Insights from a Seismic PRA of a Modern PWR Spent Fuel Pool

P. J. Amico[1], I. S. Kim[2], D. W. Lee[3]

[1] *JENSEN HUGHES, 111Rockville Pike, Suite 550, Rockville, MD, 20850, USA, pamico@jensenhughes.com*
[2] *ISSA Technology, Inc., 21318 Seneca Crossing Dr., Germantown, MD, 20876, USA, isk@issatechinc.com*
[3] *KEPCO Engineering and Construction, 269, Hyeoksin-ro, Gimcheon-si, Gyeongsangbuk-do, ROK, leedongwon@kepco-enc.com*

A Seismic Probabilistic Risk Assessment (SPRA) was conducted for seismic events that may potentially cause fuel damage in the spent fuel pool (SFP) associated with a modern (i.e., GEN 3+) PWR nuclear power plant. This SFP has a standard SFP cooling system as well as a number of back-up make-up systems, most of which are not specifically designed for seismic events, plus an additional external emergency make-up/spray system that will be designed for seismic events. The PRA found various insights regarding the seismic risk. It was determined that the high acceleration (>1.0g) seismic event completely dominates the results with about 96% contribution to the total fuel damage frequency resulting from seismic events. The Level 2 PRA results found that essentially all fuel damage events will lead to a large release. The primary reasons for this result are because the SFP is housed in the auxiliary building and this building is not a containment and is susceptible to a number of modes of release. The seismic risk is found to be very sensitive to any changes in the availability of the external emergency makeup system. Any degradation in the availability of the external makeup equipment has the potential for a significant increase in the SFP seismic risk.

I PURPOSE

The purpose of this paper is to present the method and results of the Seismic Level 1 and Level 2 PRA that has been performed for Spent Fuel Pool operations for a Gen 3+ NPP. The Seismic Probabilistic Risk Assessment (SPRA) was conducted following the technical guidance for SFP SPRA [1] developed for this project, and also consistent with the requirements set forth in the ASME/ANS PRA Standard [2] to the extent possible given that the plant being analyzed was not in operation at the time of the analysis.

II GENERAL INFORMATION

The scope of the Spent Fuel Pool (SFP) Seismic Level 1 and Level 2 PRA includes the following major technical tasks as illustrated in Figure 1.

1) Seismic Hazard Analysis (SH)
2) Seismic Fragility Analysis (SF)
3) Accident Sequence Analysis (AS)
4) Success Criteria Analysis (SC)
5) Systems Analysis (SY)
6) Human Reliability Analysis (HR)
7) Data analysis (DA)
8) Fuel Damage Frequency Quantification (QU)
9) Spent Fuel Damage Analysis (FD)
10) Large Release Frequency Analysis (LR)

A Seismic Probabilistic Risk Assessment (SPRA) consists of these major elements: 1) seismic hazard analysis, 2) fragility evaluation, and 3) plant systems and sequence analysis and seismic risk quantification [2]. The first and second elements correspond to the first and second steps of the above diagram, respectively.

The SFP Seismic Probabilistic Risk Assessment (SPRA) was performed consistent with the requirements of the ASME/ANS PRA Standard for a nuclear reactor [2] as far as they are applicable to a spent fuel pool.

III ANALYSIS

This section describes the seismic PRA modeling and analysis. It focuses on the changes and additions made to the reactor seismic model and the spent fuel pool internal events PRA model to accommodate the spent fuel pool seismic analysis.

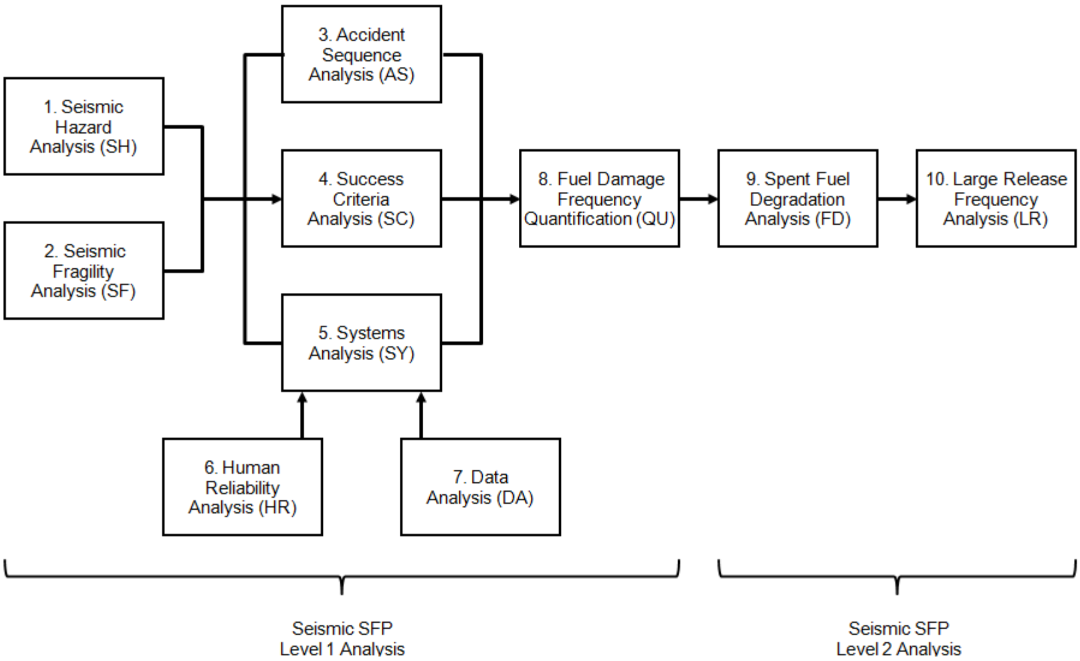

Figure 1. Overall Performance Structure of the SFP Seismic PRA

III.1 Development of the Seismic Equipment List

The SEL development started with the list of basic events from the SFP internal events model, excluding those that were already in the reactor PRA model (e.g., support system models from the reactor PRA that are linked to the SFP PRA. This list was then screened based on the generic screening criteria discussed previously. In the next step, additional equipment and structures were added to the list through examination of system drawings and general arrangement drawings. This includes equipment that constitutes the interface between the SFP model and the support systems that were developed for the reactor PRA model.

III.2 Development of the Seismic Level 1 Accident Sequence Model

This section presents the steps taken to develop the Level 1 accident sequence model for the seismic PRA of the SFP. It consists of three steps (1) selection of the seismic initiating events, (2) development of the seismic event tree, and (3) development of the top logic structure for each top event on the event tree.

III.3 Seismic Initiating Events

Each initiating event considered is presented in Table I, along with a modeling disposition:

TABLE I. Seismic Accident Scenarios Considered for the SFP PRA

Initiating Event	Modeling Disposition
Direct failure of the SFP liner and concrete support structure of the SFP.	This event can only occur as a result of failure of the SFP or failure of the building. These initiating events were screened from the model.
Failure of the SFP gates or seals causing a partial draindown of the SFP	The SFP gates and seals are considered to be an integral part of the SFP structure and liner. As such, they are screened from the model.
Seismic-induced failure of the Fuel Building crane or a heavy load drop (e.g., cask drop).	This event can only be caused by structural failure of an overhead crane (falling into the pool), either with or without a heavy load in place. Although the crane is not supposed to be directly over the pool, it may still be possible. This event is included in the model.

Initiating Event	Modeling Disposition
Sloshing of water out of SFP by seismic event.	Given the height of the pool ledge above the normal water level, and the height of the normal water level above the top of the fuel racks, the amount of water lost by sloshing will not have a significant effect on boil-off time. This event is screened from the model.
Siphoning of the SFP due to a break in a line that extends down below the surface of the SFP.	This event can only occur as the result of a pipe break. Pipe breaks are screened from the SEL based on generic high capacity. This event was not included in the model.
A break in a penetration below the normal SFP level.	Penetrations are considered as similar to pipes, so they have been screened on generic high capacity. This event is not modeled.
Loss of offsite power	Loss of offsite power was assumed in the model for all seismic events, as was done for the reactor SPRA.
Loss of SFP cooling	There are a number of SSCs on the SFP SEL that could result in loss of cooling if they failed under seismic conditions. This initiating event was included in the model.

III.4 Seismic Event Trees

The seismic event trees generally consist of two elements: a seismic master event tree that links the seismic events to initiating events and the initiating event trees that show the possible plant systems response given the initiating event. Normally this is developed on multiple event trees: one for the master response and multiple ones for the systems response. However, given the simple nature of the SFP systems and the limited number of systems available for the systems' response (since systems not designed for seismic events are not credited) this was all developed on a single event tree. This tree was based on the reactor seismic master event tree, modified to suit the needs of the SFP seismic analysis.

The seismic event tree is shown in Figure 2, and the remainder of this section discusses the tree structure.

SE: This event represents the occurrence of a seismic event. As with the reactor SPRA, three seismic events are considered in this SFP seismic PRA, and they are designated as %S1, %S2, and %S3 depending on PGA ranges and associated frequencies. Note that a loss of offsite power is assumed to take place for all seismic events considered in the SFP SPRA.

FD: This event represents possible seismic failures that can lead directly to fuel damage with no possibility of successful plant response. The primary event that falls into this category is failure of the auxiliary building crane while it is located over the SFP.

SLODC: This event represents a seismic loss of all DC power.

SLOCON: This event represents a seismic loss of the plant's digital control system given that DC power is still available. In such a case, all ability to operate plant systems supporting the SFP is lost. The only unaffected system is the external injection/spray system, so failure of this event bypasses all of the other events on the tree except external injection/spray.

SLOAC-NR: This event represents a seismic non-recoverable loss of AC power given that DC and digital control are still available.

STLOCCW: This event primarily represents a seismic total loss of CCW, including the case where this occurs due to seismic failure of the diesels, given that DC power and digital control are available and the AC distribution system is intact.

SLOAC-R: This event represents a seismically recoverable electrical distribution event given that DC, digital control, and CCW are still available. This refers to seismic failures of the electrical distribution equipment where the failure mode is serious enough that the equipment cannot operate during the earthquake (they trip or change state), but the damage is such that once the earthquake motion stops, they can be put back into service.

SSFPC: This event represents a seismic loss of SFP cooling train A (the running train), given that DC power, digital control, AC power, and CCW are available.

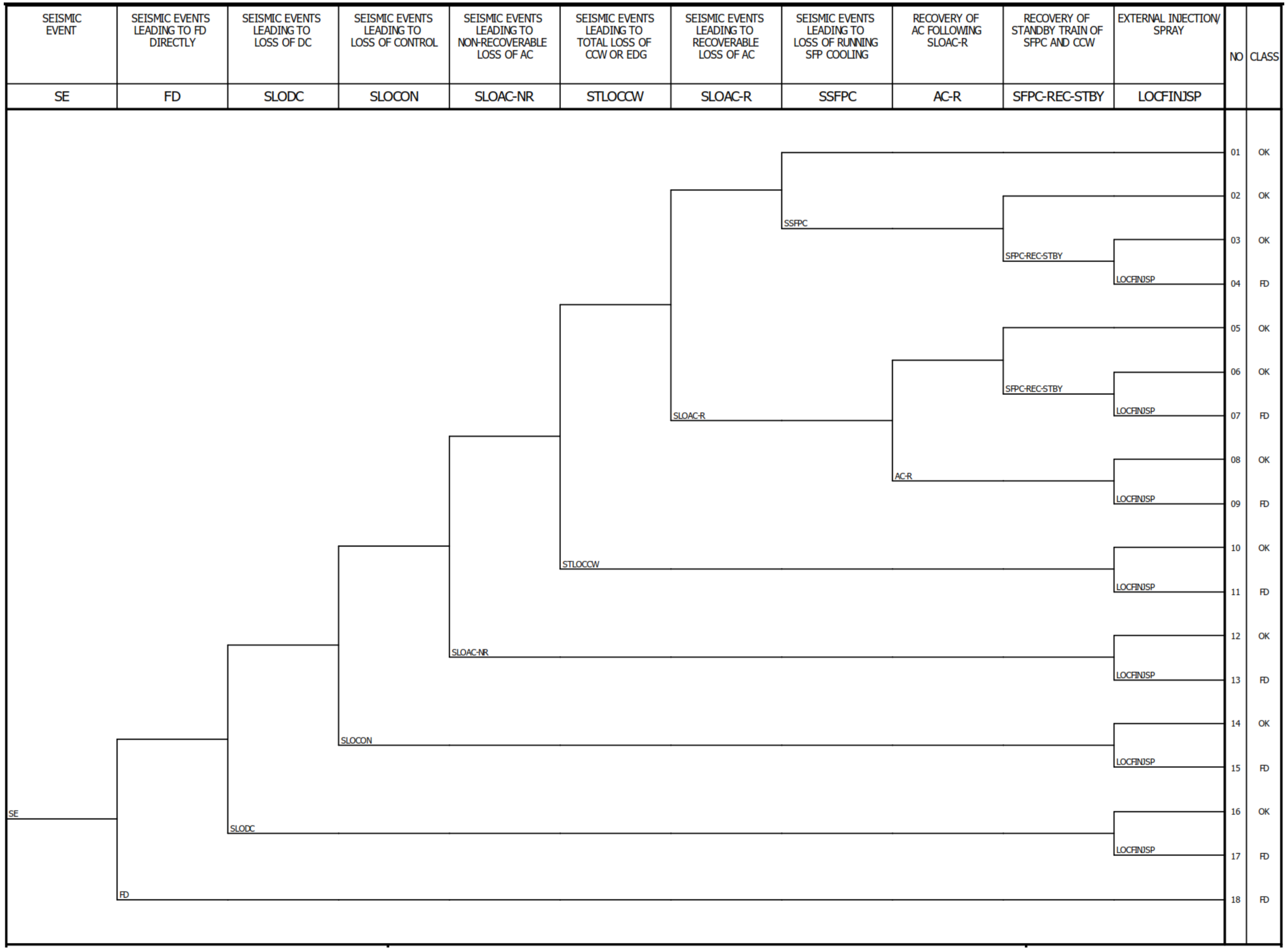

Figure 2. SFP Seismic Event Tree

AC-R: This event represents recovery of AC power given that DC, digital control, and CCW are still available and a recoverable AC power failure has occurred.

SFP-REC-STBY: This event represents recovery of SFP cooling using the standby SFP cooling train given that DC power, digital control, and CCW are still available.

LOCFINJSP: This event represents use of the external injection/spray system to provide make-up to the SFP.

III.5 Seismic Event Tree Top Logic

Each top event on the event tree is represented by a top logic structure. There are two sources of the top logic for the SFP seismic PRA: the top logic from the reactor SPRA and top logic specific to the SFP seismic PRA.

The top logic taken from the reactor PRA is for the support system top events, namely SLODC, SLOCON, SLOAC-NR, STLOCCW, SLOAC-R, and AC-R. The effect of these top events on the SFP systems is equivalent to the type of effect that would be seen for the reactor, and so use of these top event logics is technically defensible; however certain changes are required and were implemented as appropriate.

III.6 Development of the Level 1 Seismic System Response Models

This section discusses the various aspects of the model that were modified for the SFP SPRA. The SFP SPRA model started from the SFP internal events model and the reactor SPRA model, so only those things that were changed are described here.

III.6.1 Creation of Fragility Groups and Mapping

The key modification of the systems response model was the addition of the seismic failure events into the model. Starting with the SEL, fragility groups and associated fragility group IDs were created. The fragility groups represent correlated sets of seismic failures. In keeping with current international practice, equipment was considered either completely correlated (100%) or uncorrelated (0%). The criteria for establishing the fragility groups are as follows:

- Similar types of equipment
- Located in the same building
- Located on the same level within the building
- Oriented in the same direction

Equipment groups are considered perfectly correlated for seismic failure only if all four of the criteria specified above are met (i.e., seismic common-cause failure probability of 1.0) and the entire group is represented by a single fragility curve. If any of the criteria are not met, the equipment failures are considered completely independent (i.e., seismic common-cause failure probability of 0.0) and each is represented by its own fragility curve.

Once the fragility groups are developed, they need to be inserted into the model in the correct location. This requires either assigning them to a specific top event or gate, or identifying the random basic event that is represented by the seismic failure and inserting the seismic failure into the logic in the same location as the basic event.

III.6.2 Fragility Group Logic Structure

When a fragility group is added to the model, it is not added as a single event, but rather as a gate that represents three possible failure events, one for each of the seismic events in the model. The common structure for all such fault tree "modules" is shown in Figure 3.

III.7 Seismic HRA

The same tool (i.e., EPRI HRA Calculator [3]) as used for the HRA of NPP reactor PRAs was used for the SFP seismic HRA with consideration of performance shaping factors specific to the SFP and the seismic damage state. The SPAR-H method was used. HEPs for SFP actions were adjusted based on three damage bins, which were assigned to the three seismic events in the model. Seismic events %S1, %S2, and %S3 were assigned EPRI damage bins 2, 3, and 4, respectively. The EPRI Seismic HRA event tree [from EPRI 1025294] was then used to adjust the HEPs.

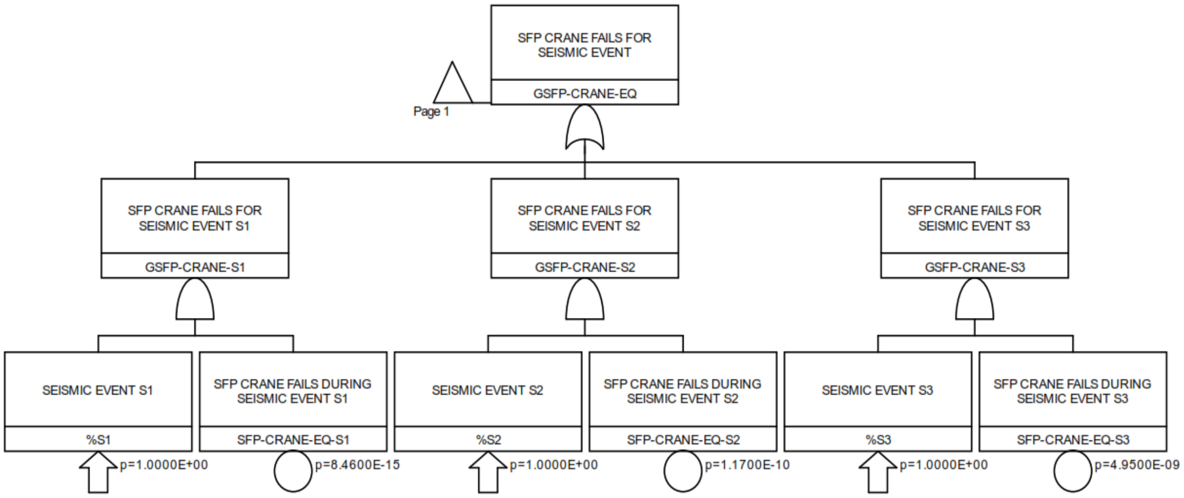

Figure 3. Example of Fault Tree Module for a Fragility Group

IV. RESULTS

This section presents the results of quantification of the seismic PRA model for the SFP.

IV.1 Quantification of Seismically-induced Initiating Event Frequency

The seismic event tree combines initiating event top events with mitigating systems top events in an integrated tree structure. There are three seismic events quantified by the model. The results by seismic event are given in Table II.

TABLE II. Fuel Damage Frequency by Seismic Event

Seismic Event	% of Total FDF
%S3 (1.0g)	88.9%
%S2 (0.6g)	11.0%
%S1 (0.3g)	0.1%

As can be seen from the table, the high acceleration (1.0g) event dominates the results. However, the medium acceleration (0.6g to 0.1g) also makes a significant contribution to the total FDF (i.e., 11%).

IV.2 Dominant Fuel Damage Seismically-Induced Initiating Events

The contribution of the seven initiating events is shown in Table III.

TABLE III. Fuel Damage Frequency by Seismically-induced Initiating Event

Seismically-induced Initiating Event	% of Total FDF
SLOCCW (Loss of Component Cooling Water)	63.6%
SLODC (Loss of DC Power)	14.0%
SLOCON (Loss of Control)	5.0%
SFD (Direct Fuel Damage)	14.3%

Seismically-induced Initiating Event	**% of Total FDF**
SLOAC-NR (Loss of AC Power, Non-recoverable)	1.2%
SLOAC-R (Loss of AC Power, Recoverable)	1.2%
SSFPC (Loss of Spent Fuel Pool Cooling)	0.7%

As can be seen, the dominant initiating event is a loss of component cooling, followed by loss of DC power and direct fuel damage. These three dominant initiating events account for about 92% of the total fuel damage frequency. All others make insignificant contributions.

IV.3 Results for Large Release Frequency (Level 2)

There are three seismic events quantified by the model. The results by seismic event for large release are given in Table IV..

TABLE IV. Large Release Frequency by Seismic Event

Seismic Event	**% of Total LRF Contribution**
%S3 (1.0g)	88.9%
%S2 (0.6g)	11.0%
%S1 (0.3g)	0.1%

As can be seen from the table, the high acceleration (1.0g) event dominates the results. However, the medium acceleration (0.6g to 0.1g) also makes a significant contribution to the total LRF (i.e., 11%).

IV.4 Dominant Large Release Seismically-Induced Initiating Events

The contribution of the seven initiating events to large release is shown in Table V.

TABLE V. Large Release Frequency by Seismically-induced Initiating Event

Seismically-induced Initiating Event	**% of Total LRF Contribution**
SLOCCW (Loss of Component Cooling Water)	63.6%
SLODC (Loss of DC Power)	14.0%
SLOCON (Loss of Control)	5.0%
SFD (Direct Fuel Damage)	14.3%
SLOAC-R (Loss of AC Power, Recoverable)	1.2%
SLOAC-NR (Loss of AC Power, Non-Recoverable)	1.2%
SSFPC (Loss of Spent Fuel Pool Cooling)	0.7%

As can be seen, the dominant initiating event is a loss of component cooling, followed by loss of DC power and direct fuel damage. These three dominant initiating events account for about 92% of the total large release frequency. All others make insignificant contributions.

IV.5 Sensitivity Analysis

A number of sensitivity analyses were performed that showed what aspects of the design were important to the risk. A few key ones are summarized in Table VI.

TABLE VI. Results of Sensitivity Analysis

Description	ΔFDF (%)	Note
Multiply all human error probabilities by 10	1,133.8%	A factor of 10 increase in the HEPs for all the human failure events results in a notable increase in the FDF (i.e., an increase of the FDF by over 12 times).
Divide all human error probabilities by 10	-2.3%	A factor of 10 decrease in the HEPs for all the human failure events does not result in a notable decrease in the FDF.
Set all Ex-MCR HEPs for seismic event S3 at 1.0	5,900.0%	The only human failure event affected is the operator failure to align the external makeup system during seismic event S3. This HFE has a considerable impact on the seismic risk
Increase external makeup equipment failure probability x3	92.1%	The FDF becomes almost double if the failure probabilities of the external makeup equipment (e.g., pump, valves) are multiplied by 3.
Decrease external makeup equipment failure probability /3	-30.7%	The FDF decreases about 30%, if the failure probabilities of the external makeup equipment (e.g., pump, valves) are divided by 3.
External Makeup HCLPF x 1.33	-23.7%	If the HCLPF for the external makeup system is increased by one-third, an FDF reduction of approximately 24% is achieved.

V. RISK INSIGHTS

The seismic risk is found to be very sensitive to any changes in the availability of the external emergency makeup system. Any degradation in the availability of the external makeup equipment has the potential for a significant increase in the SFP seismic risk. This led to certain findings regarding ways to manage and/or reduce the risk.

- improve the external makeup system availability in combination with upgrading the associated human factor aspects;
- while making the external makeup system "stronger" (increasing the HCLPF from the design goal by a factor of 1.33) does not provide marked risk reduction, decreasing it by one-third does result in a significant risk increase, so it is judged that the current specified design goal for all elements of the external makeup system is appropriate;
- the high dependence on the external makeup system and human actions to mitigate seismic events indicates very limited defense in depth, and so upgrading one of the normal make-up systems to seismic design, and making it automatic, would be highly beneficial; and
- keeping the fuel handling area overhead crane away from the spent fuel pool most of the time will result in a significant reduction in the risk associated with the crane falling into the pool

VI. REFERENCES

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