From: Robert Palla/ NRR
To: Glenn Kelly
Date: Wed, Sep 20, 2000 1:47 PM
Subject: Latest Draft of Section 3.5

is attached for your review. It incorporates the RES input (in table form) and your comments on the earlier draft. The figures and related discussions need to be added, and will depend on what Tim and Gary decide should be included.

CC: George Hubbard, Timothy Collins

L/320

3.5 Consequences and Risks Associated With SFP Accidents

This section provides an assessment of the consequences and risks associated with SFP accidents. Estimated consequences of SFP accidents are presented in Section 3.5.1. Results are provided for both early evacuation and late evacuation cases, and for two different source terms. In Section 3.5.2, severe accident consequences are assigned to each of the major types of events that lead to uncovery of the spent fuel, and then combined with the respective event frequencies to provide a scoping estimate of SFP risk. The impact of changes in EP regulations on these risk measures is discussed later in Section 4.

3.5.1 Consequences of SFP Accidents

Earlier analyses in NUREG/CR-4982 and NUREG/CR-6451 included a limited evaluation of offsite consequences for a severe SFP accident occurring up to 90 days after the last discharge of spent fuel into the SFP. These analyses showed that the consequences of a SFP accident could be comparable to those for a severe reactor accident. As part of its effort to develop generic, risk-informed requirements for decommissioning, the staff performed a further evaluation of the offsite radiological consequences of beyond-design-basis spent fuel pool accidents. An initial set of calculations were performed to extend the earlier analyses to SFP accidents occurring one year after plant shutdown, and to supplement the earlier analyses with additional sensitivity studies, including varying evacuation assumptions as well as other modeling assumptions. On the basis of these calculations the staff 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, early evacuation reduces the short-term consequences by up to a factor of 100 relative to late evacuation[1]. The likelihood of early evacuation increases with time after shutdown, 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.

The results of these calculations were documented in the Draft Final Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants, February 2000, and are reproduced as Appendix 4 in the present report.

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, the staff performed additional sensitivity studies and concluded the following:

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[1] Early evacuation refers to situations in which evacuation is initiated and completed prior to the SFP release. Situations in which the evacuation is not completed prior to release are referred to as late evacuation.

- With the exception of the ruthenium release fraction, the parameters varied neither sufficiently impacted the results, nor changed 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 for scenarios without early evacuation. This is attributable ruthenium's high dose per curie inhaled. However, consequence increases from ruthenium were demonstrated to be largely offset by early evacuation.

- Updated values for plume-spreading model parameters resulted in a 60% increase in long-term consequences and a factor of 15 decrease in short term consequences. This is still considered in the range of severe reactor accidents since similar increases are expected when these updated values are used to calculate reactor accident consequences.

The results of these calculations are documented in Appendix 4A in the present report.

To provide additional insight into the reductions in fission product inventory available for release with time, several additional consequence calculations were performed using fission product inventories at 30 and 90 days and two, five, and ten years after final shutdown. The impact of additional decay time on early fatalities, societal dose, latent cancer fatalities is summarized in Tables 3.5-1 and 3.5-2, and discussed in more detail in Appendix 4B. Also shown are risk measures related to the Commission's Safety Goal, i.e, early fatality risk to an average individual within 1 mile of the site, and the latent cancer fatality risk to an average individual within 10 miles of the site.

The consequences in Table 3.5-1 are based on an upper bound source term described in Appendix 4B. With the exception of ruthenium and fuel fines, the release fractions are from NUREG-1465, *Accident Source Terms for Light-Water Nuclear Power Plants,* (Reference 1) and include the ex-vessel and late in-vessel phase releases. The ruthenium release fraction is that for a volatile fission product. This is considered to be bounding for several reasons. First, rubbling of the spent fuel after heat-up to about 2500K is expected to limit the ruthenium release. Second, following the Chernobyl accident, ruthenium in the environment was found to be in the metallic form (Reference 2). Metallic ruthenium has a much lower dose conversion factor, that is, rem per Curie inhaled, than oxidic ruthenium which is conservatively assumed in the MACCS code. The fuel fines release fraction used in the upper bound case is that from the Chernobyl accident (Reference 3). This is considered to be bounding because the Chernobyl accident involved more extreme conditions (i.e., two explosions followed by a prolonged graphite fire) than a spent fuel pool accident.

The consequences obtained using the unmodified NUREG-1465 source term are provided in Table 3.5-2 for comparison. Although the NUREG-1465 source term was developed to represent fission product releases in a severe reactor accidents, this source term could be considered to provide a more central estimate of the releases in a SFP accident.

The consequences for the upper bound source term are driven largely by ruthenium, and decrease substantially during the first 5 years following shutdown given its one year half-life.

After about 5 years, the ruthenium contribution is reduced and consequences are dominated by cesium which decays at a slower rate. In contrast, the consequences for the NUREG-1465 source term are driven primarily by cesium and exhibit a more gradual and constant decrease throughout the entire period. The early fatality consequences for the upper bound source term are most sensitive to decay time, and decrease by about an order of magnitude within the first two years following shutdown and an additional two orders of magnitude by the 10th year following shutdown. Population dose and latent cancer fatalities, driven by longer-lived fission products, are less sensitive to decay time and decrease by only about a factor of two by the 10th year following shutdown.

These results do not consider the reduction in the number of assemblies that would be involved in a SFP in later years due to substantially lower decay heat in the oldest assemblies. Therefore, the results are believed to underestimate the decline in consequences as a function of time.

Table 3.5-1 Consequences of a SFP Accident Based on Upper Bound Source Term

Time after Shutdown	Mean Consequences For Upper Bound Source Term (Surry population, 95% evacuation)				
	Early Fatalities	Societal Dose (p-rem within 50 miles)	Latent Cancer Fatalities (within 100 miles)	Individual Risk of Early Fatality (within 1mile)	Individual Risk of Latent Cancer Fatality (within 10 miles)
Late Evacuation					
30 days	192	2.37E7	21100	4.43E-2	8.24E-2
90 days	162	2.25E7	20000	4.19E-2	8.20E-2
1 year	76.9	1.93E7	17400	3.46E-2	8.49E-2
2 years	19.2	1.69E7	15400	2.57E-2	8.42E-2
5 years	1.34	1.45E7	12600	8.96E-3	7.08E-2
10 years	0.360	1.34E7	11400	4.68E-3	6.39E-2
Early Evacuation					
30 days	6.65	1.35E7	15400	2.01E-3	4.79E-3
90 days	3.95	1.29E7	14300	1.87E-3	4.77E-3
1 year	0.951	1.12E7	11500	1.50E-3	4.33E-3
2 years	0.149	9.93E6	9480	1.12E-3	3.70E-3
5 years	0.0162	8.69E6	7620	3.99E-4	2.93E-3
10 years	0.00601	8.13E6	6490	2.05E-4	2.64E-3

Table 3.5-2 Consequences of a SFP Accident Based on NUREG-1465 Source Term

Time after Shutdown	Mean Consequences For NUREG-1465 Source Term (Surry population, 95% evacuation)				
	Early Fatalities	Societal Dose (p-rem within 50 miles)	Latent Cancer Fatalities (within 100 miles)	Individual Risk of Early Fatality (within 1mile)	Individual Risk of Latent Cancer Fatality (within 10 miles)
Late Evacuation					
30 days	2.21	5.58E6	4540	1.27E-2	1.88E-2
90 days	1.37	5.43E6	4420	9.86E-3	1.82E-2
1 year	0.736	5.28E6	4190	7.13E-3	1.68E-2
2 years	0.481	5.12E6	4020	5.64E-3	1.58E-2
5 years	0.192	4.90E6	3800	3.18E-3	1.43E-2
10 years	0.0778	4.72E6	3620	1.63E-3	1.29E-2
Early Evacuation					
30 days	0.072	4.12E6	3240	8.36E-4	9.92E-4
90 days	0.0461	4.02E6	3150	6.83E-4	9.62E-4
1 year	0.0301	3.95E6	3020	5.44E-4	9.09E-4
2 years	0.0208	3.87E6	2930	4.41E-4	8.71E-4
5 years	0.00882	3.77E6	2820	2.54E-4	8.14E-4
10 years	0.00400	3.69E6	2730	1.47E-4	7.70E-4

3.5.2 Risks of SFP Accidents

The quantitative assessment of risk involves combining the estimated frequencies of severe accident sequences with their corresponding offsite consequences. In this section, severe accident consequences are assigned to each of the major types of events that lead to uncovery of the spent fuel, and then combined with the respective event frequencies to provide a scoping estimate of risk.

The SFP accidents discussed in Section 3 can be broadly classified as either boil down or rapid drain down sequences. Rapid drain down sequences are further divided into seismically- and non-seismically-initiated events. In assigning consequences to each of these events, the staff considered whether protective measures to evacuate the population around the site would be effectively implemented prior to fission product release. This included consideration of the effectiveness of offsite notification, the delay between event initiation and fission product release (dependent on time after shutdown), the time required to initiate and complete an evacuation, and the impact that a relaxation in current EP requirements might have on these factors. As a result of this assessment, consequences were assigned based on either the early evacuation case or late evacuation case.

The frequency and consequences for each class of SFP accident are described below. The corresponding risk results are presented in Figures 3.5-1 through 3.5-8 for various risk measures as a function of time after shutdown.

Boil Down Sequences

Boil down sequences and their associated frequencies are listed in Table 3.5-3. These sequences involve heatup of the pool to boiling followed by gradual reduction in pool level until the spent fuel is eventually uncovered. This process would take several hundred hours at one year, and substantially longer at later times as shown in Table 3.3. The long delay provides sufficient time for licensee staff to effectively intervene in the large majority of these events, and results in very low frequencies of fuel uncovery. For those events that proceed to fuel uncovery, fuel heatup will continue until either steady-state conditions are achieved or cladding oxidation occurs. All boil down sequences were conservatively assumed to result in a SFP fire. Loss of inventory events are classified as boil down events since the time to uncover the fuel will be in excess of 24 hours (as described in Section 4.5.4.1 of Appendix 2a) and will provide ample time for licensee to take corrective measures.

Table 3.5-3 Frequency of Boil Down Events (one year after shutdown)

Initiating Event	Frequency (per year)
Loss of off-site power -- severe weather	1.1E-7
Loss of off-site power -- plant centered and grid related events	2.9E-8
Internal fire	2.3E-8
Loss of pool cooling	1.4E-8
Loss of coolant inventory	3.0E-9
Total	1.8E-7

The failure paths leading to a zirconium fire involve failure to acquire off-site resources to provide pool inventory makeup, despite the large amount of time available for recovery in the boil down event. For sequences involving loss of off-site power due to severe weather, the weather is assumed to drain regional resources or limit their access to the facility. The staff assumes that if it is difficult for off-site resources to reach the facility or regional resources are engaged in other efforts, then it would also be unlikely that the population in the area would be effectively notified and/or evacuated under these conditions. For the other sequences, the dominant reason that recovery is not provided in the failure paths is that there was a general breakdown in the overall facility organization. The failure to acquire off-site resources implies there is also a failure to contact regional authorities and declare a general emergency when the SFP level drops below the proceduralized limit in these sequences. Accordingly, the consequences for boil down sequences are based on results for the late evacuation case (i.e., evacuation after the release has occurred). This same assumption is applied for cases with and without EP relaxations, and for all times after shutdown.

Rapid Drain Down Due to Seismic Events

Given the robust structural design of SFPs, a seismic event with peak spectral acceleration several times larger than the safe shutdown earthquake (SSE) would be required to produce catastrophic failure of the structure. The estimated frequency of events of this magnitude differs greatly among experts and is driven by modeling uncertainties. The estimated frequency of seismic events sufficiently large to result in structural failure of the SFP is provided in Table 3.5-4 based on the use of LLNL and EPRI seismic hazard estimates.

Both the LLNL and EPRI hazard estimates are considered reasonable by the NRC. Using the LLNL hazard curves, a return frequency of 5E-6 per year for a 0.5 PGA earthquake bounds all but seven sites (4 CEUS and 3 western sites). The frequency for the remaining sites falls in the range of 7E-8 per year to 5E-6 per year. Of these sites, the majority (45 sites) have hazard estimates (for a 0.5 PGA earthquake) near 1E-6 per year and 20 sites fall below 6E-7 per year. The median value for the population of plants is approximately 1E-6 per year. If EPRI hazard estimates are used, only one site has an estimate that exceeds 1E-6 per year (excluding western sites). Ten sites are near 5E-7 per year, and the remaining 49 sites analyzed by EPRI have estimates less than 3E-7 per year, with half of these sites (25 sites) estimated at less than 7E-8 per year. The median value for the population of plants is approximately 1E-7 per year.

In characterizing the risk of seismically-induced SFP accidents for the population of sites, the staff has displayed results based on both the LLNL and EPRI hazard estimates, and has used an accident frequency corresponding to the median value for the respective distributions, i.e., a frequency of 1E-6 per year to reflect the use of LLNL hazard estimates and a frequency of 1E-7 per year to reflect use of the EPRI hazard estimates. Although use of a higher value would bound additional sites (for example, about 70 percent of the sites would be bounded using a value of 2E-6 per year and 2E-7 per year with the LLNL and EPRI hazard estimates), the differences in the frequency remain about a factor of 10. Conformance with the Pool Performance Guideline described in Appendix 4C will assure that plants above the median value continue to meet the Commission's Safety Goals.

Table 3.5-4 Frequency of Rapid Drain Down Due to Seismic Events

Source of Hazard Curve	Frequency (per year)	
	Screening Value	Median Value (approx.)
LLNL	<5E-6	1E-6
EPRI	<6E-7	1E-7

A discussion of likely SFP failure modes and locations is provided in Appendix _, and indicates that drainage of the pool would be fairly rapid and a small but uncertain amount of water is likely to remain in the pool, with post-seismic failure water depths ranging from essentially zero depth to about 4 feet of depth depending upon the critical failure mode. For purposes of consequence assessment, all seismically-initiated sequences were conservatively assumed to result in a rapid drain down followed by a SFP fire, regardless of the SFP failure mode and location.

The SFP risk estimates are strongly dependent on the assumptions regarding the effectiveness of emergency evacuation in seismic events, since these events dominate the SFP fire

frequency. In NUREG-1150, evacuation in seismic events was treated either of two ways depending on the peak ground acceleration (PGA) of the earthquake:

- for low PGA earthquakes, the population was assumed to evacuate; however, the evacuation was assumed to start later and proceed more slowly than evacuation for internally-initiated events. A delay time of 1.5 times the normal delay time and an evacuation speed of 0.5 times the normal evacuation speed was assumed for this case.

- for high PGA earthquakes, it was assumed that there would be no effective evacuation and that many structures would be uninhabitable. The population in the emergency response zone was modeled as being outdoors for the first 24 hours, and then relocating at 24 hours.

Since the SFP fire frequency is driven by seismic events with PGA several times larger than the SSE, the assumption that there would be no effective evacuation was adopted in developing the baseline estimate of the risk. This is supported by an NRC staff consultant's assessment of the expected level of collateral damage within the Emergency Planning Zone given a seismic event large enough to fail the SFP in the (Appendix _). Specifically, for ground motion levels that correspond to SFP failure in the Central and Eastern U.S., it is expected that electrical power would be lost and more than half of the bridges (including those housing communication systems and emergency response equipment) would be unsafe even for temporary use within at least 10 miles of the plant. This assumption is also consistent with previous Commission rulings on San Onofre and Diablo Canyon in which the Commission found that for those risk-dominant earthquakes that cause very severe damage to both the plant and the offsite area, emergency response would have marginal benefit because of its impairment by offsite damage.

The consequences for seismic sequences are based on results for the late evacuation case. This same assumption is applied for cases with and without EP relaxations, and for all times after shutdown. A sensitivity case was also performed to explore the impact on risk if the seismic event only partially degrades the emergency response. This is discussed in Section 4.2.1.

Rapid Drain Down Due to Non-Seismic Events

Non-seismically-initiated events leading to rapid drain down are listed in Table 3.5-5. These events are dominated by cask drop accidents, with the next highest contributor nearly two orders of magnitude lower.

Table 3.5-5 Frequency of Rapid Drain Down Due to Non-Seismic Events (one year after shutdown)

Initiating Event	Frequency (per year)
Cask drop	2.0E-7
Aircraft impact	2.9E-9
Tornado missile	<1.0E-9
Total	2.0E-7

Cask drop accidents that lead to catastrophic failure of the SFP include accidents in which the load is dropped either on the pool floor, or on or near the pool wall. Load drops on the pool floor are more likely to result in complete drain down of the pool, and creation of an air flow path through the fuel assemblies. Load drops on the pool wall would likely result in residual water in the pool which would obstruct air flow. For purposes of consequence assessment, all cask drop accidents leading to fuel uncovery were conservatively assumed to result in a rapid but partial drain down followed by a SFP fire.

Given the limiting pool failure mode and location, fuel heatup would be close to adiabatic. **(Refer to appropriate place in J. Staudenmeier section)** Under adiabatic conditions, the time of fission product release would range from about 5 to 8 hours for accidents initiated one year following shutdown to about one day or more for accidents initiated five years after shutdown or later. The actual time depends on reactor type, fuel burnup, fuel rack structure, and other plant-specific parameters, as discussed in Appendix 1.

The fuel handlers would be immediately aware of a cask drop accident. It is expected that with procedures that detail the SFP water level at which a general emergency is to be declared, the proper offsite authorities would be promptly informed. For the case in which current EP requirements are retained, it was assumed that cask drop accidents occurring one or more years following shutdown would afford sufficient time to implement protective measures before fission products are released (5 to 8 hours as discussed in Appendix 1). As such, the consequences within the first several months following shutdown are based on late evacuation, and the consequences at one year and beyond are based on early evacuation.

Relaxations in EP requirements are expected to result in additional delays in initiation and implementation of protective measures relative to the case in which current EP requirements are retained. If EP requirements were relaxed, as many as 10 to 15 hours may be required at some sites to implement an equivalent evacuation **(Supplement this statement based on info from Barss or FEMA)**. Based on adiabatic heatup rates for the reference pool, the time to fission product release is about 10 hours for PWR pools and 15 hours for BWR pools two years following shutdown. These release times increase to 23 and 33 hours for PWR and BWR pools five years following shutdown. Thus, implementation of emergency measures an ad hoc basis would provide marginally equivalent protection two years following shutdown or later, and fully equivalent protection at five years following shutdown. For the case in which current EP requirements are relaxed, the consequences within the first two years following shutdown are based on late evacuation, and the consequences at five years and beyond are based on early evacuation.

Risk Results

The frequency and consequences for each SFP accident were combined to provide a scoping estimate of the risk of SFP accidents. The frequency of each event was based on the estimated value at one year following shutdown as described above, and was assumed to remain constant over time. In reality, the frequency would vary with time, and could be somewhat higher or lower than the one-year estimate, as a result of plant configuration changes described in Section 3.1 (e.g., replacement of pool cooling and makeup systems with skid-mounted systems) and reductions in decay heat levels which would impact human reliability estimates as described in Section 3.4.7.

Figures 3.5-1 through 3.5-3 show the early fatality, societal dose, and latent cancer fatality risk measures as a function of time for each major SFP risk contributor. These results may be viewed as representing an upper value in that they are based on use of the LLNL seismic hazard curves, the upper bound source term, and a fuel burnup of 60 GWd/MTU. Also shown are the corresponding risk measures for two operating plants, Surry and Peach Bottom[2], for which risk results for both internal and seismic events are available in NUREG-1150. For Peach Bottom, the seismic risk results reported in NUREG-1150 based on the LLNL hazard curves have been reduced by a factor

Figure 3.5-1 Early Fatalities Versus Time, Upper Bound Source Term, LLNL Hazard Curve

Figure 3.5-2 Societal Dose Versus Time, Upper Bound Source Term, LLNL Hazard Curve

Figure 3.5-3 Latent Cancer Fatalities Versus Time, Upper Bound Source Term, LLNL Hazard Curve

Statement about decrease in risk with time

Statement about EP only affecting cask drop and having a relatively insignificant effect

Statement about how risk level compares with that for the operating plants

Figures 3.5-4 through 3.5-6 show the impact on the above risk measures if the seismic risk is characterized based on the EPRI rather than LLNL hazard curves.

Figure 3.5-4 Early Fatalities Versus Time, Upper Bound Source Term, EPRI Hazard Curve

Figure 3.5-5 Societal Dose Versus Time, Upper Bound Source Term, EPRI Hazard Curve

Figure 3.5-6 Latent Cancer Fatalities Versus Time, Upper Bound Source Term, EPRI Hazard Curve

Statement about the risk reduction from different hazard curve

Statement about the risk reduction from different source term

Statement about the effect of EP under these conditions

Figures 3.5-7 and 3.5-8 show the risk measures relevant to the Commissions's Safety Goal Policy statement, specifically, the individual risk of early fatality (to an individual within 1 mile of

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[2] The LLNL seismic risk results reported in NUREG-1150 are based on a 1989 version of the LLNL hazard curves. An update of these curves performed in1993 resulted in a factor of 10 reduction in the LLNL mean hazard for Peach Bottom and a smaller reduction for Surry. To provide a more meaningful comparison, the LLNL seismic risk results for Peach Bottom reported in NUREG-1150 have been reduced by a factor of 10. The results for Surry and the EPRI seismic risk results are not affected by this adjustment.

the site) and the individual risk of latent cancer fatality (to an individual within 10 miles of the site). The upper curves are based on the LLNL seismic hazard curves and the upper bound source term, and the lower curves are based on the EPRI hazard curves and the realistic source term. These results may be viewed as representing a range of credible risk results, given the conservative assumption that all SFP accidents result in a fire.

Figure 3.5-7 Individual Risk of Early Fatality

Figure 3.5-8 Individual Risk of Latent Cancer Fatality

Statement about the decrease in risk measures with time

Statement about the margins to the QHOs for SFP accidents

Statement about the significance of EP relative to the margins to the QHOs

Statement about how these margins compare to those for the operating reactors

Statement about how much lower the risk measures are using the EPRI hazard curve and realistic source term