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An Application of the Cascading Assessment Methodology for Evaluating Multi-Unit Risk

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Contents

1. Introduction

Introduction

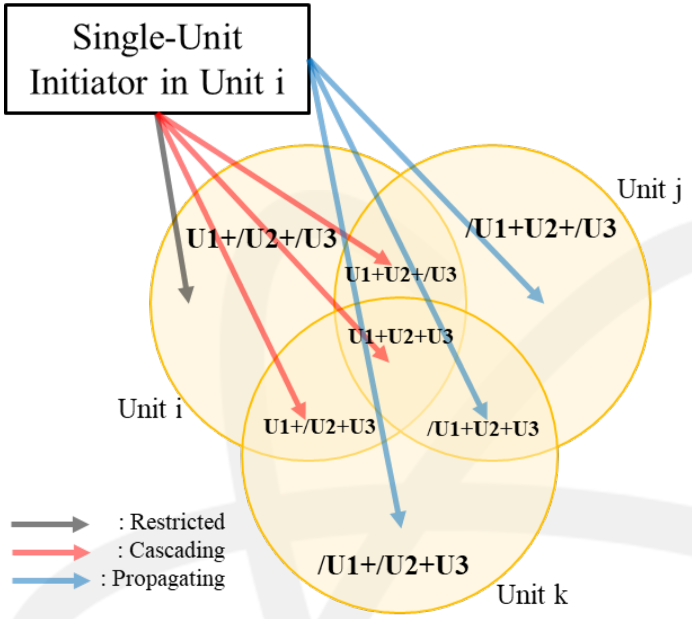
- Amendment of Nuclear Safety Acts (NSA) issued in 2016 clarifies submission of the 'Accident Management Program (AMP)' including contents of Probabilistic Safety Assessment (PSA)[1)]
- Notification of the Nuclear Safety and Security Commission (NSSC) revised in 2016 contains below:[2)]
  - "부지 인근 주민의 발전용원자로시설 사고로 인한 **초기사망 위험도 및 암사망 위험도**가 각각의 **전체 위험도의 0.1% 이하**이거나 또는 그에 상응하는 성능목표치를 만족할 것"
- After Fukushima nuclear power plant accident, public interests in multi-unit PSA have been increased

1): 원자력안전위원회, *원자력안전법 제20조(운영허가)* (2018)
2): 원자력안전위원회, *원자력안전위원회 고시 제2016-2호 제9조* (2016)

Introduction (cont'd)

- Multi-unit accidents can be initiated by CCIs and SUIs*

1. CCIs (Common Cause Initiators)
   - MULOOP (Multi-Unit Loss Of Off-Site Power)
   - MULOUHS (Multi-Unit Loss Of Ultimate Heat Sink)
   - Natural Hazards (Typhoon, Gale, Tsunami, etc.)



2. SUIs (Single-Unit Initiators)
   - Combination of restricted
   - **Cascading case**
   - Propagating case

*: Stutzke, M. A. (2014). Scoping estimates of multiunit accident risk. *Probabilistic Safety Assessment and Management PSAM, 12.*

2. Methodology and Application

Methodology and Application

- D.W. Hudson proposed the methodology for evaluating cascading multi-unit accident*
- Only representative accident scenarios selected from single-unit PSA were used for modeling two unit accident scenarios
- Two site (Peach Bottom and Surry) were considered
- Three and four single-unit accident scenarios were selected for the Peach Bottom and the Surry sites, respectively
- These single-unit accident scenarios considered to be risk-significant were from the SOARCA pilot study

Peach Bottom		**Unit 3**		
		LTSBO	STSBO-BASE	STSBO-RCIC
Unit 2	LTSBO	BWR1	BWR2	BWR3
	STSBO-BASE	BWR4	BWR5	BWR6
	STSBO-RCIC	BWR7	BWR8	BWR9

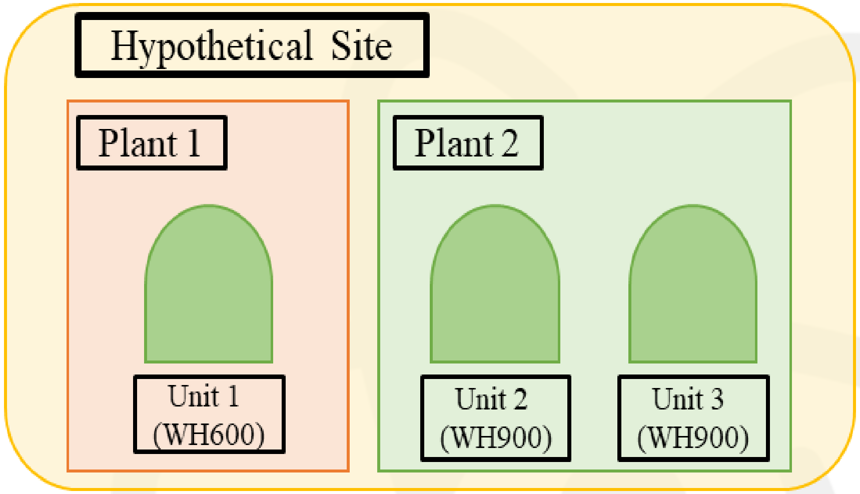
Surry		**Unit 2**			
		LTSBO	STSBO-BASE	STSBO-TISGTR	ISLOCA
Unit 1	LTSBO	PWR1	PWR2	PWR3	PWR4
	STSBO-BASE	PWR5	PWR6	PWR7	PWR8
	STSBO-TISGTR	PWR9	PWR10	PWR11	PWR12
	ISLOCA	PWR13	PWR14	PWR15	PWR16

ISLOCA=interfacing systems loss of coolant accident; LTSBO=long-term station blackout; STSBO-BASE=unmitigated short-term station blackout; STSBO-RCIC=short-term station blackout with reactor core isolation cooling system operation; STSBO-TISGTR=short-term station blackout with thermally-induced steam generator tube rupture

*: Hudson, D. W., & Modarres, M. (2017). Multiunit Accident Contributions to Quantitative Health Objectives: A Safety Goal Policy Analysis. *Nuclear Technology*, *197*(3), 227-247.

Methodology and Application (cont'd)

- Hypothetical site that consists of one WH600 and two WH900 reactor types were considered
- Unit 1 (WH600) is located in Plant 1, and Unit 2, 3 (WH900) are located in Plant 2
- Probability of interactions between Unit 2 and Unit 3 is larger than that between Unit 1 and Unit 2 (or 3)
- Key assumptions are below



- One unit always serves as the affecting unit for multi-unit accidents
- Considered accident scenarios are representative of the full spectrum of potential accident scenarios for each reactor type to their consequence distribution
- States of all units are full power operation
- Multi-unit accidents can be modelled by combination of STCs(Source Term Categories)
- CCDPs of the affected units are 1 because conditional probability of cascading contains an occurrence of core damage accident in the affected units

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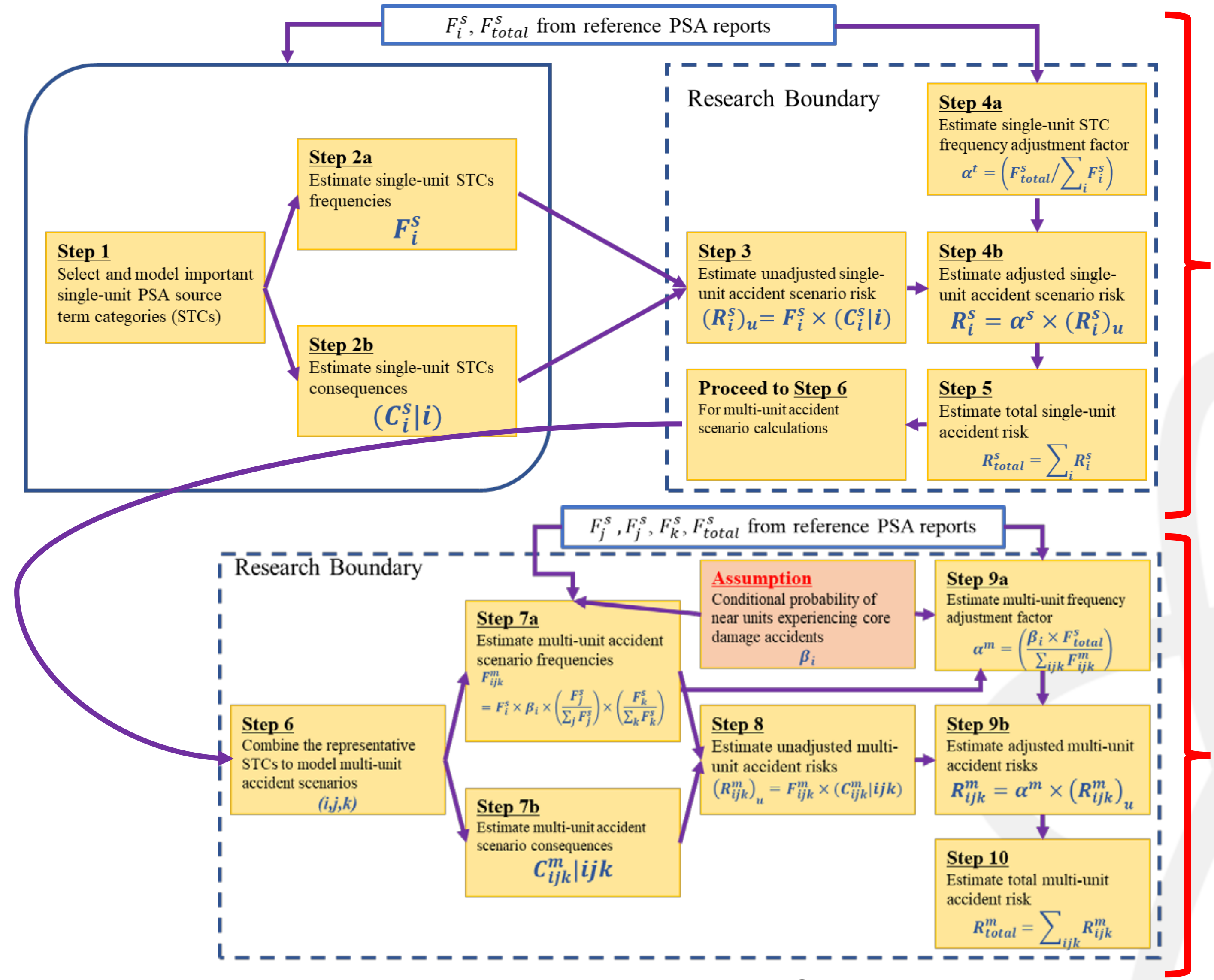
Methodology and Application (cont'd)



Estimation of the contribution from **single-unit accident scenarios**

Estimation of the contribution from **multi-unit accident scenarios**

Methodology and Application (cont'd)

Step 0: Estimate single-unit accident scenarios risk performed by the conventional PSA methodology for each unit[1, 2)]

STC #	Frequency	Representative accident sequence	Conditional consequence of representative accident sequence	Risk
1	F_1	PDS ## and CET ##	C_1	$R_1 = F_1 \times C_1$
2	F_2	PDS ## and CET ##	C_2	$R_2 = F_2 \times C_2$
⋮	⋮	⋮	⋮	⋮
m-1	F_{m-1}	PDS ## and CET ##	C_{m-1}	$R_{m-1} = F_{m-1} \times C_{m-1}$
m	F_m	PDS ## and CET ##	C_m	$R_m = F_m \times C_m$
Total single-unit accident scenario risk			$R^{Conventional} = \sum_{i=1}^{m} R_i$	

1): 한국수력원자력, 고리 2호기 Level 2 PSA 보고서(2007)
2): 한국수력원자력, 고리 3,4호기 Level 2 PSA 보고서(2008)

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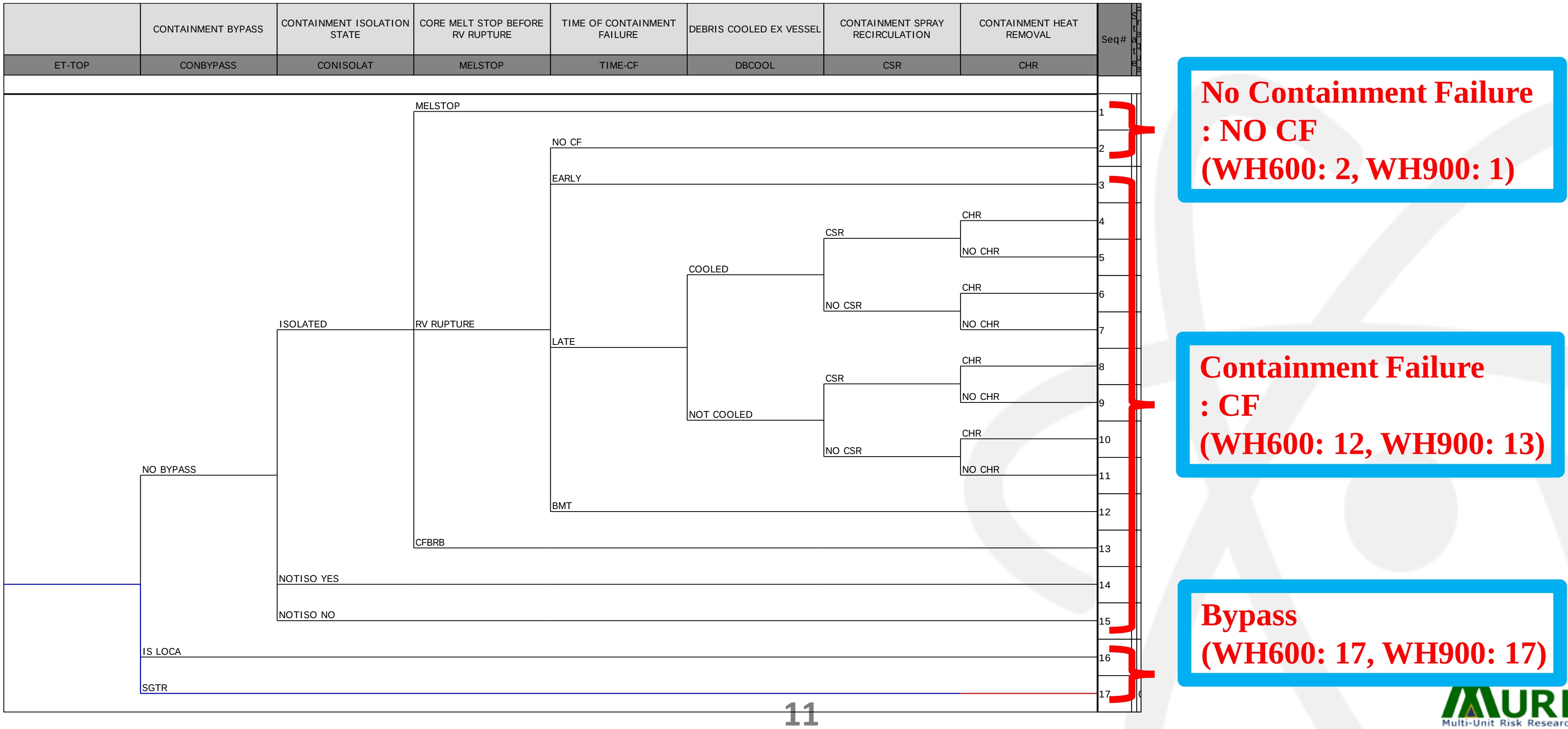
Methodology and Application (cont'd)

Step 1, 2a, and 2b

- This research considered STCs rather than IEs(Initiating Events)
- WH600 and WH900 each had 17 STCs, and 17 STCs were classified into 3 groups (Condition: Containment failure type)
- Representative STCs having the highest or the next highest frequency were selected for each case (for frequency adjustment factor)



Methodology and Application (cont'd)

Step 3: Estimate unadjusted single-unit accident scenario risk

$$(R_i^s)_u = F_i^s \times (C_i^s | i)$$

- 'Unadjusted' means the risk contribution has not been adjusted to account for the contribution to frequency from other single-unit accident scenarios in a similar class that representative scenarios are assumed to represent
- F_i^s and $(C_i^s|i)$ are the frequency and consequence of the i-th representative STC
- Consequences of the representative STCs were estimated by using the MACCS code
- Considerations in using the MACCS code are below:
  1. ATMOS and EARLY modules were considered
  2. **Emergency response actions were not considered**
  3. **Input data reflecting the domestic characteristics and results of the SOARCA pilot study was used for the ATMOS and EARLY modules**
  4. Meteorological data for 2016 was used, and population data for 2010 resulted from the 'MSPAR-SITE' code(developed by the MURRG) was used
  5. 'Population weighted risk' was utilized for risk metrics
  6. Radius of 5 km was used for early health effect, and radius of 30 km was used for latent cancer health effect considering the PAZ(Precaution Action Zone) and UPZ(Urgent Protective Action Planning Zone)*

*: 원자력안전위원회, *원자력시설 등의 방호 및 방사능 방재 대책법 제20조의2*, (2017)

Methodology and Application (cont'd)

Step 4a: Estimate single-unit frequency adjustment factor

$$\alpha^s = \left(\frac{F^s_{total}}{\sum_i F^s_i}\right)$$

- Adjustment factor was needed to correct the representative STC frequencies to account for the contribution to the frequencies from other STCs not modeled
- It was assumed that the adjustment factor could be applied to all representative STCs
- F^s_{total} is the total STCs frequency initiated by all internal events
- Adjustment factor for Unit 1 was calculated as 1.39, and adjustment factor for Unit 2,3 was calculated as 1.7

Methodology and Application (cont'd)

Step 4b: Estimate adjusted single-unit accident scenario risk

$$R_i^s = \alpha^s \times (R_i^s)_u$$

Step 5: Estimate adjusted total single-unit accident risk

$$F_{total}^s = \sum_i R_i^s$$

- Adjusted total single-unit accident risk was compared to the conventional single-unit PSA risk estimated in **Step 0**

	Early Health Effect (0~5 km)	Latent Cancer Health Effect (0~30 km)
Conventional single-unit PSA	$R_{Early}^{Conventional}$	$R_{Latent}^{Conventional}$
Adjusted total single-unit	$R_{Early}^{Adjusted}$	$R_{Latent}^{Adjusted}$

Relative error = $\left(\frac{R^{Conventional} - R^{Adjusted}}{R^{Conventional}}\right) \times 100$ %

	Early Health Effect (0~5 km)	Latent Cancer Health Effect (0~30 km)
Unit 1	12.84 %	9.34 %
Unit 2, 3	-25.13 %	-29.43 %

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Methodology and Application (cont'd)

Step 6

- Combine the representative STCs for multi-unit accident scenarios
- STC 2, 12, 17 were selected for Unit 1 (WH600), and STC 1, 13, 17 were selected for Unit 2, 3 (WH900)
- All combinations where each unit became the affecting unit were considered

Two-unit accident scenarios (Between Unit 1 and Unit 2)

Classification	Unit	STC								
Affecting	1	2	2	2	12	12	12	17	17	17
Affected	2	1	13	17	1	13	17	1	13	17

Three-unit accident scenarios (Between Unit 1, Unit 2, and Unit 3)

Classification	Unit	STC													
Affecting	1	2	2	2	2	2	2	2	2	2	12	12	12	12	12
Affected	2	1	1	1	13	13	13	17	17	17	1	1	1	13	13
Affected	3	1	13	17	1	13	17	1	13	17	1	13	17	1	13
Classification	Unit	STC													
Affecting	1	12	12	12	12	17	17	17	17	17	17	17	17	17	
Affected	2	13	17	17	17	1	1	1	13	13	13	17	17	17	
Affected	3	17	1	13	17	1	13	17	1	13	17	1	13	17	

Methodology and Application (cont'd)

Step 7a: Estimate multi-unit accident scenario frequencies

$$F_{ijk}^{m} = F_i^s \times \beta_i \times \left(\frac{F_j^s}{\sum_j F_j^s}\right) \times \left(\frac{F_k^s}{\sum_k F_k^s}\right)$$

- F_{ijk}^{m} is the multi-unit accident frequency where the index *i* means the representative STC of the affecting unit, while the index *j*, *k* mean the representative STCs of affected units
- F_i^S is the *i*-th representative STC frequency in the affecting unit
- $\left(\frac{F_j^S}{\sum_j F_j^S}\right)$ and $\left(\frac{F_k^S}{\sum_k F_k^S}\right)$ are the ratio of *j*-th and *k*-th representative STC frequencies by the total representative STC frequency for the affected unit
- β_i is conditional probability of a core damage accident occurring in the affected units which represents degree of dependency between units

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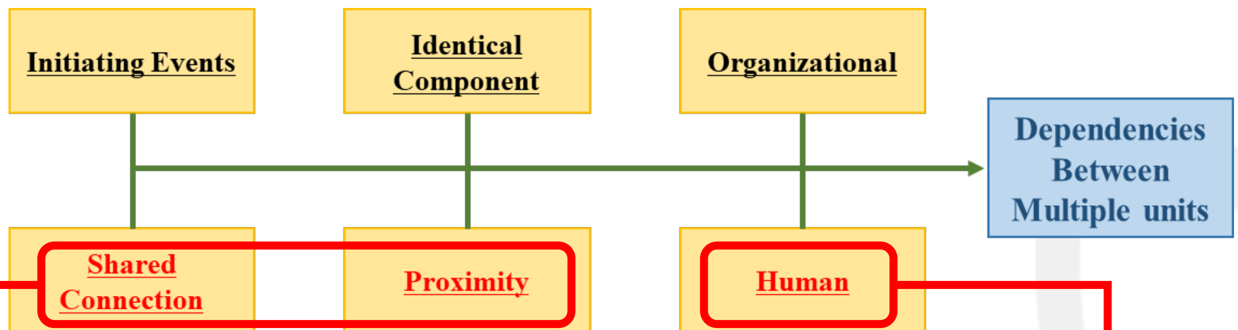
Methodology and Application (cont'd)

Step 7a: Estimate multi-unit accident scenario frequencies (cont'd)

- It was expected that multi-unit accident scenarios comprised of the different affecting unit accident scenario would have different β_i
- S. Schroer suggested six dependencies between multiple units[1)]
- 'Shared connection', 'Proximity', and 'Human' dependencies were considered in this research



From 2000 to 2015 (OPIS data)[2)]

1. All events: a
2. Cascading events in a same plant: b
3. Cascading event between different plants: c

✓ Between Unit 1 and Unit 2 (or 3):

$\beta_{S/P} = {}^{c}/_{a}$

✓ Between Unit 2 and Unit 3:

$\beta_{S/P} = {}^{b}/_{a}$

✓ Between Unit 1, Unit 2, and Unit 3:

$\beta_{S/P} = {}^{b}/_{a} \times {}^{c}/_{a}$

$$\beta_i = \beta_{S/P} \times \beta_H$$

1. There is no adequate methodology to quantitatively assess the impact of radioactive material releases on other units
2. Therefore, simple assumption was used in this research

✓ If the representative STC of the affecting unit is 'NO CF' group: $\beta_H = 1$

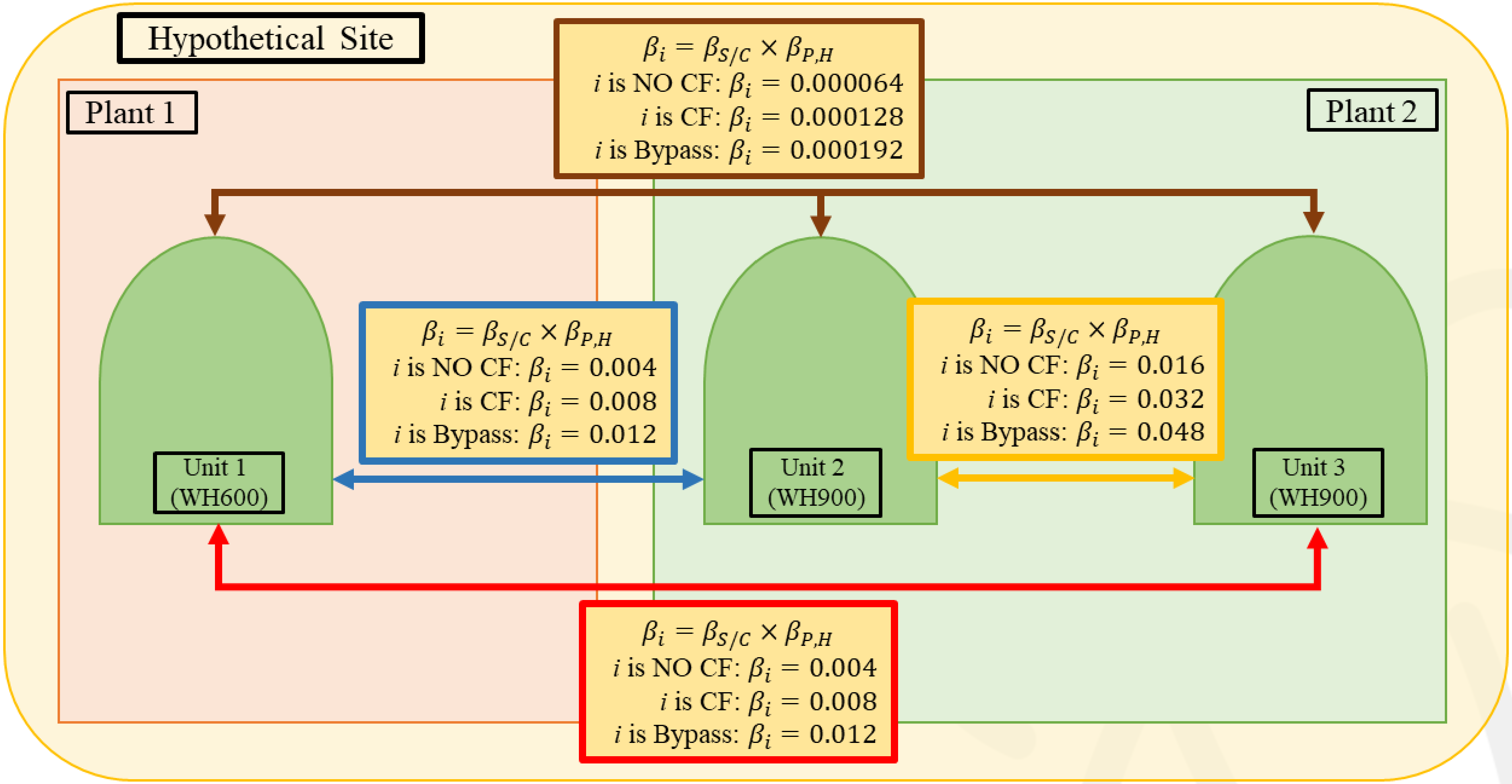
✓ If the representative STC of the affecting unit is 'CF' group: $\beta_H = 2$

✓ If the representative STC of the affecting unit is 'Bypass' group: $\beta_H = 3$

1): Schroer, S., & Modarres, M. (2013). An event classification schema for evaluating site risk in a multi-unit nuclear power plant probabilistic risk assessment. Reliability Engineering & System Safety, 117, 40-51.
2): KINS, Operational Performance Information System for Nuclear Power Plant (OPIS)

Methodology and Application (cont'd)

Step 7a: Estimate multi-unit accident scenario frequencies (cont'd)



Methodology and Application (cont'd)

Step 7b: Estimate multi-unit accident scenario consequences

$$\left(c_{ijk}^{t} \middle| ijk\right)$$

- MACCS 3.11.2 version was utilized, and 'Multiple Source Term' function was used for simulating multi-unit accidents (difference of release timing was considered)
- Input data of the single-unit representative STCs was used
- It was assumed that accidents for each unit were initiated concurrently
- Emergency response actions were not considered for consistence with single-unit accident simulations
- Release points of multi-unit accident scenarios were calculated by applying the center-of-mass location for thermal power of each unit using the 'MSPAR-SITE' code
- Radius of 5 km was used for early health effect, and radius of 30 km was used for latent cancer health effect considering the PAZ and UPZ in the MACCS code

Methodology and Application (cont'd)

Step 8: Estimate unadjusted multi-unit accident scenario risk

$$\left(R_{ijk}^{m}\right)_{u} = F_{ijk}^{m} \times \left(C_{ijk}^{m} | ijk\right)$$

Step 9a: Estimate multi-unit frequency adjustment factor

$$\alpha^{m} = \left(\frac{\beta \times F_{total}^{s}}{\sum_{ijk} F_{ijk}^{m}}\right)$$

- $\beta \times F_{total}^{s}$ means total multi-unit STC frequency from all multi-unit accident scenarios initiated by internal events

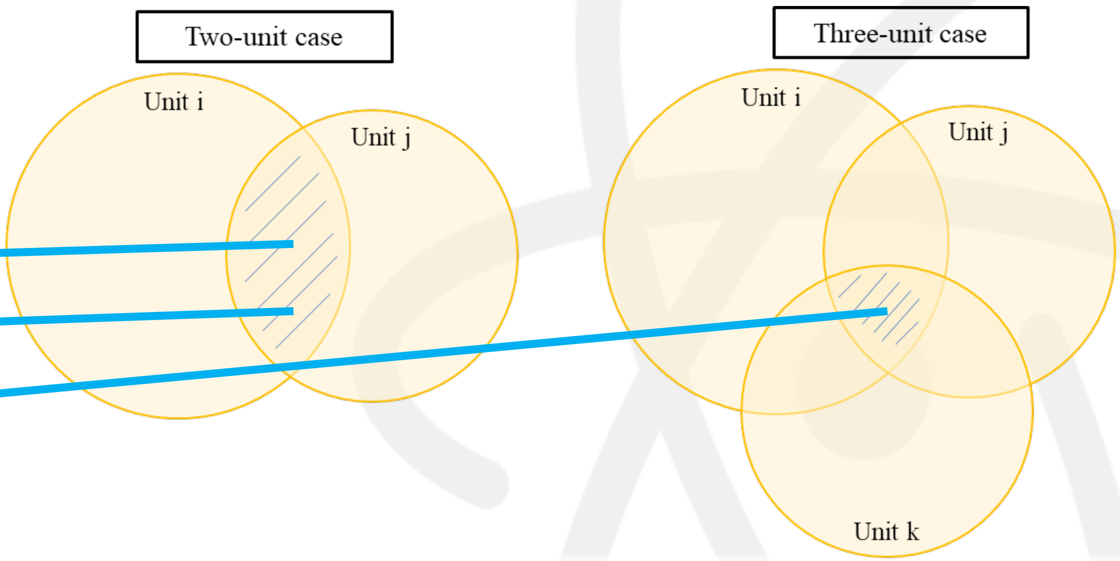
Assumptions for simply estimating $\beta \times F_{total}^{s}$

1. β is only related to cascading events
2. F_{total}^{s} is the maximum value among the total STC frequencies of each unit

✓ Between Unit 1 and Unit 2(or 3):
β =4.0E-3, F_{total}^{s} =total STC frequency of Unit 1

✓ Between Unit 2 and 3:
β =1.6E-2, F_{total}^{s} =total STC frequency of Unit 2

✓ Between Unit 1, Unit 2 and Unit 3:
β =6.4E-5, F_{total}^{s} =total STC frequency of Unit 1



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Methodology and Application (cont'd)

Step 9b: Estimate adjusted multi-unit accident scenario risk

$$R_{ijk}^{m} = \alpha^{m} \times \left(R_{ijk}^{m}\right)_{u}$$

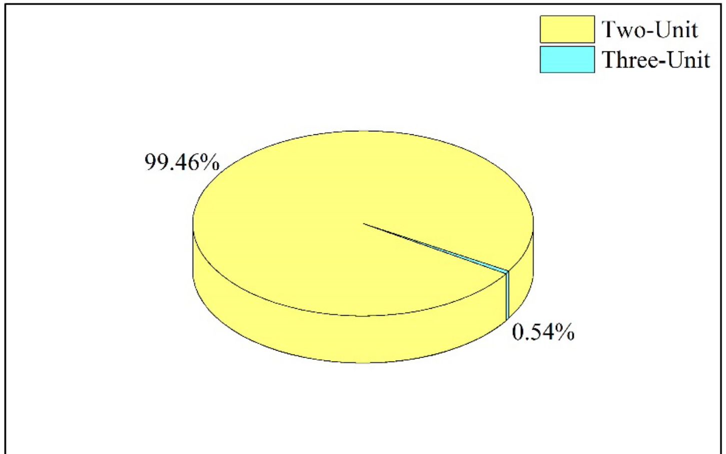
Step 10: Estimate adjusted total multi-unit accident scenario risk

$$R_{total}^{m} = \sum_{ijk} R_{ijk}^{m}$$

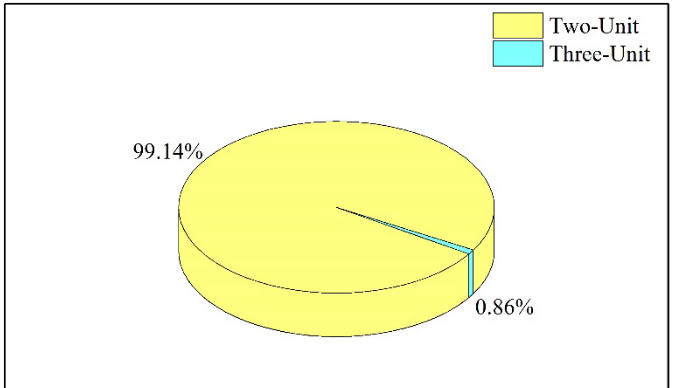
3. Results

Results

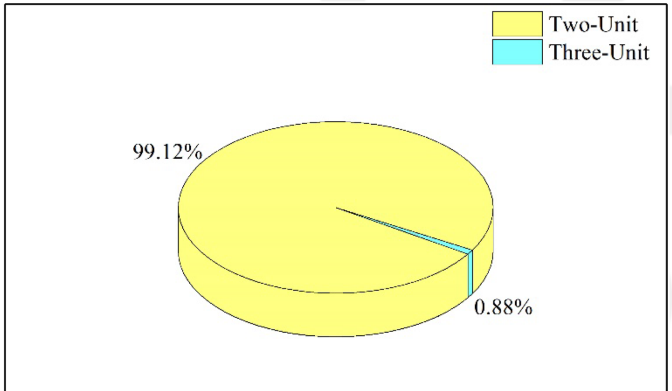
- **Two-unit accident scenarios were dominant** in frequency and risk of multi-unit accident scenarios



Frequency Distribution of Multi-Unit Accident Scenarios



Risk Distribution of Multi-Unit Accident Scenarios
(Early Health Effect)



Risk Distribution of Multi-Unit Accident Scenarios
(Latent Cancer Health Effect)

Results

- Results of multi-unit (two-unit + three-unit) accident scenarios were compared to those of single-unit accident scenarios
- **Ratio: (Result of multi-unit) / (Result of comparing case) × 100 %**

Comparison of frequency

Case	Compared to WH600	Compared to WH900	Compared to sum of total single-unit frequencies [WH600+(2×WH900)]
Ratio	**Intentionally blanked**		

Comparison of risk

Case	Compared to WH600		Compared to WH900		Compared to sum of total single-unit risks [WH600+(2×WH900)]	
Ratio	Early Health Effect (0~5 km)	Latent Cancer Health Effect (0~30 km)	Early Health Effect (0~5 km)	Latent Cancer Health Effect (0~30 km)	Early Health Effect (0~5 km)	Latent Cancer Health Effect (0~30 km)
	Intentionally blanked					

If emergency response actions and CCDPs of the affected units are considered, a much smaller results will be estimated!

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4. Conclusion

Conclusion

- Methodology for evaluating multi-unit accident scenario frequency and risk due to cascading effect were studied in this research
- Highly conservative assessments were performed because the CCDPs of the affected units were assumed to be 1 and emergency response actions were not considered
- Results of two-unit accident scenarios contributed most to the results of multi-unit accident scenarios
- Frequency and risk of multi-unit accident scenarios were estimated to be much smaller than those of total single-unit accident scenarios
- For a more detailed research of multi-unit accident risk by cascading effect, it would be sufficient to consider only two-unit accident scenarios and sensitivity analysis should be performed
- In addition, research on multi-unit accident risk by CCIs and propagating effect should be performed
- Results of this research will contribute to establishing a developed multi-unit PSA methodology where it is not possible to model all multi-unit accident scenarios

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Thank you for listening!