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August 25, 2000

MEMORANDUM TO: Gary M. Holahan, Director
Division of Systems Safety and Analysis
Office of Nuclear Reactor Regulation

FROM: Farouk Eltawila, Acting Director
Division of Systems Analysis and Regulatory Effectiveness
Office of Nuclear Regulatory Research

SUBJECT: RISK-INFORMED REQUIREMENTS FOR DECOMMISSIONING

As part of its effort to develop generic, risk-informed requirements for decommissioning, NRR requested (Reference 1) an evaluation of the offsite radiological consequences of beyond-design-basis spent fuel pool accidents. In response to that user need, we completed an in-house analysis (Reference 2) that concluded the following:

- The short-term consequences (i.e., early fatalities) decreased by a factor of two when the fission product inventory decreased from that for 30 days to that for one year after final shutdown.
- At one year after final shutdown, the short-term consequences decreased by up to a factor of 100 as a result of early evacuation. Early evacuation is likely after one year, because of the decreased decay heat level and the number of hours required for the fuel with the highest decay power to heat up to the point of releasing fission products.
- The long-term consequences (i.e., cancer fatalities and societal dose) were unaffected by the additional decay and early evacuation.

Although the reductions in the short-term consequences were significant, emergency planning requirements could not be relaxed solely on the basis of these reductions. NRR also used our consequence evaluation in the Draft Final Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants, February 2000, as an absolute measure of spent fuel pool accident consequences and concluded that the consequences were generally comparable to those of reactor accidents.

Subsequently, the ACRS raised issues with the source term and plume modeling associated with spent fuel pool accidents. In particular, the ACRS believed that the ruthenium and fuel fines releases and plume spreading were too low. To address these issues, we completed a series of sensitivity studies and concluded:

- With the exception of the ruthenium release fraction, the parameters varied did not sufficiently impact the results, nor change the conclusion that the consequences were generally comparable to those of reactor accidents.
- Increasing the ruthenium release fraction from that for a non-volatile ($2x10^{-5}$) to that for a volatile (.75) resulted in a large increase in both short-term and long-term consequences due to ruthenium's high dose per curie inhaled. However, consequence increases from ruthenium were demonstrated to be largely offset by early evacuation.
- Although using updated values for plume-spreading model parameters resulted in up to a 60% increase in long-term consequences, similar increases are expected when these updated values are used to calculate reactor accident consequences. Using updated values also resulted in up to a factor-of-15 decrease in short-term consequences.

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The results of these sensitivity studies are described in Attachment 1, which was written, at NRR request, to be incorporated into the final technical study as an appendix. The range of consequences for a beyond-design-basis spent fuel pool accident occurring one year after final shutdown is shown below for early evacuation. This range reflects the uncertainty in the ruthenium and fuel fines release fractions. NRR also requested our assistance in responding to the public comments on the Draft Final Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants. Our responses to these comments in the areas of offsite radiological consequences and emergency response are provided in Attachment 2.

End of Range	Consequences within 100 Miles (Surry population density)		
	Early Fatalities	Societal Dose (rem)	Cancer Fatalities
Lower	.005	$4x10^6$	2,000
Upper	.5	$8x10^6$	7,000

Recently, NRR requested additional consequence calculations using fission product inventories at 30 and 90 days and two, five, and ten years after final shutdown to provide additional insight into the effect of reductions in inventory available for release. We are currently performing these calculations and expect to provide the results shortly.

References:
1. Memorandum from G. Holahan to T. King dated March 26, 1999
2. Memorandum from A. Thadani to S. Collins dated November 12, 1999

Attachments:
1. Effect of Source Term and Plume-Related Parameters on Consequences
2. Response to Public Comments on the Consequence Assessment

cc: T. Collins
R. Barrett
J. Hannon
J. Wermiel

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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 unaffected 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.

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	2×10^{-5}	1.01	4.54×10^{6}	2,320
11	Surry	1	95.3	9.53×10^{6}	9,150
21	uniform	2×10^{-5}	9.33	5.05×10^{6}	2,490
22	uniform	1	134	9.46×10^{6}	6,490
13[a]	Surry	2×10^{-5}	.0048	4.18×10^{6}	1,990
14[a]	Surry	1	.132	6.75×10^{6}	6,300
15[a]	uniform	2×10^{-5}	.045	4.65×10^{6}	2,170
16[a]	uniform	1	.277	6.38×10^{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 $1x10^{-6}$ 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	$2x10^{-5}$	.02	.002	.002	$1x10^{-6}$	$1x10^{-6}$	1.01	$4.54x10^{6}$	2,320
45	1	1	.02	.002	.002	$1x10^{-6}$	$1x10^{-6}$	92.2	$9.50x10^{6}$	9,150
45a	1	1	.02	.01	.01	.01	.01	103	$1.33x10^{7}$	11,700
45b	.75	.75	.02	.01	.01	.01	.01	54.9	$1.17x10^{7}$	10,300
46[a]	1	1	.02	.002	.002	$1x10^{-6}$	$1x10^{-6}$	1.32	$6.84x10^{6}$	6,430
46a[a]	1	1	.02	.01	.01	.01	.01	1.54	$8.89x10^{6}$	8,160
46b[a]	.75	.75	.02	.01	.01	.01	.01	.543	$7.94x10^{6}$	6,880
46c[a]	.75	.75	.75	.01	.01	.01	.01	.544	$7.94x10^{6}$	6,880
46d[a]	.75	.75	.75	.75	.01	.01	.01	.544	$7.94x10^{6}$	6,880
46e[a]	.75	.75	.75	.75	.75	.01	.01	.644	$1.01x10^{7}$	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 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	$9.53x10^6$	9,150
NUREG/CR-6244	10th percentile	.527	$9.04x10^6$	8,343
	50th percentile	8.89	$1.26x10^7$	10,100
	mean	54.1	$1.28x10^7$	10,100
	90th percentile	171	$1.66x10^7$	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	$6.75x10^6$	6,300
NUREG/CR-6244	10th percentile	.00197	$7.00x10^6$	6,010
	50th percentile	.00855	$1.03x10^7$	7,730
	mean	.118	$1.07x10^7$	7,810
	90th percentile	.0637	$1.46x10^7$	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, increasing the release fraction of each fission product group resulted in a negligible to modest (less than 40%) increase in consequences. Increasing the ruthenium release fraction resulted in a larger increase in consequences. However, these consequence increases were demonstrated to be largely offset by beginning the evacuation before the release begins. Such an 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 to heat up to the point of releasing fission products.

Other sensitivity calculations involved examining the effect of (1) decreasing the amount of fuel releasing fission products from the entire spent fuel pool inventory to the final core offload and (2) decreasing the percentage of the population evacuating from 99.5% and 95%. For cases with a small ruthenium release, the main effect of decreasing the amount of fuel releasing fission products was a large reduction in prompt fatalities. However, for cases with a large ruthenium release, the prompt fatalities did not change as much, because most of the ruthenium is in the final core offload due to its one-year half-life. With regard to the percentage of the population evacuating, the main difference between 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 sensitivity 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 60% increase in societal dose and cancer fatalities, because of the additional plume spreading associated with the updated plume-spreading parameter values.

References

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 Energy from Air Oxidation in Spent Fuel Storage Pool*, Sandia National Laboratories, August 7, 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

Attachment 2

Response to Public Comments on the Consequence Assessment

Public Comment #1:

Page 2, ACRS: The staff made additional MACCS calculations which assumed 100% release of the ruthenium inventory. For a 1 year decay time with no evacuation, the prompt fatalities increase by 2 orders of magnitude over those in the draft report which did not include ruthenium release. The societal dose doubled, and the cancer fatalities increased four-fold. [Ref. 11]

The staff has included, in Appendix 4A, the additional MACCS calculations with a large ruthenium release fraction. These calculations show an increase in consequences over the cases with the small ruthenium release fraction characteristic of fission product releases under steam conditions. However, the increased consequences resulting from a large ruthenium release are demonstrated to be largely offset by a consequence reduction due to early evacuation which is likely given the long time it takes for a spent fuel pool to heat up.

Public Comment #2:

Page 2, ACRS: The ACRS is concerned about the appropriateness of the source term used in the study. The staff did consider the possibility that "fuel fines" could be released from fuel with ruptured cladding (as a result of decrepitation). It did not, believe these fuel fines could escape from the plant site. Evidence suggests that fuel fines could be entrained in the vigorous natural convection flows produced in a SFP accident. Nevertheless, the staff considered the effect of $6x10^{-6}$ release fraction of fines. This minuscule release fraction did not affect the calculated findings. There is no reason to think that such a low release fraction would be encountered with decrepitating fuel. [Ref. 11]

The staff has included, in Appendix 4A, additional MACCS calculations with a fuel fines release fractions of .001 and .01. These calculations show a negligible to modest (less than 40%) increase in consequences.

Public Comment #3:

Page 3, ACRS: The uncertainties associated with many of the critical features of the MACCS code do not seem to have been considered in the analyses of the SFP accident. [Ref. 11]

-One of the uncertainties is that the spread of the radioactive plume from a power plant site is much larger than what is taken as the default spread in the MACCS calculations.
- The initial plume energy assumed in the MACCS calculations, which determines the extent of plume rise, was taken to be the same as that of a reactor accident rather than one appropriate for a zirconium fire.
-The consequences found by the staff tend to overestimate prompt fatalities and underestimate latent fatalities just because of the narrow plume used in the MACCS calculations and the assumed default plume energy.

The consequence 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 (a) a spent fuel pool does not have a containment as a heat sink and (b) 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 parameters in MACCS version 2. NUREG/CR-6244, *Probabilistic Accident Consequence Uncertainty Analysis*, January 1995, provides updated values for the plume-spreading model parameters.

The staff has included, in Appendix 4A, additional MACCS calculations using different plume heat contents and updated values for the plume-spreading model parameters. The sensitivity calculations 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 model parameters to those in NUREG/CR-6244 results in a decrease in early fatalities and up to a 60% increase in societal dose and cancer fatalities, because of the additional plume spreading associated with the updated values.

<u>Public Comment #4</u>:

Page 3, ACRS: The staff needs to review the air oxidation fission products release data from Oak Ridge National Laboratory and from Canada that found large releases of cesium, tellurium, and ruthenium at temperatures lower than 1000°C. Based on these release values for ruthenium, and incorporating uncertainties in the MACCS plume dispersal models, the consequence analysis should be redone. [Ref. 11]

The release values for ruthenium and the uncertainties in the MACCS plume dispersal models are discussed in the responses to Public Comment #1 and Public Comment #3, respectively. The consequence evaluation documented in Appendix 4 uses a cesium release fraction of one and a tellurium release fraction of .02. Also, the staff has included, in Appendix 4A, additional MACCS calculations using a tellurium release fraction of .75. No change in consequences were seen, because of the small inventories of the tellurium isotopes after one year of decay.

<u>Public Comment #5</u>:

Page 3, Mats Sjöberg/ Ferenc Müller on report, [Ref. 9]: Is a gap release considered to give moderate off-site consequences at the time when Zr-fire is no longer a threat?

NUREG/CR-4982, *Severe Accidents in Spent Fuel Pools in Support of Generic Safety Issue 82*, July 1987, provides societal doses for spent fuel pool accidents involving a fuel melt release and a gap release. These societal doses, which are for the population within 50 miles, are $3x10^6$ rem and 4 rem for a fuel melt release and a gap release, respectively. The NUREG/CR-4982 gap release includes releases of noble gases and iodine, but does not include releases of the less-volatile fission products. The fission product inventory used for the gap release case is for one year after final reactor shutdown. These societal dose results indicate that a gap release is expected to give negligible off-site radiological consequences at the time when rapid zirconium oxidation is no longer a threat.

In the Appendix 4A consequence assessment, a one-year decay time was used. However, the decay time for when rapid zirconium oxidation is no longer a threat is expected to be about five years. After five years of decay, the time available for mitigation, evacuation, and relocation will be much greater. An adiabatic heat-up calculation shows that, after five years of decay, fuel with a burn-up of 60 Gwd/t will take over a day to reach 600°C, the temperature at which it takes cladding 10 hours to rupture. Also, after five years of decay, the fission product inventory available for release will be much smaller. Finally, given the low decay power after five years, there may not be sufficient heat to carry released fission products out of the spent fuel pool and off-site. Based on these considerations, a gap release is expected to give negligible off-site radiological consequences at the time when rapid zirconium oxidation is no longer a threat.

Public Comment #6:

Orange County comment: Draft study does not address where people who have been relocated from uninhabitable land will reside while the land recover from radioactive contamination. Furthermore, the study does not explain the regulatory basis for using 4 rem over 5 years as the threshold dose for relocation **(RES to address)**. Finally, the study fails to address the social and economic implications of losing the use of thousands of square kilometers of land for several generations. [Ref. 8]

EPA 400-R-92-001, *Manual of Protective Action Guides and Protective Actions for Nuclear Incidents*, May 1992, states that, after the early phase of a nuclear incident, protective actions should be taken to limit the dose received by an individual to 2 rem in the first year, .5 rem/year after the first year, and 5 rem over 50 years. These Protective Action Guides are implemented in the MACCS code by limiting the dose to 4 rem over 5 years, that is, 2 rem in the first year plus .5 rem for each of the second through fifth years.