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INCORPORATING FLEX STRATEGIES IN MULTI-UNIT PROBABILISTIC RISK ASSESSMENT

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ABSTRACT

The catastrophic Fukushima nuclear accident reminded the nuclear community about potential extreme accident scenarios, including those involving multiple reactor units on the same site. In response to the Fukushima accident, the nuclear power industry developed and implemented a series of strategies, including Diverse and Flexible Coping Strategies (FLEX), to enhance the capacities of nuclear power plants (NPPs) to cope with extreme accidents. This study examines the impact of FLEX strategies on the overall risk from all reactor units located at the same NPP site, including risks from accidents involving either a single unit or multiple units. The fundamental, methodological element of this study is Multi-Unit Probabilistic Risk Assessment (MUPRA) requiring a shift in Probabilistic Risk Assessment (PRA) from a one-reactor-at-a-time mindset to a consideration of all reactors sharing a site. An integrated modeling approach for multi-unit event sequence development is leveraged to develop the MUPRA model and address intra-unit and inter-unit dependencies. Systems Analysis Programs for Hands-on Integrated Reliability Evaluations (SAPHIRE), a PRA software developed and maintained by Idaho National Laboratory for the U.S. Nuclear Regulatory Commission, serves as the platform for MUPRA modeling. This study selects loss of offsite power (LOOP) as a representative initiating event potentially occurring on a generic two-unit NPP site and impacting both reactor units. First, an MUPRA model, including multi-unit event trees, is developed to obtain single-unit and multi-unit accident scenarios. Next, different FLEX strategies are assumed; for example, whether FLEX equipment for multiple units can be used in a cross-connected manner. Lastly, the effectiveness of each postulated FLEX strategy is evaluated by incorporating the corresponding FLEX equipment and deployment logic into the MUPRA model.

Keywords: Multi-Unit Probabilistic Risk Assessment, Diverse and Flexible Coping Strategies, loss of offsite power, Systems Analysis Programs for Hands-on Integrated Reliability Evaluation

1. INTRODUCTION

In the Fukushima Daiichi nuclear accident, the earthquake and resulting tsunami affected all six reactor units on the site, leading to severe damage in three reactor cores. As evidenced by the Fukushima accident and other operating experience, accidents involving multiple reactors on the same site are “not a question of possibility, but rather one of probability”[1]. Risk estimates for most reactors worldwide are available through single-unit probabilistic risk assessment (SUPRA); however, site-wide risk cannot be calculated in as straightforward a manner as the linear sum of the risks from all reactors on the same site, but requires development of multi-unit probabilistic risk assessment (MUPRA) capable of addressing complex intra- and inter-unit dependencies among reactor units on the same site.

This paper presents the preliminary results of developing a site-wide risk profile given loss of offsite power (LOOP) and examining the impact of Diverse and Flexible Coping Strategies (FLEX), a post-Fukushima safety enhancement, on site-wide risk. The results are obtained by leveraging an integrated multi-unit event sequence modeling approach [2] and expanding a generic, single-unit pressurized water reactor (PWR) PRA model to a dual-unit one. Systems Analysis Programs for Hands-on Integrated Reliability Evaluations

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(SAPHIRE), a PRA software developed and maintained by Idaho National Laboratory for the U.S. Nuclear Regulatory Commission, serves as the platform for multi-unit modeling.

2. METHOD

The underlying method of this study is an integrated, stage-by-stage modeling approach for multi-unit event sequence development [2]. This approach has two modeling features. One is that the accident progression logic of all the reactor units on the same site are modeled in an integrated manner using the same event tree. The top events of all the units are modeled sequentially in the event tree in a clear and intuitive manner. The other feature is the adoption of a stage-by-stage evolution method to avoid an extremely large event tree structure. This feature can be operationalized in SAPHIRE using the event tree transferring technique. The integrated event tree is broken down into a set of smaller event trees developed over multiple stages. The sequences developed in one stage will be grouped into several intermediate end states and fed to the next stage's event trees as the initiating events (IEs).

The case study is based on an assumed two-unit nuclear power plant (NPP) site subject to LOOP impact. The following methodological steps are adopted: (1) IE analysis, (2) event tree structure determination, and (3) event tree development for each modeling stage.

2.1 Initiating Event Analysis

In this study, LOOP is selected as the IE. It should be noted that LOOP may solely affect either a single reactor unit (i.e., single-unit LOOP [SULOOP]) or all the reactor units on the same site (multi-unit LOOP [MULOOP]). The SULOOP and MULOOP frequencies are calculated based on statistics for LOOP events occurring at U.S. NPPs from 1987 to 2017 (Table 1) [3].

TABLE 1: LOOP STATISTICS [3]

IE	(per reactor year)	
LOOPGR	1.10E-02	3.24E-01
LOOPPC	3.36E-03	2.27E-02
LOOPSC	1.01E-02	1.23E-01
LOOPWR	6.21E-03	3.25E-01

In Table 1, LOOP events are categorized as grid-related (LOOPGR), plant-centered (LOOPPC), switchyard-centered (LOOPSC), or weather-related (LOOPWR). The SULOOP and MULOOP frequencies are calculated using the following equations:

(1)

(2)

where (or) is the frequency of SULOOP affecting Unit 1 (or Unit 2) only, is the frequency of MULOOP affecting both units, is the LOOP category index. is the frequency of the i-th LOOP category, and is the conditional probability of an i-th category LOOP affecting all units at a multi-unit site, both from Table 1. The calculated LOOP frequencies are provided in Table 2.

TABLE 2: SINGLE-UNIT AND MULTI-UNIT LOOP FREQUENCIES

IE			(per site year)
	(per reactor year)		
LOOPGR	7.44E-03	7.44E-03	3.56E-03
LOOPPC	3.28E-03	3.28E-03	7.63E-05
LOOPSC	8.86E-03	8.86E-03	1.24E-03
LOOPWR	4.19E-03	4.19E-03	2.02E-03
SUM	2.38E-02	2.38E-02	6.90E-03

2.2 Event Tree Structure Determination

Based on the generic SAPHIRE PRA model, multiple top events are included in the LOOP event tree, leading to numerous sequences. As the focus of this study is to examine the impact of FLEX strategies on site-wide risk, the LOOP event tree structure is reduced by only retaining those sequences that experience extended loss of AC power (ELAP) conditions in which FLEX strategies are called upon.

In the reduced LOOP event tree, two modeling stages are determined. Stage 1 uses LOOP as the IE and ends in two states: ELAP and non-ELAP (NA). Stage 2 starts with ELAP and ends in two states, core damage (CD) and accident mitigated with no radiological release (OK).

2.3 Event Tree Development: Stage 1

In Stage 1, three event trees are developed: two single-unit event trees and one multi-unit event tree.

2.3.1 Single-Unit Modeling

The first event tree in Stage 1 uses LOOP-SU-1 (affecting Unit 1 only) with an IE frequency of . This event tree ends in two end states: ELAP-SU-1 (representing ELAP in Unit 1 only), which will be used as an IE for the next stage, and NA, representing non-ELAP conditions not to be opened for subsequent modeling. Similarly, the second event tree in Stage 2 starts with LOOP-SU-2 with an IE frequency of and ends in ELAP-SU-2 and NA. As an example, the first event tree in Stage 1 is provided in Figure 1.

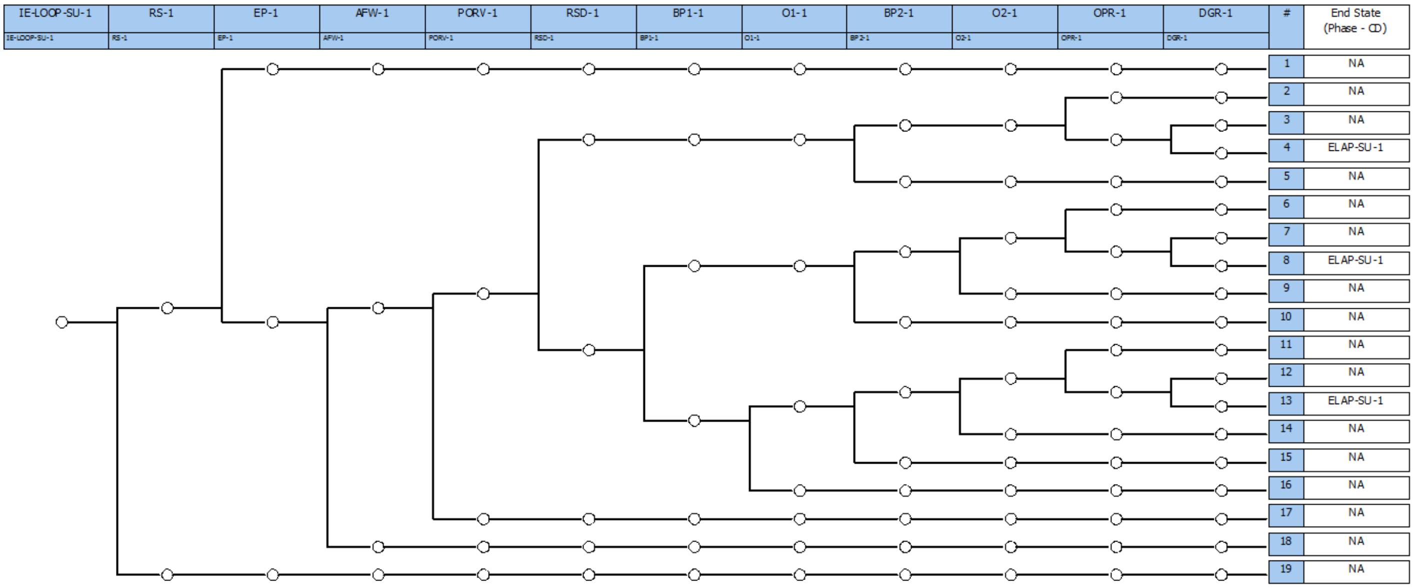

FIGURE 1: SINGLE-UNIT LOOP EVENT TREE (UNIT 1)

Top events in Stage 1 include:

- RS: Reactivity control
- EP: Onsite emergency power
- AFW: Auxiliary feedwater
- PORV: Power operated relief valves
- RSD: Depressurization of reactor coolant system
- BP1 (or BP2): Binding and popping failure of reactor coolant pump (RCP) seal at first or second stage
- O1 (or O2): Integrity of the O-ring for RCP seal at first or second stage
- OPR: Recovery of offsite power within 4 hours
- DGR: Recovery of a diesel generator within 4 hours.

The probabilities of these top events (Table 3) in the first and second event trees in Stage 1 are obtained by solving the fault trees in the generic SAPHIRE PRA model. As an example, the sequence frequencies of the first event tree are provided in Table 4.

TABLE 3: TOP EVENT PROBABILITIES (GIVEN SINGLE-UNIT LOOP)

Top Event (i=1, 2)	Failure (denoted as X)	Success (denoted as /X)
RS-i	1.21E-06	1.00E+00
EP-i	2.22E-05	1.00E+00
AFW-i	5.75E-05	1.00E+00
PORV-i	5.03E-07	1.00E+00
RSD-i	1.48E-03	9.99E-01
BP1-i	1.25E-02	9.88E-01
O1-i	5.00E-01	5.00E-01
BP2-i	2.00E-01	8.00E-01
O2-i	5.00E-01	5.00E-01
OPR-i	6.83E-01	3.17E-01
DGR-i	7.30E-01	2.70E-01

TABLE 4: SINGLE-UNIT ELAP SEQUENCES (UNIT 1)

No.	Sequence	Frequency*
04	LOOP-SU-1, /RS-1, EP-1, /AFW-1, /PORV-1, /RSD-1, /BP2-1, OPR-1, DGR-1	2.10E-07
08	LOOP-SU-1, /RS-1, EP-1, /AFW-1, /PORV-1, RSD-1, /BP1-1, /BP2-1, OPR-1, DGR-1	3.08E-10
13	LOOP-SU-1, /RS-1, EP-1, /AFW-1, /PORV-1, RSD-1, BP1-1, /O1-1, BP2-1, O2-1, OPR-1, DGR-1	2.44E-13
SUM		2.10E-07

* Per reactor year

2.3.2 Multi-Unit Modeling

The third event tree in Stage 1 uses LOOP-MU (affecting both units) as the IE with a frequency of . This event tree ends in four end states: ELAP-SU-1 (ELAP in Unit 1, and NA in Unit 2), ELAP-SU-2 (ELAP in Unit 2, and NA in Unit 1), ELAP-MU (ELAP in both units), and NA (non-ELAP in both units).

The sequences of this multi-unit event tree can be generated by concatenating and processing sequences of the other two single-unit event trees. For instance, by concatenating ELAP-SU-1 sequences from the first event tree and ELAP-SU-2 sequences from the second event tree, nine ELAP-MU sequences can be obtained. To address inter-unit dependencies, such concatenated sequences can be processed using appropriate rules per category of inter-unit dependency [4]. This case study involves multiple types of inter-unit dependency, including IE dependency, cross-connection dependency, common-cause failure (CCF) dependency, and human action dependency.

For IE dependency, two single-unit IEs are deleted, and a multi-unit IE added. Cross-connection dependency represents a case in which, given a single-unit IE, mitigation equipment of the unaffected reactor unit can be credited to the affected reactor unit; however, such cross-connection cannot be allowed given a multi-unit IE, as both reactor units are affected. Crediting or not crediting cross-connected equipment affects the fault tree structure, in turn resulting in different failure probabilities. CCF dependency exists between identical mitigation systems in two reactor units. In this paper, the beta factor model is adopted (shown in the following equations), and "system-level" beta factors are used to model CCF dependency.

(3)

(4)

(5)

(6)

where is the probability of top event X in Unit 1, is the CCF probability of X in both units, is the beta factor of top event X, is the probability of concurrent top event X in both units.

All the system-level beta factors are tentatively assumed to be 0.1. Human action dependency is treated in a similar fashion to CCF (i.e., assuming a beta factor of 0.1). These assumptions will be further investigated and refined in near-term research.

As an example, processing steps of multi-unit ELAP Sequence 04-04 (concatenating sequences 04 and 04 from both single-unit event trees) is provided in Table 5. It should be noted that EP'-MU requires replacing failure probability of top event EP (allowing cross connection) with EP' (not allowing cross connection).

TABLE 5: EXAMPLE OF MULTI-UNIT ELAP SEQUENCE PROCESSING (SEQUENCE 04-04)

Event Pair	Dependency	Action
LOOP-SU-1 LOOP-SU-2	IE	Delete both events Add LOOP-MU
/RS-1 /RS-2	CCF	Delete both events Add /RS-MU
EP-1 EP-2	Cross-connection CCF	Delete both events Add EP'-MU
/AFW-1 /AFW-2	CCF	Delete both events Add /AFW-MU
/PORV-1 /PORV-2	CCF	Delete both events Add /PORV-MU
/RSD-1 /RSD-2	CCF	Delete both events Add /RSD-MU
/BP2-1 /BP2-2	CCF	Delete both events Add /BP2-MU
OPR-1 OPR-2	Human action	Delete both events Add OPR-MU
DGR-1 DGR-2	Human action	Delete both events Add DGR-MU

By concatenating and processing the sequences, nine ELAP-MU sequences are obtained, the frequencies of which are shown in Table 6.

TABLE 6: ELAP-MU SEQUENCE FREQUENCIES

No.	Before Processing*	After Processing*
04-04	5.38E-13	2.06E-07
04-08	7.90E-16	2.72E-10
04-13	6.25E-19	1.71E-13
08-04	7.90E-16	2.72E-10
08-08	1.16E-18	3.03E-11
08-13	9.16E-22	1.88E-14
13-04	6.25E-19	1.71E-13
13-08	9.16E-22	1.88E-14
13-13	7.25E-25	1.01E-15
SUM	5.40E-13	2.07E-07

* Per site year

2.4 Event Tree Development: Stage 2

In Stage 2, three event trees are developed: two single-unit event trees and one multi-unit event tree.

2.4.1 Single-Unit Modeling

The first event tree in Stage 2 uses ELAP-SU-1, which was obtained from both the first and third event trees in Stage 1, as the initiating event. This event tree ends in two end states: CD-SU-1 (core damage in Unit 1 only) and OK (accident mitigated with no radiological release). Similarly, the second event tree in Stage 2 starts with ELAP-SU-2, which was obtained from both the second and third event trees in Stage 1, as the initiating event and ends in CD-SU-2 and OK. As an example, the first event tree in Stage 2 is provided in Figure 2.

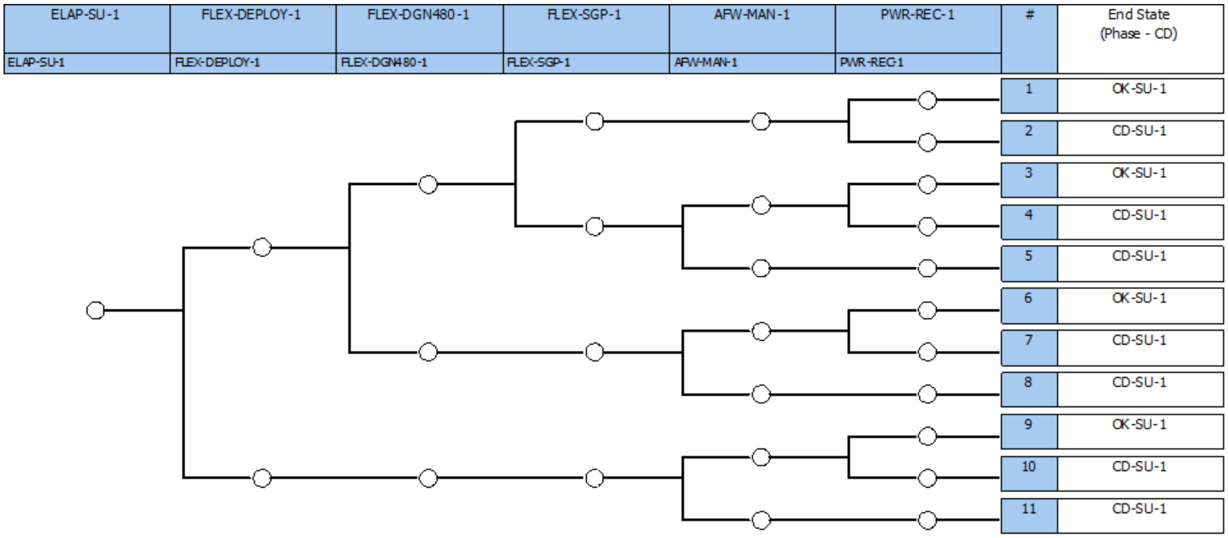

FIGURE 2: SINGLE-UNIT ELAP EVENT TREE (UNIT 1)

Top events in Stage 2 include:

- FLEX-DEPLOY: FLEX equipment deployment
- FLEX-DGN480: FLEX diesel generators
- FLEX-SGP: FLEX steam generator pumps
- AFW-MAN: Manual control of AFW pump
- PWR-REC: Recovery of AC power within 24 hours.

The probabilities of these top events (Table 7) used in the first and second event trees in Stage 2 are obtained by solving the fault trees in the generic SAPHIRE PRA model. The failure probability of PWR-REC-i is assumed to be 1 in this study—something requiring further exploration.

TABLE 7: TOP EVENT PROBABILITIES (GIVEN SINGLE-UNIT ELAP)

Top Event (i=1, 2)	Failure (denoted as X)	Success (denoted as /X)
FLEX-DEPLOY-i	1.00E-01	9.00E-01
FLEX-DGN480-i	1.02E-01	8.98E-01
FLEX-SGP-i	1.15E-01	8.85E-01
AFW-MAN-i	3.00E-01	7.00E-01
PWR-REC-i	0.00E+00	1.00E+00

2.4.2 Multi-Unit Modeling

The third event tree in Stage 2 uses ELAP-MU, obtained from the third event tree in Stage 1, and it ends in four end states: CD-SU-1 (CD in Unit 1, and OK in Unit 2), CD-SU-2 (CD in Unit 2, and OK in Unit 1), CD-MU (CD in both units), and OK. Similarly, the multi-unit sequences can be obtained by concatenating and processing single-unit sequences.

3. RESULTS AND DISCUSSION

The preliminary results of this case study are provided in Tables 8 and 9. Table 9 also provides results given a base case with no FLEX deployment and two FLEX deployment options. The first FLEX deployment option allows cross-connecting FLEX equipment between two reactor units. The second FLEX deployment option does not allow cross-connection with FLEX equipment dedicated to a single unit.

TABLE 8: ELAP Frequencies from Stage 1

End State	IE	Frequency
ELAP-SU-1*	LOOP-SU-1	2.17E-07
	LOOP-MU	4.60E-06
	SUM	4.82E-06
ELAP-SU-2*	LOOP-SU-2	2.17E-07
	LOOP-MU	4.60E-06
	SUM	4.82E-06
ELAP-MU**	LOOP-MU	2.07E-07

* Per reactor year
** Per site year

TABLE 9: CD Frequencies from Stage 2

End State	IE	Frequency		
		Base	Option 1	Option 2
CD-SU-1*	ELAP-SU-1	1.45E-06	4.12E-07	5.15E-07
	ELAP-MU	3.91E-08	1.82E-08	1.82E-08
	SUM	1.49E-06	4.30E-07	5.33E-07
CD-SU-2*	ELAP-SU-2	1.45E-06	4.12E-07	5.15E-07
	ELAP-MU	3.91E-08	1.82E-08	1.82E-08
	SUM	1.49E-06	4.30E-07	5.33E-07
CD-MU**	ELAP-MU	2.13E-08	3.02E-09	3.02E-09

* Per reactor year
** Per site year

Based on these preliminary results, it can be observed that the frequency of a multi-unit sequence is substantially higher than the product of the frequencies of two single-unit sequences. For instance, compared to the product of ELAP-SU-1 and ELAP-SU-2 (2.32E-11), the frequency of ELAP-MU is 2.07E-07. Also, it can be found that the frequency of CD-MU is far lower than the frequency of CD-SU. Taking Option 1 as an example, compared to the sum of CD-SU (8.60E-07) for both units, the frequency of CD-MU is 3.02E-09; however, this does not conclude that CD-MU is negligible, as CD-MU involves radiological releases from both reactor units and thus the consequences are more severe.

As shown in Table 9, it can be observed that, by crediting FLEX, both single-unit risk and multi-unit risk can be reduced. Also, it can be found that different FLEX deployment options lead to different risk values. Option 1 has lower single-unit risk (measured in CD-SU frequency) than Option 2, and both options have the same multi-unit risk (measured in CD-MU frequency).

4. CONCLUSION

This paper presents the preliminary results of a multi-unit modeling case study via SAPHIRE for an assumed two-unit NPP site experiencing LOOP. The accident progression logic of two reactor units are modeled in an integrated manner using an identical set of event trees developed over gradual stages. Multi-unit sequences are developed and quantified by concatenating and processing single-unit sequences with inter-unit dependencies addressed. The intermediate outputs of this case study include the frequencies of ELAP in one or both reactor units. The ultimate outputs include frequencies of core damage in one or both reactor units. The impact of different FLEX deployment options on the outputs are also evaluated and compared.

It should be noted that the results presented in this paper are based on a simplified methodology for preliminary investigation of FLEX's impact on MUPRA. This simplified methodology is primarily limited in regard to: (1) not addressing dependencies between top events (e.g., dependencies due to shared supporting systems) and (2) implicit modeling of common-cause failure between top events (e.g., using 0.1 as a system-level beta factor). These limitations will be explored and overcome in future work by developing a fully functional MUPRA model.

DISCLAIMER

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