Risk Effectiveness Analysis of FLEX using Plant Specific PRA

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Abstract: After Fukushima nuclear accident, nuclear industry began to think about to have an effective alternative core cooling method to against severe nature hazard. The solution of most nuclear power plant will be the potable equipment, or called FLEX, which can be easily lined up when they were demanded. This paper performed the risk impact analysis of FLEX by estimating CDF. It is expected that the FLEX can be effective for scenarios that the operating crew can lineup the whole system in time. The effectiveness of FLEX will depend on the existence of early core cooling, the time available to lineup and the plant damage status that may block the access way to lineup. Three cases were selected to show how sensitive of parameters that defined the failure of FLEX. The results of three example plant suggested that the FLEX may have significant risk effectiveness to CDF. The risk reduction can be anywhere between 25% and 50%. The procedure that guides the operating crew to lineup the FLEX is the key of the risk effectiveness of FLEX. The licensee may need to pay more attention on preparing a good procedure as well as the necessary supporting equipment that can help the operating crew to lineup FLEX during severe plant damage after the occurrence of initiating event.

Keywords: Risk Impact Analysis, FLEX, Probabilistic Risk Assessment.

1. INTRODUCTION

Lesson learned from Fukushima nuclear accident suggested that nuclear power plant may need to investigate the ability to against unexpected and beyond design base accident. One of the solutions from most nuclear power plant will be the preparation of additional portable equipment as well as the associate operating procedure. In the nuclear industry, it is known as the diverse and flexible coping strategies or FLEX. As the effectiveness of FLEX strongly depends on the characteristic of the accident scenario, it is not easy to predict if a planned FLEX will be effective on the aspect of risk.

The FLEX procedure designed to mitigate severe accident can be event based or symptom based. The major difference between both strategies is all about the entry point of FLEX procedure. Some procedures guide the operating crew to enter the procedure under limited plant status such as station blackout, loss of ultimate heat sink or severe tsunami attack. Such event based procedure implied that FLEX can be effective only for those events listed in procedure. Even for the symptom based procedure, FLEX is not always effective since the plant may need considerable time to lineup portable equipment (FLEX equipment). That means the nuclear fuel in reactor pressure vessel need to have adequate cooling for maybe several hours before the success lineup of FLEX equipment.

This paper provides a simplified methodology to account for the risk reduction of FLEX. Index of annual core damage frequency was selected to represent the risk of a nuclear power plant. A decision tree was developed to define the characteristic of different accident scenario. Five simple questions were asked to classify the category of a specific plant status. To help users easily define the category of accident scenario, the answers of the questions can be found directly from the plant specific probabilistic risk assessment (PRA). In other word, users can predict the risk effectiveness of FLEX from existed PRA without any additional development of event tree or fault tree.

Three example nuclear power plants were then examined to demonstrate the process flow of risk effectiveness analysis. To save research resources, the estimation of risk reduction will be applied on limited risk significant initiating event categories and accident sequences which contributed most of the core damage frequency.

2. METHODOLOGY

After Fukushima nuclear accident in 2011, the nuclear industry came up a solution to deal with the severe nuclear accidents. The concept of the solution is quite simple. Every plant must seek for alternate mitigation function that is independent to the existed plant safety features. For economic consideration, FELX equipment that is secured outside the plant major buildings (such as reactor building, turbine building, control building and control building) will be a good choice. Those industry grade equipment can be cheap and easy to operate. One question is that, an operating procedure should be developed to guide the operating crew to lineup FLEX equipment in time.

In addition to the operating procedure, the effectiveness of FLEX may depend on the time available for the operating crew to lineup the FLEX equipment. With no automatic signal available and most the equipment was stored outside the plant major building, it may take hours to lineup the equipment manually. It implies that fuel integrity should be maintained before the FLEX being active. Furthermore, the controlled core depressurization will be necessary to prevent fuel from uncover if steam driven system was used for core cooling.

As issues discussed above, the effectiveness of FLEX will be strongly dependent on the characteristic of the accident scenario. To evaluate the risk effectiveness of FLEX, or the risk reduction of implementing FLEX, it is necessary to define the plant damage status for every accident sequence of plant PRA. Then, estimate a FLEX failure probability associate to the specific plant damage status to quantify the risk reduction.

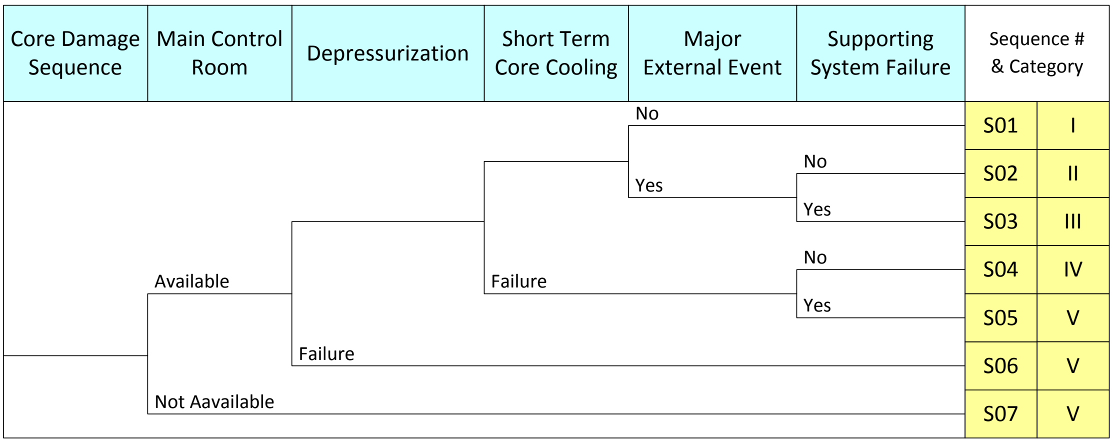

Figure 1: Decision Tree for Plant Damage Status Categorization

Figure 1 shows a decision tree that help users to categorize the plant damage status of an accident scenario. It starts from a core damage sequence in the event tree of plant PRA. Five questions were designed to categorize any accident scenario into five categories. Each accident scenario category is unique for estimating an individual FLEX failure probability that can be applied to all accident sequences that were categorized into the category. The risk reduction of implementing FLEX can be obtained through the summation of risk changes as shown in Equation 1.

$$\sum_i (1 - P_i) \times CDF_i \qquad (1)$$

CDF_i : *core damage frequency of* i^{th} *accident sequence*

P_i : *FLEX failure probability for* i^{th} *accident sequence*

<u>Question 1 : Main Control Room</u>

FLEX can only be activated manually following the order from main control room. It is crucial that the reactor operators in main control room can diagnose the plant damage status through various indication and alarm inside main control room. Decision of entering FLEX procedure can be made in time only if the main control room is functional. While entering the FLEX procedure, reactor operators inside the main control room have to maintain adequate core cooling until operating crew success lineup alternate core cooling. In the meantime, reactor operators also need to control the reactor depressurization process without interrupting ongoing core cooling. It is very unlikely for main control room to loss its function during an accident. Insight from PRA suggested that, such kind of risk significant initiating events may include main control room fire, common cause failure of digital instrumentation and control system, earthquake and tsunami. If main control room losses its function during an accident, it is expected that FLEX will not be able to prevent fuel from damage.

Question 2 : Depressurization

In most cases, FLEX introduces industry grade portable pumps (instead of nuclear grade) to inject water into reactor core. Sometimes, fire truck may be served as a backup way to inject fresh water. Usually, those industry grade pumps or fire trucks are not designed to inject water into high pressure environment. It will be necessary to depressurize reactor core in advance. The depressurization process may cause dramatic core water inventory loss. Also, pressure drop in core may disable the turbine driven safety injection system which rely on the steam that generated in core. To solve the problem, reactor operators were asked by the procedure to perform so called controlled depressurization. The idea is to manually depressurize the core to a lowest preset pressure. Meanwhile, ensure the steam driven safety injection remain functional. To achieve manually depressurization, reactor operator will open one or more safety relief valves. Answer for this question can be found from event tree of the accident sequence. Without proper core depressurization process, fuel may be damaged after uncontrolled core water inventory loss. Or, the FLEX equipment is not able to inject water due to high pressure in core.

Question 3 : Short Term Core Cooling

To provide enough time for operating crew, reactor operator may have to maintain fuel integrity temporary until the FLEX equipment can be successfully lined up. In most case, FLEX is required while nuclear power plant encountered a severe accident such as station blackout or loss of ultimate heat sink. Short term core cooling can be achieved by steam driven systems or low capacity alternative core coolant makeup. Answer for this question can be found from event tree of the accident sequence. With short term core cooling available, plant operating crew will have more time to response to the accident which will significantly increase the success probability of FLEX.

Question 4 : Major External Event

External event such as earthquake or tsunami will cause multiple system failure and accompany with severe damage on the roads or buildings inside the plant. In some cases, external event may injure the on duty operating crew. Multiple system failure may cause reactor operator hard to diagnose plant damage status. Misunderstanding of plant damage status may lead to wrong decision making or take a considerable time to make right decision. Severe damage on the roads or buildings inside the plant may block the access way while transporting FLEX equipment. If plant staff were injured in an accident, operating crew may need more time to complete the operation steps required by the FLEX procedure. In summary, major external event can significantly decrease the success probability of FLEX. Answer for this question can be found by identifying the initiating event of the accident sequence. Uses should examine the accident sequence carefully and make sure the external event will significantly decrease the success probability of FLEX.

Question 5 : Supporting System Failure

Supporting systems such as electrical power supply, room cooling or heat sink are designed to support the operation of several safety systems at the same time. Failure of supporting system may lead to failure of multiple systems. In some particular cases, reactor operators may need more time to identify what happened to the plant and try to figure out plant damage status. Some plant abnormal operation procedure may ask operating crew to recover system that is suspected to be malfunction. In general, failure of supporting system will potentially decrease the success probability of FLEX. Answer for this question may be found from event tree of the accident sequence. Sometimes, uses may need to review the minimal cut sets of the accident sequence to have a better understanding on the accident sequence.

3. FAILRE PROBABILITY OF FLEX

To estimate the risk reduction of FLEX, it is necessary to define the failure probability of FLEX. As discussed above, failure probability of FLEX is dependent to the scenario and the plant response. One assumption of the paper is that the example plant has developed a good procedure of FLEX and the procedure itself is symptom based.

A conservative estimation performed by U.S. Nuclear Regulatory Commission (USNRC) suggested that success probability of FLEX equipment in preventing core melt can be 0.6 per demand [1]. The FLEX success probability was estimated based on the results of PRA. It includes random failures of the FLEX equipment, seismically induced failures of in-plant equipment that interface with the FLEX equipment, and operator performance. The success probability can be used as a generic data for estimating plant risk reduction of implementing FLEX. Instead of adopting generic data, this study attempts to evaluate FLEX failure probabilities that are correlated to the scenario and the plant response. As shown in Figure 1, accidents sequences can be categorized into five different categories. Each category should have its FLEX failure probability when the characteristic of the sequence was put into consideration. The generic data suggested by USNRC is a good starting point.

Failure probability for FLEX equipment may be close to 1 if it is nearly impossible for FLEX equipment to be active before core melt. The applicable plant status was defined as Category V in Figure 1. For accident sequences with no short term core cooling available and failure of important supporting system, i.e. S05 in Figure 1, it is assumed that operating crew will spend most of the time available to diagnose plant damage status and the recovery of failed components. Those actions are required by plant abnormal procedures, and the priority is higher than jumping into FLEX procedure. Thus there will be no adequate time available to lineup FLEX equipment. For accident sequences with failure of depressurization (S06) or malfunction of main control room (S07), reactor operator cannot prepare a low pressure environment for FLEX equipment. It is impossible to have alternate core cooling from FLEX equipment.

For accident sequences with no short term core cooling available but the plant damage status is quite simple, plant may enter the FLEX procedure in time. Reactor core will have some possibility to have cooling from FLEX equipment. The generic FLEX failure probability of 0.4 is adopted for the accident sequences categorized into Category IV in Figure 1.

For S02 and S03 in Figure 1, it is assumed that major external event damaged the access roads for FLEX equipment. With short term core cooling available, the failure probability will depend on the time that operating crew takes to lineup the FLEX equipment. In this case, human error dominates the FLEX failure probability. A conservative human error probability of 0.01 is adopted for Category II sequences, as plant will enter FLEX procedure earlier. The time available for operating crew to lineup FLEX equipment is much longer than the time takes by operating crew. For the case of supporting system failure, i.e. Category III sequences, the time needed for plant entering FLEX procedure is much longer. Thus, a conservative human error probability of 0.1 is adopted for Category III sequences.

The category I sequences represent the event that caused the loss of long term core cooling or containment cooling. Most PRA defined both core and containment long term cooling as the success criteria of fuel integrity. Since the operating crew will have considerable time to lineup FLEX equipment, human error is negligible when estimating FLEX failure probability. A conservative hardware failure probability of 0.001 is adopted for Category I sequences.

4. CASE STUDY

Three nuclear power plants were selected as examples in the analysis to show the risk effectiveness of implementing FLEX. Risk profiles of these nuclear power plants are shown in Table 1. Those example plants are located at seismic sensitive region and have great demand for implementing FLEX. As more than 50% of core damage frequency resulting from seismic related event, the FLEX equipment were stored in various buildings that can withstand major earthquake. Also, those buildings are either located at higher elevation or are designed to be waterproof to avoid damage during tsunami attack.

Table 1: CDF Contribution of Individual Initiating Event (Base Case)

Reactor Type	Internal Events			External Events		
	Transients[1]	Flood	Fire	Strong Wind	Seismic	Tsunami
BWR-4	**18.0%**	2.2%	**28.4%**	<0.1%	**50.1%**	1.3%
BWR-6	**19.2%**	8.9%	7.5%	<0.1%	**64.3%**	0.2%
PWR	**13.9%**	1.1%	4.2%	2.7%	**69.7%**	**8.4%**

* This table reflects the risk with no FLEX available;
* BWR: Boiling Water Reactor: PWR: Pressurized Water Reactor
[1] Transients include all kind of loss of coolant accidents and various system failures

To simplify the estimation, only risk significant initiating events were selected to quantify risk reduction resulting from implementing FLEX. The selected initiating events were indicated in bold characters and were underlined in Table 1. Transients and seismic events are risk significant for all three example plants. For the BWR-4 plant, events of internal fire were included for its high percentage of risk. The scenario of internal fire is similar to the transient events but more likely to have supporting system failure. For the PWR plant, event of tsunami was included also for its relative high percentage of risk. Usually, tsunami is caused by major submarine earthquake and may cause the plant to loss its offsite power before tsunami attack. The plant damage caused directly by tsunami attack will be limited on the service water system that is located at seashore.

The base case of the analyses will be the plant risk without FLEX. As shown in Table 2, three cases were conducted to estimate the risk reduction of implementing FLEX. Each risk significant accident sequence was categorized into one of the five categories by the decision tree on Figure 1. Then, failure probability of FLEX for each category was applied to estimate the risk change of individual sequence. The summary of risk change from all accident sequences will be the risk reduction of implementing FLEX.

Table 2: Case Study on FLEX Failure Probabilities

Case	Accident Sequence Category					Note
	I	II	III	IV	V	
Case 1	0.4	0.4	0.4	0.4	1	Generic FLEX failure probability was used
Case 2	0.01	0.1	0.1	0.4	1	Plant with pool or unverified FLEX procedure
Case 3	0.001	0.01	0.1	0.4	1	Plant with high quality FLEX procedure

* Accident sequence category was defined in Figure 1

In Case 1, generic FLEX failure probability of 0.4 was adopted for all sequences. It represents the plant that had prepared FLEX equipment as a mitigation of severe accidents. Case 2 represent the case that human error will dominate the FLEX failure probability. The plant staff may not be well trained through exercise and required more time to successfully lineup FLEX equipment. For Case 3, plant FLEX procedure was confirmed to be feasible through rigorous verification process. Plant staff is familiar with actions required by the FLEX procedure. The FLEX failure probability discussed in Section 3 will be adopted. Note that, for Category V sequences, FLEX is not feasible due to the characteristic of accident sequence. No credit for FLEX will be taken and the FLEX failure probability was set to 1 in all cases instead of using generic FLEX failure probability.

Table 3: Results of Risk Reduction of Implementing FLEX

Reactor Type	Case 1	Case 2	Case 3
BWR-4	35.6%	50.3%	50.6%
BWR-6	29.7%	44.2%	44.3%
PWR	24.5%	35.2%	35.4%

Table 3 summarized the risk reduction in percentage to show the risk effectiveness of implementing FLEX. The results suggested that FLEX can be effective in reducing total core damage frequency even using generic FLEX failure probability. More detailed estimation results on Case 2 and Case 3 showed that there will be 25% to 50% risk reduction when FLEX procedure was prepared to guide the plant staff. Table 4 breaks down the risk reduction into the percentage of each initiating event. Since more than 50% of risk came from seismic event as shown in Table 1, it is not surprised that seismic event contributed most risk reduction in all cases.

Table 4: Percentage of Risk Reduction from Individual Initiating Event

Case	BWR-4			BWR-6		PWR		
	Transients	Fire	Seismic	Transients	Seismic	Transients	Seismic	Tsunami
Case 1	32.6%	12.9%	54.5%	26.8%	73.2%	16.2%	69.9%	13.9%
Case 2	32.1%	11.4%	56.5%	27.8%	72.2%	13.2%	72.3%	14.5%
Case 3	32.1%	11.8%	56.2%	27.9%	72.1%	13.1%	72.3%	14.5%

With FLEX in service, it will probably alter the risk insight of plant PRA. Table 5 showed the risk profile for three example plants for Case 3. Significant change on BWR-4 plant was observed. The fire risk increased from 28.4% to 45.3% of total core damage frequency. And transient risk decreased from 18.0% to 3.7% of core damage frequency. It appears that FLEX can significant reduce plant risk and may change the contribution of individual initiating event risk to the total plant risk.

Table 5: CDF Contribution of Individual Initiating Event (Case 3)

Reactor Type	Internal Events			External Events		
	Transients[1]	Flood	Fire	Strong Wind	Seismic	Tsunami
BWR-4	3.7%	4.4%	45.3%	<0.1%	43.9%	2.7%
BWR-6	12.2%	16.0%	13.4%	<0.1%	58.1%	0.3%
PWR	14.3%	1.7%	6.5%	4.2%	68.3%	5.1%

* This table reflects the risk with FLEX available;
* BWR: Boiling Water Reactor: PWR: Pressurized Water Reactor
[1] Transients include all kind of loss of coolant accidents and various system failures

If plant developed an event base FLEX procedure instead of symptom base procedure assumed in this study. The FLEX equipment will be effective only for events declared in the procedure. For the three example plants, FLEX procedure may be specifically developed to deal with seismic event and tsunami event. If it is the case, the percentage of risk reduction will significantly decrease as shown in Table 6 when compared with the results of Table 3. In general, it is still a very risk effective FLEX procedure. In addition, the plant can benefit from the event base FLEX procedure. It will be much easier on developing FLEX procedure, preparing FLEX equipment and training the operating crew.

Table 6: Results of Risk Reduction of Implementing FLEX (Extra Cases)

Reactor Type	Event Based FLEX Procedure			Negligible External Event Risk		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
BWR-4	19.4%	28.4%	28.4%	34.9%	47.1%	47.7%
BWR-6	21.6%	31.9%	31.9%	41.4%	64.0%	64.5%
PWR	20.5%	30.5%	30.8%	28.7%	33.4%	33.5%

For plant with negligible external event risk, the internal event risk will dominate the plant total risk. If it is the case for the three example plants, FLEX is still risk effective on the reduction of internal event risk as shown in Table 6. Most plant damage caused by internal event can be correctly diagnosed by reactor operator. The results of Case 2 and Case 3 are more likely to represent the actual situation.

5. CONCLUSION

A simplified methodology was developed in this study to account for the risk effectiveness of FLEX. Risk reduction on core damage frequency was selected as the index to show the risk effectiveness. Users can predict a conservative risk reduction by examine the accident sequences from the event trees of plant specific PRA. Three example plants of different reactor type were selected to estimate the risk effectiveness of implementing FLEX. The results suggested that FLEX can significantly decrease core damage frequency no matter it is event based or symptom based. Even for those plants with negligible external event risk, FLEX is still an effective way to significantly reduce plant risk. It is important that a specific FLEX procedure should be developed to provide guidance for both reactor operator and other operating crew. It helps to reduce the FLEX failure probability. Note that, implementing FLEX may alter the risk insight of plant PRA. Before planning any risk reduction activity, detailed analysis on plant risk with FLEX available is necessary to obtain realistic risk insight.

References

[1] USNRC, "*Evaluation of the Containment Protection and Release Reduction for Mark I and Mark II Boiling Water Reactors Rulemaking Activities*", SECY-15-0085, (2015).