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Appendix 4A Effect of Source Term and Plume-Related Parameters on Consequences

Introduction

Appendix 4 documents the staff's evaluation of the offsite consequences of a spent fuel pool accident involving a sustained loss of coolant, leading to a significant fuel heatup and resultant release of fission products to the environment. The objectives of the consequence evaluation were (1) to assess the effect of one year of decay and (2) to assess the effect of early versus late evacuation because spent fuel pool accidents are slowly evolving accidents. The staff's evaluation was an extension of an earlier study performed by Brookhaven National Laboratory (BNL) for spent fuel pools at operating reactors, which assessed consequences using inventories for 30 days after shutdown.[1]

To perform the evaluation documented in Appendix 4, the staff used the MACCS code (MELCOR Accident Consequence Code System)[2] with fission product inventories for 30 days and 1 year after final shutdown. The evaluation showed that short-term consequences (early fatalities) decreased by a factor of two when the fission product inventory was changed from that for 30 days after final shutdown to that for one year after final shutdown. It also showed that, at one year after final shutdown, early evacuation decreased early fatalities by up to a factor of 100. Long-term consequences (cancer fatalities and societal dose) were less affected by the additional decay and early evacuation. Representative results for the Surry population density are shown in Table 1.

Table 1 Representative Results
(99.5% evacuation, Surry Population Density)

Decay Time Prior to Accident	Mean Consequences (within 100 miles)		
	Early Fatalities	Societal Dose (person-rem)	Cancer Fatalities
30 days	1.75	4.77×10^6	2,460
1 year	1.01	4.54×10^6	2,320
1 year[a]	.0048	4.18×10^6	1,990

[a] Based on evacuation before release.

As noted above, the staff's consequence evaluation was an extension of an earlier consequence evaluation to gain insight into the effect of one year of decay and of early evacuation. Subsequent reviews of the staff's consequence evaluation identified issues with the earlier evaluation performed by BNL in the areas of fractional release from the fuel of each fission product (i.e., fission product source term) and plume-related parameters. To address these issues, the staff performed additional MACCS sensitivity calculations which are documented below.

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Fission Product Source Term

The Appendix 4 consequence assessment was based on the release fractions shown in Table 2, which are from the BNL study.[1] It also was based on releasing fission products from a number of fuel assemblies equivalent to 3.5 reactor cores. These release fractions include relatively small release fractions for the low-volatile and non-volatile fission products.

Table 2 Fission Product Release Fractions from the BNL Study

xenon, krypton	iodine	cesium	tellurium	strontium	barium	ruthenium	lanthanum	cerium
1	1	1	$2x10^{-2}$	$2x10^{-3}$	$2x10^{-3}$	$2x10^{-5}$	$1x10^{-6}$	$1x10^{-6}$

A subsequent review of the staff's spent fuel pool risk assessment indicated that significant air ingression, influencing fission product release, will occur in accidents involving quick drain-down, and the staff's consequence assessment should accommodate any reasonable uncertainty in the progression of the accident with the possible exception of an increase in the ruthenium release. The ruthenium release fraction used in the staff's consequence assessment was $2x10^{-5}$. Small-scale Canadian experiments show that, in an air environment, significant ruthenium releases begin after the oxidation of 75% to 100% of the cladding, and that the ruthenium release fraction can be as high as the release fraction of the volatile fission products. However, in a spent fuel pool accident, rubbling of the fuel may limit the ruthenium release fraction to a smaller value than that of the volatile fission products.

With regard to the number of fuel assemblies releasing fission products, the thermal-hydraulic evaluation in the BNL study indicated that, as a result of radioactive decay, assemblies other than those from the final core may not reach temperatures high enough to release fission products. The number of assemblies assumed to release fission products in the Appendix 4 consequence assessment is equivalent to 3.5 cores. With regard to the release fractions of the low-volatile and non-volatile fission products, higher release fractions than those in the BNL study may be possible as a result of the release of fuel fines due to fuel pellet decrepitation associated with high fuel burnup.

Ruthenium:

To assess the sensitivity of the consequences to the ruthenium release fraction, the staff performed consequence calculations with and without significant ruthenium releases. The starting point for this assessment was the Base Case calculation from Appendix 4. Then, sensitivity cases were run with a ruthenium release fraction of one and a uniform population density of 100 people/mile^2. The results of these cases (i.e., Base Case, Cases 11, 21, 22) are given in Table 3. For these cases, the effect of ruthenium is to increase the number of prompt fatalities by a factor of ten to 90. The effect on societal dose and cancer fatalities is a more modest increase, with the largest effect being a factor-of-four increase in cancer fatalities for the Surry population density.

Table 3 Results of Ruthenium Release Sensitivities
(99.5% evacuation)

Case	Population Density[b]	Ruthenium release fraction	Mean Consequences (within 100 miles)		
			Prompt Fatalities	Societal Dose (person-rem)	Cancer Fatalities
Base Case	Surry	$2x10^{-5}$	1.01	$4.54x10^{6}$	2,320
11	Surry	1	95.3	$9.53x10^{6}$	9,150
21	uniform	$2x10^{-5}$	9.33	$5.05x10^{6}$	2,490
22	uniform	1	134	$9.46x10^{6}$	6,490
13[a]	Surry	$2x10^{-5}$	.0048	$4.18x10^{6}$	1,990
14[a]	Surry	1	.132	$6.75x10^{6}$	6,300
15[a]	uniform	$2x10^{-5}$	.045	$4.65x10^{6}$	2,170
16[a]	uniform	1	.277	$6.38x10^{6}$	4,940

[a]Based on evacuation before release.
[b]The uniform population density site has a population density of 100 people/mile^2 with an Exclusion Area Boundary of .75 miles.

The Base Case calculation assumed that evacuation begins about an hour after the fission product release begins. However, Appendix 1 states that, after a year of decay, it will take a number of hours for the fuel with the highest decay power density to heat up to the point of releasing fission products in the fastest progressing accident scenarios. As a result, it is more likely to have evacuation before the release begins. Therefore, the Base Case calculation then was modified to begin the evacuation three hours before the fission product release begins. This modified Base Case is called Case 13. Starting with Case 13, sensitivity cases were run with a ruthenium release fraction of one and a uniform population density of 100 people/mile^2. The results of these cases (i.e., Cases 13, 14, 15, 16) are given in Table 3. For these cases, the effect of ruthenium is to increase the number of prompt fatalities by a factor of six to 30. The effect on societal dose and cancer fatalities is a more modest increase, with the largest effect being a factor-of-three increase in cancer fatalities for the Surry population density.

For the cases in Table 3, the total number of prompt fatalities increases by a larger factor for Surry than for the uniform population density when a significant ruthenium release is included. Therefore, as part of the ruthenium sensitivity assessment, the staff further examined the effect of population density on prompt fatalities. For the cases with late evacuation (i.e., Base Case, Cases 11, 21, 22), Table 4 gives the MACCS results for the individual risk of a prompt fatality in each radial ring which is composed of 16 sectors. The individual risk of a prompt fatality is a function of the dose to an individual and is independent of the population density. The total number of prompt fatalities is calculated in MACCS by multiplying, in each sector, the individual risk of a prompt fatality by the total number of people in that sector. Table 5, which is the result of multiplying the individual risk of a prompt fatality in each ring from Table 4 by the population in each ring, indicates that Surry's higher increase in prompt fatalities is caused by the jump in the Surry population density at 8.1 km shown in Table 4.

Table 4 Individual Risk of a Prompt Fatality for Cases with Late Evacuation

Distance (km)	Individual risk of a prompt fatality		Ratio	Surry population density* (persons/ km^2)
	Base Case and Case 21, Ru release fraction of $2x10^{-5}$	Cases 11 and 22, Ru release fraction of 1		
0 - .2	.146	.169	1.16	0
.2 - .5	.0302	.0657	2.18	0
.5 - 1.2	.0138	.0374	2.71	1.33
1.2 - 1.6	.00828	.0301	3.64	1.13
1.6 - 2.1	.00575	.0266	4.63	1.80
2.1 - 3.2	.00326	.0216	6.63	1.58
3.2 - 4.0	.00151	.0146	9.67	7.15
4.0 - 4.8	.00167	.0132	7.90	7.77
4.8 - 5.6	.00171	.0110	6.43	7.84
5.6 - 8.1	.0000672	.0131	194.94	8.07
8.1 - 11.3	.000000254	.00301	11850.39	117.80
11.3 - 16.1	0	.0000225	NA	118.36
16.1 - 20.9	0	0	NA	83.75

*This data is from the MACCS input file SURSIT.INP.

Table 5 Number of Prompt Fatalities in Each Radial Ring for Cases with Late Evacuation

Distance (km)	Number of early fatalities with Surry population density		Number of early fatalities with uniform population density	
	Base Case, Ru release fraction of $2x10^{-5}$	Case 11, Ru release fraction of 1	Case 21, Ru release fraction of $2x10^{-5}$	Case 22, Ru release fraction of 1
0 - .2	0	0	0	0
.2 - .5	0	0	0	0
.5 - 1.2	.0690	.1870	0	0
1.2 - 1.6	.0331	.1204	1.1329	4.1184
1.6 - 2.1	.0633	.2926	1.3564	6.2750
2.1 - 3.2	.0945	.6264	2.3060	15.2788
3.2 - 4.0	.1963	1.8980	1.0609	10.2574
4.0 - 4.8	.2923	2.3100	1.4521	11.4777
4.8 - 5.6	.3523	2.2660	1.7357	11.1653
5.6 - 8.1	.0564	10.9909	.2699	52.6050
8.1 - 11.3	.0058	69.2661	.0019	22.7135
11.3 - 16.1	0	1.1027	0	.3599
16.1 - 20.9	0	0	0	0
Total	1.16	89.06	9.32	134.25

The staff also performed sensitivity calculations to determine which isotope in the ruthenium group is responsible for the increase in consequences when a significant ruthenium release is included in the consequence calculations. Sensitivity calculations were performed with different ruthenium-group isotopes included in the consequence calculations. The ruthenium-group isotopes remaining after a year of radioactive decay are Co-58, Co-60, Ru-103, and Ru-106. These cases were run starting with the Base Case. The results of these calculations are shown in Table 6. These results show that the dominant isotope in the ruthenium group is Ru-106.

Table 6 Cases with Different Ruthenium-Group Isotopes Included

Case	Ruthenium Release Fraction	Isotopes Included	Mean Consequences (within 100 miles)		
			Prompt Fatalities	Societal Dose (person-rem)	Cancer Fatalities
Base Case	$2x10^{-5}$	Co-58,Co-60,Ru-103,Ru-106	1.01	$4.54x10^6$	2,320
11	1	Co-58,Co-60,Ru-103,Ru-106	95.3	$9.53x10^6$	9,150
11a	1	Ru-103,Ru-106	94.4	$9.51x10^6$	9,120
11b	1	Ru-106	94.3	$9.51x10^6$	9,120
11c	1	Ru-103	1.02	$4.54x10^6$	2,320

The amounts of the dominant cesium isotope, Cs-137, and the dominant ruthenium isotope, Ru-106, in a spent fuel pool at one year after final shutdown are about the same. After one year, the inventories of Cs-137 and Ru-106 are $8.38x10^{17}$ Bq and $5.77x10^{17}$ Bq, respectively. This would suggest a modest increase in the individual risk of a prompt fatality ruthenium is included in the consequence calculation. However, Table 4 shows large increases in the individual risk of a prompt fatality. A comparison of the dose conversion factors for Cs-137 and Ru-106 is given in Table 7. These dose conversion factors were taken from the MACCS input file DOSDATA.INP. An examination of these dose conversion factors indicates that the large Ru-106 inhalation dose conversion factor in MACCS used to calculate acute doses is partly responsible for the increase in individual risk of a prompt fatality beyond what would be expected as a result of the additional amount of Ru-106.

Table 7 Dose Conversion Factors for Ru-106 and Cs-137

	organ	cloud-shine (Sv sec/ Bq m^3)	ground-shine (Sv sec/ Bq m^2)	inhalation/ acute (Sv/Bq)	inhalation/ chronic (Sv/Bq)	ingestion (Sv/Bq)
Ru-106	lungs	7.99E-15	1.58E-16	2.09E-08	1.04E-06	1.48E-09
	red marrow	8.05E-15	1.61E-16	8.74E-11	1.77E-09	1.48E-09
Cs-137	lungs	2.88E-14	4.35E-16	8.29E-10	8.80E-09	1.27E-08
	red marrow	2.22E-14	4.41E-16	5.63E-10	8.30E-09	1.32E-08
Ratio of Ru-106 to Cs-137	lungs	.4	.4	**25**	118	.1
	red marrow	.4	.4	.2	.2	.1

Fuel Fines:

The staff performed MACCS calculations with different fuel fines release fractions to assess the sensitivity of the consequences. The results of these calculations are shown in Table 8. Case 11, which used a ruthenium release fraction of one, is the shown in the second row of Table 8 and was the starting point for these calculations. Then, Case 96 was run with the large fuel fines release fraction of .01. As a result of increasing the fuel fines release fraction from $1x10^{-6}$ to .01, a small increase in the offsite consequences was seen.

Table 8 Results of Release Fraction Sensitivities
(99.5% evacuation, Surry Population Density)

Case	Release Fraction							Mean Consequences (within 100 miles)		
	I,Cs	Ru	Te	Ba	Sr	Ce	La	Early Fatalities	Societal Dose (person-rem)	Cancer Fatalities
Base	1	$2x10^{-5}$	.02	.002	.002	$1x10^{-6}$	$1x10^{-6}$	1.01	$4.54x10^{6}$	2,320
11	1	1	.02	.002	.002	$1x10^{-6}$	$1x10^{-6}$	95.3	$9.53x10^{6}$	9,150
96	1	1	.02	.01	.01	.01	.01	106	$1.33x10^{7}$	11,700
95	.75	.75	.02	.01	.01	.01	.01	57.0	$1.17x10^{7}$	10,400
94	.75	.75	.02	.002	.002	.001	.001	50.2	$8.35x10^{6}$	7,850
14[a]	1	1	.02	.002	.002	$1x10^{-6}$	$1x10^{-6}$	.132	$6.75x10^{6}$	6,300
97[a]	1	1	.02	.01	.01	.01	.01	.154	$8.74x10^{6}$	7,990

[a]Based on evacuation before release.

The evaluation documented in Appendix 4 used a conservative release fraction of one for the volatile fission products. NUREG-1465, *Accident Source Terms for Light-Water Nuclear Power Plants*, February 1995, specifies a more realistic release fraction of .75 for volatile fission products. As part of the sensitivity of the effect of fuel fines release fraction, this more realistic release fraction was used. In Case 95, the consequences decreased as a result of decreasing the volatile fission product release fraction from 1 to .75. In this case, a factor-of-two decrease in the early fatalities and a small decrease in the long-term consequences were seen.

Finally, Case 94 was run to investigate the sensitivity of the consequences to a fuel fines release fraction intermediate between $1x10^{-6}$ and .01. This case used a fuel fines release fraction of .001. As a result of decreasing the fuel fines release fraction from .01 to .001, a small decrease in the consequences was seen.

In Case 11, evacuation begins about an hour after the fission product release begins. However, Appendix 1 states that, after a year of decay, it will take a number of hours for the fuel with the highest decay power density to heat up to the point of releasing fission products in the fastest progressing accident scenarios. As a result, it is more likely to have evacuation before the release begins. Therefore, a sensitivity calculation on fuel fines release fraction also was run using Case 14 as the starting point; Case 14 includes evacuation three hours before the release begins. Case 97 was run with a fuel fines release fraction of .01. As a result of increasing the fuel fines release fraction from 1×10^{-6} to .01, a small increase in the offsite consequences was seen.

The above sensitivity calculations for fuel fines release fractions were performed with 99.5% of the population evacuating. This translates into one person in 200 not evacuating. It has been suggested that the percentage of the population evacuating may be smaller. Therefore, the staff performed additional calculations with 95% of the population evacuating. This translates into one person in 20 not evacuating. The results of these calculations are shown in Table 9. Case 45, which used a ruthenium release fraction of one, is the shown in the second row of Table 9 and was the starting point for these calculations. Then, Case 45a was run with a fuel fines release fraction of .01, and Case 45b was run with a volatile fission product release fraction of .75. The same trends were seen as in the 99.5% evacuation cases, Cases 11, 96, and 95.

Table 9 Results of Release Fraction Sensitivities
(95% evacuation, Surry Population Density)

Case	Release Fraction							Mean Consequences (within 100 miles)		
	I,Cs	Ru	Te	Ba	Sr	Ce	La	Early Fatalities	Societal Dose (person-rem)	Cancer Fatalities
1	1	2×10^{-5}	.02	.002	.002	1×10^{-6}	1×10^{-6}	1.01	4.54×10^{6}	2,320
45	1	1	.02	.002	.002	1×10^{-6}	1×10^{-6}	92.2	9.50×10^{6}	9,150
45a	1	1	.02	.01	.01	.01	.01	103	1.33×10^{7}	11,700
45b	.75	.75	.02	.01	.01	.01	.01	54.9	1.17×10^{7}	10,300
46[a]	1	1	.02	.002	.002	1×10^{-6}	1×10^{-6}	1.32	6.84×10^{6}	6,430
46a[a]	1	1	.02	.01	.01	.01	.01	1.54	8.89×10^{6}	8,160
46b[a]	.75	.75	.02	.01	.01	.01	.01	.543	7.94×10^{6}	6,880
46c[a]	.75	.75	.75	.01	.01	.01	.01	.544	7.94×10^{6}	6,880
46d[a]	.75	.75	.75	.75	.01	.01	.01	.544	7.94×10^{6}	6,880
46e[a]	.75	.75	.75	.75	.75	.01	.01	.644	1.01×10^{7}	8,350

[a]Based on evacuation before release.

In addition, the staff performed calculations with 95% of the population evacuating with the evacuation beginning three hours before the release begins. The results of these calculations are shown in Table 9. The starting point for these calculations was Case 46, which includes evacuation beginning three hours before the release begins. Then, Case 46a was run with a fuel fines release fraction of .01. The same trends were seen as in the 99.5% evacuation cases, Cases 14 and 97.

The main difference between the results for 99.5% and 95% evacuation is in the area of early fatalities for cases with evacuation before release. In comparing Cases 14 and 97 with Cases 46 and 46a, a factor-of-ten increase in early fatalities is seen, because of the factor-of-ten increase in persons not evacuating. Cases 14 and 97 use one out of 200 people not evacuating, while Cases 46 and 46a use ten out of 200 people not evacuating.

The staff also performed sensitivity calculations for tellurium, barium, and strontium by increasing their release fractions to that of the volatile fission products, that is, .75. In Case 46c, the release fraction for tellurium was increased from .02 to .75. In Case 46d, the release fraction for barium was increased from .01 to .75. No change in consequences were seen in these two cases, because of the small inventories of these isotopes after a year of decay. In Case 46e, the release fraction for strontium was increased from .01 to .75. A small increase in the consequences was seen in this case.

The results in Table 9 are the total number of early fatalities, societal dose, and cancer fatalities for the population within 100 miles of the facility. However, the NRC's quantitative health objectives are given in terms of individual risk of an early fatality within one mile and individual risk of a cancer fatality within ten miles. The MACCS results in terms of these two consequence measures are given in Table 10.

Table 10 Results of Release Fraction Sensitivities (95% evacuation, Surry Population Density)

Case	Release Fraction							Mean Consequences	
	I,Cs	Ru	Te	Ba	Sr	Ce	La	Individual Risk of an Early Fatality (within one mile)	Individual Risk of a Cancer Fatality (within ten miles)
45a	1	1	.02	.01	.01	.01	.01	3.66×10^{-2}	5.16×10^{-2}
45b	.75	.75	.02	.01	.01	.01	.01	3.23×10^{-2}	4.98×10^{-2}
46a[a]	1	1	.02	.01	.01	.01	.01	1.61×10^{-3}	2.83×10^{-3}
46b[a]	.75	.75	.02	.01	.01	.01	.01	1.40×10^{-3}	2.55×10^{-3}

[a]Based on evacuation before release.

Amount of Fuel Releasing Fission Products:

To assess the sensitivity to the fission product inventory released, the staff performed calculations with all of the spent fuel (i.e., 3.5 cores) and the final core offload releasing fission products. These calculations were run for cases with evacuation beginning after the release begins. The inventories used in the MACCS calculations for one core are the Table A.5 inventories in the BNL study reduced by one year of radioactive decay. The results of the MACCS calculations are given in Table 11.

Table 11 Sensitivities on Amount of Fuel Assemblies Releasing Fission Products (99.5% evacuation)

Case	Population Density	Ruthenium Release Fraction	# of cores	Mean Consequences (within 100 miles)		
				Prompt Fatalities	Societal Dose (person-rem)	Cancer Fatalities
Base Case	Surry	$2x10^{-5}$	3.5	1.01	$4.54x10^6$	2,320
31	Surry	$2x10^{-5}$	1	.014	$3.23x10^6$	1,530
11	Surry	1	3.5	95.3	$9.53x10^6$	9,150
32	Surry	1	1	50.5	$7.25x10^6$	7,360
21	uniform	$2x10^{-5}$	3.5	9.33	$5.05x10^6$	2,490
33	uniform	$2x10^{-5}$	1	.177	$3.10x10^6$	1,480
22	uniform	1	3.5	134	$9.46x10^6$	6,490
34	uniform	1	1	103	$6.59x10^6$	4,960

For the cases with a ruthenium release fraction of $2x10^{-5}$, the reduction in prompt fatalities is caused by the reduction in the Cs-137 inventory which decreases from $8.38x10^{17}$ Bq to $2.11x10^{17}$ Bq in going from 3.5 cores to one core. This was confirmed by rerunning Case 33 with a Cs-137 inventory of $8.38x10^{17}$ Bq. The reductions in prompt fatalities for uniform and Surry population densities are factors of 52 and 72, respectively. These reductions are more than proportional to the factor-of-four reduction in Cs-137 inventory, because of the combined effects of individual risk of early fatality and non-uniform population density as discussed in the above analysis of the effect of ruthenium on offsite consequences.

For the cases with a ruthenium release fraction of one, the reduction in prompt fatalities is caused by the reduction in the Ru-106 inventory which decreases from $5.77x10^{17}$ Bq to $4.59x10^{17}$ Bq in going from 3.5 cores to 1 core. This was confirmed by rerunning Case 34 with a Ru-106 inventory of $5.77x10^{17}$ Bq. The reductions in prompt fatalities for uniform and Surry population densities are factors of 1.30 and 1.89, respectively. These reductions are nearly proportional to the factor of 1.26 reduction in the Ru-106 inventory. Again, deviations from being proportional are due to the combined effects of individual risk of early fatality and non-uniform population density. Overall, the effect of reducing the number of assemblies on prompt fatalities is less pronounced for the cases with a ruthenium release fraction of one, in part, because the additional 2.5 cores has a small amount of Ru-106 (one year half-life) in comparison with Cs-137 (30 year half-life). Finally, in all of the cases, the effect of reducing the amount of fuel releasing fission products from 3.5 cores to one core is a modest decrease (20 to 40%) in societal dose and cancer fatalities.

Plume-Related Parameters

The evaluation documented in Appendix 4 used the plume heat content associated with a large early release for a reactor accident. The plume heat content for a spent fuel pool accident may be higher, because (1) a spent fuel pool does not have a containment as a heat sink and (2) the heat of reaction for zirconium oxidation is 85% higher in air than in steam. Also, the evaluation documented in Appendix 4 used the default values for the plume-spreading model in MACCS version 2.[2] NUREG/CR-6244, *Probabilistic Accident Consequence Uncertainty Analysis*, January 1995, provides improved values for these parameters.

Plume Heat Content:

The staff estimated that the complete oxidation in air (in a half hour) of the amount of zircalloy cladding in a large BWR core would generate 256 MW. Subsequently, Sandia National Laboratories (SNL) performed a more detailed assessment of the plume heat content for a spent fuel pool accident.[3] SNL calculated that oxidation of 36% of the zircalloy cladding and fuel channels by the oxygen in the air flow would heat up the accompanying nitrogen and the spent fuel to 2500 K. Once the spent fuel reaches 2500 K, it will degrade into a geometry in which continued exposure to air and, therefore, oxidation, will be precluded. For a spent fuel pool accident involving the amount of fuel in a large BWR core, SNL estimated the heat content of the nitrogen plume to be 43.2 MW. The SNL estimate was made by subtracting (a) the energy absorbed by the spent fuel in heating up to 2500 K from (b) the energy released by the oxidation of 36% of the zircalloy cladding and fuel channels.

The staff performed calculations with different plume heat contents to assess the sensitivity of the consequences. The results of these calculations are shown in Table 12. Case 45, which used a ruthenium release fraction of one, is shown in the second row of Table 12 and was the starting point for these calculations. Case 45 used a plume heat content of 3.7 MW, which is associated with a large early release for a reactor accident. Then, Cases 47 and 49 were run with plume heat contents of 83.0 MW and 256 MW, respectively. Increasing the plume heat content from 3.7 MW to 83.0 MW resulted in a factor-of-two decrease in the early fatalities and no change in the long-term consequences. Increasing the plume heat content from 83.0 MW to 256 MW resulted in a factor-of-three decrease in the early fatalities and a small decrease in the long-term consequences.

Table 12 Results of Plume Heat Content Sensitivities (95% evacuation, Surry Population Density)

Case	Release Fraction							Plume Heat Content (MW)	Mean Consequences (within 100 miles)		
	I,Cs	Ru	Te	Ba	Sr	Ce	La		Early Fatalities	Societal Dose (person-rem)	Cancer Fatalities
1	1	$2x10^{-5}$	.02	.002	.002	$1x10^{-6}$	$1x10^{-6}$	3.7	1.01	$4.54x10^{6}$	2,320
45	1	1	.02	.002	.002	$1x10^{-6}$	$1x10^{-6}$	3.7	92.2	$9.50x10^{6}$	9,150
47	1	1	.02	.002	.002	$1x10^{-6}$	$1x10^{-6}$	83.0	57.3	$9.24x10^{6}$	9,280
49	1	1	.02	.002	.002	$1x10^{-6}$	$1x10^{-6}$	256.0	18.3	$8.24x10^{6}$	8,380
46[a]	1	1	.02	.002	.002	$1x10^{-6}$	$1x10^{-6}$	3.7	1.32	$6.84x10^{6}$	6,430
48[a]	1	1	.02	.002	.002	$1x10^{-6}$	$1x10^{-6}$	83.0	.00509	$7.28x10^{6}$	7,060
50[a]	1	1	.02	.002	.002	$1x10^{-6}$	$1x10^{-6}$	256.0	.00357	$6.96x10^{6}$	6,650

[a]Based on evacuation before release.

Cases 45, 47, and 49 were based on evacuation about an hour after the release began. The staff also performed calculations based on evacuation beginning three hours before the release begins. Case 46, which used a ruthenium release fraction of one and evacuation beginning three hours before the release begins, is shown in the fourth row of Table 12 and was the starting point for these calculations. Then, Cases 48 and 50 were run with plume heat contents of 83.0 MW and 256 MW, respectively. Increasing the plume heat content from 3.7 MW to 83.0 MW resulted in a factor-of-300 decrease in the early fatalities and a small increase in the long-term consequences. Increasing the plume heat content from 83.0 MW to 256 MW resulted in a small decrease in the early fatalities and a small decrease in the long-term consequences.

Plume Spreading:

MACCS uses a Gaussian plume model with the amount of spreading determined by the parameters σ_y and σ_z, where y is the cross-wind direction and z is the vertical direction. In NUREG/CR-6244, phenomenological experts provided updated values for σ_y and σ_z. However, the experts did not provide single values of these parameters. Instead, they provided probability distributions. To assess the sensitivity of spent fuel pool accident consequences to the updated values for σ_y and σ_z, Sandia National Laboratories performed MACCS calculations using values for σ_y and σ_z randomly selected from the experts distributions.[4] These MACCS calculations were based on Cases 11 and 14 (see Table 3), which use the Surry population density and a ruthenium release fraction of one. Case 11 has evacuation beginning about an hour after the release begins, while Case 14 has evacuation beginning three hours before the release begins. A total of 300 MACCS runs were performed to generate distributions of early fatalities, population dose, and cancer fatalities. The results of these MACCS runs are shown in Tables 13 and 14. For the late evacuation case, Case 11, the 50th percentile and mean results using NUREG/CR-6244 plume spreading are lower for early fatalities and higher for societal dose and cancer fatalities. The same trend is seen for the early evacuation case, Case 14. Overall, the effect of the plume spreading model on offsite consequences is not large.

Table 13 Results of Plume-Spreading Model Sensitivity for Case 11 (99.5% evacuation, Surry Population Density)

Plume-Spreading Model	Point in Distribution	Early Fatalities	Societal Dose (rem)	Cancer Fatalities
default	not applicable	95.3	9.53×10^6	9,150
NUREG/CR-6244	10th percentile	.527	9.04×10^6	8,343
	50th percentile	8.89	1.26×10^7	10,100
	mean	54.1	1.28×10^7	10,100
	90th percentile	171	1.66×10^7	11,900

Table 14 Results of Plume-Spreading Model Sensitivity for Case 14 (99.5% evacuation, Surry Population Density)

Plume-Spreading Model	Point in Distribution	Early Fatalities	Societal Dose (rem)	Cancer Fatalities
default	not applicable	.132	6.75×10^6	6,300
NUREG/CR-6244	10th percentile	.00197	7.00×10^6	6,010
	50th percentile	.00855	1.03×10^7	7,730
	mean	.118	1.07×10^7	7,810
	90th percentile	.0637	1.46×10^7	9,590

Conclusion

Appendix 4 documents the staff's evaluation of the offsite consequences of a spent fuel pool accident involving a sustained loss of coolant, leading to a significant fuel heatup and resultant release of fission products to the environment. The objectives of the staff's evaluation were (1) to assess the effect of one year of decay and (2) to assess the effect of early versus late evacuation because spent fuel pool accidents are slowly evolving accidents. The staff's evaluation was an extension of an earlier study performed by BNL for spent fuel pools at operating reactors, which assessed consequences using inventories for 30 days after shutdown. Subsequent reviews of the staff's consequence evaluation identified issues with the earlier evaluation performed by BNL in the areas of fission product source term and plume-related parameters. To address these issues, the staff performed additional MACCS sensitivity calculations which are documented in the current appendix.

With regard to the fission product source term, sensitivity calculations were performed using different release fractions for the nine fission product groups. These calculations also included variations in population density, evacuation start time, percentage of the population evacuating, and number of fuel assemblies releasing fission products. With regard to plume-related parameters, sensitivity calculations were performed using different plume heat contents and updated values for the plume-spreading parameters.

With the exception of ruthenium, the effect of increasing the release fractions was relatively small (less than 40%). Increasing the ruthenium release fraction resulted in larger increases in consequences. However, these increases in consequences were offset by beginning the evacuation before the release begins. Early evacuation is likely, because after a year of decay, it will take a number of hours for the fuel with the highest decay power density to heat up to the point of releasing fission products in the fastest progressing accident scenarios.

The main effect of decreasing the amount of fuel releasing fission products from the entire spent fuel pool inventory to the final core offload was a large reduction in prompt fatalities for cases with a small ruthenium release. For cases with a large ruthenium release, the prompt fatalities did not change much, because most of the ruthenium was in the final core offload because of its one-year half-life.

replace

With regard to the percentage of the population evacuating, the main difference between the results for 99.5% and 95% evacuation is in the area of early fatalities for cases with evacuation before release. In these cases, the number of early fatalities increases by a factor of ten, because a change from 99.5% to 95% is a factor-of-ten increase in the number of persons not evacuating.

The staff's calculations also showed that increasing the plume heat content resulted in reductions in early fatalities and no change in societal dose or cancer fatalities. In addition, updating the values of the plume-spreading parameters to those in the NUREG/CR-6244 expert elicitation results in a decrease in early fatalities and up to a factor-of-1.6 increase in societal dose and cancer fatalities, because of the additional plume spreading associated with the updated plume-spreading parameter values.

<u>References</u>

1. *Severe Accidents in Spent Fuel Pools in Support of Generic Safety Issue 82*, NUREG/CR-4982, July 1987

2. *Code Manual for MACCS2*, NUREG/CR-6613, May 1998

3. *Analysis of Plume Heat Content Associated with Spent Fuel Pool Accidents*, Sandia National Laboratories, July xx, 2000

4. *Task 7 Letter Report: Investigation of Plume Spreading Uncertainties on the Radiological Consequences Associated with a Spent Fuel Pool Accident*, Sandia National Laboratories, June 2000