out are for continuing displacement, not for property loss, however.[99] The average annual payment to the 88,000 compulsory relocatees has been about ¥6.3 million (∼$60,000) per year for about five years. Businesses appear to have been compensated in a similar continuing manner.

The NRC staff estimate is lower in part because it assumed that decontamination by a factor of up to 15 could be carried out within a year and that therefore virtually the entire relocated population could return home within a year.[100] Achievement of such a rapid and effective decontamination is not consistent with the experience in Japan. Recently, the State of New York challenged the NRC to produce the basis for its assumptions on this critical matter. The NRC was unable to do so and agreed that "real-world data emerging from the Fukushima accident will provide significantly more relevant modern-day sources for assessing the decontamination times and costs of a severe reactor accident with offsite consequences."[101]

The NRC's cost-benefit methodology also does not take into account indirect losses. Perhaps the largest such loss in Japan was from the shutdown of almost all of Japan's nuclear power reactors for at least five years. Five years after the accident, of the 43 Japanese reactors still listed on the IAEA's Power Reactor Information System as "operational," only three were operating. Another four had been licensed to operate under the upgraded post-Fukushima safety rules but two had been blocked from doing so by a court order. Required safety upgrades of the other two were not scheduled to be completed until 2019. The utilities had applied for licenses to restart an additional 18 reactors with required safety improvements reportedly averaging about ¥100 billion ($1 billion) per reactor. In addition to the four units at Fukushima Daiichi 1–4 that had been destroyed by the accident, the utilities had decided to retire eight other power reactors. Finally, they had not yet decided to apply for permission to restart eighteen others. If they believed that permission might be received, they would be highly motivated to do so. Collectively, the utilities have paid about ¥14.4 trillion (∼$144 billion) for fossil fuel to provide replacement power for the shutdown reactors during the period 2011–2015.[102]

Compare this indirect impact of the Fukushima Daiichi accident with the assumptions in the NRC staff's cost-benefit analysis on expedited transfer. The staff assumed that only the nuclear power plant involved in the accident would be shut down and that the cost of the loss of its power over 7 years would total only $16 million.[103] Given that the staff calculated that the accident would result in the relocation of a population forty times larger than was displaced by the Fukushima accident (see Tables 2 and 3), the permanent shutdown of all the nuclear power plants in the United States and most other countries seems more likely.

An indirect cost entirely omitted from the NRC cost-benefit analyses was the loss of tourism in and food exports from neighboring non-evacuated areas. France's Institut de Radioprotection et de Sûreté Nucléaire (IRSN) has estimated that, after a Fukushima-scale accident[104] in France, the loss of tourism and exports of food products due to international fears of radioactive contamination would accumulate over time to about €166 (∼$200) billion.[105]

NRC cost-benefit analyses also do not consider the psychological impact of major radiological releases. A survey of the psychological wellbeing of Ukraine's population 20 years after the Chernobyl accident found that an extra radiation dose equivalent to only about one year's natural external background exposure was correlated with reduced life satisfaction, an increase in diagnosed mental disorders and a reduction in subjective life expectancy. The authors found that the extra governmental services required by this population amounted to about 0.5% of Ukraine's gross domestic product (GDP). When they compared the negative effect of the accident on the life-satisfaction of the more irradiated portion of Ukraine's population with the positive effect of increased income, they found an aggregate welfare loss equivalent to 2 to 6% of Ukraine's GDP or $5 to 15 billion per year.[106]

Japan, whose experience with radiation fears includes the doses from the explosions over Hiroshima and Nagasaki, provides compensation for "mental anguish" to those displaced by the Fukushima accident. For temporarily displaced individuals, the payments are ¥100,000 (∼$1,000) per month. For individuals from areas where the contamination is so heavy that return is considered unlikely, there is a lump payment of ¥6 million (∼$60,000).[107]

Thus, even though the NRC staff estimate in its sensitivity case of $700 billion for the damages due to a high-density spent-fuel pool fire in the United States is much more than the estimated $150 billion (2015$) economic cost of Hurricane Katrina (2005), the most costly natural disaster in the U.S. since 1980, it still may be an underestimate by a significant factor. The hurricane displaced about 600,000 households and severely damaged or destroyed about 126,000 housing units.[108] A fire in a high-density spent fuel pool in the United States that displaced on the order of ten million people for years therefore would be an extraordinary peacetime catastrophe.

In calculating the probability of a spent-fuel pool fire, the NRC's cost-benefit analysis explicitly excluded the possibility of a terrorist-caused release, arguing, "security issues are effectively addressed in the existing regulatory program."[109] There is no way, however, that the NRC staff could establish confidently that its requirements for plant security have reduced the probability of a successful terrorist attack on a spent fuel pool to a level much lower than its very low estimate of the probability of a release due to accidental causes. The staff could equally well have declared that "safety issues are effectively addressed in the existing regulatory program" and set the probability of a spent fuel pool fire in the United States equal to zero.

Quantitative health objectives

In its regulatory analysis of expedited spent fuel transfer, the staff stated that, irrespective of the results of its cost-benefit analysis, the NRC is not required to promulgate a new regulation if the risk from a nuclear power plant does not breach either of the NRC's two Quantitative Health Objectives.[110]

The QHOs, which were adopted by the NRC in 1986, require that:[111]

1. "The risk to an average individual in the vicinity of a nuclear power plant of prompt fatalities that might result from reactor accidents [i.e. death from high radiation doses within weeks] should not exceed … (0.1%) of the sum of prompt fatality risks resulting from other accidents to which members of the U.S. population are generally exposed."
2. "The risk to the population in the area near a nuclear power plant of cancer fatalities that might result from nuclear power plant operation [i.e. radiation doses from an accidental release of radionuclides] should not exceed … (0.1%) of the sum of cancer fatality risks resulting from all other causes."

With regard to the first QHO, the risk of dying from a dose of radiation within weeks is essentially zero below a short-term dose of 100 rem.[112] The NRC staff assumed that the population would be relocated from areas where the projected dose would exceed 2 rem during the first year or 0.5 rem per year during the subsequent years. This assumption resulted in the calculated probability of a prompt fatality being zero.[113]

With regard to the second QHO relating to cancer risk, the per capita average risk from dying of cancer in the United States is about 0.2% per year.[114] One tenth of a percent of that risk would be 2×10^{-6} per year. The risk of cancer death from ionizing radiation depends upon dose. The NRC staff estimates[115] the cancer risk per rem, including weighted non-fatal cancers as 7.3×10^{-4}. It calculates the cancer risk for the second QHO on the basis of the average expected dose to the population within 10 miles of the nuclear power plant prior to and during evacuation, and after its return for 50 years if the radiation level in the area can be reduced to an acceptable level by decontamination. On this basis, the staff estimated a lifetime cancer death risk of 4.4×10^{-4} per large release corresponding to an average estimated dose of 0.6 rem.[116] This risk must be multiplied by the estimated probability of the event. If the estimated probability of massive radiation release from a nuclear power plant is less than once in 220 years per site, this QHO will be met.

Thus, the NRC's second QHO can be met as long as the estimated probability of a major radiation release from a nuclear power plant is less than 0.45% per year. Given that the United States has 61 operating nuclear power plants—some with multiple reactors[117]—the QHO screening criteria could be met even if there were major nuclear power plant accidents in the United States every four years. This has led some experts to suggest adding a "societal-risk" QHO that would set a limit on the probability that a large number of people would suffer long-term displacement as a result of a major radiological release from a U.S. nuclear power plant.[118]

In spring 2014, the Nuclear Regulatory Commission voted by 4 to 1 to accept the staff's recommendation "that additional studies and further regulatory analyses of this issue not be pursued, and that this …activity be closed."[119]

The politics of nuclear regulation

Given the political pressure on the NRC from the nuclear-energy industry and its Congressional supporters to limit the regulatory burden on the industry, it is not surprising that the NRC's regulatory system has become skewed against safety upgrades. The pressure is especially intense today when the utilities have been shutting down nuclear power plants because of their inability, even with their capital costs long paid off, to compete with natural-gas-fired and wind power plants.[120]

Nuclear industry lobbyists put pressure on the Commission through Congress in two primary ways:

1. They persuade sympathetic members of Congress to block the confirmation of nominees to the Nuclear Regulatory Commission seen as likely to favor new safety regulations that the industry deems too costly.[121]
2. They put pressure on the NRC through Congressional committees responsible for NRC funding and oversight.

Former Senator Domenici took credit for being a vehicle for the second approach in 1998, when he moved to curb what he judged to be the NRC's too-aggressive regulation. At the time, he chaired the Energy and Water Subcommittee of the Senate's Appropriation Committee, which, with its House counterpart, sets the level of the NRC's funding.

Domenici's book, *A Brighter Tomorrow: Fulfilling the Promise of Nuclear Energy* (2004), contains a section titled "The NRC's Day of Reckoning." In it, Domenici recounts that some nuclear utilities had complained to him that the NRC was "too focused on creating more regulations" and "had dramatically increased the number of citations for minor infractions." In 1998, therefore, he invited NRC Chair Shirley Jackson to his office and told her of his intention to cut NRC's budget by one third. He was pleased to see that, "As a result, NRC streamlined its adjudicatory process, made improvements to its inspection process, and moved to risk-based regulations." The NRC staff still remembers this event as a "near-death experience."[122]

Even if probability-based cost-benefit analyses find that the benefits for the public of a proposed regulation do not exceed its cost to the nuclear utilities, the Commission has the authority to act if, in its judgment, that is required "to provide reasonable assurance of adequate protection to public health and safety or common defense and security."[123]

In 2012, in another regulatory analysis stemming from the Fukushima accident, the NRC staff urged that the Commission invoke this authority to require the installation of filtered vents on the primary containment structures of U.S. reactors of the Fukushima type, i.e., boiling water reactors with small-volume containments. If, during an accident, the pressure in a containment building builds up to the point of failure, as happened during the Fukushima accident, the filtered vent would give operators the option of relieving the pressure while removing most of the radioactivity from the released gas. The staff acknowledged that, because of the estimated low probability of a reactor core meltdown in the United States, "A comparison of only the quantifiable costs and benefits of the proposed modifications would not, by themselves, demonstrate that the benefits exceed the associated costs." It argued, "However, when qualitative factors such as the importance of containment systems within the NRC's defense-in-depth philosophy are considered … a decision to require the installation of engineered filtered vent systems is justified."[124] The staff also noted that most European power reactors had been required to install filtered vents before the Fukushima accident and a number of other countries including Japan had decided to do so after the accident.[125]

The staff's recommendation provoked a furious letter from the Nuclear Energy Institute, the nuclear utilities' lobbying organization, "The industry is concerned that the use of qualitative factors as proposed …would create a serious negative precedent for the agency."[126] The Republican majority of the NRC's House of Representatives oversight committee also weighed in, expressing concern "about the agency's [NRC's] departure from rigorous technical and cost-benefit analysis."[127]

The Commission rejected the staff's recommendation by a vote of three to two. In explaining his vote, one of the Commissioners in the majority stated, "This step breaks with previous NRC precedent. The use of qualitative factors as applied by the staff in this [regulatory analysis] goes well beyond previous Commission guidance and the use of such an approach renders the Backfit Rule [the requirement that the benefit exceed the cost] essentially meaningless."[128]

Conclusion

According to U.S. Nuclear Regulatory Commission estimates, a fire in a dense-packed U.S. spent-fuel pool could release 100 times as much cesium-137 into the atmosphere as was released by the three reactor meltdowns that occurred in Fukushima. The NRC staff calculated that, on average, such an accident would cause the relocation of 3.5 million people. In making these estimates, however, the staff apparently used the Environmental Protection Administration's recommendation for projected unshielded radiation doses for relocation and added a shielded factor. Without the shielding factor the relocation area becomes about three times larger.

On the basis of its Quantitative Health Objectives and a cost-benefit analysis, the NRC decided not to order a transition to low-density storage in U.S. spent fuel pools. This decision can be questioned on a number of grounds including the following:

- The Quantitative Health Objectives used by the NRC to screen proposals for required safety enhancements do not include as an objective limiting the risk of forced relocations of millions of people from their homes and places of work.
- The NRC's cost-benefit analysis underestimated the benefits of low-density storage by: excluding terrorism as a potential cause of a spent fuel fires; excluding consideration of the consequences beyond 50 miles; not updating the value assigned to reduced radiation doses to the public; underestimating the economic losses to relocated populations by assuming without any basis that virtually all would be back in their decontaminated homes and businesses within one year; using a shielded rather than unshielded projected dose for its population relocation assumptions; not taking into consideration the likelihood that all U.S. nuclear power plants would be closed down indefinitely after such a huge accident; not including the indirect losses due to reduced property values, tourism income and agricultural sales from neighboring regions contaminated below action thresholds; and not considering the impacts of psychological distress from the perceived hazards of having involuntarily received even a small radiation dose.

Furthermore, evaluating risk in terms of probability times consequences without systematically taking into account the uncertainties is simplistic because the uncertainties of estimates of risks from low-probability, high-consequence events are much larger than those of high-probability, relatively low-consequence events that have the same product of estimated consequences and estimated probability. One can reliably predict on the basis of actuarial data, for example, that there will be two to three thousand deaths in home fires in the United States next year.[129] But one cannot predict with any confidence whether or not there will be a single terrorist event that will kill three thousand people, as happened in 2001. Also, adding up the individual costs of large-consequence events does not take into account the social disruption that large-scale catastrophes bring with them. A fire in a high-density spent-fuel pool would have major societal and global implications, especially if it were caused by a terrorist attack. Recall U.S. responses to the 9/11 attack.

The NRC estimated that, neglecting the risk of terrorism, the probability of a spent fuel pool fire during the remaining licensed lives of the current fleet of U.S. reactors is between 0.14 and 6%. It did not take into account the fact that it is currently considering extending their licenses by another 20 years. Even though it estimated that the consequences of a spent fuel fire in a dense-packed pool would result on average in the forced long-term displacement of millions of people, it judged that the probability is low enough so that it is not necessary to ask U.S. nuclear utilities to spend about $50 million per spent fuel pool, about 1% of the capital cost of a new nuclear power reactor, to move to low-density storage.

If members of the public and NGOs disagree, they can press the NRC and its Congressional overseers for the extra protection. By only publishing consequences multiplied by uncertain probabilities, however, the NRC has made it virtually impossible for journalists, Congress and the public to understand the potential magnitude of the consequences of a fire in a dense-packed spent-fuel pool. A primary purpose of this article has been to make that information more accessible.

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Notes and references

1. References are given in the more detailed discussion below.
2. The gamma ray is actually emitted by the 2.6-minute half-life Ba-137m decay product of cesium-137.
3. "Lessons Learned from the Fukushima Nuclear Accident for Improving the Safety of U.S. Nuclear Plants, Phase 2," National Academy Press, 2016.
4. William Freebairn, "Nuclear safety upgrades post-Fukushima cost $47 billion," 29 March 2016, http://blogs.platts.com/2016/03/29/nuclear-safety-upgrades-post-fukushima/ (with an estimated cost of $27 billlion for Japan or an average of $640 million per reactor); Max Colchester, "EDF Pegs Nuclear Upgrade Cost at $13 Billion," *Wall Street Journal*. 3 January 2012.
5. The cores of reactors 1, 2, and 3 contained a total of 700 PBq (19 MCi) of cesium-137, Kenji Nishihara et al., "Estimation of Fuel Compositions in Fukushima-Daiichi Nuclear Power Plant," Japan Atomic Energy Agency, #2012-018, 2012. The release has been estimated in the range of 6–20 PBq (0.16–0.54 MCi), "Report of the United Nations Scientific Committee on the Effects of Atomic Radiation," UNSCEAR, UN, 2013, para. 25.

6. "Lessons Learned from the Fukushima Nuclear Accident for Improving the Safety of U.S. Nuclear Plants," Phase I report, National Academy Press, 2014, 90–91.
7. TEPCO, "Fukushima Nuclear Accident Analysis Report," 2012, Attachment 9–5, 1.
8. TEPCO, "Fukushima Nuclear Accident Analysis Report," 2012, 345.
9. Transcripts of the discussions at the NRC Operations Center from 11 to 20 March, http://pbadupws.nrc.gov/docs/ML1205/ML120520264.html.
10. Shunsuke Kondo, "Rough Description of Scenario(s) for Unexpected Situation(s) Occurring at the Fukushima Daiichi Nuclear Power Plant," 25 March 2011, released by Japan's Cabinet Office, 30 January 2012. An English translation can be found at http://kakujoho.net/npp/kondo.pdf.
11. Kondo briefing, *op. cit*. MBq (mega-Becquerels) and Ci (Curies) are measures of radioactivity: 10^6 and 3.7×10^{10} disintegrations per second respectively. In the area of strict radiation control, residents were allowed to stay but decontamination was carried out and certain activities such as eating locally-grown foods were constrained to limit doses.
12. UN Scientific Committee on the Effects of Atomic Radiation, "Sources and Effects of Ionizing Radiation," UN, 2000, Volume II, Annex J, "Exposures and effects of the Chernobyl Accident," paras. 107–108 and Table 26.
13. Randall Gauntt et al., SNL Model of the unit 4 Spent Fuel Pool in "Fukushima Daiichi Accident Study, (Status as of April 2012)," Sandia National Laboratories, SAND2012-6173, 2012, 176–199.
14. Kenji Nishihara et al., "Estimation of Fuel Compositions in Fukushima-Daiichi Nuclear Power Plant," *op. cit.*, 114. The Cs-137 inventory in the fuel was about 4 TBq (10^5 Ci)/kg, corresponding to an average spent fuel "burnup" of about 35 MWt-days/kg.
15. TEPCO, "Fukushima Nuclear Accident Analysis Report," 2012, Attachment 9-1, product of columns 2 and 4 of Table 4(4).
16. The heat capacity of water is about 4.2 MJ/(ton-°C). For an initial decay heat power of 2.3 MWt in the pool, heating 1400 tons of water by 75°C would require 2.2 days if there were no heat losses.
17. Evaporation was the primary form of heat loss from the water in the pool but there also were relatively small losses to convective cooling and radiation to the air and heat conduction through the pool walls and floor.
18. Sandia National Laboratories, "Fukushima Daiichi Accident Study," *op. cit.*, Fig. 118. As a back-of-the-envelope check, the decay heat output of the spent fuel in pool 4 was 2.3 MWt or 200,000 megajoules (MJ) per day as of 11 March 2011 and fell to 1.9 MWt on 20 April, *op. cit.*, 159, for an average of 2.1 MWt or 180,000 MJ/day. It takes about 2300 MJ of heat to evaporate one metric ton of water, so (180,000 MJ/day)/(2300 MJ/ton) = 78 tons/day.
19. Assuming that the initial temperature of the added water was 20°C, it would require 3.4 MWt-days to heat the added water to 90°C or about 1.7 days given the 2-MWt heat output of the spent fuel.
20. For a diagram of the piping that allowed TEPCO to determine the depth of water in the skimmer tank of spent fuel pool 4, see TEPCO, "Fukushima Nuclear Accident Analysis Report," 2012, Attachment 9-2, Figure 2, which shows the arrangement in unit 1.
21. TEPCO, "Fukushima Nuclear Accident Analysis Report," 2012, Attachment 9-5, Figure 2. In our redrawing, there is one point per day based on the highest water level that day, i.e. after water addition on days the "giraffe" added water. Not all the measurements are shown.
22. Adapted from "Lessons Learned from the Fukushima Nuclear Accident for Improving the Safety of U.S. Nuclear Plants, Phase 2," *op. cit.*, Figure 2–15.
23. "Lessons Learned from the Fukushima Nuclear Accident for Improving the Safety of U.S. Nuclear Plants, Phase 2," *op. cit.*, Figure 2.4. In a boiling water reactor, there is hardware

above the reactor core to remove droplets of entrained water, i.e. to "dry" and "separate" droplets from the steam before it goes to the turbine.

24. TEPCO, "Fukushima Nuclear Accident Analysis Report," 2012, Attachment 9-5, Figure 5.
25. TEPCO, "Fukushima Nuclear Accident Analysis Report," 2012, Attachment 9/1, Table 3 gives the volume of spent fuel pool 4 as 1390 m^3 and the combined volumes of the reactor well and dryer-separator pit as 1400 m^3. The depth of the dryer-separator pit and reactor well are only about 7 m vs. 12 m for the spent fuel pool, however, so the total area of the dryer-separator pit and reactor well must be 172 m^2 versus (9.9 m)$*$ (12.2 m) = 121 m^2 for the pool, Sandia National Laboratory, "Fukushima Daiichi Accident Study," *op. cit.*, 177, a factor of 1.42. Assuming that the water in the reactor well and dryer-separator pit had a depth of 5.5 m after losses due to sloshing and 2 m as of 12 April (see Figure 4), about 600 m^3 would have flowed into the spent fuel pool. A detailed analysis of the leakage may be found in the National Academy report, "Lessons Learned from the Fukushima Nuclear Accident for Improving the Safety of U.S. Nuclear Plants, Phase 2," chapter 2.
26. Adapted from Sandia National Laboratories, "Fukushima Daiichi Accident Study," *op. cit.*, Fig. 119. The lead author of the Sandia study believes that the fuel cladding temperature shown is that of the recently discharged core, email from Randall Gautt, 14 April 2016.
27. Based on a comparison of the measurements of the Cs-137 contamination levels as of 29 April as shown in the 15 June 2011 presentation by John E. Kelly, Deputy Assistant Secretary for Nuclear Reactor Technologies, U.S. Department of Energy, "DOE Response to Fukushima Dai-ichi Accident," with the map of evacuation areas shown in "Final Report: The Follow-up IAEA International Mission on Remediation of Large Contaminated Areas Off-Site the Fukushima Daiichi Nuclear Power Plant, Tokyo and Fukushima Prefecture, Japan, 14–21 October 2013," IAEA, 23 January 2014, 7. For reasons of administrative convenience, Japan extended these relocation areas to include less contaminated areas within 20 km of the plant and to town and village boundaries.
28. A.F. Stein, et al. "NOAA's HYSPLIT atmospheric transport and dispersion modeling system," *Bulletin of the American Meteorological Society* 96 (2015): 2059–2077.
29. S. Saha et al., "NCEP Climate Forecast System Version 2 (CFSv2) 6–hourly Products," Research Data Archive at the National Center for Atmospheric Research, Computational and Information Systems Laboratory, 2011, http://dx.doi.org/10.5065/D61C1TXF.
30. Derived from Sandia National Laboratories, "Fukushima Daiichi Accident Study," *op. cit.*, Figure 121. That report's lead author, confirmed that a % mark on the vertical axis in Figure 121 was a typo, email from Randall Gautt, 14 April 2016.
31. "Report of the United Nations Scientific Committee on the Effects of Atomic Radiation," *op. cit.*, UNSCEAR, UN, 2013, para. 25.
32. The height of the release is determined by the plume rise due to the heat produced in the spent fuel pool fire. The 1331 spent fuel assemblies in pool 4 contained about 70 tons of zirconium and the associated 45 spent fuel racks contained about 170 tons of steel, Sandia National Laboratories, "Fukushima Daiichi Accident Study," *op. cit.*, Tables 21 and 22 and Figure 111. If all of this material oxidized over 4 days, the average power output would be about 3 MWt. Using formula 25 of James Carson and Harry Moses, "The Validity of Several Plume Rise Formulas," *Journal of the Air Pollution Control Association* 19 (1969): 862–866, and neglecting the plume momentum term, the plume would rise 75/U m for an atmosphere with a stable vertical temperature structure, 100/U m for a neutral atmosphere and 380/U m for an unstable atmosphere, where U is the wind velocity in m/s. During 19–22 March 2011, the average wind speed at 100 m above ground level at the Fukushima Daiichi Nuclear Power Plant was about 4 m/s. With high cloud coverage and low to medium insolation, the stability class during daytime was between neutral and slightly unstable. The night-time stability class was between neutral and slightly stable. On

this basis, the initial plume rise would have added between 25 and 75 m to the 50 m height of the reactor building. For the scenario shown in Figure 5, it therefore was assumed that the cesium-137 would be released from a vertical line source extending from 75 to 125 m above ground level.

33. "Rise in atmospheric radiation levels in Tokyo and Kanagawa" (*Majirox News*, 7 October 2011) http://www.majiroxnews.com/2011/10/07/rise-in-atmospheric-radiation-levels-in-tokyo-and-kanagawa/, based on "Results of Airborne Monitoring Survey by MEXT in Tokyo Metropolitan and Kanagawa Prefecture," Japan Ministry of Education, Culture, Sports, Science and Technology, 6 October 2011.
34. "Spent Fuel Pool Study (SFPS) MACCS2 Output Fields," http://pbadupws.nrc.gov/docs/ML1328/ML13282A535.html, ML13282A564, LNT 3.4 High Density, 13 November 2012, 2, lines 131–140 and 9, line 764, posted by the NRC in response to a request from the Attorney General of New York (see http://pbadupws.nrc.gov/docs/ML1334/ML13341A003.pdf, 409).
35. A. Stohl et al., "Xenon-133 and caesium-137 releases into the atmosphere from the Fukushima Dai-ichi nuclear power plant: determination of the source term, atmospheric dispersion, and deposition," *Atmospheric Chemistry and Physics* 12 (2012): 2313–2343.
36. A poor-resolution copy of WASH-740 may be found at http://www.dissident-media.org/infonucleaire/wash740.pdf.
37. David Burnham, "AEC files show effort to conceal safety perils," *New York Times*, 9 November 1974.
38. "Reactor Safety Study," *op. cit.*, Appendix I, 173.
39. Elisabeth Cardis et al., "Estimates of the cancer burden in Europe from radioactive fallout from the Chernobyl accident," *International Journal of Cancer* 119 (2006): 1224–1235. Twenty-eight plant workers did die of radiation illness within 4 months after the Chernobyl accident.
40. Jan Beyea et al., "Accounting for long-term doses in "worldwide health effects of the Fukushima Daiichi nuclear accident," *Energy and Environmental Science* 6 (2013): 1042–1045. Neither the "Report of the United Nations Scientific Committee on the Effects of Atomic Radiation," UNSCEAR, UN, 2013, nor the World Health Organization's, "Health risk assessment from the nuclear accident after the 2011 Great East Japan Earthquake and Tsunami based on a preliminary dose estimation," World Health Organization, 2013, contains estimates of population dose or cancer consequences.
41. See e.g. Joel Yellin, "The Nuclear Regulatory Commission's Reactor Safety Study," *Bell Journal of Economics* 7 (Spring, 1976): 317–339.
42. "Report to the APS by the study group on light-water reactor safety," *Reviews of Modern Physics* 47 (1975): Supplement 1.
43. "Risk Assessment Review Group Report to the U. S. Nuclear Regulatory Commission," NUREG/CR-0400, 1978.
44. NRC Statement on Risk Assessment and the Reactor Safety Study Report, WASH-1400, in "Light of the Risk Assessment Review Group Report," 18 January 1979.
45. Anthony Andrews, "Nuclear Fuel Reprocessing: U.S. Policy Development," Congressional Research Service, 27 March 2008.
46. In 2013, about 50,000 tons of spent fuel were stored in pools in the United States and the rate of spent fuel discharge was about 2,200 tons per year, "Spent Nuclear Fuel Management," U.S. Governmental Accountability Office, 2014, 11–12. The quoted tonnage corresponds to the amount of uranium originally in the spent fuel.
47. A more comprehensive review of studies of this subject done for the NRC may be found in "Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool

for a U.S. Mark I Boiling Water Reactor," U.S. Nuclear Regulatory Commission, NUREG-2161, 2013, 10–17.

48. N.A. Pisano et al., "The Potential for Propagation of a Self-Sustaining Zirconium Oxidation Following Loss of Water in a Spent Fuel Storage Pool," unpublished study prepared for the U.S. Nuclear Regulatory Commission by Sandia Laboratories, January 1984, referenced in V. L. Sailor et al. in "Severe Accidents in Spent Fuel Pools in Support of Generic Safety Issue 82," Brookhaven National Laboratory, NUREG/CR-4882, BNL-NUREG-52093, 1987.
49. Brookhaven National Laboratory, "Severe Accidents in Spent Fuel Pools in Support of Generic Safety Issue 82," *op. cit.*, 79.
50. E.D. Throm, "Regulatory Analysis for the Resolution of Generic Issue 82, "Beyond Design Basis Accidents in Spent Fuel Pools," U.S. Nuclear Regulatory Commission, NUREG-1353, 1989.
51. "Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants," U.S. NRC, NUREG-1738, 2001, Executive Summary.
52. Robert Alvarez et al., "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the United States," *Science & Global Security 11* (2003): 1.
53. Matthew L. Wald, "Study Warns Attack on Fuel Could Pose Serious Hazards," *New York Times*, 30 January 2003.
54. "Safety and Security of Commercial Spent Nuclear Fuel Storage," Public Report, National Academy Press, 2006. Shankar Vedantam, "Storage of Nuclear Spent Fuel Criticized," *Washington Post*, 28 March 2005.
55. "Staff Evaluation and Recommendation for Japan Lessons-Learned Tier 3 Issue on Expedited Transfer of Spent Fuel," Nuclear Regulatory Commission, COMSECY-13-0030, Enclosure 1, 12 November 2013.
56. "Consequence Study of a Beyond-Design-Basis Earthquake Affecting the Spent Fuel Pool for a U.S. Mark I Boiling Water Reactor," U.S. Nuclear Regulatory Commission, NUREG-2161, 2013.
57. NUREG-2161, *op. cit.*, Table 27.
58. There is also a tradeoff between time and the amount of hydrogen generated. The NRC staff found that for a scenario in which the fuel in a dense-packed pool became uncovered over a period of about 20 hours (a "small" leak) enough hydrogen was produced for an explosion but not if the uncover period was reduced to 3 hours (a "moderate" leak) NUREG-2161, *op. cit.*, Figures 28, 29, 85, and 92.
59. The reason more cesium-137 does not leak is probably that its two main chemical forms, CsI and Cs2MoO4 do not remain airborne for long and would condense in particles and settle out or on cool surfaces within the intact reactor building, "MELCOR Best Practices as Applied in the State-of-the-Art Reactor Consequence Analyses (SOARCA) Project," U.S. NRC, NUREG/CR-7008, 2014.
60. NUREG-2161, *op. cit.*, Tables 27 and 28.
61. "Report of the United Nations Scientific Committee on the Effects of Atomic Radiation," UN, 2013, para. 25 and UN, 2000: Vol. 1, Annex J, "Exposures and Effects of the Chernobyl Accident," para. 23; and (for Fukushima Daiichi), "Report of UNSCEAR," UN, 2013, para. 25.
62. COMSECY-13-0030, Enclosure 1, *op. cit.*, Tables 1, 35, 52. Assuming an average burnup of 45 MWt-days/kg uranium, 3.2 Ci of Cs-137 per MWt-day and 20% loss of cesium-137 due to ten years of decay, the average pool would contain 570 tons of spent fuel or several cores. See also *op. cit.*, 78–79 and Table 72.
63. BWR I (II) = boiling-water reactor with a Mark I (II) primary containment. PWR = pressurized water reactor, AP-1000 = advanced 1000-MWe PWR.

64. NUREG-2161, *op. cit.*, Table 33 assuming that a population dose of 17 Sieverts would result in one cancer death, "Reassessment of NRC's Dollar Per Person-Rem Conversion Factor Policy," NUREG-1530, Rev. 1, Draft Report for Comment, 2015, 22.
65. The NRC staff also considered population distributions for three sites with lower average population densities within 50 miles than for the Peach Bottom Nuclear Power Plant but assuming Peach Bottom weather, COMSECY-13-0030, Enclosure 1, *op. cit.*, Table 53. Ranked in terms of population within 50 miles, Peach Bottom is fifth in the United States with 5.5 million people. Indian Point is first with 17.2 million, http://msnbc.msn.com/id/42555888/.
66. COMSECY-13-0030, Enclosure 1, *op. cit.*, Table 10 takes into account only consequences within 50 miles and values avoided population radiation doses at \$2000/rem. Tables 27–30 are for a sensitivity case in which the 50-mile limit is removed and radiation doses are valued at \$4000/rem.
67. NRC response to question 6b from the NAS Committee on Lessons Learned from the Fukushima Nuclear Accident, 16 July 2015, available from the National Academy of Sciences' Public Access Records Office, item #457. This response was for the difference between the interdicted areas and populations for fires in high-density and low-density pools. The numbers shown are from a later communication to the authors on 1 June 2016 in which the numbers were given separately. The NRC's habitability criterion was 2 rem in the first year and 0.5 rem annually thereafter, COMSECY-13-0030, Table 59. The habitability criterion in NUREG-2161 was 0.5 rem in the first year as well (p. D-21) in conformity to the stricter requirements of Pennsylvania. The numbers for interdicted areas and populations therefore differ between the two studies.
68. Area contaminated to a level greater than 40 Ci/km^2, "UNSCEAR Report," UN, 2000, Vol. 1, Annex J, "Exposures and Effects of the Chernobyl Accident", Table 8. In addition, an area of 4,000 square miles contaminated to between 0.56 and 1.48 MBq/m^2 (15 and 40 Ci/km^2) was declared an area of strict radiation control, *op. cit.*, para. 108.
69. The compulsory relocation area includes the entire land area out to 20 km from the Fukushima-Daiichi Nuclear Power Plant. Beyond that, parts of each town included in the compulsory relocation area are contaminated to above 1 MBq/m^2 (27 Ci/km^2) "Results of the 2nd Airborne Monitoring by [Japan's] Ministry of Education, Culture, Sports, Science and Technology and the U.S. Department of Energy," 16 June 2011.
70. NRC response to question 6b from the NAS Committee on Lessons Learned from the Fukushima Nuclear Accident and follow up clarification with the authors, *op. cit.*
71. UNSCEAR Report (UN, 2000) Vol. 1, Annex J, "Exposures and Effects of the Chernobyl Accident," *op. cit.*, para. 95. In addition, a net of about 123,000 (∼45%) had migrated out of the area of strict radiation control by 1995, para. 108.
72. "UNSCEAR Report," UN, 2013, para. 24. Including voluntary evacuations, the number peaked at 165,000, "Fukushima nuclear evacuees fall below 100,000," *Japan Times*, 9 January 2016.
73. "Spent Fuel Pool Study (SFPS) MACCS2 Output Fields," MACCS2 output file ML13282A564 (LNT 3.4 High Density) *op. cit.*, lines 68, 635–698, and, 13–15.
74. H-N Jow, et al., "MELCOR Accident Consequence Code System (MACCS) Model Description," Sandia National Laboratories, NUREG/CR-4691, SAND86-1562, Vol. 2, 1990 chapter 2.
75. "PAG Manual: Protective Action Guides and Planning Guidance for Radiological Incidents," U.S. Environmental Protection Agency, Draft for Interim Use and Public Comment, March 2013, Table 3.1.
76. Including the dose from the short-lived (2.6-minute half-life) decay product Ba-137m (94.6% of Cs-137 decays), "Preliminary Report on Operational Guidelines Developed for

Use in Emergency Preparedness and Response to a Radiological Dispersal," DOE/HS-0001 ANL/EVS/TM/09-1, 2009, Table 3.2.

77. The weathering factor that the NRC uses in MACCS2 to parameterize the effect on the dose coming from contaminated ground as the cesium-137 sinks deeper into the soil is 0.5exp(-t/0.73) + exp(-t/128), where t is measured in years. It will be seen that the radiation rate decreases by almost half in the first year and then very slowly thereafter, "Spent Fuel Pool Study (SFPS) MACCS2 Output Fields," MACCS2 output file ML13282A564 (LNT 3.4 High Density) *op. cit.*, 92, lines 32–35.
78. For the wind "rose" for Peach Bottom Nuclear Power Plant, i.e., a plot of the frequency for the wind blowing in each of 16 directions, see "State-of-the-Art Reactor Consequence Analyses Report," U.S. Nuclear Regulatory Commission, NUREG-1935, 2012, Figure 8. Most wind roses indicate the direction *from* which the wind is blowing. The NRC's convention is the opposite.
79. With wet deposition turned off, the average area contaminated above 1 MBq/m^2 is 51,000 km^2 and the average interdicted population falls to 11.3 million.
80. COMSECY-13-0030, *op. cit.*, Enclosure 1, Table 53. The range given for the NRC results may include both variations in site and weather.
81. Questions sent to Kevin Witt, Project Manager, Japan Lessons Learned Division, Office of Nuclear Reactor Regulation, U.S. Nuclear Regulatory Commission, 7 June 2016 and by Senator Edward Markey to NRC Chair Stephen G. Burns on 30 June 2016.
82. "PAG Manual," *op. cit.*, Table 3.1.
83. "Spent Fuel Pool Study (SFPS) MACCS2 Output Fields," MACCS2 output file ML13282A564 (LNT 3.4 High Density) *op. cit.*, 21, line 38. The population interdiction criterion used by the NRC staff in this case was 0.5 rem in the first year because the Peach Bottom Nuclear Power Plant is in Pennsylvania, which has established its own standard.
84. "MACCS Best Practices as Applied in the State-of-the-Art Reactor Consequence Analyses (SOARCA) Project," U.S. Nuclear Regulatory Commission, NUREG/CR-7009, 2014, Table 4.14, entry for "Normal Activity Shielding Factor for all but Cohort 4," (institutionalized populations).
85. COMSECY-13-0030, *op. cit.*, Enclosure 1, Table 60.
86. "Spent Fuel Pool Study (SFPS) MACCS2 Output Fields," MACCS2 output file ML13282A564 (LNT 3.4 High Density) *op. cit.*, 9, lines 779 and 781.
87. The ratio of initial dose rates per Bq/m^2 is 2.7, "External Dose-Rate Conversion Factors for Calculation of Dose to the Public," (U.S. Department of Energy, DOE/EH-0070, 1988, 152.
88. NRC revised response to a portion of question 6b from the NAS Committee on "Lessons Learned from the Fukushima Nuclear Accident," 8 March 2016 available from the National Academy of Sciences' Public Access Records Office, item #472.
89. COMSECY-13-0030, Enclosure 1, *op. cit.*, Table 43.
90. COMSECY-13-0030, Enclosure 1, *op. cit.*, Table 1.
91. "NRC drafts guidance for 80-year lives," *World Nuclear News*, 21 December 2015.
92. COMSECY-13-0030, Enclosure 1, *op. cit.*, Tables 11–14.
93. "Spent Fuel Pool Study (SFPS) MACCS2 Output Fields," MACCS2 output file ML13282A564, (LNT 3.4 High Density), *op. cit.*, 135–136.
94. "Reassessment of NRC's dollar per person-rem conversion factor policy," *op. cit.*, 2015.
95. COMSECY-13-0030, 70.
96. Base-case benefits reported in COMSECY-13-0030, Table 10, pool weighted according to the number of pools in U.S. power-reactor groups 1 through 4 as given in *op. cit.*, Enclosure 1, Table 1.
97. "Japan approves increase in Fukushima compensation to $57 billion," *Reuters*, 28 July 2015.

98. TEPCO, "Records of Applications and Payouts for Indemnification of Nuclear Damage," 8 April 2016, http://www.tepco.co.jp/en/comp/images/jisseki-e.pdf.
99. Toyohiro Nomura and Taro Hokubo, "The Japanese Nuclear Liability Regime and the TEPCO Fukushima Daiichi Accident," OECD/NEA Workshop on Nuclear Damages, Liability Issues and Compensation Schemes, 10–11 December 2013, Vienna, slide 23 and TEPCO, "Records of Applications and Payouts for Indemnification of Nuclear Damage" 8 April 2016, *op. cit*.
100. "Spent Fuel Pool Study (SFPS) MACCS2 Output Fields," MACCS2 output file ML13282A564 (LNT 3.4 High Density) *op. cit.*, 92, lines 11–14.
101. "Memorandum and Order in the Matter of Entergy Nuclear Operations, Inc. (Indian Point Nuclear Generating Units 2 and 3)" 4 May 2016, 39.
102. Ministry of Economy, Trade and Industry, "Report of the Power Supply and Demand Verification Subcommittee of the Advisory Committee on Energy and Natural Resources," April 2016, http://www.meti.go.jp/press/2016/04/20160428010/20160428010-2.pdf (in Japanese) p. 40.
103. COMSECY-13-0030, Enclosure 1, *op. cit*., 93. The 61 U.S. nuclear power plants produced an average of 1.3 billion kWh in 2015, IAEA, Power Reactor Information System. Over seven years, that would be 9.1 billion kWh. The NRC's estimate therefore corresponds to a cost of 0.017 cents/kWh. When the National Academy's Fukushima Lessons Learned Committee asked for an explanation of this tiny cost, the NRC staff responded that it was the estimated cost difference between generating electricity from the nuclear power plant or an alternative source, NRC response to a question from the "NAS Committee on Lessons Learned from the Fukushima Nuclear Accident," 24 September 2015, available from the National Academy of Sciences' Public Access Records Office, item #465.
104. The assumed "major release" to the atmosphere included 19 PBq (0.5 MCi) of cesium-137. In the IRSN scenario, an area of about 625 km^2 would be contaminated by cesium-137 above 0.59 MBq/m^2 (16 Ci/km^2) Emmanuel Raimond, IRSN, personal communication, 4 Sept. 2013. The release from the Fukushima Daiichi accident has been estimated as 6–20 PBq (see above).
105. In Japan, tourism was down by $3 billion (about 20%) during 2011 relative to the average of 2010 and 2012. In France, tourism and food exports bring in annually about $60 billion and $75 billion respectively. In the United States., the numbers are $160 and $215 billion respectively. All tourism and food export revenue numbers from World Bank tables: "International tourism, receipts (current US$)," "Food Exports (percent of merchandise exports)," and "Merchandise exports (current US$)" for 2014.
106. Alexander M. and Natalia Danzer, "The Long-Run Consequences of Chernobyl: Evidence on Subjective Well-Being, Mental Health and Welfare," *Journal of Public Economics* 135 (2016): 47–60.
107. "Japan's Compensation System for Nuclear Damage as Related to the TEPCO Fukushima Daiichi Nuclear Accident," OECD, 2012, 34.
108. Andy Newman, "Hurricane Sandy vs. Hurricane Katrina," *New York Times*, 27 November 2012; and National Oceans and Atmospheric Administration, "U.S. Billion-dollar Weather and Climate Disasters, 1980–2015," http://www.ncdc.noaa.gov/billions/events.pdf.
109. COMSECY-13-0030, *op. cit.*, v.
110. In COMSECY-13-0030, 6–7, the NRC staff explained, "Although the base case [in its cost-benefit analysis] is used as the primary basis for the staff's recommendation [not to proceed with requiring expedited transfer of spent fuel] the staff also analyzed additional cases where key parameters are varied to provide low and high estimates of the calculated benefits …The combination of high estimates for important parameters assumed in some of the sensitivity cases presented in Enclosure 1 result in large economic consequences,

such that, the calculated benefits from expedited transfer of spent fuel to dry cask storage for those cases outweigh the associated costs …. However, even in these cases, there is only a limited safety benefit when using the QHOs [Quantitative Health Objectives] and the expected implementation costs would not be warranted."

111. U.S. Nuclear Regulatory Commission, "Safety Goals tor the Operations of Nuclear Power Plants; Policy Statement," Federal Register, 21 August 1986, 30028.
112. "United Nations Scientific Committee on the Effects of Atomic Radiation, UNSCEAR 2012 Report," UN, 2015, Table A3.
113. COMSECY-13-0030, Enclosure 1, *op. cit.*, 3. Note, however, that in the workbook for the NRC's radiological assessment system for consequence analysis, RASCAL 3.0.5 (NUREG-1889, 2007) the example for a spent fuel fire (p. 116) results in a 4-day dose above 450 rem downwind out to 10 miles.
114. For a U.S. population of 316 million in 2013, U.S. Centers for Disease Control, "Deaths and Mortality," http://www.cdc.gov/nchs/fastats/deaths.htm.
115. Including weighted non-lethal cancer effects, Draft NUREG-1530, *op. cit*.
116. NUREG-2161, *op. cit.*, Table 33.
117. https://www.eia.gov/tools/faqs/faq.cfm?id=207&t=3
118. Vicki Bier et al., "Development of an Updated Societal-Risk Goal for Nuclear Power Safety," Proceedings of the Conference on Probabilistic Safety Assessment and Management, Honolulu, Hawaii, 22– 27 June, 2014; and Richard Denning and Vinod Mubayi, "Insights into the Societal Risk of Nuclear Power Plant Accidents," *Risk Analysis*, 16 February 2016 [electronic publication].
119. For the staff's recommendation, see COMSECY-13-0030, *op. cit.*, 2. The Commissioners' individual written opinions may be found at http://www.nrc.gov/reading-rm/doc-collections/commission/comm-secy/2013/2013-0030comvtr.pdf.
120. "Market-Driven Reactor Shutdowns Threaten Local Economies" (Nuclear Energy Institute Fact Sheet) February 2015; and "Nuclear power plants warn of closure crisis" (*The Hill*, 5 November 2015). The Nuclear Energy Institute is the lobbying arm of the U.S. nuclear-energy industry.
121. A notable recent exception was Gregory Jaczko, who began his public policy career in the office of a prominent critic of the nuclear industry, then Representative and now Senator Edward Markey. Jaczko later worked on the staff of Nevada Senator and Senate Majority Leader Harry Reid who arranged Jaczko's appointment to the Commission in 2005. In 2009, Jaczko was appointed chairman of the NRC by the Obama Administration. Three years later, however, he was forced to resign after clashes with his fellow commissioners over both policy and his management style, John Broder and Matthew Wald, "Chairman of N.R.C. to Resign Under Fire," *New York Times*, 21 May 2012.
122. Personal communication from a recent Commissioner.
123. Code of Federal Regulations, Title 10, Part 52, Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants," Section 171, "Finality of manufacturing licenses; information requests," paragraph (a)(1). See also the presentation on this point, "Adequate Protection in NRC Decision-Making" by NRC Commissioner William Ostendorff to the Nuclear Energy Institute on 7 March 2011.
124. "Consideration of Additional Requirements for Containment Venting Systems for Boiling Water Reactors with Mark I and Mark II Containments," U.S. Nuclear Regulatory Commission, SECY-12-0157, 26 November 2012, p. 2. The cost-benefit analysis for a requirement of filtered vents had all of the same flaws discussed above for the *Regulatory Analysis* of expedited spent fuel transfer to dry-cask storage. It concluded that the total off-site cost of a Fukushima-type accident in the United States would be about $3 billion vs the approximately $200 billion experienced in Japan, "Lessons Learned from the Fukushima Nuclear Accident for Improving the Safety of U.S. Nuclear Plants," *op. cit*., Appendix L.

125. SECY-12-0157, *op. cit.*, Enclosure 3, "Foreign Experience", 19–20. Information was not available for China, Hungary, Russia and South Africa.
126. Letter to Allison MacFarlane, Chair of the NRC, from Anthony R. Pietrangelo, Senior Vice President and Chief Nuclear Officer of the Nuclear Energy Institute, 25 January 2013.
127. Letter to Allison MacFarlane, Chair of the NRC, from 21 Republican members of the House Committee on Energy and Commerce, 15 January 2013, https://energycommerce.house.gov/sites/republicans.energycommerce.house.gov/files/letters/20130115NRC.pdf.
128. Commissioner Magwood in "Nuclear Regulatory Commission, Decision Item: SECY-12-0157, Commission Voting Record," 19 March 2013, http://www.nrc.gov/reading-rm/doc-collections/commission/cvr/2012/2012-0157vtr.pdf.
129. "Home Fires" (National Fire Protection Association, http://www.nfpa.org/research/reports-and-statistics/fires-by-property-type/residential/home-fires.