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Damages from a Major Release of ^{137}Cs into the Atmosphere of the United States*

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We report estimates of costs of evacuation, decontamination, property loss, and cancer deaths due to releases by a spent fuel fire of 3.5 and 35 MCi of ^{137}Cs into the atmosphere at five U.S. nuclear-power plant sites. The MACCS2 atmospheric-dispersion model is used with median dispersion conditions and azimuthally-averaged radial population densities. Decontamination cost estimates are based primarily on the results of a Sandia study. Our five-site average consequences are $100 billion and 2000 cancer deaths for the 3.5 MCi release, and $400 billion in damages and 6000 cancer deaths for the 35 MCi release. The implications for the cost-benefit analyses in "Reducing the hazards" are discussed.

INTRODUCTION

"Reducing the hazards from Stored Spent Fuel in the United States" (*Science & Global Security* 11, pp. 1–51), of which we were coauthors, quoted the results of

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a 1997 Brookhaven study,[1] which estimated the damages from a release of 8–80 MCi of ^{137}Cs into the atmosphere as $117–$566 billion and 54,000–143,000 cancer deaths. "Reducing the hazards" also included (in footnote 29) damage estimates calculated using the "wedge" atmospheric-dispersion model for releases of 3.5 and 35 MCi assuming a uniform population density of 250/km^2. In this note, we present the results of a calculation based on real radial population density distributions around five U.S. reactor sites and using the Sandia MACCS2 atmospheric-dispersion model.[2]

Population Density

We have used year-2000 population distributions averaged azimuthally around five sample locations chosen to represent the range of U.S. reactor sites. They are: Catawba, near Rock Hill, South Carolina; Indian Point, on the Hudson River near New York City; LaSalle County near Springfield, IL; Palo Verde, near Phoenix, AZ; and Three Mile Island, near Harrisburg, PA.

Figure 1 shows the cumulative populations within a given radius out to 1600 km from each of these nuclear power plants multiplied by a factor of

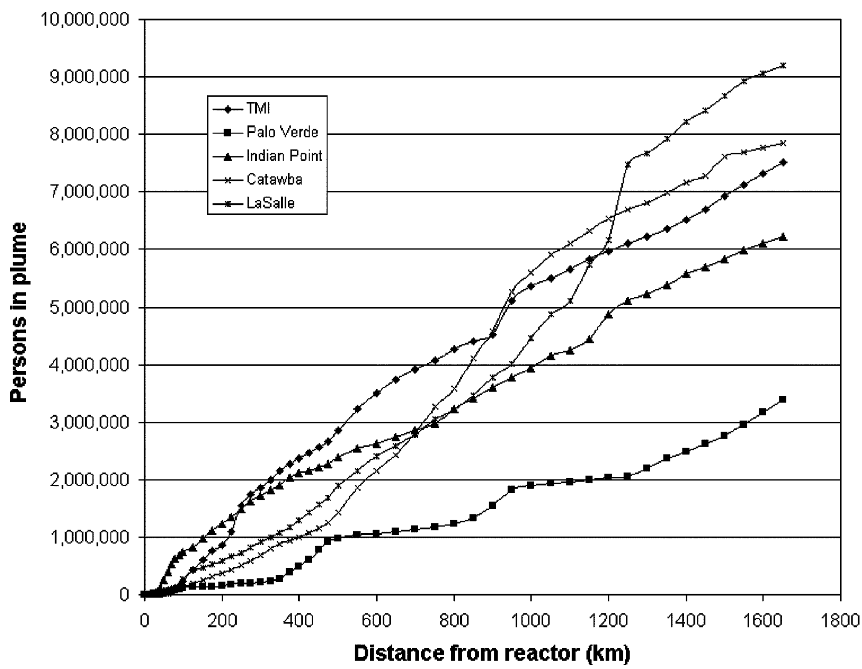

Figure 1: Cumulative population as a function of distance from five U.S. nuclear power plants multiplied by a plume-width factor of 0.038.

Table 1: EPA unshielded radiation dose limits for long-term occupation of contaminated land and corresponding derived ^{137}Cs surface contamination levels.

		^{137}Cs contamination level (Ci/km^2)	
Period	**EPA dose limit (rem)**	**EPA[4]**	**MACCS2[5]**
First year after release	2	44.4	41
Second year after release	0.5	17.2	14.4
Cumulative 50-year dose	5	8.2	6

$0.24/(2\pi)$.[3] This factor is used so that the figure can be used to convey a sense of the size of the population that might be within a downwind plume, which we have approximated for this purpose as a radial wedge with a 0.24-radian opening angle. We do not include the populations of Canada or Mexico.

Contamination Thresholds for Evacuation

The EPA has proposed allowable radiation-dose limits for *unshielded* individuals above which relocation would be recommended. These limits are shown in Table 1, along with the corresponding contamination limits calculated by the EPA and in the MACCS2 model.

We have chosen a ^{137}Cs contamination level of 15 Ci/km^2 as our threshold for decontamination. This corresponds approximately to EPA's limit of no more than 0.5 rem unshielded dose in the second year of exposure. This contamination level would give cumulative 50-year doses more than twice the EPA's limit of 5 rem. However, on a threshold of 15 Ci/km^2 corresponds to the definition of the zone of "strict radiation control" established within the area contaminated by the Chernobyl accident. According to a recent U.N. study of the consequences of the Chernobyl accident, "[w]ithin these areas radiation monitoring and preventative measures have been generally successful in maintaining annual effective dose within [0.5 rem/yr]."[6] An area approximately equal to that contaminated above 50 Ci/km^2 by the Chernobyl accident remains evacuated.[7]

Decontamination

The most recent and detailed study of the effectiveness and costs of radioactive decontamination was done for Sandia National Laboratories in 1996.[8] The study was of the problem of decontamination after plutonium dispersal by a warhead accident but was based mostly on experiments with fission products. Contamination levels were defined as "lightly-contaminated" (requiring a decontamination factor [DF] of 2–5); "moderately-contaminated" (DF = 5–10); and "heavily contaminated" (DF > 10).[9]

For heavily contaminated areas, the study finds that:

> we have been unable to discover any practical method that could reliably achieve successful decontamination short of completely demolishing buildings and disposing of the material in a licensed burial facility.[10]

We assume that, at the edge of heavily contaminated areas there would be a "gray zone" where a few years of radioactive decay will reduce the contamination to a level where decontamination by a factor of eight would make the area habitable again. However, the value of the property is assumed in the MACCS2 model to depreciate at an exponential rate of 20 percent per year so that, after a few years, the average residual value of the property will be less than the cost of decontamination.

Decontamination in the lightly and moderately contaminated areas is described in the Sandia report as involving the following measures:[11]

Lightly-contaminated areas (DF 2–5). "[P]rompt vacuuming of all structural exteriors [and streets, sidewalks and driveways] followed by detergent scrubbing and rinsing. Building interiors would be cleaned by . . . for example, repeated vacuuming followed by shampooing for carpets . . . Turf in lawns [and any paved areas that could not be adequately decontaminated by less costly means] would be removed and replaced . . . Tree foliage would be hosed down, with the wash water collected to prevent runoff, and the trunks would be scrubbed."

Moderately contaminated areas (DF 5–10). "Roofing would be removed and replaced, all landscape materials, including trees, would be removed, and flooring furniture and personal effects would be removed from the interior."

The Chernobyl experience suggests, however, that decontamination by a factor of more than three may be unachievable. The U.N. study reports:[12]

> The effect of decontamination procedures on external dose was studied . . . before and after decontamination of the Belarusian village of Kirov. Decontamination procedures included replacing road surfaces, replacing roofs on buildings, and soil removal. The results . . . suggest that decontamination were most effective for school children and field workers [decontamination factors of 1.5 and 1.3 respectively] but had limited effect on other members of the population. Similar estimates have been obtained with regard to the decontamination of Russian settlements in 1989. The average external dose ratio measured after and before

Table 2a: Per capita contamination costs estimated in the Sandia report.

Decontamination factor	2–5	5–10	>10
Decontamination	$19,000	$42,000	$31,000
Compensation	$20,000	$30,000	$135,000
Subtotal	*$39,000*	*$72,000*	*$166,000*
Waste disposal	$14,000–57,000	$15,000–60,000	$32,000–130,000
Total (rounded)	$50,000–100,000	$90,000–130,000	$200,000–300,000

decontamination was found to range from 0.70 to 0.85 [DF 1.2–1.4] for different settlements.

Nevertheless, we assume that decontamination by up to a factor of eight would be feasible. In our calculations, the boundary between lightly and moderately contaminated areas has been set at a decontamination factor of three and that between moderately and heavily contaminated areas at eight.

Table 2a shows by level of contamination the estimates made in the Sandia report of the per capita costs for decontamination, compensation, and radioactive waste disposal in a mixed-use urban area.[13]

Compensation costs are based on replacement cost for lost property and 3, 6, and 12 months rental for displaced residents during decontamination of lightly, moderately and heavily contaminated areas, respectively.[14] For the residents of condemned properties, it was assumed that the properties would be paid for within a year. It was assumed that, in moderately contaminated areas, motor vehicles, furnishings and appliances would have to be replaced. During the decontamination period, displaced persons would also receive allowances for "clothing, electronic entertainment items, household articles, and work related tools." It was assumed compensation would be paid to commercial establishments for their complete stocks and for their average payrolls and net income for 3, 6 or 12 months for lightly, moderately or heavily contaminated areas respectively.

The Sandia study found the costs of disposing of radioactive decontamination wastes to be a significant part of the total cleanup costs. Both on-site and off-site disposal were considered. For on-site disposal, it was assumed that the waste would be containerized, cement stabilized, and emplaced in reinforced-concrete lined trenches buried under 5 meters of cemented broken rock and an 0.61 m thick concrete cap. This resulted in a cost estimate of $318/m^3 of waste. This cost would be reduced by approximately a factor of two "for a less protective [on-site] disposal system that just met current requirements."[15] Off-site disposal was assumed to involve truck shipment in steel containers 1000 miles to a government facility that would accept low-level transuranic waste (recall that this study is for a plutonium contamination accident). The resulting cost estimate was \$666/m^3 with transportation accounting for slightly over half the cost. The waste-disposal costs shown in Table 2 are for a range of costs from \$167 to \$666/m^3. We have used the bottom of this range in making our own cost estimates.[16]

The authors of the Sandia report state that, "[a]lthough in some instances we have chosen parameter values conservatively, the resultant bias is compensated to some unknown extent by the many potential costs that have been omitted from our estimates."[17] Some of the omitted costs discussed in the report are the following:

- "If mistakes or deficiencies were found, it is possible that some actions might need to be redone or augmented, at additional expense. We have not attempted to account for those possible additional costs."[18]
- "Administrative and support costs for the cleanup of Enewetak Atoll were roughly equal to the direct cost of conducting remediation . . . [A]fter the Chernobyl accident, the Swedish government's cost tabulation for its emergency response programs showed that indirect administration and support were roughly equal to the cost of direct actions . . . We believe . . . that it might be reasonable to double the cost estimates provided [here] in order to account for indirect costs."[19]
- "[D]econtamination appears to become less effective with the passage of time. Most experiments have been conducted within a few days, or at most a few months of deposition."[20]
- "Possible litigation costs are not addressed . . . Because of the adverse impact of delays, costs could increase even if lawsuits proved unsuccessful."[21]
- "We assumed that properties acquired by the government [for remediation and restoration] would be resold without loss."[22]
- "The cost estimates . . . do not include downtown business and commercial districts, heavy industrial areas, or high-rise apartment buildings. Inclusion of these areas would increase costs."[23]

The Sandia results don't quite match to the input requirements of the MACCS2 code, which, for example, does not allow for the inclusion of decontamination costs in permanently evacuated areas. We have therefore made the changes shown in Table 2b.

Table 2b: Per capita contamination cost assumptions used in our MACCS2 runs.

Decontamination factor	<3	<8	>8[24]
Decontamination[25]	$19,000	$42,000	$0–42,000
Compensation	$25,000[26]		$30,000–132,000[27]
Relocation[28]	0	$3,600	$3,600
Waste disposal[29]	$14,000	$15,000	$0–15,000
Total	$58,000	$85,600	$90,600–135,600

DAMAGE ESTIMATES

Our consequence estimates for the five sites, for 3.5 and 35 MCi ^{137}Cs releases, are shown in Table 3.

The economic damages averaged over the five sites for the 3.5 and 35 MCi releases are approximately $100 and $400 billion, respectively. For comparison, the cost estimates in "Reducing the hazards," using the wedge model and assuming a uniform population density of 250/km^2, were $50 and $700 billion, respectively. The economic damages would largely be incurred within a few hundred km of the reactors. The population density within 400 km of the five sites averages about 80/km^2.

The five-site average of the estimated number of cancer deaths is 1900–5700, much less than the 50,000–250,000 estimated in "Reducing the hazards" using the wedge model and assuming a uniform population density. The difference is due in large part to the fact that most of the population radiation dose occurs at large distances (small doses to large numbers of people) and the five-site average population density beyond 400 km is approximately 20/km^2—much less than the 250/km^2 assumed in "Reducing the hazards." An additional

Table 3: Estimates of economic losses ($billions) and cancer deaths.

Site	Release (MCi)	Total costs	Condemned property	Other losses[30]	Temporary relocation	Decontamination[31]	Cancer deaths[32]
Catawba	3.5	71	10	32	0	29	3,100
	35.0	547	145	192	11	199	7,650
Indian	3.5	145	43	42	5	56	1,500
point	35.0	461	282	85	8	86	5,600
LaSalle	3.5	54	2	23	1	27	2,100
	35.0	270	10	121	7	131	6,400
Palo Verde	3.5	11	1	5	0	5	600
	35.0	80	24	26	2	29	2,000
Three-Mile	3.5	171	13	65	6	87	2,300
Island	35.0	568	278	134	11	144	7,000
Averages	3.5	91					1,900
	35.0	385					5,700

reduction of about a factor of two can be attributed to the fact that a larger fraction of the ^{137}Cs deposits on the ground close to the reactor in the MACCS2 plume model than in the wedge-model because of the smaller vertical extent of the plume within the first 200 km and correspondingly higher ground-level concentration of the plume. These close-in deposits result in fewer cancers as a result of permanent evacuation and decontamination.

IMPACT ON THE COST-BENEFIT CALCULATION

The five-site average of costs, including cancer deaths (valued at $4 million each) for releases of 3.5 and 35 MCi is $100 and $370 billion. The corresponding estimates in "Reducing the hazards" (endnotes 29 and 70) were $250 and $1700 billion. Then we compared the costs of taking spent fuel out of the pool and placing it into dry storage with the potential benefits of subsequently avoiding a spent fuel fire. In so doing, we sought to take into account our assumption that the cost of placing the spent fuel in dry storage would on average be incurred 15 years before the probabilistic benefit of avoiding a spent fuel fire.[33] Discounting the accident costs by an extra15 years led to the value of $100–$750 billion that was compared with the cost of transferring the spent fuel to dry storage.

To a large extent, however, discounting reflects the assumption that society will be wealthier in the future and that the same expenditures later will therefore be a smaller fraction of this increasing wealth. In the present case, an increasingly wealthy society will also have more to lose from a spent-fuel fire. The two effects work in opposite directions. In this note, therefore, we have not discounted the estimated $100–$400 billion economic damages when comparing with the cost of early partial unloading of the spent fuel pools.

In "Reducing the hazards," the cost of a spent-fuel fire was compared with the cost of placing into dry casks all of the spent fuel in the pools older than five years (estimated at 35,000 tons in 2010). This cost was estimated as falling in the range $3.5–$7 billion. We then used a mid-range number of $5 billion for our cost-benefit estimate. Dividing this cost by the $100–$400 billion cost of a spent-fuel fire estimated here gives break-even probabilities for a spent-fuel fire occurring during the 30-year period ranging from 1.3 to 5 percent. The corresponding range calculated in "Reducing the hazards" (endnote 70) was 0.7 to 5 percent. In reality, the break-even probability would be somewhat higher, since removal of a fraction of the spent fuel would not entirely eliminate the risk of a spent-fuel fire.

It was noted in "Reducing the hazards" that removing one out of five fuel assemblies could result in each of the fuel assemblies remaining in the pool

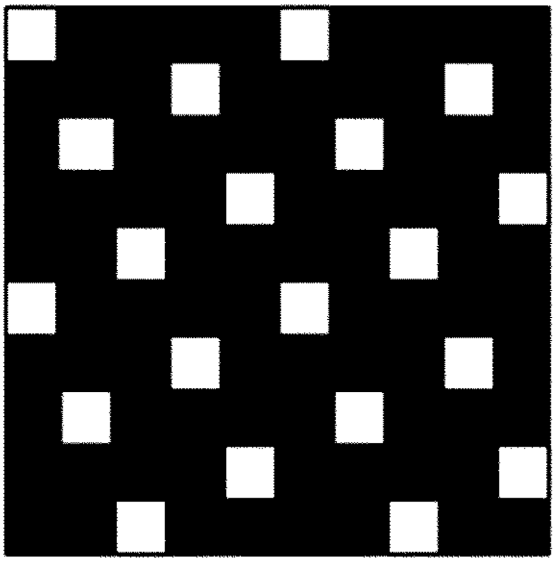

Figure 2: Removal of one fifth of the spent-fuel assemblies could result in every fuel assembly having one side exposed to an empty channel.

having one side exposed to an empty channel in the rack (see Figure 2). If further analysis reveals that such a configuration could be convectively air cooled, then only 9,000 tons of the 45,000 tons of spent fuel projected to be stored in U.S. spent-fuel pools in 2010 would have to be removed instead of 35,000 tons. In this case, the extra cost of dry spent-fuel storage would go down by approximately a factor of four and the break-even spent-fuel fire probability would go down correspondingly, although, once again, some correction would be needed to account for the residual probability of a fire. In this configuration, the cesium inventory would not be greatly reduced while it would be reduced by approximately a factor of four if all the spent fuel more than five years old were discharged.

NOTES AND REFERENCES

1. *A Safety and Regulatory Assessment of Generic BWR and PWR Permanently Shutdown Nuclear Power Plants* by R. Travis et al., (Brookhaven National Lab, BNL-NUREG-52498, 1997).

2. D. I. Chanin and M. L. Young, *Code Manual for MACCS2: Volume 1, User's Guide*, Sandia National Laboratories, Albuquerque, NM, SAND97-0594, March 1997. As in "Reducing the hazards," we assume a steady 5 m/sec wind, no rain, a mixing layer

height of 1000 meters, median (D-type) atmospheric dispersion conditions and a ^{137}Cs deposition velocity of 0.01 m/sec.

3. The radial population densities were calculated using year-2000 computerized census-tract data available from GeoLytics, ⟨http://www.censuscd.com⟩. According to the Bureau of the Census, "census tracts generally have between 1,500 and 8,000 people" ⟨http://www.census.gov/geo/www/cob/tr_metadata.html⟩.

4. *Manual of Protective Action Guides and Protective Actions for Nuclear Incident* (Office of Radiation Programs, U.S. EPA, 1991), Table 7-1, ⟨http://www.epa.gov/radiation/rert/pags.htm⟩.

5. The MACCS2 model calculates the unshielded dose rate from ^{137}Cs as $[0.032\text{rem}/(\text{yr} - \text{Ci/km2})] \times \exp[-t \ln 2/(30)] \times [\exp(-t \ln 2/0.5) + \exp(-t \ln 2/88.8)] = 0.032[\exp(-1.4\text{t}) + \exp(-0.031t)]$ rem/(yr-Ci/km2) with t measured in years. The 30-year half-life decay factor reflects the radioactive decay of ^{137}Cs. The second two-exponential factor takes into account that the ^{137}Cs sinks into the soil—rapidly at first and more slowly later. The ratio of the second-year to the first-year dose is 0.71. The ratio of the dose for the first three months to that of the first year is 0.3.

6. *Sources and Effects of Ionizing Radiation*, Vol. II. *Effects*, Annex J, "Exposures and effects of the Chernobyl accident" (U.N., 2000), para. 108, hereafter cited as *Sources and Effects.*

7. The area within 30 km of Pripyat (the village near the reactor where Chernobyl workers lived) remains evacuated (2800 km^2 with a population of 90,000). Some highly contaminated areas outside the 30-km zone with a total population of 3600 were also evacuated. The total area contaminated to greater than 50 Ci/km^2 has been estimated at 3100 km^2 (*Sources and Effects*, Annex J) paras. 91–93 and Table 5.

8. *Site Restoration: Estimation of Attributable Costs from Plutonium-Dispersal Accidents* by David Chanin and Walter Murfin (Sandia National Laboratories, SND96-0957, 1996), p. 5–7, hereafter cited as *Site Restoration.*

9. The decontamination factor is defined as the ratio of the external gamma dose rate before decontamination to that after.

10. *Site Restoration*, p. F-10.

11. *Site Restoration*, p. 5-9.

12. *Sources and Effects*, Annex J, para. 129.

13. *Site Restoration*, p. F-33, using a population density of 1344/km^2 (p. G-23) plus the per capita costs in Tables F-4, F-5, and F-6.

14. *Site Restoration*, p. F-7.

15. *Site Restoration*, pp. F-24, F-27.

16. Waste produced as result of decontamination following an hypothetical spent fuel accident will fall into the lowest of the U.S. Nuclear Regulatory Commission's categories of low level radioactive waste, Class A, in which ^{137}Cs has a concentration less than one Ci/m^3 (NRC Regulations, 10 CFR, Part 61.55 –Waste Classification ⟨http://www.nrc.gov/reading-rm/doc-collections/cfr/part061/⟩) The U.S. Army Corps of Engineers negotiated contracts with Envirocare for disposal of Class A debris at

\$320/m^3 in 1998 and \$559/m^3 in 1997, not including handling or transport (*The Disposition Dilemma: Controlling the Release of Solid Materials from Nuclear Regulatory Commission-Licensed Facilities*, Washington, DC: National Academy Press, 2002. p. 80, assuming a averaged debris density of 1200 kg/m^3). However, the total amount of Class-A waste needing disposal following a spent fuel accident is likely to be of the order of 100-million m^3 for a 3.5 MCi release (one million affected persons times 90 m^3 per person) which exceeds the annual amount of LLRW currently disposed of in the United States each year by a factor of about one thousand. (About 3 million cubic feet (0.08 million m^3) of DOE and commercial LLRW were disposed of per year in 1998 and 1999, *Texas Compact Low-Level Radioactive Waste Generation Trends and Management Alternatives Study: Technical Report*, Rogers & Associates Engineering Branch URS Corporation, Salt Lake City, 2000, RAE-42774-019-5407-2, Tables 3.1 and 3.4). Consideration would therefore be given to other landfill options. Cost of disposal at Resource Conservation and Recovery Act Subtitle C hazardous waste landfills is typically \$90/m^3, exclusive of waste preparation, handling, and transportation (*The Disposition Dilemma*, p. 78). Once again, however, the projected capacity for such landfills, both currently and projected to 2013, is only about 1.5 million tons per year (*National Capacity Assessment Report: Capacity Planning Pursuant To CERCLA Section 104(C)(9)*, "Demand for Commercial Hazardous Waste Capacity from Recurrent Landfill Expected to be Generated In State (tons)," at ⟨http://www.epa.gov/epaoswer/hazwaste/tsds/capacity/appa_lf.pdf⟩ (25 March 2004)). Municipal waste (Subtitle D) landfills, would typically charge \$25/m^3 (*The Disposition Dilemma*, p. 78) but the concentration of ^{137}Cs is likely to exceed by an order of magnitude the 11 pCi/g concentrations associated with expected doses less than one mrem/yr to critical groups that have been discussed as possible consensus standards for disposal without controls (*The Disposition Dilemma*, pp. 119, 173). For soil with a bulk density of 1.3 g/cm^3 removed to a depth of 10 cm, the average ^{137}Cs concentration would be 115 pCi/g for a surface contamination level of 15 Ci/km^2. The contamination levels of other types of debris would generally be higher.

17. *Site Restoration*, p. F-1.

18. *Site Restoration*, pp. 6-3, 6-4.

19. *Site Restoration*, p. 6-3. The factor might not be as great in the current case, however, because of economies of scale.

20. *Site Restoration*, p. 5-7.

21. *Site Restoration* p. 6-4.

22. *Site Restoration*, p. 2-5.

23. *Site Restoration*, p. 6-2.

24. Decontamination by a factor of eight would make regions near the edge of this zone habitable during the few-year period before depreciation reduces the value of the property to the point where decontamination is no longer cost effective. MACCS2 does not include the decontamination costs that *Site Restoration* estimates would be incurred in areas where structures would be so heavily contaminated that they would have to be condemned.

25. From *Site Restoration.*

26. MACCS2 allows only one value for all decontaminated areas. We have therefore used the average of the values calculated in *Site Restoration* for light and medium

contamination. Loss of income for a period of 4.5 months would amount to $13,500. (U.S. per capita income in 2000 was $35,000, *Statistical Abstracts of the United States: 2001*, U.S. Census Bureau, 2003, Table 646). *Site Restoration* includes in addition compensation for losses of business inventories, personal property and relocation time beyond 90 days.

27. $30,000 if the property can be decontaminated after a minimal period of depreciation. $132,000 if the property is so heavily contaminated that it must be condemned. The year-2000 average per capita value of U.S. fixed assets was $107,000 and the per capita value of residential land, using the MACCS2 default value of 20% of the value of U.S. housing value in 2001, was $7,000, (*Statistical Abstracts of the United States: 2002*, U.S. Census Bureau, 2003, Tables 1 and 679). We add six months lost income.

28. 90 days at $40/day in areas where the projected unshielded dose for the first year would exceed 2 rem. The 1989 *Manual of protective action guides* (p. E-9) estimated $26/day.

29. We have assumed the bottom end of the range given in *Site Restoration*, i.e., onsite disposal in a facility whose design "just met current requirements."

30. Heavily contaminated furnishings, business inventory and vehicles. Also depreciation of property when radioactive decay is required in addition to DF = 8 before reoccupation is possible.

31. Including disposal of radioactive decontamination waste at a cost of $167/m^3.

32. Assuming an average dose-reduction factor of one third due to shielding by buildings and ground roughness and one cancer death per 2000 whole-body rem population dose.

33. Assuming that safety concerns resulted in spent fuel being placed in dry storage 30 years earlier otherwise.