From: Jason Schaperow RES
To: Diane Jackson
Date: Wed, May 26, 1999 9:35 AM
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Attachment

Assessment of Offsite Consequences for a Severe Spent Fuel Pool Accident

Introduction

Spent fuel pool accidents involving a sustained loss of coolant have the potential for leading to significant fuel heatup and resultant release of fission products to the environment. Such an accident would involve decay heat raising the fuel temperature to the point of exothermic cladding oxidation, which would cause additional temperature escalation to the point of fission product release. Because fuel in a spent fuel pool has a lower decay power than fuel in the reactor vessel of an operating reactor, it will take much longer for the fuel in the spent fuel pool to heat up to the point of releasing radionuclides than in some reactor accidents. However, offsite releases from a spent fuel pool can be significant due to the lack of a containment around the spent fuel pool. These offsite releases have the potential to be of a similar magnitude to releases from severe reactor accidents.

Earlier analyses (NUREG/CR-4982[1] and NUREG/CR-6451[2]) have assessed the frequency and consequences of spent fuel pool accidents. These analyses included a limited evaluation of offsite consequences of a severe spent fuel pool accident. NUREG/CR-4982 results included consequence estimates for the societal dose for accidents occurring 30 days and 90 days after the last discharge of spent fuel into the spent fuel pool. NUREG/CR-6451 results included consequence estimates for societal dose, prompt fatalities, and cancer fatalities for accidents occurring 12 days after the last discharge of spent fuel. The work described in this current report extends the earlier analyses by calculating offsite consequences for a severe spent fuel pool accident occurring up to one year after discharge of the last load of spent fuel, and supplements that earlier analysis with additional sensitivity studies, including varying evacuation assumptions as well as other modeling assumptions. The overall objective of this analysis was to provide estimates of offsite consequences to combine with the estimated frequency of a severe spent fuel pool accident to calculate the total risk from severe spent fuel pool accidents. A primary objective of the dose calculation specifically was to assess the effect of extended storage in a spent fuel pool, and the resulting radioactive decay, on offsite consequences. However, as part of this work we also evaluated the sensitivity to a variety of other parameters.

This analysis used the MACCS code[3] (version 2) to estimate offsite consequences for a severe spent fuel pool accident. Major input parameters for MACCS include radionuclide inventories, radionuclide release fractions, evacuation and relocation criteria, and population density. The specification of values for these input parameters for a severe spent fuel pool accident is discussed below.

Radionuclide Inventories

The earlier NUREG/CR-4982 consequence assessment used the CRAC code[4] to estimate offsite consequences at 30 days and 90 days after the last discharge to the spent fuel pool. The more recent NUREG/CR-6451 assessment used the MACCS code (version 1.5.11.1) to estimate offsite consequences at 12 days after the last discharge. As discussed above, this current work was undertaken to assess the magnitude of the decrease in offsite consequences that could result from up to a year of decay in the spent fuel pool. To perform this work, it was

necessary to have radionuclide inventories in the fuel pool at times up to 1 year. NUREG/CR-4982 contains radionuclide inventories at 30 days, 90 days, and 1 year. The inventories in the NUREG/CR-6451 analysis have not been retrievable. Therefore, it was decided to use the inventories based on the work in NUREG/CR-4982 and adjust those inventories as needed.

NUREG/CR-4982 gives spent fuel pool inventories for a BWR (Millstone 1) and a PWR (Ginna). Because this work may also be used as part of the Level 3 analysis of spent fuel pool accidents for the Susquehanna plant which is a BWR, the spent fuel inventories for Millstone 1 were used for this work. The inventories used were those in Table 4.1 of NUREG/CR-4982. Also, because the thermal power of Susquehanna is 1.7 times higher than that of Millstone 1, the Millstone 1 inventories were increased by a factor of 1.7 for this analysis.

Release Fractions

NUREG/CR-4982 also provided the fission product release fractions assumed for a severe spent fuel pool accident. These fission product release fractions are shown in Table 1. NUREG/CR-6451 provided an updated estimate of fission product release fractions. The release fractions in NUREG/CR-6451 (also shown in Table 1) are the same as those in NUREG/CR-4982, with the exception of lanthanum and cerium. NUREG/CR-6451 stated that the release fraction of lanthanum and cerium should be increased from $1x10^{-6}$ in NUREG/CR-4982 to $6x10^{-6}$, because fuel fines could be released offsite from fuel with high burnup. While RES believes that it is unlikely that fuel fines would be released offsite in any substantial amount, a sensitivity was performed using a release fraction of $6x10^{-6}$ for lanthanum and cerium to determine whether such an increase could even impact offsite consequences.

Radionuclide Group	Release Fractions	
	NUREG/CR-4982	NUREG/CR-6451
noble gases	1	1
iodine	1	1
cesium	1	1
tellurium	$2x10^{-2}$	$2x10^{-2}$
strontium	$2x10^{-3}$	$2x10^{-3}$
ruthenium	$2x10^{-5}$	$2x10^{-5}$
lanthanum	$1x10^{-6}$	$6x10^{-6}$
cerium	$1x10^{-6}$	$6x10^{-6}$
barium	$2x10^{-3}$	$2x10^{-3}$

Table 1. Release fractions for a severe spent fuel pool accident with no mitigation.

Modeling of Emergency Response and Other Areas

Modeling of emergency response was basically the same as that used for Surry in NUREG-1150. The timing of events is given in Table 2. For emergency response actions during the first week of the accident, two groups of people were modeled. Group 1 consisted of 99.5% of the people, and group 2 consisted of the remaining .5% of the people. The people in

group 1 located within 10 miles of the spent fuel pool evacuate exactly two hours after emergency response officials receive notification to take protective measures. This results in the evacuation beginning approximately 1.4 hours after the release starts. The people in group 1 located outside of 10 miles relocate to uncontaminated areas after a specified period of time depending on the dose they are projected to receive in the first week. Details of emergency response actions for group 1 are given in Table 3. All of the people in group 2 relocate to uncontaminated areas on the same basis as the people in group 1 located outside of 10 miles.

Event	Time (sec)	Time (hour)
Accident initiation	0	0
Notification given to off-site emergency response officials	1300	.4
Start time of plume	3700	1
Evacuation begins	8500	2.4

Table 2. Timing of events.

Evacuation Zone	
size	10 miles
sheltering	none
evacuation time	evacuation begins 2 hours after notifying emergency response officials to initiate protective measures
evacuation direction	radially outward
evacuation speed	4 miles/hr
other	after evacuee reaches 20 miles from fuel pool, no further exposure is calculated

Table 3. Emergency response modeling for 99.5% of the population.

Offsite Consequence Results

MACCS calculations for accidents occurring 30 days, 90 days, and 1 year after the last discharge of spent fuel were performed to assess the magnitude of the decrease in the offsite consequences resulting from extended decay prior to the release. These calculations were performed for a Base Case along with a number of sensitivity cases to evaluate the impact of alternative modeling. These cases are summarized in Table 4. The results of these calculations are discussed below.

Case	Population Distribution	Radionuclide Inventory	Evacuation Start Time	La/Ce Release Fraction	Evacuation Fraction
Base Case	Surry	11 batches* plus rest of last core	1.4 hours after release begins	$1x10^{-6}$	99.5%
1	Surry	11 batches plus rest of last core	1.4 hours after release begins	$1x10^{-6}$	95%
2	Surry	11 batches	1.4 hours after release begins	$1x10^{-6}$	95%
3	100 people/mi^2	11 batches	1.4 hours after release begins	$1x10^{-6}$	95%

4	100 people/mi^2	11 batches plus rest of last core	1.4 hours after release begins	1x10^{-6}	95%
5	100 people/mi^2	11 batches plus rest of last core	3 hours before release begins	1x10^{-6}	95%
6	100 people/mi^2	11 batches plus rest of last core	3 hours before release begins	6x10^{-6}	95%
7	100 people/mi^2	11 batches plus rest of last core	3 hours before release begins	1x10^{-6}	99.5%

* These 11 batches of spent fuel contain the number of fuel assemblies in about 3 cores.

Table 4. Cases examined using the MACCS2 consequence code.

The results of the Base Case, which used the Surry population distribution and an evacuation fraction of 99.5%, are shown in Table 5. This case was chosen as the Base Case, because it is the most self-consistent in that it uses population data and meteorology data which are both for the Surry site. In addition, the other modeling it uses, such as evacuation fraction, is from the NUREG-1150 consequence assessment model for Surry.

Decay Time in Spent Fuel Pool	Distance (miles)	Prompt Fatalities	Societal Dose (person-Sv)	Cancer Fatalities
30 days	0-100	1.75	47,700	2,460
	0-500	1.75	571,000	25,800
90 days	0-100	1.49	46,300	2,390
	0-500	1.49	586,000	26,400
1 year	0-100	1.01	45,400	2,320
	0-500	1.01	595,000	26,800

Table 5. Mean consequences for the Base Case (and for Case 1).

The results in Table 5 show significant offsite consequences for a severe spent fuel pool accident at each of the decay times examined. However, these results show virtually no change in offsite consequences as a function of decay time for societal dose and cancer fatalities. These results also show a factor of two reduction in prompt fatalities from 30 days to 1 year of decay. As a rough check on the prompt fatality results, the change in decay power was evaluated for an operating reactor shut down for 30 days and for 1 year. The decay power decreased by about a factor of three. This is consistent with a factor of two decrease in prompt fatalities. This would also suggest that the reduction in radionuclide inventory resulting from radioactive decay may be felt more strongly in the estimate of the time to heat up the spent fuel (factor of 3) than in the estimate of offsite consequences (factor of 2 or less). Overall, the results of the staff's calculations indicate that decay of radionuclides from 30 days to 1 year has a small impact on the potentially large offsite consequences from a severe spent fuel pool accident.

The results of Case 1, which used a lower evacuation fraction than the Base Case, are identical to the results of the Base Case. Although it might be expected to see an increase in prompt fatalities from reducing the evacuation fraction, no such increase was observed. This is due to the assumption that the release begins at one hour, while the evacuation does not begin until 2.4 hours.

Case 2, shown in Table 6, used a radionuclide inventory that consisted of 11 batches of spent fuel, but did not include the remaining two-thirds of the core in the vessel. This was done to allow comparison of the consequence results with the results of the analyses in NUREG/CR-4982 and NUREG/CR-6451. In addition, this was done to examine the relative contribution of the short-lived radionuclides, most of which remain in the vessel following discharge of the refueling batch. Use of 11 batches of spent fuel without the remaining two-thirds of the core resulted in a factor of two reduction in the prompt fatalities and no change in the societal dose and cancer fatalities. This factor of two reduction is consistent with the factor of three reduction in the inventories of the short-lived radionuclides when the remaining two thirds of the core in the vessel is not included in the consequence calculation.

Decay Time in Spent Fuel Pool	Distance (miles)	Prompt Fatalities	Societal Dose (person-Sv)	Cancer Fatalities
30 days	0-100	.89	44,900	2,280
	0-500	.89	557,000	25,100
90 days	0-100	.78	44,500	2,250
	0-500	.78	554,000	25,000
1 year	0-100	.53	43,400	2,180
	0-500	.53	567,000	25,500

Table 6. Mean consequences for Case 2.

The results of the next case, Case 3, are shown in Table 7. This case used a generic population distribution of 100 persons/mile^2 (uniform). This was done, in part, to allow comparison of the consequence results with the results of the analyses in NUREG/CR-4982 and NUREG/CR-6451. A uniform population density of 100 persons/mile^2 results in an order of magnitude increase in prompt fatalities and relatively small changes in the societal dose and cancer fatalities.

Decay Time in Spent Fuel Pool	Distance (miles)	Prompt Fatalities	Societal Dose (person-Sv)	Cancer Fatalities
30 days	0-100	11.7	50,100	2,440
	0-500	11.7	449,000	20,300
90 days	0-100	10.6	50,300	2,460
	0-500	10.6	447,000	20,200
1 year	0-100	8.19	49,000	2,380
	0-500	8.19	453,000	20,500

Table 7. Mean consequences for Case 3.

The results of the next case, Case 4, are shown in Table 8. This case uses the remaining two-thirds of the core in the vessel. This was done, in part, to allow comparison of the consequence results with the results of the analysis in NUREG/CR-6451. As discussed above in the comparison of Case 1 with Case 2, this changes the prompt fatalities by about a factor of two with no change in the societal dose or cancer fatalities.

Decay Time in Spent Fuel Pool	Distance (miles)	Prompt Fatalities	Societal Dose (person-Sv)	Cancer Fatalities
30 days	0-100	18.3	53,500	2,610

	0-500	18.3	454,000	20,600
90 days	0-100	16.3	52,100	2,560
	0-500	16.3	465,000	21,100
1 year	0-100	12.7	50,900	2,490
	0-500	12.7	477,000	21,600

Table 8. Mean consequences for Case 4.

Heat up of fuel in a spent fuel pool following a complete loss of coolant takes much longer than in some reactor accidents. Accordingly, it has been suggested that it may be possible to begin evacuating before the release begins. Case 5, which uses an evacuation start time of three hours before the release begins, was performed to assess the impact of early evacuation. As shown in Table 9, prompt fatalities were significantly reduced and societal dose and cancer fatalities remained unchanged.

Decay Time in Spent Fuel Pool	Distance (miles)	Prompt Fatalities	Societal Dose (person-Sv)	Cancer Fatalities
30 days	0-100	.96	48,300	2,260
	0-500	.96	449,000	20,200
90 days	0-100	.83	47,500	2,220
	0-500	.83	460,000	20,700
1 year	0-100	.67	46,700	2,180
	0-500	.67	473,000	21,300

Table 9. Mean consequences for Case 5 (and for Case 6).

Case 6 was performed to assess the potential impact of a release of lanthanum and cerium that NUREG/CR-6451 estimated to be a factor of six higher than that originally estimated in NUREG/CR-4982. The Case 6 consequence results were identical to those of Case 5. Therefore, even it were possible for fuel fines to be released offsite, there would be no change in offsite consequences as a result.

The final case, Case 7 was performed to examine the impact of a 99.5% evacuation for a case with evacuation before the release begins. This sensitivity (see Table 10) showed an order of magnitude decrease in the prompt fatalities. Again, as expected, no change in the societal dose or cancer fatalities was observed.

Decay Time in Spent Fuel Pool	Distance (miles)	Prompt Fatalities	Societal Dose (person-Sv)	Cancer Fatalities
30 days	0-100	.096	48,100	2,250
	0-500	.096	449,000	20,200
90 days	0-100	.083	47,400	2,210
	0-500	.083	460,000	20,700
1 year	0-100	.067	46,600	2,170
	0-500	.067	473,000	21,300

Table 10. Mean consequences for Case 7.

As a check on the above calculations and to provide additional insight into the consequence

analysis for severe spent fuel pool accidents, the above calculations were compared to the consequence results reported in NUREG/CR-4982 and NUREG/CR-6451. As noted above, NUREG/CR-4982 results included consequence estimates for societal dose for accidents occurring 30 days and 90 days after the last discharge of spent fuel into the spent fuel pool. Case 3 results were compared against the NUREG/CR-4982 results, because Case 3 uses the same population density as NUREG/CR-4982 which is a uniform population density of 100 persons/mile^2. It also uses 11 batches of spent fuel in the spent fuel pool. Case 3 results generally compared well with the NUREG/CR-4982 results.

The NUREG/CR-6451 results included consequence estimates for societal dose, prompt fatalities, and cancer fatalities for accidents occurring 12 days after the last discharge of spent fuel. Case 4 results were compared against the NUREG/CR-6451 results, because Case 4 included the entire last core of fuel in the spent fuel pool as did NUREG/CR-6451. However, three differences between Case 4 and NUREG/CR-6451 were the population density, the amount of spent fuel in the pool, and the exclusion area size. To provide a more consistent basis to compare NUREG/CR-6451 results with Case 4 results, Case 4 was rerun using population densities, an amount of spent fuel, and an exclusion area size similar to NUREG/CR-6451. Case 4 results generally compared well with NUREG/CR-6451 results. These calculations indicated a very strong dependence of offsite consequences on population density and a small dependence (about 10% change in prompt fatality results) on exclusion area size.

Comparison of Spent Fuel Pool and Reactor Accident Offsite Consequences

Steam generator tube rupture accidents are risk significant for PWRs in part because of their high offsite release which is a result of containment bypass. These accidents and their offsite releases have been studied extensively by RES over the last several years using the MELCOR, SCDAP/RELAP5, and VICTORIA severe accident codes. Using the offsite releases from these studies, RES has estimated offsite consequences using the MACCS code. These estimates of offsite consequences are described in References 5 and 6. A comparison of these offsite consequences with those of a severe spent fuel pool accident indicates that the offsite consequences are comparable.

Conclusions

A number of conclusions can be drawn from the above evaluation of offsite consequences of a severe spent fuel pool accident. These conclusions include the following:

a. The offsite radiological consequences of a severe spent fuel pool accident are comparable in magnitude to those of a severe reactor accident.

b. The consequences of a severe spent fuel pool accident are most sensitive to population density both near the plant and away from the plant.

c. A factor of two reduction in prompt fatalities is seen if the accident occurs after 1 year of decay instead of after 30 days. Long-term consequences (societal dose and cancer fatalities) are not affected, because they are controlled by emergency response actions and inventories of radionuclides with long half-lives.

d. Beginning the evacuation before the fission product release begins can reduce the

prompt fatalities by an order of magnitude. However, an early evacuation not unexpectedly has very little impact on long-term consequences.

References

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

2. NUREG/CR-6451, A Safety and Regulatory Assessment of Generic BWR and PWR Permanently Shutdown Nuclear Power Plants, August 1997

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

4. NUREG/CR-2326, Calculations of Reactor Accident Consequences Version 2, CRAC2: Computer Code, February 1983

5. "Offsite Consequence Evaluation of Steam Generator Tube Leaks and Induced Steam Generator Tube Ruptures," memorandum from Charles E. Ader to Robert C. Jones, July 24, 1996

6. "Offsite Consequence Evaluation of Steam Generator Tube Leaks, Steam Generator Tube Ruptures, and Induced Steam Generator Tube Ruptures," memorandum from Charles E. Ader to Robert C. Jones, August 30, 1996

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