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Economic Losses From a Fire in a Dense-Packed U.S. Spent Fuel Pool

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ABSTRACT

In 2013, the staff of the U.S. Nuclear Regulatory Commission estimated the reduction of the off-site economic losses from a fire in a drained U.S. spent fuel pool if fuel that had cooled for more than five years were transferred to dry cask storage—an option it called "expedited transfer." In this article, it is shown that the savings would be much higher than the NRC estimated. Savings increase to about $2 trillion if: losses beyond 50 miles are included; the land-contamination threshold for long-term population relocation is changed to that used for the Chernobyl and Fukushima accidents and recommended by the U.S. Environmental Protection Agency; and, based on the experience of Japan, decontamination of land areas to levels acceptable for population return is assumed to take at least four years. If expedited transfer were implemented, the off-site economic losses would be reduced by about 98%.

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Introduction

The authors' previous article, "Reducing the Danger from Fires in Spent Fuel Pools,"[1] (hereafter RDSFP) analyzed the consequences from a spent fuel fire in a dense-packed pool following a loss of water. It was found that the U.S. Nuclear Regulatory Commission (NRC) staff had greatly underestimated the radiological consequences from such an accident. The staff's estimate had been made as a part of a cost-benefit analysis of a proposal for "expedited transfer": the transfer of spent fuel to dry-cask storage after 5 years of pool cooling.[2] The staff's underestimate was part of a regulatory analysis that led the NRC to reject the proposal on two grounds: i) The cost of expedited transfer would exceed its probability-weighted benefits; and ii) It would not be a "safety-significant enhancement" since the probability-weighted health risks from U.S. nuclear power plants to individuals living nearby are already below the NRC's Quantitative Health Objectives.

Since RDSFP was published, the NRC staff has revealed that the radioactive contamination threshold used in its computer code for calculating where it would

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be necessary to relocate populations was increased by the assumption of a radiation shielding factor of 0.18. As we will show, this assumption raised the relocation contamination threshold to three times the thresholds used in the Chernobyl and Fukushima accidents and recommended by the U.S. Environmental Protection Administration (EPA). An estimate is provided in this article of the effect of that assumption on the NRC staff's calculation of the cost of a spent fuel fire.

An estimate is also provided of the effect on the cost of changing the NRC's assumption that decontamination would take a year, after which the relocated population could return to its homes and workplaces. The NRC has acknowledged that it has been unable to find a basis for that assumption and that it is inconsistent with experience in Fukushima Prefecture where the first returns of relocated populations to the least contaminated parts of a much smaller interdicted area were permitted only 5 years after the accident.[3] As will be shown below, if the time of return is delayed beyond four years, the economic loss from temporary relocation of the population, calculated according to the NRC's methodology, will exceed the cost of abandoning the contaminated area, i.e., permanent relocation.

Radioactive releases to the atmosphere from a spent fuel pool fire

The NRC staff used the Surry Nuclear Power Plant in Virginia for its base-case calculations because the population within 50 miles of Surry is close to the average for U.S. reactor sites.[4] The calculations of economic costs and population doses presented below are therefore for a spent fuel fire at the Surry site.

In calculating the benefits in reduced accident consequences of moving from high-density to low-density storage in spent fuel pools, the NRC calculated the difference between the consequences of a fire in a dense-packed pool and for a release from a fire in a pool after the removal of spent fuel that had cooled for more than five years.

In a dense-packed pool, after the top of the spent fuel became uncovered, the chemical reaction of the steam from the evaporating water and the hot zirconium cladding of the spent fuel would generate hydrogen that, per the NRC staff estimates, would drive the concentration in the air above the pool to explosive levels. A hydrogen explosion would destroy the building and its effectiveness as a containment, as happened to three reactor buildings during the Fukushima accident due to the explosion of hydrogen generated from uncovered reactor cores. In the case of a spent fuel pool fire in the United States, about two thirds of the cesium-137 inventory in the pool, an average of 1,600 PBq (43 MegaCuries) by the NRC staff's estimate, would be released into the atmosphere—about one hundred times more than was released from the Fukushima reactor containments.

After transfer of the older spent fuel to dry cask storage, the average pool would contain one third as much cesium-137. The NRC staff estimate of the release of cesium-137 from a fire in the lower-density pool, however, was only 23 PBq, i.e., a reduction by more than 98%. The explanation for this huge effect is the staff finding that the hydrogen generation in a drained low-density pool would be insufficient to drive the concentration above the pool to explosive levels. If the building above the pool remained intact, the staff estimated that only 3% of the cesium-137 inventory in the pool would leak into the atmosphere vs two thirds if a hydrogen explosion destroyed the covering building.[5]

Impact of the NRC's shielding factor on relocation thresholds

To first order, the economic losses from a spent fuel fire would be proportional to the size of the population displaced by radioactive contamination (see below). The size of the displaced population depends on which areas are deemed uninhabitable—either temporarily until decontaminated or indefinitely if decontamination to inhabitable levels is not feasible or would be so costly or take so long that compensation for the full value of the contaminated property would be less than paying for cleanup and years of interim relocation.

In calculating the size of the area that would have to be interdicted after a spent fuel fire, the NRC staff stated that it followed the EPA's *Protective Action Guides and Planning Guidance for Radiological Incidents*, which recommends relocating a population at risk of a greater than "2 rem (20 mSv) projected dose in the first year [or] 0.5 rem (5 mSv)/year projected dose in the second and subsequent years."[6] In its calculations, the NRC used a composite five-year relocation dose of 4 rem: the sum of the EPA's 2-rem first-year dose plus 0.5 rem per year for the subsequent four years.[7]

The EPA guidance states that its dose recommendations "conservatively do not account for shielding provided by being indoors part of each day of the projection year."[8] An inability to reproduce the NRC results, however, led to the suggestion in RDSPF that perhaps the NRC had assumed a shielding factor. After publication of RDSPF, it was learned that the NRC staff had used a shielding factor of 0.18.[9] That is, the average gamma dose received by the population in an area contaminated with radioactivity had been taken to be 18% of the dose that would have been received outdoors on a flat surface.

Thirty-year half-life cesium-137 dominates the long-term radiation dose. In the absence of shielding, the NRC's projected 5-year threshold dose of 4 rem for relocation would translate into a cesium-137 contamination level of about 0.81 MBq/m^2.[10] Including a shielding factor of 0.18 would increase the NRC's contamination threshold for relocation to 4.5 MBq/m^2.

The contamination threshold for relocation after the Chernobyl accident was about 1.5 MBq/m^2 (40 Ci/km^2).[11] For Fukushima, a first-year unshielded dose of about 2 rem (20 mSv) was used, which is the same as the EPA's recommended limit on the first-year relocation dose.[12] In the absence of shielding, this limit corresponds to a cesium-137 contamination threshold of 1.5 MBq/m^2. The impact on the NRC staff's accident cost calculation of changing the relocation threshold from 4.5 to 1.5 MBq/m^2 is estimated below.

Estimates of contaminated areas

A constant-rate 36-hour release of cesium-137 was assumed[13] and the HYSPLIT model[14] was used for calculating atmospheric dispersion and deposition over seven days for historical atmospheric conditions available from the U.S. National Center for Atmospheric Research.[15] Deposition was calculated on a 30°x30° grid centered on the Surry Nuclear Power Plant (i.e., about 1,700 km to the north and south and 1,300 km to the east and west). The affected populations were calculated using an estimated U.S. population density distribution for the year 2015 available from the U.S. National Aerospace and Space Administration's Socioeconomic Data and Applications Center.[16] Calculations were made for releases starting on the first day of each month of 2015.[17] The model was run for releases of 1,600 PBq and 23 PBq to estimate the reductions in interdicted areas and relocated populations that would result from expedited transfer.

Table 1 shows, as a function of the interdiction threshold, the differences in the average areas interdicted and populations relocated for fires in high- and low-density pools as well as the ratios of those average areas and populations. For a relocation threshold of either 1.5 or 4.5 MBq/m^2, expedited transfer of spent fuel to dry-cask storage reduces the size of the interdicted area and displaced population by 98 to 99%. The entries for differences in interdicted areas and displaced populations shown in Table 1 therefore are also equal within 2% to the average interdicted areas and displaced populations for a fire in a dense-packed pool.

Despite its use of a very different atmospheric dispersion model, the NRC staff's estimate of the average reduction in the relocated population due to expedited transfer, also shown in Table 1, is roughly consistent with the results shown for a relocation contamination threshold of about 4.5 MBq/m^2. Our calculations also show that decreasing the interdiction threshold to the Fukushima-Chernobyl and EPA recommended level of 1.5 MBq/m^2 increases the displaced population by an average factor of about 2.7 because of the larger interdicted area.

Reduction in off-site costs and doses resulting from expedited transfer

The NRC staff estimated that the transfer of spent fuel cooled for more than five years to dry cask storage would cost an average of about $50 million per pool due to the earlier purchase of more dry-storage casks.[19]

Table 1. Differences in and ratios of average interdicted areas and relocated populations for cesium-137 releases from fires in high- and low-density pools (1,600 and 23 PBq respectively) at the U.S. Surry Nuclear Power Plant. The ranges of reductions for the 12 different runs are shown in parentheses.

Contamination thresholds (MBq/m^2)	NRC[18]	4.5	2.5	1.5	1	0.5
Reduction of average interdicted area in 1,000 km^2 (and range)	31 (14–48)	20 (5.0–49)	30 (7.6-66)	43 (10–83)	56 (17–102)	86 (26–151)
(Low release)/(high release) area ratio		0.9%	1.5%	2.0%	2.4%	3.3%
Reduction in average relocated population in millions (and range)	3.5 (1.3–8.8)	3.0 (0.4–12)	5.5 (0.4–33)	8.1 (1.1–41)	10 (1.3–44)	16 (2.5–48)
(Low release)/(high release) relocated population ratio		1.6%	1.7%	1.7%	1.8%	2.4%

In the NRC's cost-benefit analysis, this estimated extra cost for expedited transfer was compared to the probability-weighted reduction in the consequences of a spent fuel pool fire.[20] The reduction in damages was multiplied by an estimated average fire probability of 4.3×10^{-6} per pool-year and then by an estimated average discounted 10.7 years of remaining licensed reactor operating life.[21] This resulted in an estimated discounted average probability of a spent fuel fire of about 5×10^{-5} per pool during the remaining licensed operating lives of U.S. nuclear power reactors. The possibility that a terrorist act might cause a loss of water from a pool was excluded from consideration.[22]

The NRC staff multiplied this estimated accident probability by its estimate of $125 billion in reduced accident consequences to obtain an average probability-weighted and discounted base-case benefit from expedited transfer of $7 million ($0.16–139 million) per pool. Although the estimated $50 million average cost for expedited transfer was within the uncertainty range for the benefits of expedited transfer, the staff focused on the central "base-case" value and concluded that expedited storage was "not cost beneficial."[23]

The staff did point out, however, that the NRC's rules for cost-benefit calculations had required it to:

1) Exclude accident consequences beyond 50 miles;
2) Not update a 1995 valuation of $2,000 for the benefit of an averted person-rem dose; and
3) Discount accident costs relative to the costs of expedited transfer by 7% per year during the period between the investment in expedited transfer and a hypothetical accident.

The staff therefore provided sensitivity tests for the effects on the calculated benefits of expedited transfer of:

1) Accounting for accident consequences out to 1,000 miles;
2) Assuming a value of $4,000 per avoided person-rem; and
3) Assuming a real discount rate of 2% per year.

The staff found that changes 1 and 2 combined would increase the estimated average reduction in damage due to expedited transfer from $125 to $700 billion. Of the $700 billion saving, $435 billion would be due to a reduced population dose of about 110 million rem and $265 billion due to reduced property losses from radioactive contamination.[24]

The combined effect of changes 1, 2 and 3 would raise the base-case probability-weighted discounted benefits of expedited transfer to $39 ($1.6–1124) million, with the base case comparable with the estimated $50 million average cost for expedited transfer.[25]

These issues were discussed in a National Academy report published in May 2016.[26] As discussed above, since that report, two additional assumptions made in the NRC's cost-benefit analysis have come to light:

1. Populated areas would be decontaminated within a year; and
2. Population doses would be reduced by a shielding factor of 0.18.

Below, we estimate the impact on the NRC cost estimates of changing the contamination threshold for relocation and the duration of relocation. We then estimate the impact of the changed relocation threshold on the total population radiation dose and finally calculate the overall impact of these changes on the NRC's estimate of the benefits of expedited transfer.

Losses due to relocation

As noted above, when the NRC staff lifted the 50-mile limit on its consequence calculations, it calculated relocation costs of $265 billion in 2012 dollars. The average cost per individual displaced was calculated as $76,000.[27]

Above, it was estimated that the relocated population would increase by a factor of 2.7 if the contamination threshold were reduced from the NRC staff's 4.5 to 1.5 MBq/m^2, the threshold used for Chernobyl and, in effect, for Fukushima, and recommended by the EPA for the first-year projected dose. Multiplying the NRC's $265 billion relocation cost by this factor would increase it to about $700 billion.

The second calculation that must be made is of how much the $76,000 per capita loss would be increased if the assumed relocation time were increased from one to several years, as occurred in Japan.

The NRC staff estimate of the per capita cost of population relocation is a sum of four terms: 1) the cost of the relocation itself, 2) the cost of decontamination, 3) loss of value of the property while it is abandoned, and 4) the loss of use of the property during the relocation period.

Cost of relocation

The computer output from the MACCS2 calculations used by the NRC staff for its regulatory analysis shows that the cost of relocation was assumed to be $12,000 per capita. As has been noted, it also was assumed that virtually the entire population could return home after one year. The $12,000 is therefore the assumed per capita cost of one year's relocation.[28]

Cost of decontamination

The NRC staff set its target level for decontamination to a dose rate of 0.5 rem/year,[29] which, for the assumed shielding factor of 0.18, would correspond during the second year to a contamination level of 3 MBq/m^2. The staff assumed furthermore that it would be possible to decontaminate down to this level by a factor of three, i.e., from contamination levels of up to 9 MBq/m^2, for a cost of $7,110 per capita and that it would be possible to decontaminate by a factor of fifteen, i.e., from a contamination levels of up to 45 MBq/m^2, for a per capita cost of $19,000.[30] Based on the experience in Japan, the higher decontamination factor is completely unrealistic. The largest dose-rate reductions achieved outdoors in the residential areas of Fukushima Prefecture have been by a factor of three.[31] The area contaminated to the higher level would be relatively small, however. It is therefore neglected here and a decontamination cost of $7,110 per capita is assumed for the population in the entire relocation zone.

Loss of property value and use

The NRC based its estimate of the per capita loss from the relocated population losing access to its property on the per capita value of U.S. farm and non-farm property.[32] Since the total value of farm assets was only 4% of non-farm assets in 1997,[33] they are neglected in the discussion below. The total value of U.S. reproducible assets (i.e., not including the value of unimproved land) was estimated at $48.5 trillion in 2009 or $158,000 per capita.[34] Using the consumer price index for inflation between 2009 and 2012 gives a per capita property value in 2012, not including land, of $168,000.[35] This is close to the value of $172,000 per capita obtained using the NRC's methodology.[36] In addition, in 2000, the value of unimproved land in the United States was estimated at 17% of U.S. reproducible assets.[37] That same ratio is assumed below for 2012. Including land increases the average per capita property value to about $200,000.

The NRC staff adjusted the average per capita value of property in each county by multiplying the average national per capita value by the ratio of the county per capita income to the national average.[38] For the purposes of a rough calculation, we approximate that every county has the national average per capita property value.[39]

The staff assumed a loss of *value* ("depreciation") of non-land property during the relocation period of 20% per year. In addition, it valued the loss of *use* of property, including land, at 12% of its total value per year.[40] Calculation of the depreciation over t years is then done by multiplying the $172,000 per capita value of non-land assets by $[1\text{-}\exp(-0.2^{*}t)]$. On this basis, the loss due to depreciation for one year would be $31,000. Multiplying the total per capita property value of $200,000 by 12% per year yields a value for loss of use of $24,000 per year. The total per capita cost of relocation for one year is therefore $12,000 for the relocation itself, plus $7,110 for decontamination, plus $31,000 for depreciation, plus $24,000 for loss of use for a total of $74,110, which is close to the $76,000 result reported by the NRC.

If the calculation were done for a 3 to 4-year relocation, the per capita relocation cost calculated as above would become $36,000 to 48,000; the depreciation loss would become $78,000 to $95,000; and the value of loss of use would become $72,000 to 96,000. Including the approximately $7,000 decontamination cost, this adds up to a total of about $193,000–246,000. Early in the fourth year, therefore, the total cost would exceed the entire value of the assets left behind. In that case, the NRC staff would cap the per capita loss at the total value $200,000 of the interdicted property or 2.6 times its estimated one-year relocation cost of $76,000. Given the pace of decontamination in Japan and the fact that the NRC staff has been unable to provide any basis for its one-year decontamination assumption,[41] this seems a more plausible estimate. Indeed, it is probably a minimum estimate since, as in Japan, it might be decided that it is unacceptable to abandon such a large area and decontamination efforts could be continued for years longer than dictated by pure economic logic.

Multiplying the \$700 billion loss from a one year relocation by 2.6 would increase it to about \$1.9 trillion.

As a sensitivity test, we consider what the effect would be on this cost estimate if decontamination by a factor of three of the most heavily contaminated areas could be achieved much more rapidly than in Japan, i.e., within one or two years. In that case, the population from the areas originally contaminated to levels up to 4.5 MBq/m^2 and decontaminated to 1.5 MBq/m^2 could move back to their homes and places of work after that period. Referring to Table 1, it can be seen that, on average, out of the 8.1 million relocated people from >1.5 MBq/m^2 areas, 3 million, i.e., 37% are from > 4.5 MBq/m^2 areas. For this part of the population, we assume full loss of the value of their property, i.e., 2.6 times the NRC estimate as calculated above. The remaining 5.1 million people, or 63%, could return to areas that have been decontaminated to safe levels. If they moved back in one year, then their per capita loss would be the same as calculated by the NRC. If they moved back after two years, their per capita loss would be 1.67 times that for the NRC's assumed one-year relocation period. The population-weighted multiplier for the NRC estimate would therefore be 1.59–2.01 and the corresponding economic loss would be reduced from \$1.9 to \$1.1–\$1.4 trillion.

Reduction in radiation-caused cancers

The NRC staff added to its estimate of the reductions in economic losses from expedited transfer an estimate of the benefit from a reduction in radiation-caused cancers. According to repeated reviews by the National Academy of Sciences, for low doses and dose rates of ionizing radiation, such as from land contamination by Cesium-137, the evidence best supports the "linear hypothesis" that the number of cancers would be linearly proportional to population dose, i.e., the sum of individual radiation doses.[42] The population dose is a sum of three components: 1) the dose to the relocated population after its reoccupation of the decontaminated area; 2) the radiation dose to the population outside the relocation area, whose boundary the NRC staff assumed to be the 4.5 MBq/m^2 and we assume to be the 1.5 MBq/m^2 contamination contour; and 3) The dose to the relocated population during the relocation period. The cancer dose calculated is the 50-year dose. In the absence of shielding, for a contamination level of 1 MBq/m^2, the 50-year radiation dose would be 13.1 rem. This dose would be reduced indoors, however, which is most of the time for most people. Although the NRC staff used an average shielding factor of 0.18 in its cost-benefit analysis, elsewhere it recommends a "best practice" value of 0.33.[43]

To reproduce the NRC's population dose estimate of a 110 million rem dose, it is assumed that after decontamination the contamination level within the 4.5 MBq/m^2 contour is uniform. Then the 50-year dose for the average of 3 million people within this contour for the NRC's 0.18 shielding factor would be 32 million person-rem.

Outside this contour, an average population dose of 61 million person-rem is calculated using HYSPLIT for a total of 93 million person-rem. Given the difference in dispersion models, this is as close to the NRC's result as could reasonably be expected.

For permanent evacuation from inside the 1.5 MBq/m^2 contamination contour, it is assumed conservatively that the relocated population gets a zero dose and the NRC "best practice" shielding factor of 0.33 is used to calculate the dose to the population outside the 1.5 MBq/m^2 contour. This yields a population dose of about 50 million person-rem. Using the NRC-staff-recommended updated value for averted cancers of $5,100 per rem,[44] the monetized benefit of reduced cancers due to expedited transfer becomes about $270 billion. Because a much larger population is assumed to be permanently relocated (8.1 vs. 3 million) this is less than the $435 billion calculated by the NRC assuming a cost of $4,000/rem and a shielding factor of 0.18 (see above).

Total benefits

Adding the $270 billion benefit of reduced population dose to the $1.9 trillion reduction in economic loss, the estimated total benefit due to expedited transfer if a spent fuel pool fire should occur is about $2.2 trillion in 2012 dollars if decontamination takes at least 4 years and the losses for the population within the 1.5 MBq/m^2 contour equal the full value of their property values. If the area between the 1.5 and 4.5 MBq/m^2 contours could be decontaminated and reoccupied in one or two years, this benefit would be reduced to $1.4 or $1.7 trillion respectively.

These numbers are 11 to 18 times higher than the $125 billion used by the NRC in its cost-benefit analysis. Multiplying by an average discounted probability for a spent fuel pool fire of 5×10^{-5} per pool during the next 20 years (see above) gives an average probability-weighted discounted benefit of $70 to $110 million. This is more than the NRC staff's mid-value estimate of $50 million per pool for the average cost for expedited transfer. Accounting for avoided psychological and other indirect costs outside the relocation zone would further increase the benefits.[45] As with the NRC calculations, however, there is a large uncertainty range of the probability-weighted benefits because of the large uncertainty range in the estimated probability of a spent fuel pool fire, including the possibility of a successful terrorist attack.

A real-life indicator of the magnitude of the NRC's underestimates of the consequences of nuclear accidents can be obtained from its estimate of the economic impact of a Fukushima-scale radioactive release in the United States. This was as a part of another post-Fukushima policy-option study in which the NRC staff examined the costs and benefits of installing filters on the vents of U.S. boiling water reactors with small-volume containments.[46] If the gas pressure inside a containment must be relieved during an accident—as was required at Fukushima—the filter system would cleanse radioactive particles and soluble gases, including the cesium-137, from the gas as it was being released. In the NRC's cost-benefit analysis of the filtered vent option, the base-case unfiltered release was estimated at 1.3% of the cesium-137 core inventory of one of the Peach Bottom reactors or about 5 PBq[47]—comparable to the combined 6-20 PBq release from the three core melt-downs at Fukushima.[48] The NRC staff estimated the off-site economic loss due to the release would be \$1.9 billion.[49] The December 2016 official estimate of costs for off-site decontamination and compensation for the Fukushima accident was 60 times larger, ¥13.5 trillion (∼\$117 billion).[50]

Conclusion

If expedited transfer were implemented at U.S. spent fuel pools, the average estimated economic losses from a spent fuel fire could be reduced by 98% or by \$2.2 trillion. That result has been obtained using the NRC's methodology for calculating the damages, starting with the staff's estimate of the consequences if the NRC's 50-mile limit were removed. Two factors in that staff calculation were corrected: 1) the population relocation criterion was adjusted to the contamination threshold used for interdiction following the Chernobyl and Fukushima accidents and recommended by the EPA, and 2) the population relocation duration was adjusted to four years, which is still less than after Fukushima. The estimated benefit from reduction in radiation-caused cancers was smaller than the NRC staff estimate because of the larger population relocated as a result of the lower contamination interdiction threshold.

In the event of an actual spent fuel pool fire, the economic costs could be larger or smaller than this average depending upon weather conditions at the time of the event. For an interdiction threshold of 1.5 MBq/m^2 and the 12 historical weather weeks considered for Surry, the estimated size of the population relocated because of a fire in a high-density pool and therefore the economic losses ranged from 7 times less to 5 times greater than the average. Based on the \$1.9 trillion average value calculated above, this corresponds to a range, due only to the weather conditions, of \$0.3 to \$10 trillion. This range would expand if calculations were done for different sites with different surrounding populations. One indicator of the sensitivity to site is the fact that the average relocated population for Peach Bottom, the NRC's 90-percentile site in terms of population within 50 miles, is about twice that for Surry, the average case.[51]

Two trillion dollars is 16 times larger than the \$125 billion estimate of the reduction in damages within 50 miles used by the NRC in its cost-benefit analysis of expedited transfer. This correction provides a compelling justification for reconsideration of the NRC's rejection of expedited transfer.

Notes and references

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5. Pool-weighted average releases based on COMSECY-13-0030, Tables 35 and 52.
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10. The initial ground dose rate for a cesium-137 contamination level of 1 MBq/m^2 is 1.75 rem/year, Eckerman, K. F., and Jeffrey Clair Ryman. "External exposure to radionuclides in air, water, and soil: exposure-to-dose coefficients for general application, based on the 1987 federal radiation protection guidance," Washington, D.C.: U.S. Environmental Protection Agency, Office of Radiation and Indoor Air, 1993. The "weathering" function (i.e., the reduction factor due to the cesium-137 sinking into the ground) used in the NRC's MELCOR Accident Consequence Code System 2 (MACCS2) is 0.5exp(-t/0.73) + exp(-t/128) where t is measured in years, "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. In calculating integrated doses, this weathering factor is multiplied by an exponential factor corresponding to the 30-year decay half-life of cesium-137.
11. "Sources and Effects of Ionizing Radiation 2000," Vol. II, Annex J. Exposures and effects of the Chernobyl accident. Vienna: UNSCEAR. Table 8.
12. "Progress on off-site Cleanup and Interim Storage in Japan," slide 4.
13. The NRC has posted the computer output for the MACCS2 runs on which the consequence estimates of COMSECY-13-0030 are based. The relevant large-release case is ML13282A564, LNT 3.4 High Density, 13 November 2012, for which the release rate is relatively uniform over a period of 31.4 hours. See p. 8, lines 635–698 for the release intervals and pp. 13–14 for the quantity released in each interval.
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17. Over the seven days of simulated deposition, an average of 83% (36–99%) of the released activity was deposited within the 30°x30° grid, an average of 44% (10–99%) over land and an average of 39% (1–82%) in the Atlantic due to Surry's near-coast location. We believe that most of the activity not deposited within the grid was blown by the prevailing easterly winds over the Atlantic beyond the grid.
18. The NRC numbers are quoted in, National Academies of Sciences, "Lessons learned from the Fukushima nuclear accident for improving safety and security of U.S. nuclear plants. Phase 2," 2016, Table 7.2.
19. Due to the limits set on the cladding temperature of stored spent fuel, a smaller tonnage of 5-year-cooled than 25-year cooled fuel can be accommodated in each cask. Earlier purchase of casks also increases their weight in the NRC's cost calculations. For the NRC's base-case

discount rate of 7% per year, purchase of a cask 20 years earlier increases its weight in the cost calculation by a factor of four. However, in COMSECY-13-0030, Table 9, the costs appear to be relatively insensitive to changing the discount from 7 to 2% per year. We have not been able to reproduce the NRC staff's cost calculations to better than a factor of two. We have asked the NRC staff members who did the cost-benefit calculations for help but, as of the time this article went to press, had not received a response.

20. In all cases, averages cited here are pool-weighted for the four classes of reactor pools considered in COMSECY-13-0030.
21. COMSECY-13-0030, Tables 43 and 1. The pool-weighted remaining licensed life of the reactors was 20.5 years but these years were reduced 7% per year because the benefit of the reduced consequences would occur later than the investment in extra dry casks and it was assumed that, if they did not invest in dry casks, nuclear utilities could realize an average real return of 7% per year in the stock market, *ibid.*, 70.
22. COMSECY-13-0030, 8.
23. COMSECY-13-0030, Table 10.
24. "Lessons Learned from the Fukushima Nuclear Accident," Table 7.2.
25. Pool-weighted averages of numbers in COMSECY-13-0030, Tables 27–30. Low-end and mid-range numbers are for a 7% discount rate corresponding to the staff's base case and high-end for a 2% discount rate.
26. "Lessons Learned from the Fukushima Nuclear Accident, Phase 2," Chapter 7.
27. "Lessons Learned from the Fukushima Nuclear Accident, Phase 2," Table 7.2.
28. "POPCST" (population relocation cost) ML13282A564, LNT 3.4 High Density, 13 November 2012, 92, Record #30. See also the discussion in *Code Manual for MACCS2: Volume 1, User's Guide*, 3-13, where the cost is attributed to a per diem during relocation.
29. ML13282A564, LNT 3.4 High Density, 13 November 2012, 92, Record #7.
30. "CDNFRM" (cost for decontamination, non-farm) ML13282A564, LNT 3.4 High Density, 13 November 2012, 92, Records #17 and #18.
31. Tetsuo Yasutaka and Wataru Naito, "Assessing cost and effectiveness of radiation decontamination in Fukushima Prefecture, Japan," *Journal of Environmental Radioactivity* 151(2016): 512–520, Table 1.
32. The NRC's property-value database is compiled in "SECPOP2000: Sector Population, Land Fraction, and Economic Estimation Program" (NRC, NUREG-6525, Rev. 1, 2003). The values in 1997 were projected to 2002 and then escalated to 2011 by a factor of 1.25, COMSECY-13-30, 99.
33. SECPOP2000, Table 5.7, 55.
34. "Statistical Abstracts of the United States, 2012," Tables 2 and 723.
35. Consumer Price Index from the Bureau of Labor Statistics, "CPI Detailed Report," November 2016, Table 24.
36. The value for the national average property value given in "SECPOP2000," Table 5.7 is incorrect. We have recalculated using SECPOP2000, equation 5-2 and the source numbers in SECPOP2000, Table 5.7.
37. "Decennial Census of Housing-Based price index: aggregate land data, annual, 1930–2000," Lincoln Institute of Land and Policy, http://datatoolkits.lincolninst.edu/subcenters/land-values/price-and-quantity.asp.
38. "SECPOP2000," 55.
39. Average per capita income by county is compiled by the U.S. Department of Commerce's Bureau of Economic Analysis. In 2015, the median U.S. county per capita income was $44,700 and 90% of the population was in counties with per capita incomes between 71% and 164% of that value, Bureau of Economic Analysis, http://www.bea.gov/iTable/iTable.cfm?reqid=70&step=1&isuri=1&acrdn=7#reqid=70&step=25&isuri=1&7022=

20&7023=7&7024=non-industry&7033=-1&7026=xx&7027=2015&7001=720&7028=-1&7031=xx&7040=-1&7083=levels&7029=20&7090=70.

40. The cost model is described in *Code Manual for MACCS2: Volume 1, User's Guide*, We obtain the NRC's assumptions for depreciation rate (DPRATE) and rate of return (DSRATE) from ML13282A564, LNT 3.4 High Density, 13 November 2012, 92, Records #28 and #29.
41. U.S. NRC, "Memorandum and Order in the Matter of Entergy Nuclear Operations, Inc. (Indian Point Nuclear Generating Units 2 and 3)" 4 May 2016, 39.
42. The most recent review was National Academies of Sciences, "Health Risks from Exposure to Low Levels of Ionizing Radiation," BEIR VII, Phase 2, 2006, 6–8.
43. U.S. NRC, "MACCS Best Practices as Applied in the State-of-the-Art Reactor Consequence Analyses (SOARCA) Project," NUREG/CR-7009, 2014, Table 4.14, entry for "Normal Activity Shielding Factor for all but Cohort 4," (institutionalized populations).
44. U.S. NRC, "Reassessment of NRC's Dollar Per Person-Rem Conversion Factor Policy," NUREG-1530, Rev. 1, Draft Report for Comment, 2015, 22.
45. For a discussion of the monetization of psychological costs, see "Lessons Learned from the Fukushima Nuclear Accident, Phase 2," 181–183. For a discussion of other indirect costs not considered by the NRC, see the Phase 1 report, Appendix L.
46. U.S. NRC, "Consideration of Additional Requirements for Containment Venting Systems for Boiling Water Reactors with Mark I and Mark II Containments," SECY-12-0157, 2012.
47. SECY-12-0157, Enclosure 5b, Table 2, base case shows a 1.3% release. We assume a cesium-137 core inventory of each of the Peach Bottom reactors of 374 PBq based on U.S. NRC, "State-of-the-Art Reactor Consequence Analyses Project: Peach Bottom Integrated Analysis," NUREG/CR-7110, Rev. 1, 2012, Vol. 1, Table A-3.
48. United Nations, "Report of the United Nations Scientific Committee on the Effects of Atomic Radiation," UNSCEAR 2013, Vol. I, Scientific Annex A, para. 25.
49. SECY-12-0157, Enclosure 5C, Table 7, Case 2. See also the discussion in National Academies of Sciences, "Lessons Learned from the Fukushima Nuclear Accident for Improving Safety and Security of U.S. Nuclear Plants, Phase 1," 2014, Appendix L.
50. Yuka Obayashi and Kentaro Hamada, "Japan nearly doubles Fukushima disaster-related cost to $188 billion," Reuters, 9 December 2016. That total includes ¥8 trillion (∼$80 billion) for decommissioning the Fukushima Daiichi nuclear power plant. For more detail, see http://www.jiji.com/jc/article?k=2016120900050&g=eco (in Japanese).
51. Based on a comparison of Table 1 in this article with Table 3 of RDSFP for a relocation threshold of 1.5 MBq/m^2.