PSAM18-HI217

Sequential Uncertainty Modeling for Unfolding Phenomena (SUM-UP) Method for Estimating Event Probabilities Specific to Level 2 MUPRA

Nuclear Risk Research Center (NRRC)
Central Research Institute of Electric Power Industry (CRIEPI)

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Outline

1.1. Background

Background

- During the Fukushima Daiichi Nuclear Power Plant accident, various multi-unit (MU) events were observed.
  - ➢ Examples:
    - Shared equipment and interconnections,
    - Hindrances to outdoor work due to hydrogen explosions,
    - Increased radiation doses in the surrounding area

Our Research

- We have been advancing the technical development of Level 1 MUPRA.
- We have established evaluation methods for various MU events.
  - ➢ Interdependencies between units and loss of function in shared equipment
  - ➢ Common-cause failures between components in different units
  - ➢ Evaluation methods for the impact on human behavior under MU accident conditions, etc.

We have also been developing a Level 1 Seismic MUPRA methodology.

- ➢ Identification of seismically induced multi-unit IE
- ➢ Joint failure probability of components across units
- ➢ Enormous computational costs

1.2. Objectives

Remaining Gap for Level 2 MUPRA

- To consider the effects and events on accident mitigation in other units resulting from the loss of containment function (L2 MU events)
  - ➢ The existing Level 2 SUPRA performs accident sequence analysis up to the loss of containment function.
  - ➢ No methodology has been established to evaluate L2 MU events.

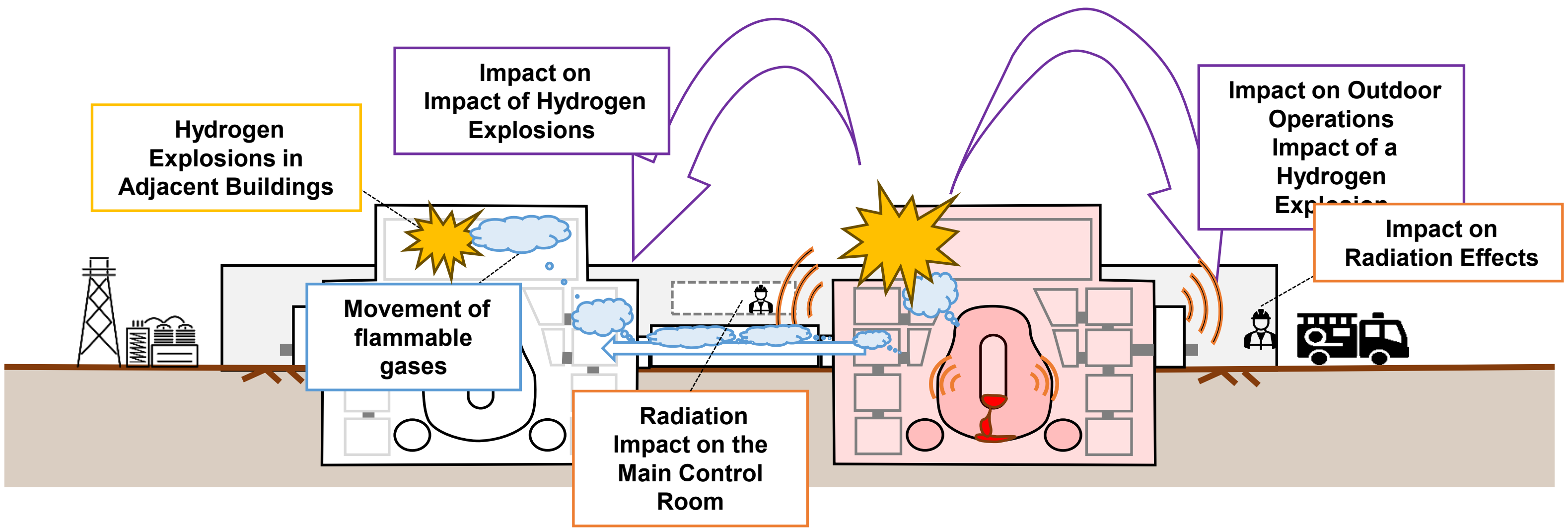
Objectives

- To develop a common evaluation framework that serves as a foundation for the evaluation of L2 MU events.
- To provide a probability estimation method for a cascading phenomenon which has not been analyzed thoroughly yet.
  - ➢ The method needs to be flexible to balance evaluation cost and quality to fit its objective and level of maturity.

Outline

2.1. What Is an L2 MU Event?

L2 MU Events (Images) to Consider



Elements of L2 MU Events

What kind of impact

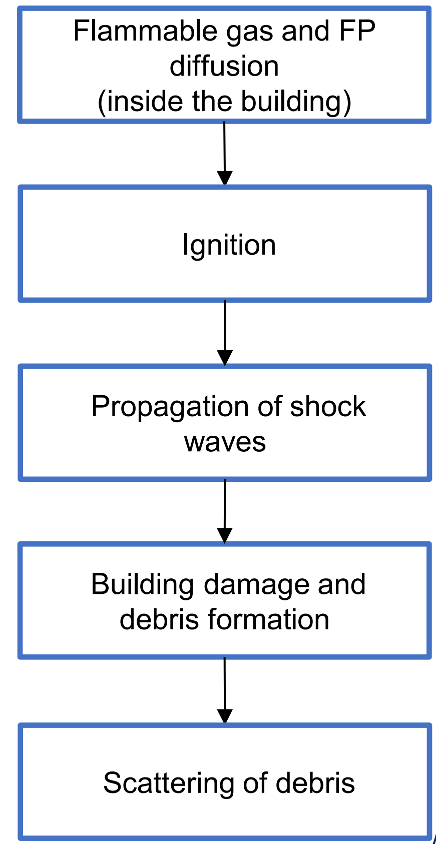
Spread in what way

and what it caused

Elements of L2 MU Events	Definition
Causative Event	An event that directly or indirectly affects the consequential event Example: In the case of "Damage to the alternative water injection line caused by debris scattered during a hydrogen explosion," "hydrogen explosion" is the causative event
Propagation Mode	The mechanism by which the causative event triggers the consequential event Example: In the case of "Damage to the alternative water injection line caused by debris scattered during a hydrogen explosion," "flying debris" is the relevant mode
Consequential Event	An event that occurs as a direct or indirect result of the causative event Example: "Damage to the alternative water injection line (caused by flying debris)" and "Interruption of on-site operations (due to evacuation orders or evacuation decisions)" are examples

2.2. Characteristics of L2 MU Events

- L2 MU events consist of multiple phenomena with distinct characteristics.
  - ➢ They require a multi-stage phenomena analysis.
    - There is no evaluation environment (tool) in place that can evaluate all steps at once.
    - The maturity of evaluation methods varies by step. (In some cases, evaluation techniques are still immature.)
      - Uncertainties are inherent in the inputs and outputs of each step.
      - The number of cases that can be evaluated varies by step.
      - The evaluation methods themselves at each step are subject to uncertainty.



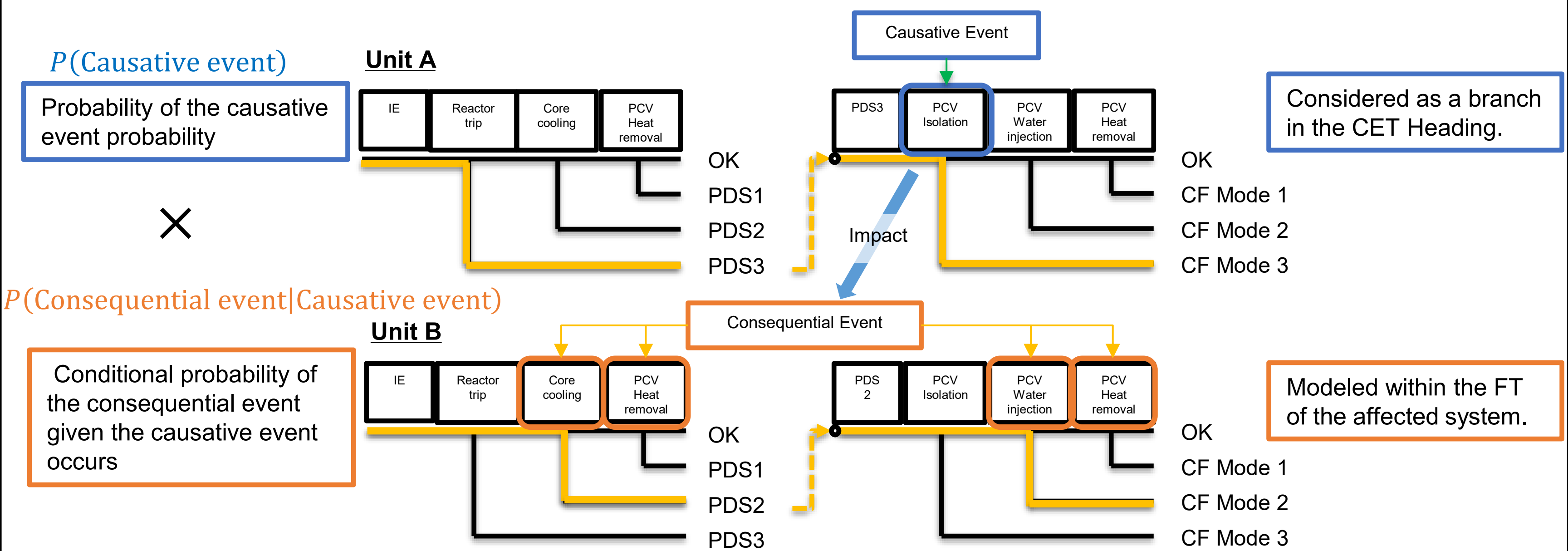
Outline

3.1. Level 2 MUPRA Modeling Method and L2 MU Event Modeling Strategies

Level 2 MU-AS model development methodology developed by NRRC

The accident sequences for each unit are logically combined in a way that allows them to be identified individually, and the result is evaluated as a multi-unit accident sequence.

L2 MU Event Modeling Strategy



$$P(\text{L2 MU event}) = P(\text{Causative event}) \times P(\text{Consequential event}|\text{Causative event})$$

3.2. Estimation of the Conditional Probability of Occurrence of Consequential Events

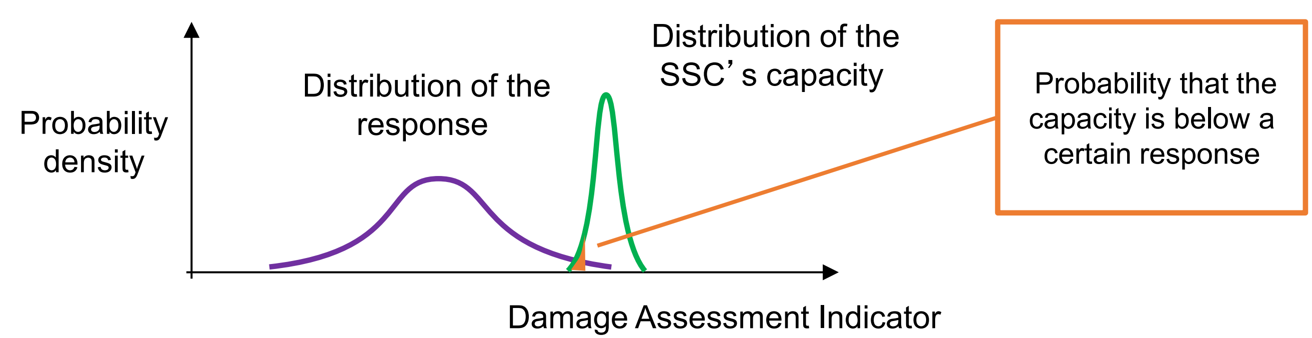
Introduces the same approach used in general fragility analysis, such as seismic PRA

What it causes (Equivalent to a capacity)

How it works (Equivalent to a response)

$$P(\text{Consequential event}|\text{Causative event } i) = \int P(\text{Consequential event}|\text{s}) \times P(s|\text{Causative event } i)ds$$

s: Strength of damage assessment indicator



3.3. Evaluation Framework for L2 MU Events

(a) Identification of L2 MU Events to Be Evaluated

(b) Scenario Unfolding of L2 MU Events

(c) Identify the Certainty of Consequential Event Occurrence after Causative Event

Probabilistic

Deterministic

(d) “Response”* Analysis

(e) “Capacity”** Estimation

(f) Estimation of the Probability of Consequential Events

(g) Estimation of the Effects of Consequential Events

(h) Incorporation into the PRA model

*Represents the severity of a phenomenon’s impact and corresponds to the response in a fragility analysis.
**Represents the resistance of SSCs and other factors related to the phenomenon, corresponding to the capacity in fragility analysis.

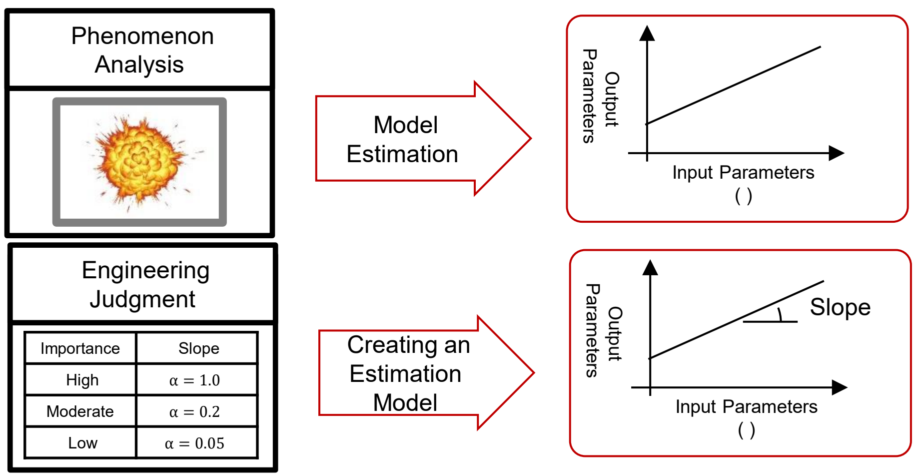
Outline

1. Background and Objectives
2. Characteristics of L2 MU Events
3. Evaluation Framework for L2 MU Events
4. **Response Analysis Using the SUM-UP Method**
5. Summary

4.1. Proposal of the SUM-UP Method

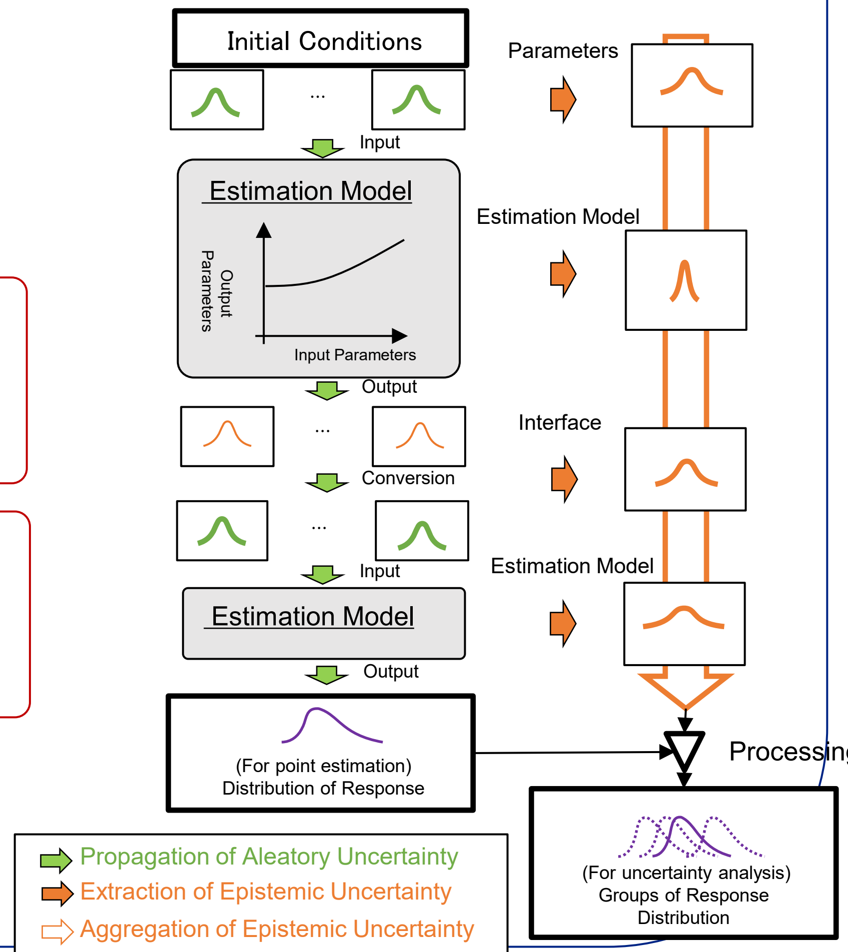
◆ We propose the SUM-UP method as an evaluation framework for systematically propagating uncertainty in a chain of analyses.

① Replace the estimation model simulating the phenomenon analysis with a simple functional form.
⇒ This allows for a unified approach even when methods with varying levels of maturity in analysis techniques and knowledge are mixed. (See figure below)



Importance	Slope
High	α = 1.0
Moderate	α = 0.2
Low	α = 0.05

② Distinguish between aleatory uncertainty and epistemic uncertainty and propagate them accordingly.
⇒ This enables point estimation and uncertainty analysis. (Figure on the right)

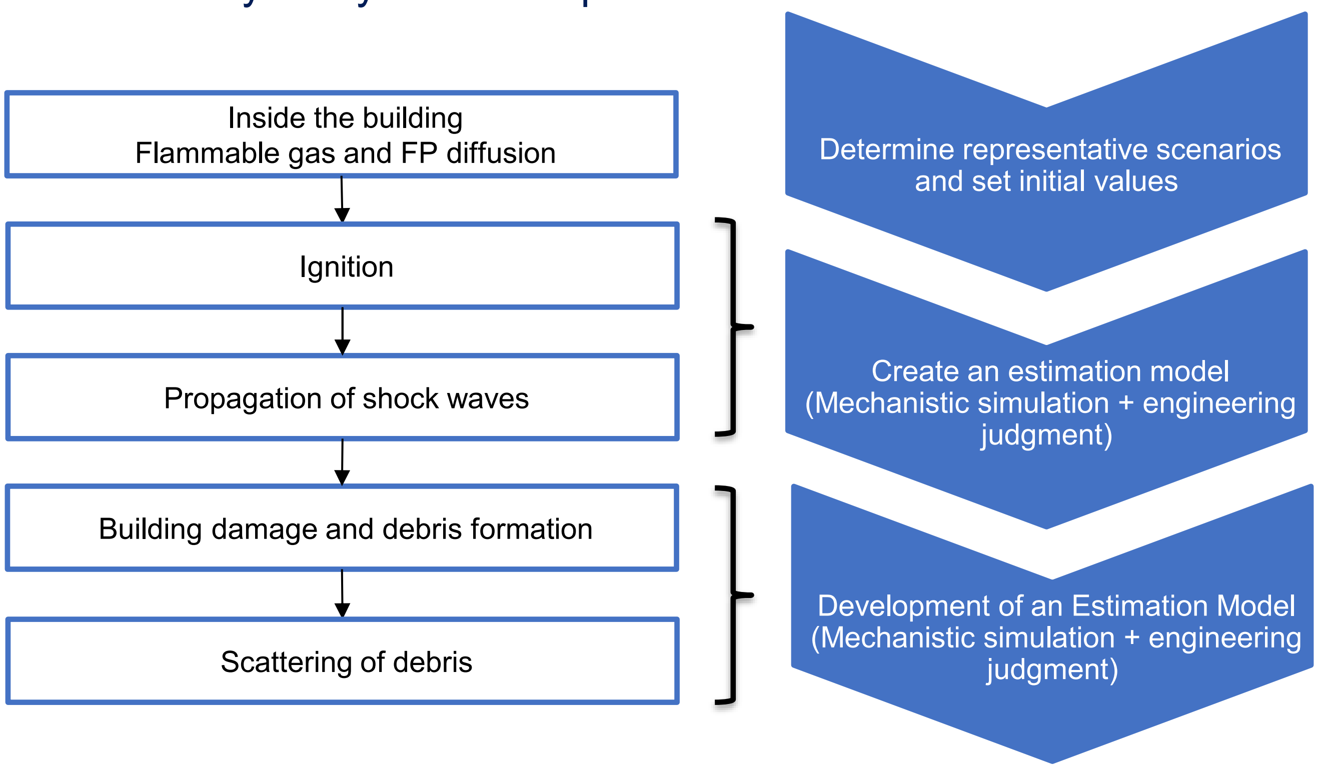


4.2. Capabilities of the SUM-UP Method

What the SUM-UP Method Can Do

- Enables evaluation of response analysis for chained events (constituent events*)
- Allows for flexible selection of evaluation methods (phenomenon simulation, engineering judgment, etc.) for each constituent event
- Uncertainty analysis can be performed

*Individual analysis units for phenomenon analysis

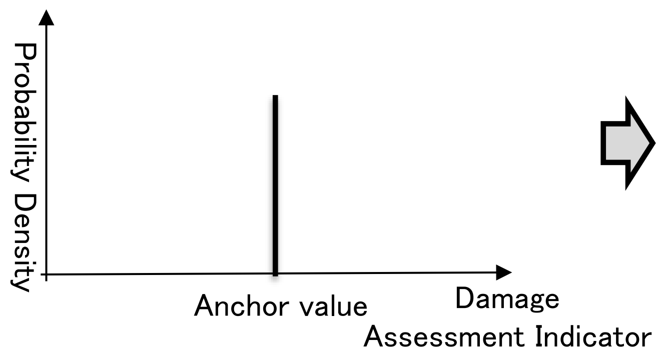


4.3. Overview of the SUM-UP Method

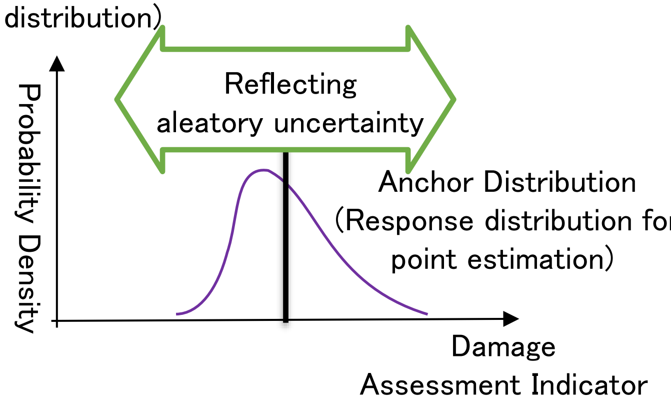
Illustration of How Uncertainty Is Handled in Response Analysis (SUM-UP Method)

- Point Estimation

Procedure (i) Estimation of Representative Values (Anchor Values)

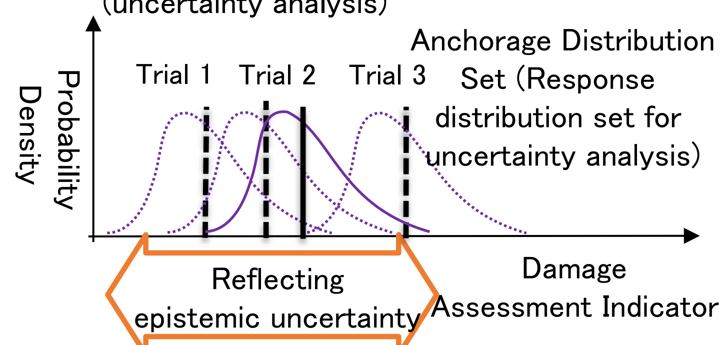


Procedure (ii) Estimation (point estimation) of the distribution reflecting aleatory uncertainty (anchor distribution)



- Uncertainty Analysis

Procedure (iii) Development of a set of distributions reflecting epistemic uncertainty (uncertainty analysis)



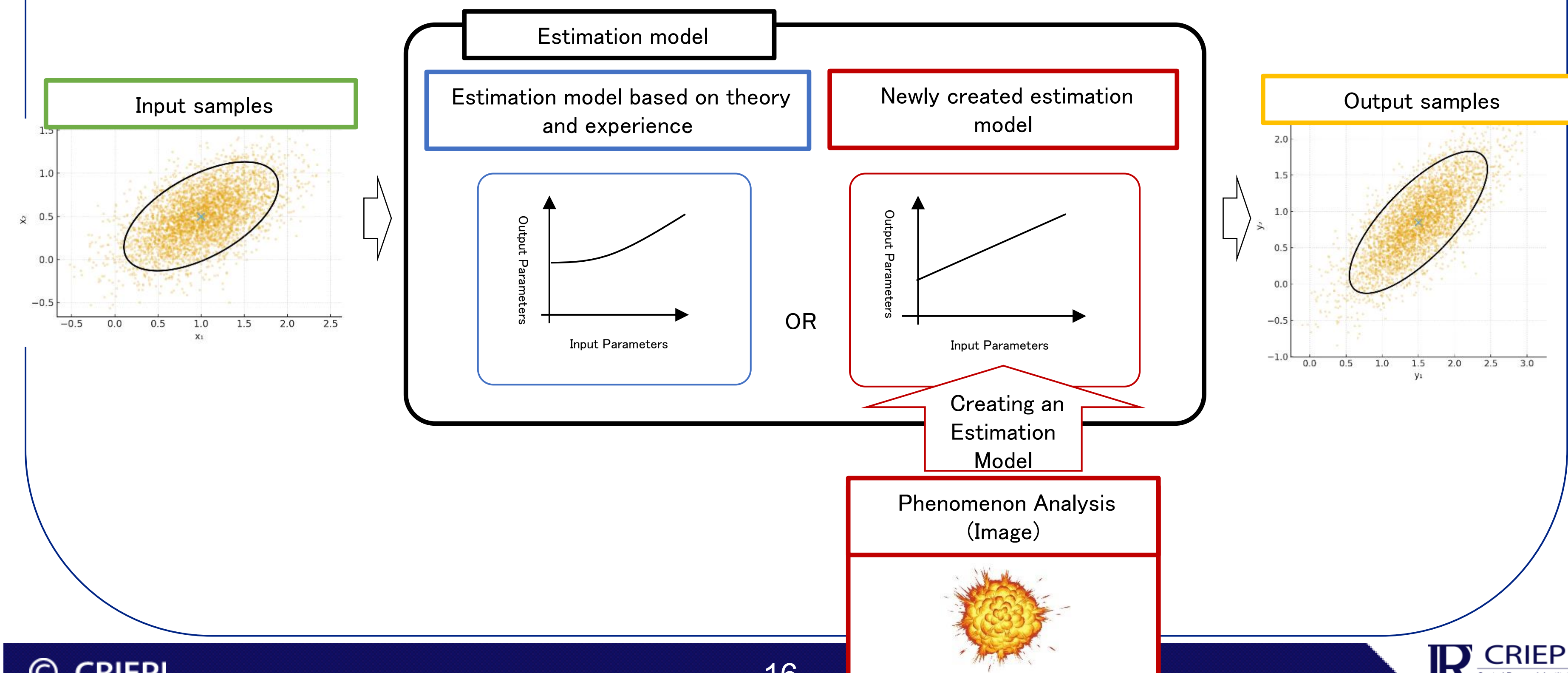
The uncertainty inherent in the estimation model can be considered as epistemic uncertainty

4.4. Point Estimation
Estimation of the Response Distribution (Anchor Distribution)

1. Organizing the Correspondences Between Input and Output Parameters and Splitting the Output
2. Conducting a base case analysis (analysis of anchor values)
3. Selection and development of estimation models

$$\Delta y_j = f_{j|1}(\Delta x_1) + f_{j|2}(\Delta x_2) + \cdots + f_{j|k}(\Delta x_k) = \sum_{i=1}^{k} f_{j|i}(\Delta x_i)$$

4. Propagation of aleatory uncertainty via Monte Carlo sampling

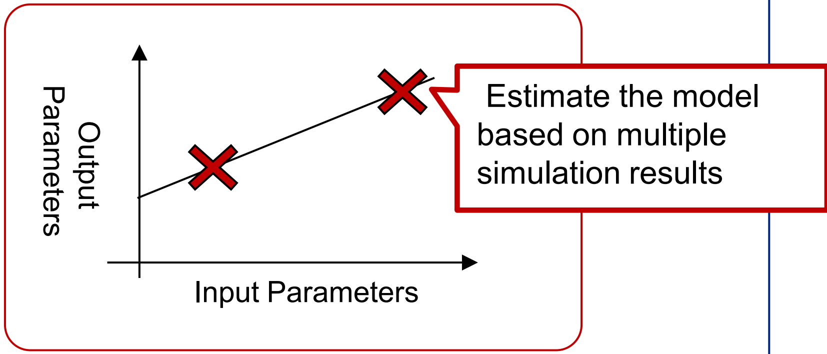


4.4. Point Estimation
Creating an Estimation Model

How to Create an Estimation Model

① Simulation

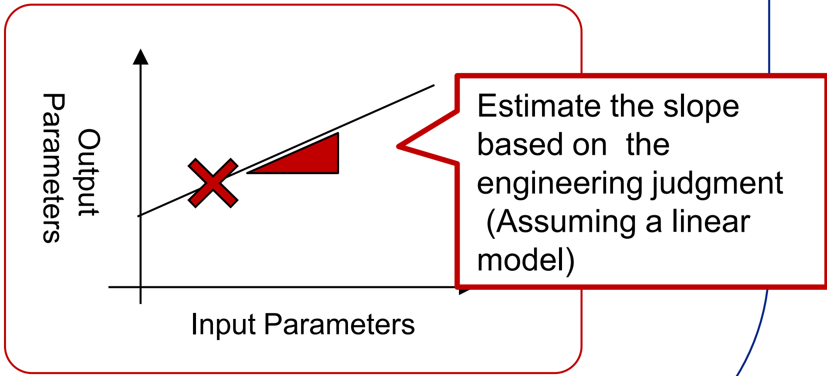
- Nonlinear estimation models can also be created
- Created based on analysis results from multiple cases



② Engineering Judgment

- Estimate the slope between input and output (relative sensitivity coefficient) based on engineering judgment

$$S_{j|i} = \frac{\partial y_j}{\partial x_i} \times \frac{x_i}{y_j}\bigg|_{base\ case}$$

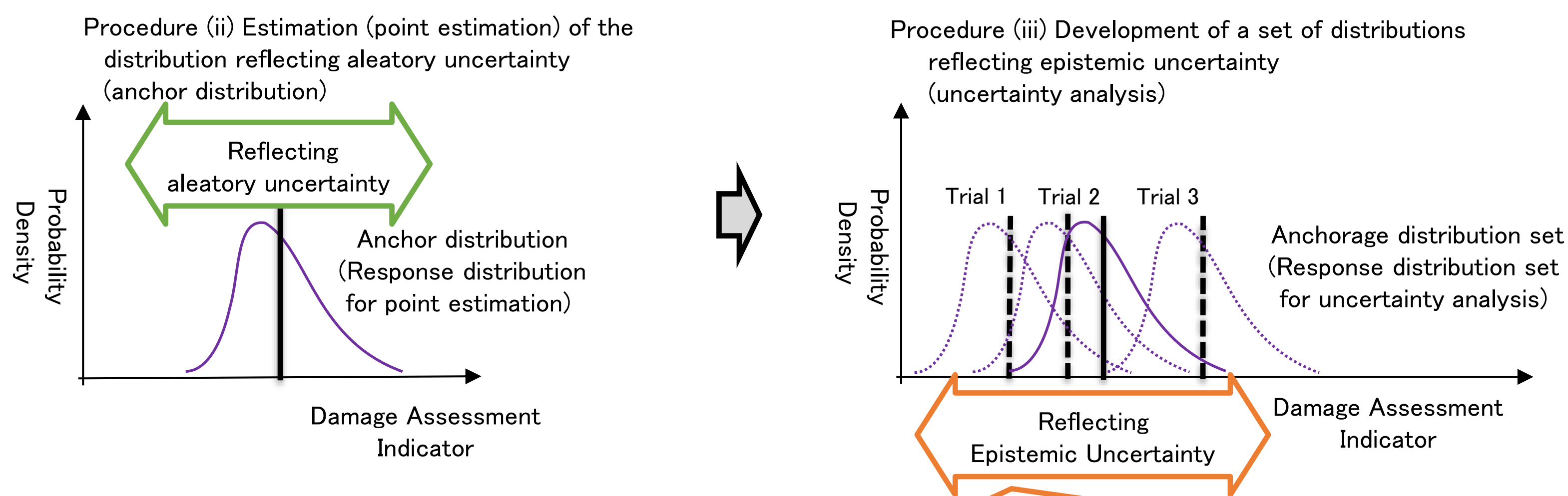


Proposed Guidelines for Setting Relative Sensitivity Coefficients

Importance (Magnitude of Impact)	Value of the sensitivity coefficient (S)
High	$S = 1.0$
Moderate	$S = 0.2$
Low	$S = 0.05$

4.5. Uncertainty Analysis
Assigning Epistemic Uncertainty to Input Parameters

- Incorporating Epistemic Uncertainty in Input Parameters



The entire set of anchor distributions for point estimation is distributed according to epistemic uncertainty.
The uncertainty involved is calculated as follows.
It is necessary to estimate the global relative sensitivity coefficient ($S_{D|i}$).

$$\sigma_{D,u} \approx \sqrt{\sum_i \left(S_{D|i} \frac{D}{p_i} \sigma_{p_i,u} \Big|_{base\ case} \right)^2}$$

4.6. Illustration of the SUM-UP Method

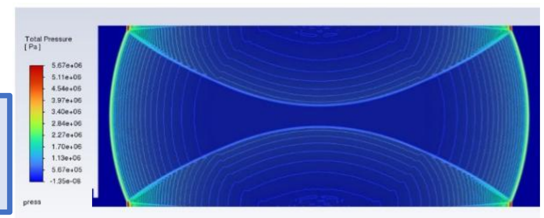
《Scenario Development》

- Inside the building Flammable gas and FP diffusion
- Ignition
- Propagation of shock waves
- Building damage and debris formation
- Scattering of debris

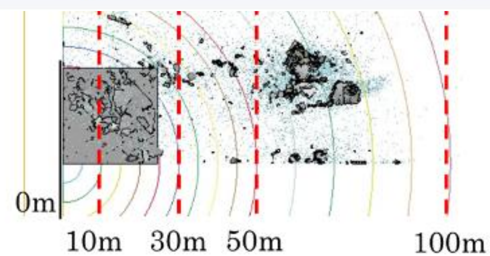
《Estimation of Anchor Values and Development of Estimation Models Through Detailed Analysis》

This is propagated as aleatory uncertainty—specifically, as uncertainty in the input parameters for the point estimation in the SUM–UP method.

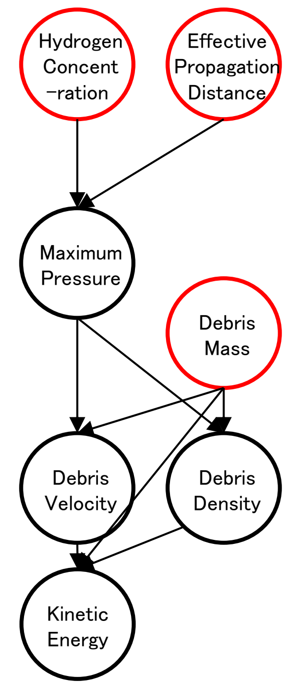
Phenomenon Analysis ①
(Estimation Model ①)



Phenomenon Analysis ②
(Estimation Model ②)



《Uncertainty Propagation》



Outline

1. Background and Objectives
2. Characteristics of L2 MU Events
3. Evaluation Framework for L2 MU Events
4. Response Analysis Using the SUM-UP Method
5. Summary

5. Conclusion

1. Proposal of an L2 MU Event Evaluation Framework

- To estimate the probability of occurrence of L2 MU events, we propose an evaluation framework that estimates and compares the severity of the event's impact (response) at the installation site and the target's —such as SSC's— capacity to resist that impact (capacity) with respect to a damage assessment indicator that cause damage, thereby estimating the probability and its distribution.

2. Proposal of the SUM-UP Method

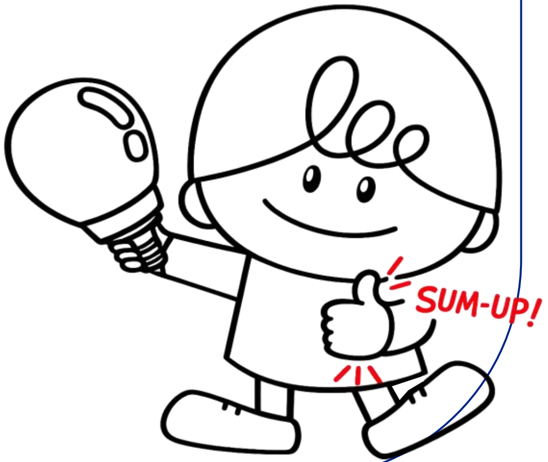
- We propose the SUM-UP method as a technique for estimating the response within the L2 MU event evaluation framework.

Features of the SUM-UP Method:

1. By replacing estimation models that simulate phenomenon analysis with simple functional forms, it enables a unified approach even when methods with varying levels of maturity in analytical techniques and insights are mixed.
2. It enables point estimation and uncertainty analysis by distinguishing between aleatory uncertainty and epistemic uncertainty and propagating them accordingly.

Thank you!

- Level 1 Internal Event MUPRA
  - ➢ Framework and technical methods, such as the MU-AS model and MU-HRA
    - CRIEPI Report, “Development of Level 1 Multi-Unit PRA Methodology - 2025 update -” (NR25011), 2026.
  - ➢ Inter-unit CCF
    - “A systematic approach to estimate an inter-unit common-cause failure probability,” Reliability Engineering & System Safety, Vol. 215, 107802, 2021.
    - “Inter-Unit Common Cause Failure Analysis Based on Data From Intra-Unit Cases,” Proceedings of the 2020 International Conference on Nuclear Engineering (ICONE2020), Paper No. ICONE2020-16819, 2020.
- Level 1 Seismic MUPRA
  - ➢ Seismically Induced MU-IE
    - “An evaluation method for a seismic-induced multi-unit initiating event extending an initiating event classification tree for a nuclear power station,” Mechanical Engineering Journal, Vol. 11, No. 2, 23-00415, 2024.
  - ➢ Seismically Induced Joint Failure Probability
    - “Theoretical comparison of models for a seismically induced joint failure probability,” Proceedings of the 16th Probabilistic Safety Assessment & Management Conference (PSAM16), 2022.
    - “An analytical comparison of the multivariate normal model and the Reed–McCann procedure,” Reliability Engineering & System Safety, Vol. 265, 111518, 2026.
    - “Development of methods to model the uncertainty distribution of seismically induced joint failure probability for seismic probabilistic risk assessment,” Journal of Nuclear Science and Technology, 2026.
    - “A fragility curve based on the transformation of a random variable,” Journal of Nuclear Science and Technology, 2023.
- Level 2 MUPRA
  - ➢ L2 MU Event Evaluation
    - CRIEPI Report, “Development of an evaluation framework and the SUM-UP method for multi-unit events specific to Level 2 MUPRA” (NR25004), 2026.



BACK SLIDES

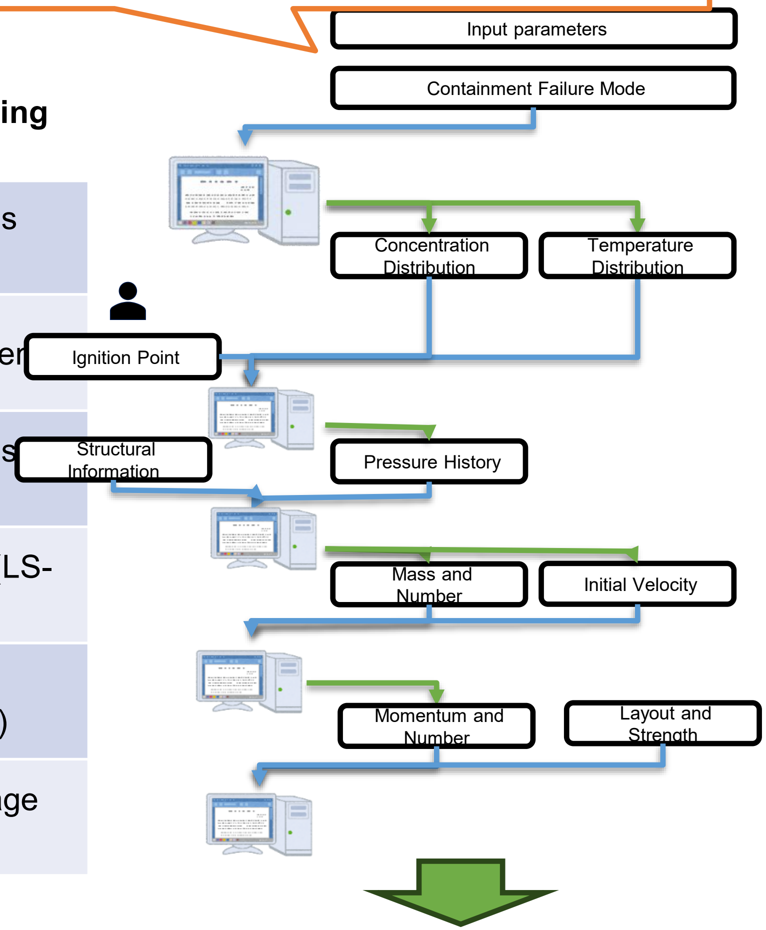
2.3. Conceptual Illustration of L2 MU Event Probability Estimation

Analytical and estimation techniques vary in maturity (some are still immature).

There is uncertainty in the parameters.
There are dependencies between parameters and between assessments.

A sequence of events with different dominant phenomena

	Methods for Analyzing Events
Diffusion of flammable gases inside a building	Numerical Analysis (GOTHIC)
Occurrence of an explosion	Engineering Judgment
Propagation of shock waves	Numerical Analysis (FLUENT)
Debris formation in the building due to explosion loads	Numerical Analysis (LS-DYNA)
Scattering of debris	Surrogate Model (Parabolic Impact)
Impact on components, etc.	Collision and Damage Assessment



Probability of an L2 MU event occurring

3.-. Construction of a Multi-Unit Accident Sequence (MU-AS) Model

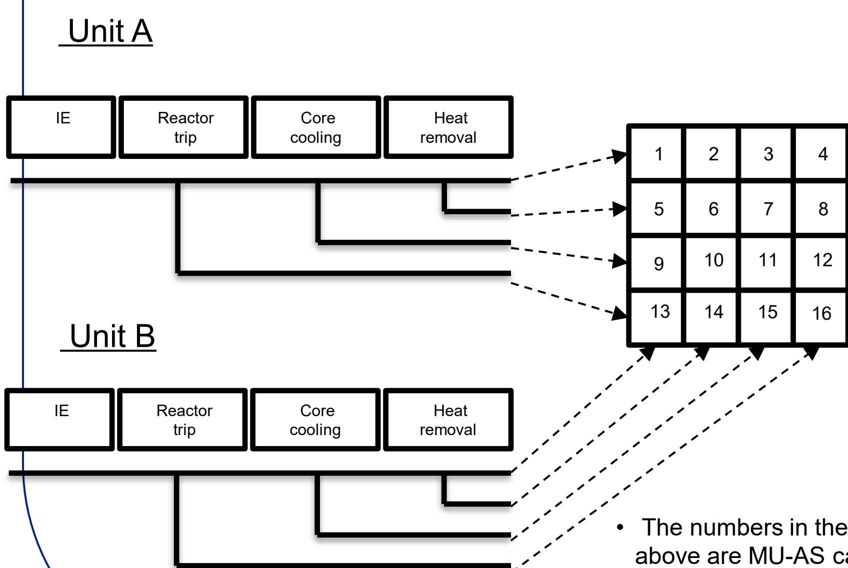
- Develop logic models for quantification directly from ETs in the SUPRA model without developing individual ETs for multi-unit accident sequences.
  - This process was automated in our study.

(0) ET in the SUPRA model

(1) Generation of comprehensive MU-AS candidates

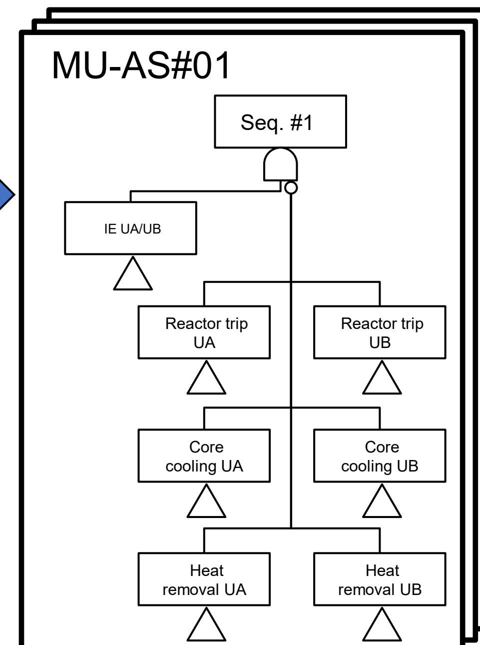
(2) Incorporation of inter-unit interactions into MU-AS candidates

(3) Development of logic models for quantification



- Delete MU-ASs that cannot logically occur due to failure or competition for shared equipment
- Adjust success criteria based on the progress of incidents in other units, etc.

- The numbers in the matrix above are MU-AS candidate numbers.
- For two units, the number will range from tens to hundreds of thousands.



Develop a logic model for each MU accident sequence

3.4. Evaluation Framework for L2 MU Events

(a) Identification of L2 MU Events to Be Evaluated
Identify the L2 MU events to be evaluated based on the accident scenarios and plant/site information from the single-unit PRA.

(b) Scenario Unfolding of L2 MU Events
Break down the L2 MU event into constituent events to understand the continuous sequence of phenomena from the occurrence of the causative event to the propagation of its effects. Identify the SSCs and countermeasures where consequential events may occur from temporal and spatial perspectives. Additionally, establish damage assessment indicator.

(c) Identify the Certainty of Consequential Event Occurrence after Causative Event
Once the causative event occurs, does the consequential event occur with certainty?

Probabilistic

Deterministic

(d) "Response"* Analysis
Numerically analyze the phenomena and calculate the response of the L2 MU event (representative values, uncertainty) by using the proposed SUM-UP method.

(e) "Capacity" Estimation**
Estimate the capacity of SSCs and operator actions against the response (representative values, uncertainty).

(f) Estimation of the Probability of Consequential Events
Estimate the probability of consequential events from the response and capacity of the SSCs and operator actions.

(g) Estimation of the Effects of Consequential Events
Estimate the effects of each consequential event on the operator actions.

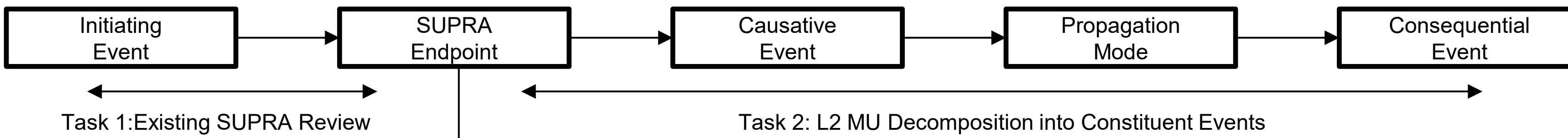
*Represents the severity of a phenomenon's impact and corresponds to the response in a fragility analysis.
**Represents the resistance of SSCs and other factors related to the phenomenon, corresponding to the capacity in fragility analysis.

(h) Incorporation into the PRA model
Incorporate the estimated probabilities and effects of the consequential events into the PRA model.

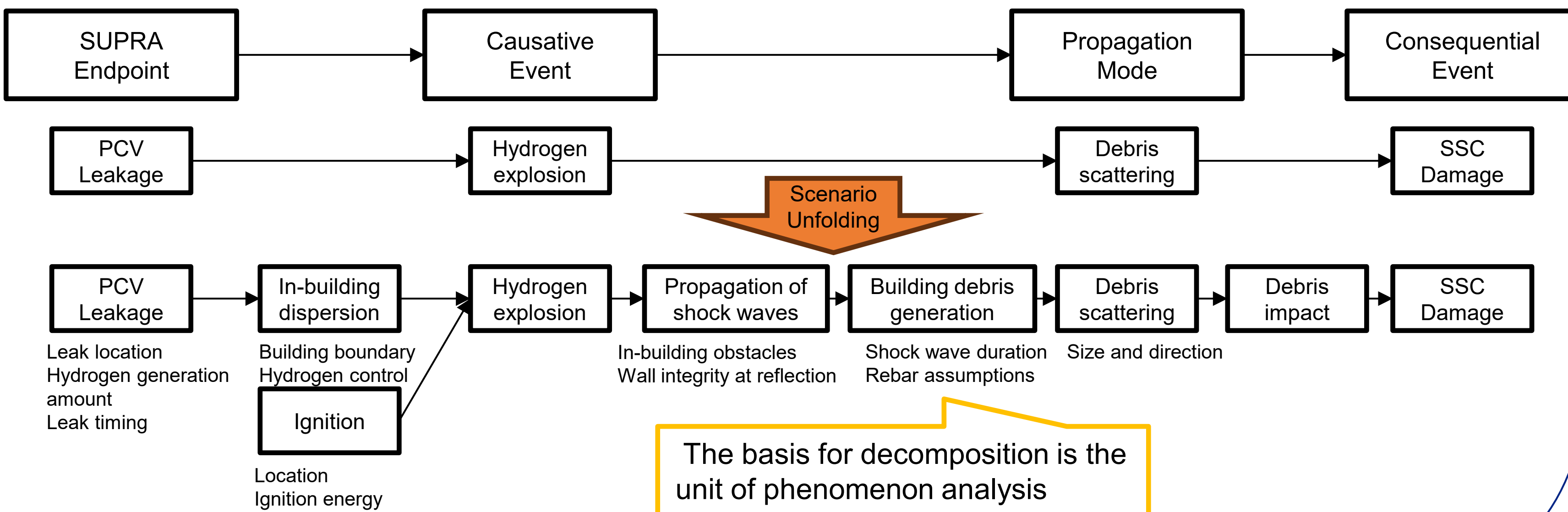
3.4. Evaluation Framework for L2 MU Events
Step (b): Scenario Unfolding of L2 MU Events

Procedure

- Task 1: Review of the Existing SUPRA



- Task 2: Break down the L2 MU event into its constituent events and identify variation factors



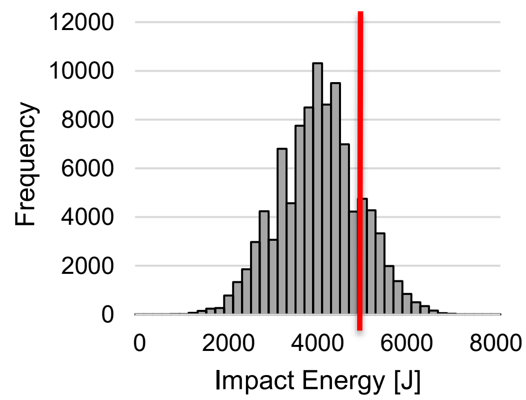
- Task 3: Determining Evaluation Scenarios

3.4. Evaluation Framework for L2 MU Events
Step (f): Estimation of the Probability of Consequential Events

- The probability of consequential events is estimated based on the response to the event and the capacities of the SSCs and other components under evaluation.
- Consequential events occur when the capacities fall below the response. Determine the probability that the capacities fall below the response.

Example: Hydrogen explosion inside a building (scattering of debris)

$$P(\text{Consequential event}|\text{Causative event}) \approx \frac{k}{N} = \frac{17698}{100000} = 0.177$$



3.4. Evaluation Framework for L2 MU Events
Step (g): Estimation of the Effects of Consequential Events

The effect of each consequential event on the plant’s response is estimated.

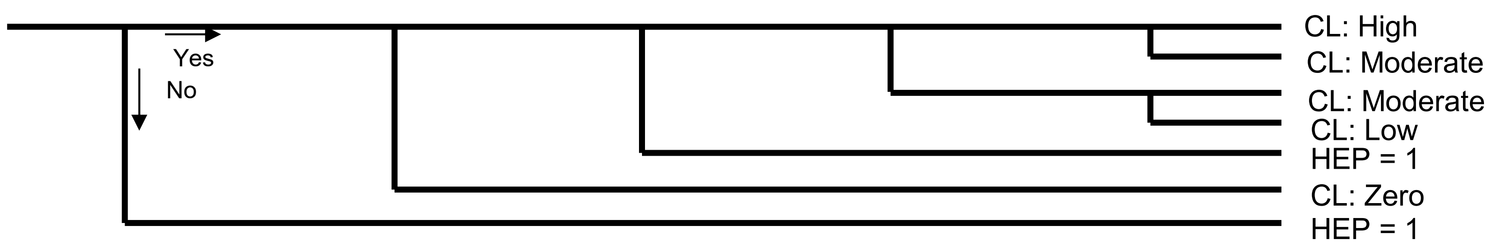
- The impact on the SSC is expressed as a loss of function of the relevant equipment.
- The impact on personnel and operations includes operational stress and effects on accessibility.
  - ➢ For consequential events affecting personnel and operations, the impact on the human error probability (HEP) in existing assessments is taken into account.

Loss of Containment Function (Risk of Hydrogen Explosion)

➢ When applying the simplified MU-HRA method proposed by this institute, the correction level (CL) is set to “High” as this scenario corresponds to “outdoor operations” under “chaotic conditions.”

CL: Correction level

Sufficient response personnel?	Initiating events occur at adjacent units?	Accessible and habitable?	Continuous state of confusion?	Task involves non-MCR (TSC) personnel?

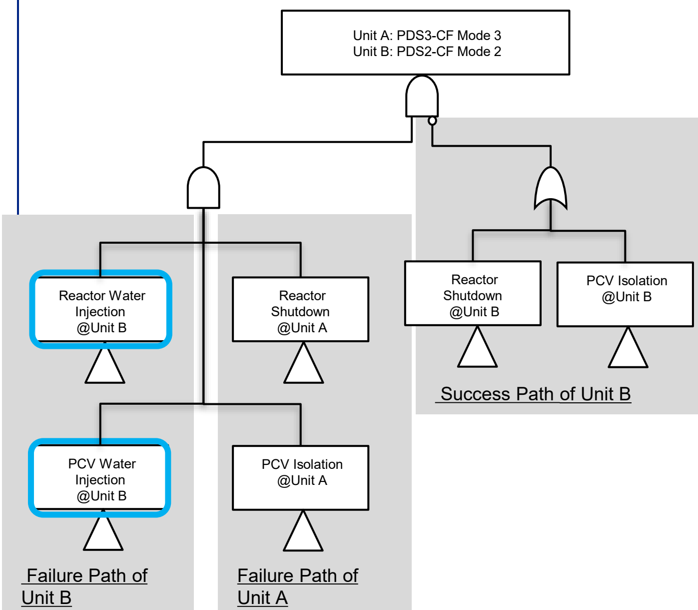


From the Central Research Institute of Electric Power Industry report “Development of a Level 1 Multi-Unit PRA Method for Internal Events” (NR22003)

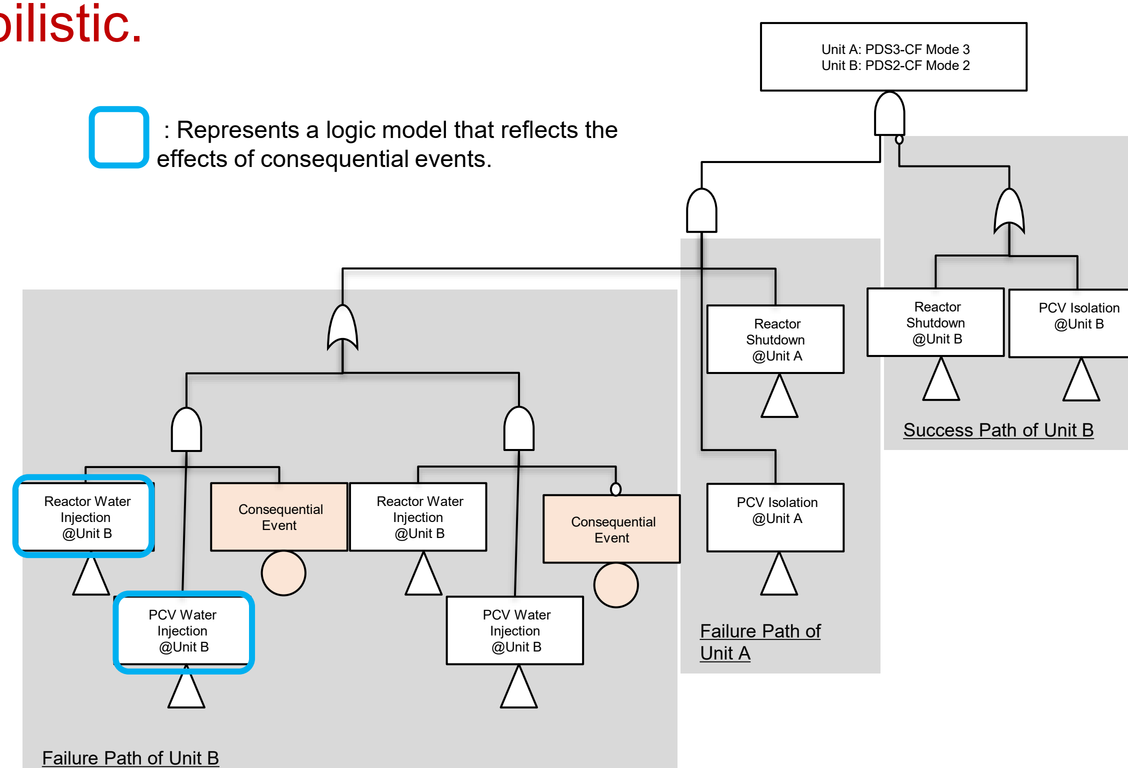
3.4. Evaluation Framework for L2 MU Events
(h) Incorporation into the PRA Model

- The modeling method differs depending on whether the event is deterministic or probabilistic.

: Represents a logic model that reflects the effects of consequential events.



Logic Model for Deterministic Consequential Events

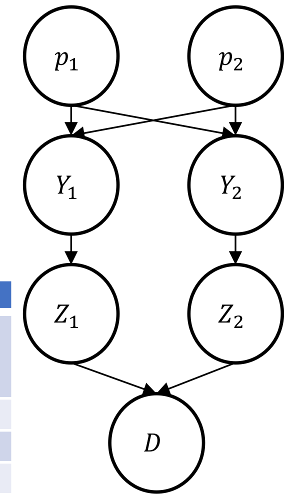


Logic Model for Probabilistic Consequential Events

4.5. Uncertainty Analysis
Estimating Global Relative Sensitivity Coefficients

- Method Using Relative Sensitivity Coefficients for Each Constituent Event

$$S_{D|i} \approx \sum\nolimits_{\pi} \left(S_{D|k_{\pi}} \prod\nolimits_{i=j}^{k_{\pi}-1} S_{\pi,i+1|i} \right)$$



Path 1			Path 2			Path 3			Path 4		
Child Variable Name	Parent variable name	Relative Sensitivity	Child variable name	Parent Variable Name	Relative Sensitivity	Child variable name	Parent Variable Name	Relative Sensitivity	Child variable name	Parent Variable Name	Relative Sensitivity
$\boldsymbol{Y_1}$	p_1	1	Y_2	p_1	1	Y_1	p_2	0.2	Y_2	p_2	0.05
$\boldsymbol{Z_1}$	Y_1	1	Z_2	Y_2	0.2	Z_1	Y_1	1	Z_2	Y_2	0.2
$\boldsymbol{D}$	Z_1	0.2	D	Z_2	1	D	Z_1	0.2	D	Z_2	1

$$S_{D|1} \approx 0.4$$
$$S_{D|2} \approx 0.05$$

$$\sigma_{D,u} \approx \sqrt{\left(0.4\frac{3.5}{0.5}0.05\right)^2 + \left(0.05\frac{3.5}{600}50\right)^2} = 0.14$$

- Method Based on Engineering Judgment

Importance (Magnitude of Impact)	Value of the relative sensitivity coefficient (S)
High	$S = 1.0$
Moderate	$S = 0.2$
Low	$S = 0.05$

4.5. Uncertainty Analysis
Assigning Epistemic Uncertainty to the Estimation Model

- It is difficult to quantitatively determine the uncertainty inherent in an estimation model.
- Therefore, to reduce the number of unknowns and facilitate engineering decisions, we use the following equation based on the coefficient of variation ($CV_{p_i} = \left.\frac{\sigma_{p_i}}{p_i}\right|_{base\ case}$).

$$\Delta\sigma_{D,u} \approx \sqrt{\left(S_{D|p_i} D \cdot \left.CV_{p_i}\right|_{base\ case}\right)^2}$$

Proposed Guidelines for Setting the Relative Sensitivity Coefficient

Importance (Magnitude of Impact)	Value of the Relative Sensitivity Coefficient (S)
High	$S = 1.0$
Moderate	$S = 0.2$
Low	$S = 0.05$

Proposed Guidelines for Setting the Coefficient of Variation

Model Accuracy	Value of the coefficient of variation (CV_X)
High	$CV_X = 0.1$
Moderate	$CV_X = 0.2$
Low	$CV_X = 0.3$