Probabilistic Safety Assessment & Management (PSAM) 16
Honolulu, Hawaii
June 26 – July 1, 2022

Uncertainty Analysis of Dynamic PRA Using Nested Monte Carlo Simulations and Multi-Fidelity Models

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Acknowledgement: Part of the research has been performed within the project of “Methodology Improvement and Application Investigations of Level 1 Dynamic PRA” which is sponsored by the Nuclear Regulation Authority (NRA) of Japan

Introduction

- In Japan, risk-informed decision-making (RIDM) is being practiced to improve safety of nuclear power plants, for example,
  - In 2020, Risk-Informed Inspection System (inspired by ROP of USNRC) was newly launched by Nuclear Regulation Authority of Japan (JNRA).
  - Japan's utility companies are practicing RIDM for plant operation management and external hazard defense.

Role of JAEA

- While sophisticating PRA approaches and improving the reliability of risk information, JAEA is making recommendations and providing tools to JNRA, and applying them to own facilities.

Implementations at JAEA

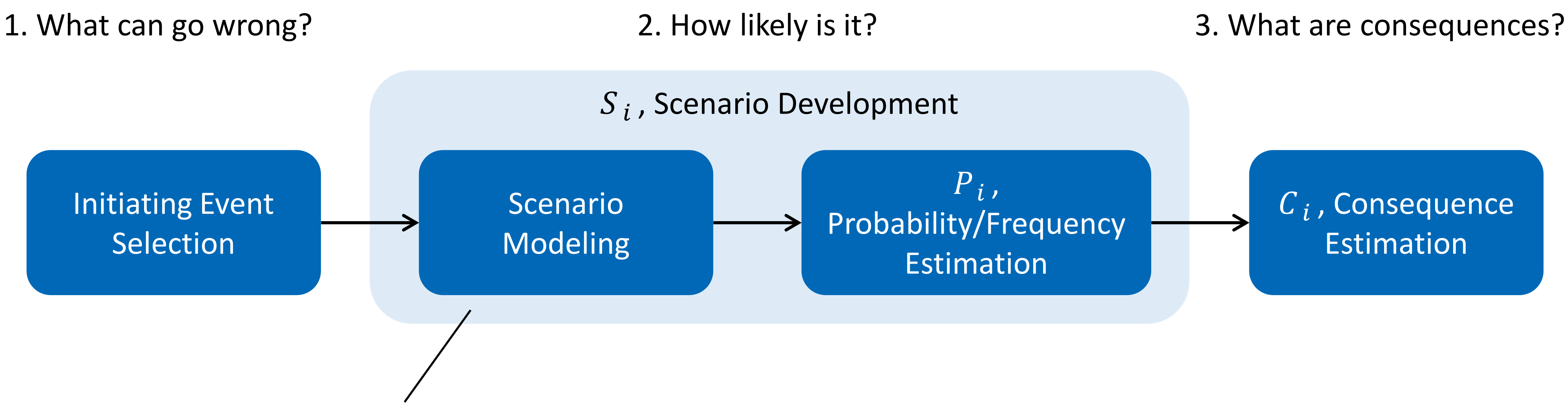
- Developing a simulation-based dynamic PRA approach and a simulation platform for risk quantification.
- Because epistemic uncertainties inevitably exist in PRA, we are trying to investigate how uncertainty analysis can be treated in dynamic PRA.

Background of Probabilistic Risk Assessment (PRA)

- By quantifying Risk Triplet, PRA is an important methodology to provide reliable information for decision-making under uncertainty in nuclear engineering.

$$R = \{\langle S_i, P_i, C_i \rangle\}, i = 1, 2, \cdots, N$$

Ref: Kaplan and Garrick, On the quantitative definition of risk (1981)

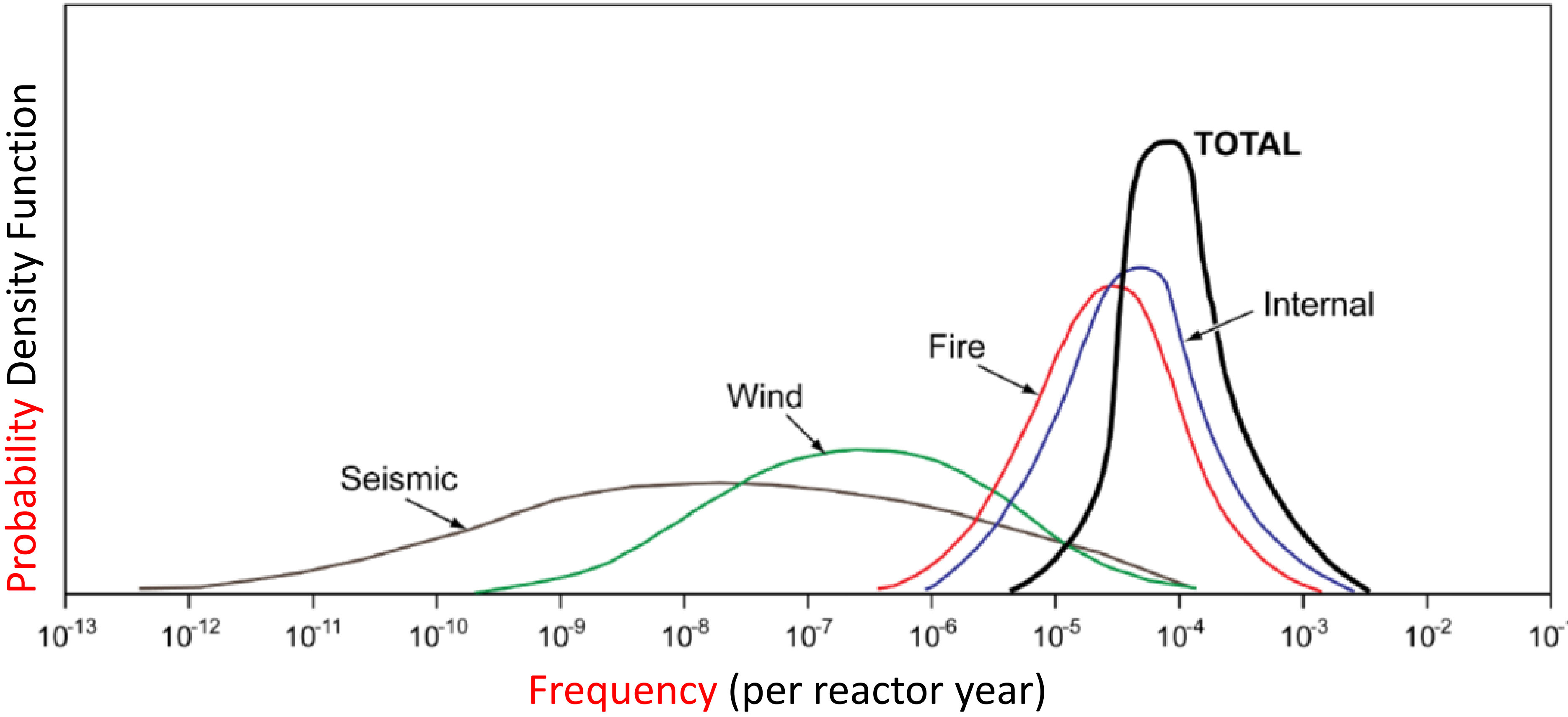


Constructed by using binary-logic-based ET/FT models and engineering judgements, PRA models have limitations (epistemic uncertainties) to reflect the real-world risk

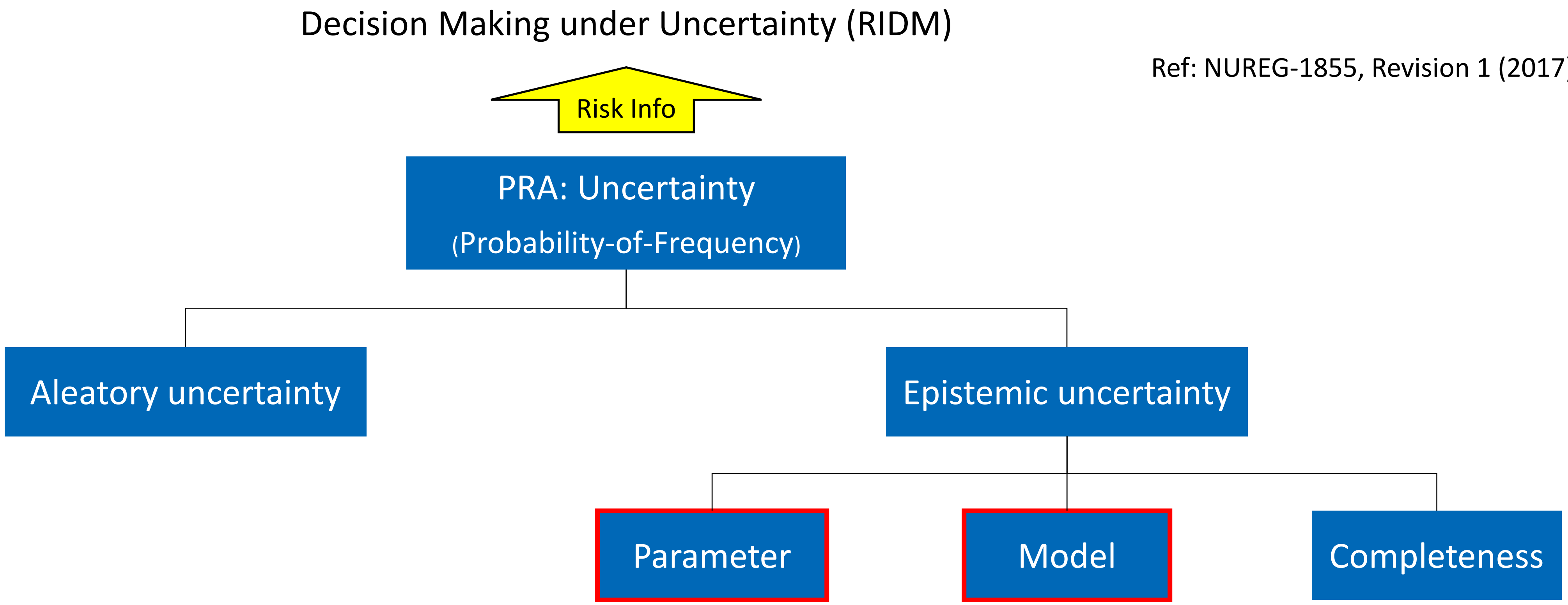
PRA Uncertainties in the Form of Probability-of-Frequency

- An example of PRA uncertainty analysis:
  Core damage frequencies (CDFs) induced by different initiating events at Indian Points NNP (1980s)

Ref: Uncertainty and uncertainties, USNRC Lecture 3-2 of NPP PRA and RIDM, (2019)



Type of Uncertainties



Ref: NUREG-1855, Revision 1 (2017)

Parameter uncertainty: uncertainty in the input parameters used to quantifying the frequencies/probabilities of the events in the PRA logic model.

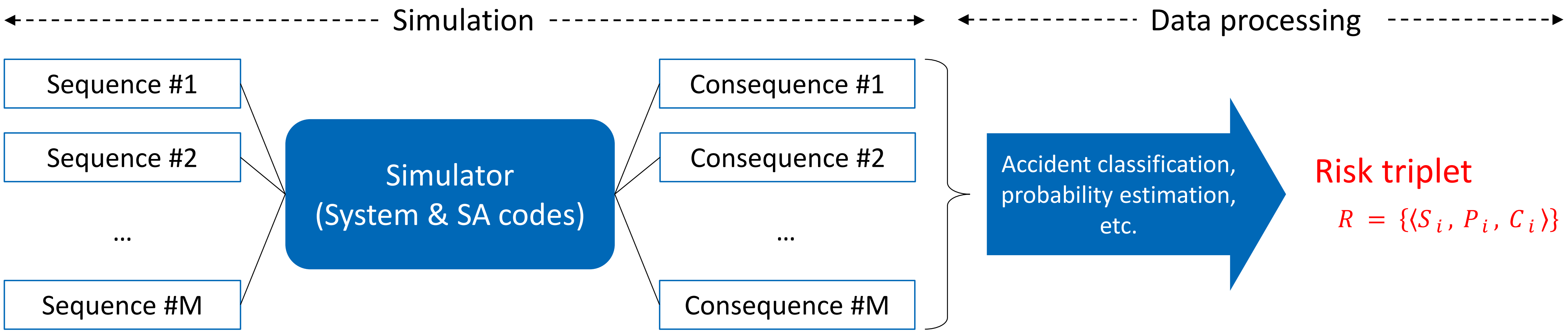
Possible sources of Model uncertainty:

- Unclear phenomena such as behavior of gravity-driven passive systems during a severe accident
- SSC behavior under accidental conditions: usually inferred from generic failure database, etc.

Simulation-Based Dynamic PRA

Reference: IAEA Technical Meeting on Enhancement of Methods, Approaches and Tools for Development and Application of PSA (2020)

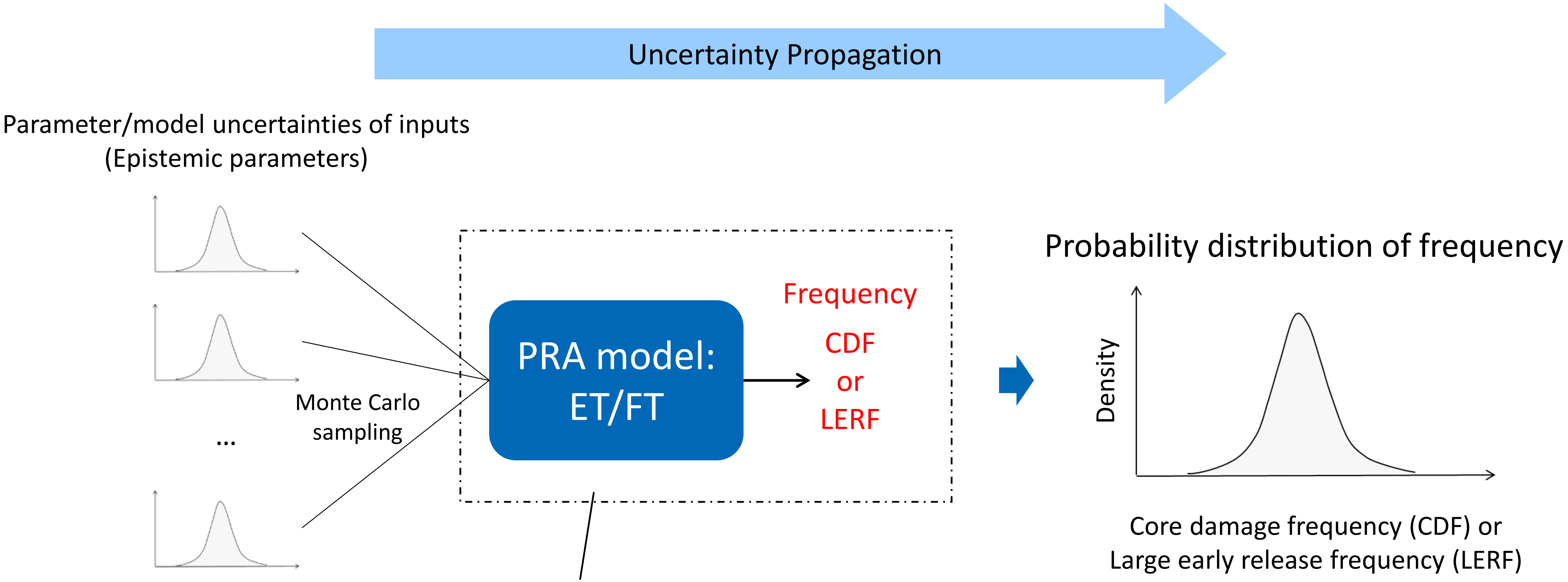
- Dynamic PRA (DPRA) explicitly models system dynamics and interactions by employing simulation in a more general manner, for example,
  - Events change system dynamics
  - System dynamic status affects event likelihood



- Dynamic PRA is a promising approach which can reduce subjective judgments, and reduce model uncertainties by using time-dependent failure modeling, etc.
- But there are still residual uncertainties.

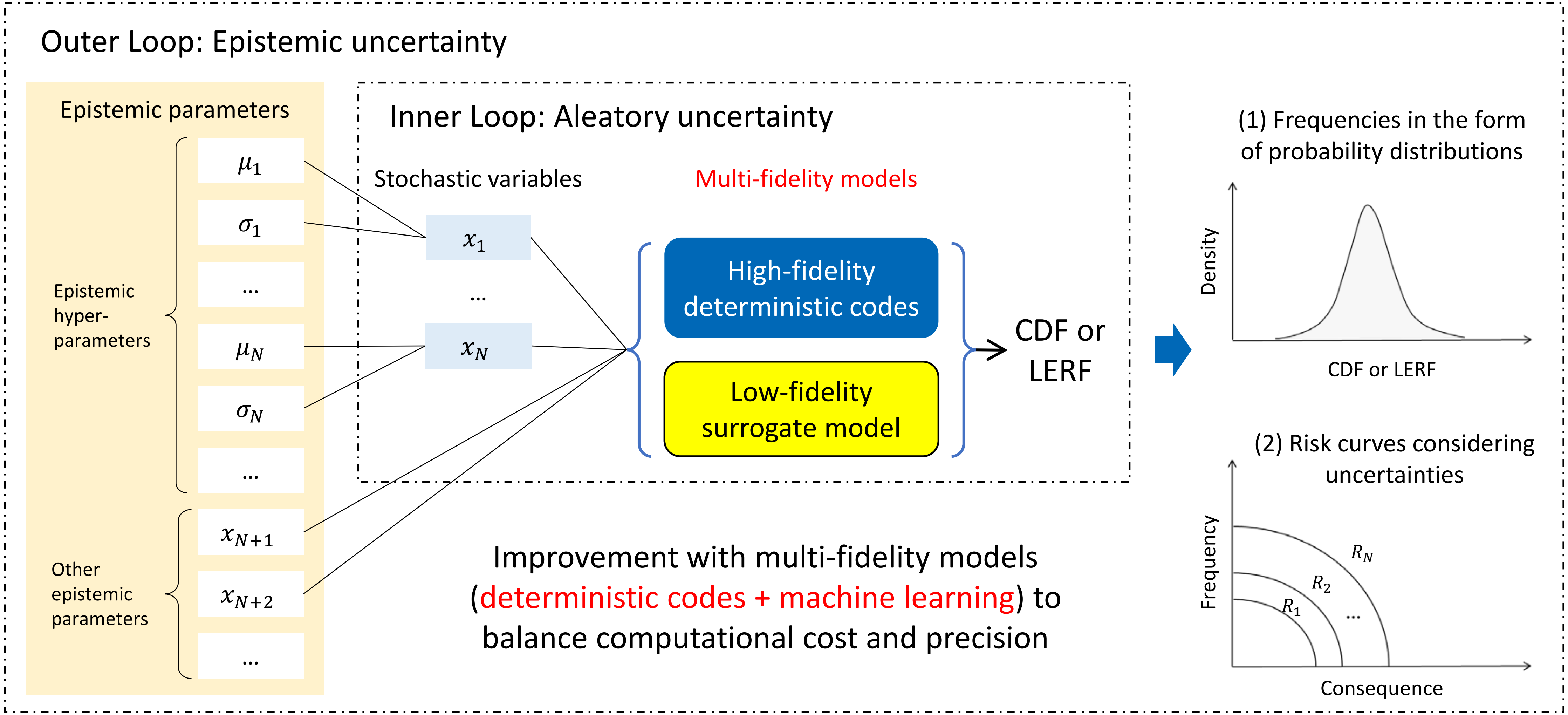
Review: Standard Approach of PRA Uncertainty Analysis

Reference: M. Modarres and I.S. Kim, Probabilistic Risk Assessment, Encyclopedia of Nuclear Energy, Vol.2 (2021)



Dynamic PRA uses simulation to replace logic-based models, so it requires a nested Monte Carlo structure

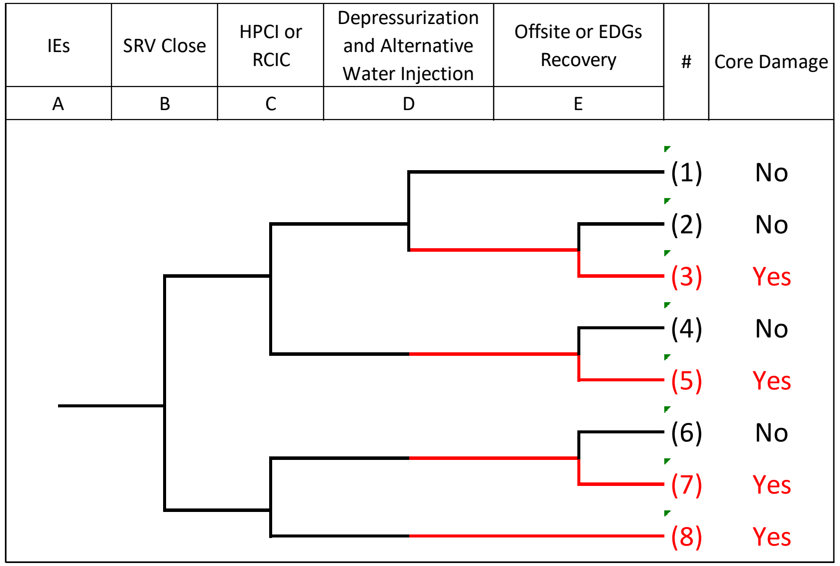
Nested Monte Carlo for Uncertainty Treatment in Dynamic PRA



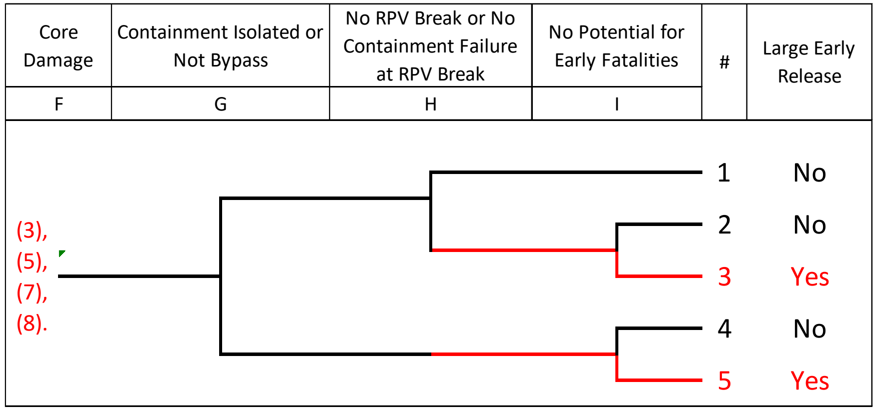
Ref: E. Hofer, et al. An approximate epistemic uncertainty analysis approach in the presence of epistemic and aleatory uncertainties, RESS 77: 229-238 (2002)

Combined Level 1 and 2 PRA Modeling for Dynamic PRA

Level 1 PRA (SBO Event Tree)



Level 2 PRA (Containment Event Tree)



Determination of stochastic variables according to headings in ET

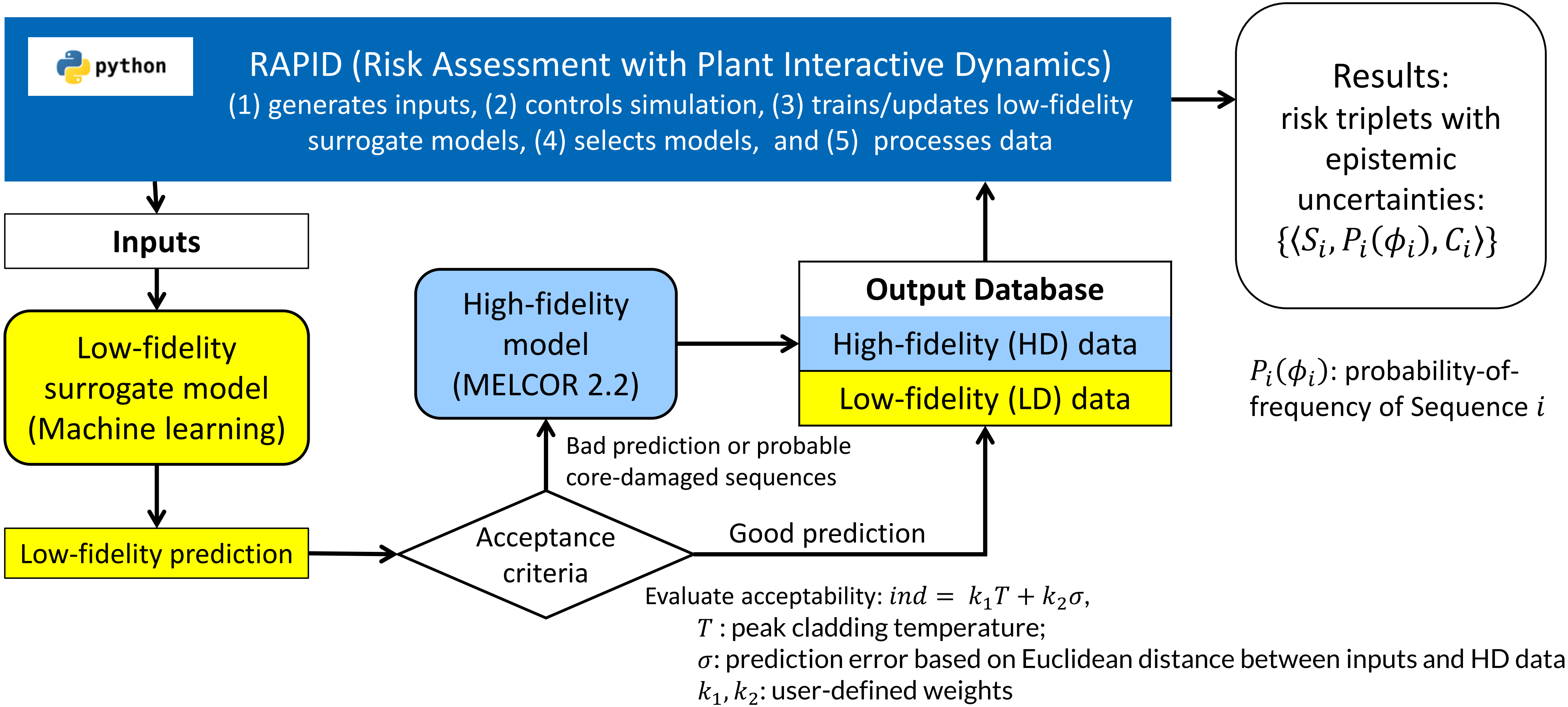
Stochastic variables for frequency estimation	Distributions	Parameters of distribution
EDGs recovery time (h) Power grid recovery time (h)	Lognormal	μ_1, σ_1
Battery life (h)	Triangular	a, b, c
Number of cycles before SRV stuck open happens	Geometric	p
RCIC failure time (h) HPIC failure time (h)	Exponential	λ
RCIC extended time (h)	Lognormal	μ_2, σ_2
Alternative water available time (h) Manual automatic depressurization activation (h)	Lognormal	μ_3, σ_3

Selection of epistemic parameters that affect Level 1&2 PRA

Epistemic parameters for uncertainty estimation		Distributions or constants
Parameters of distributions	$\mu_1, \sigma_1, a, b, c, p, \lambda, \mu_2, \sigma_2, \mu_3, \sigma_3$	Uniform
Containment bypass time (h)		Uniform
Containment early failure pressure (Pa)		Lognormal
Criteria for early and large [20]		Early: 4 hours after EAL-GE (declaration: 5 mins after the loss of AC and DC powers), Large: 3% of initial radionuclide inventory including Cs, I and Te)

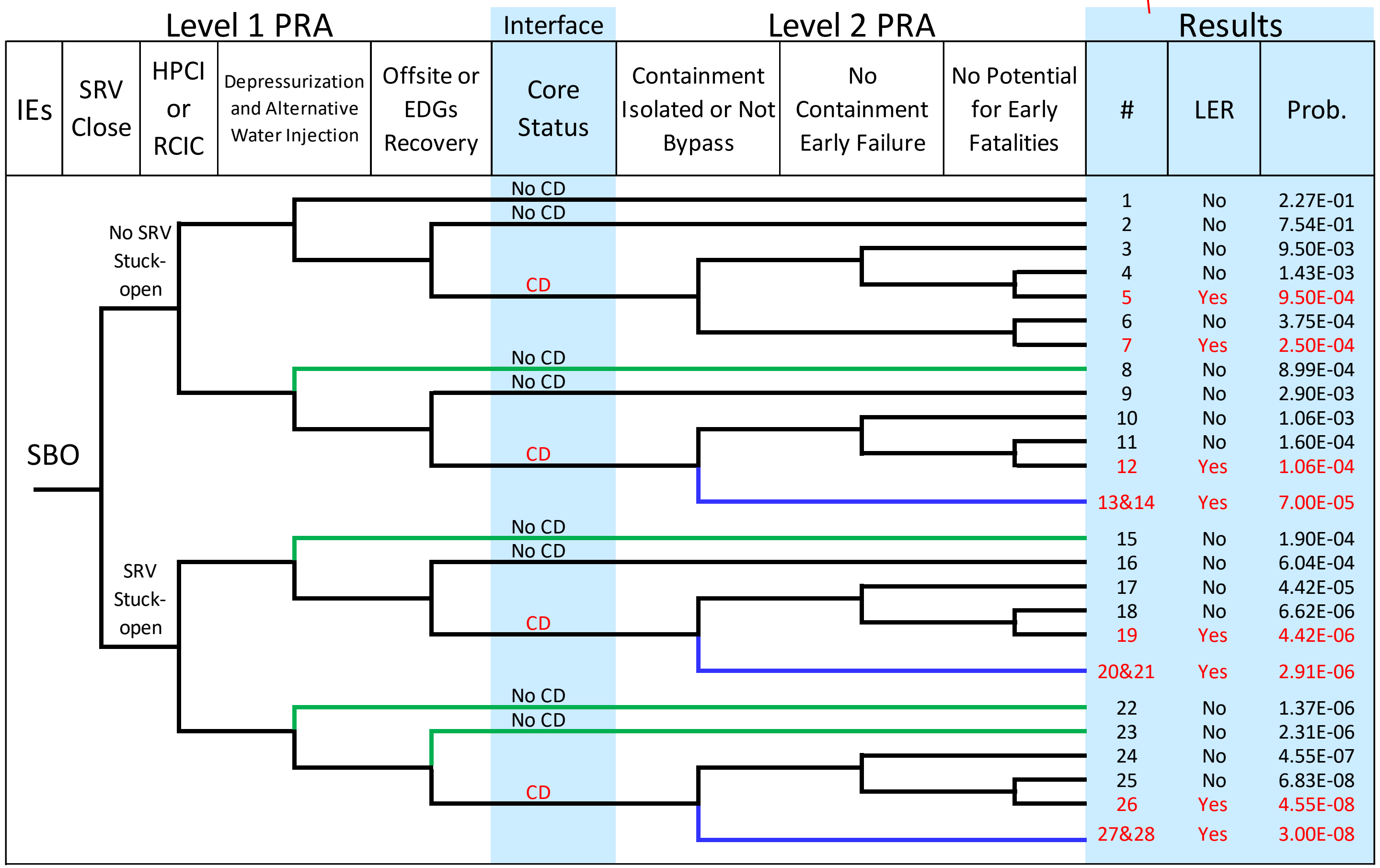
Risk Simulation Using MELCOR2.2 and RAPID

Implemented Multi-Fidelity Monte Carlo (MFMC) to JAEA's dynamic PRA tool for saving computational cost of dynamic PRA

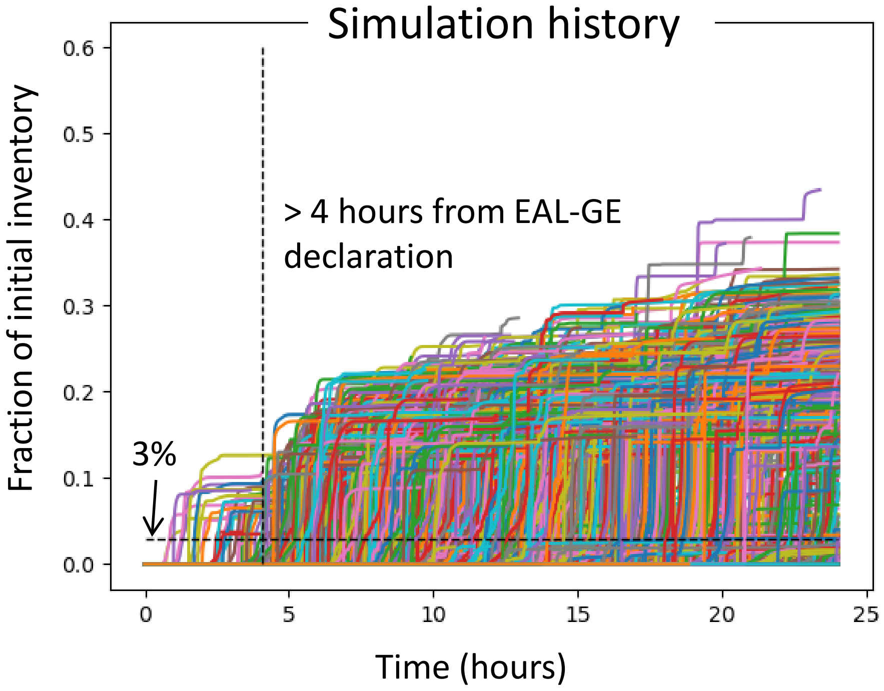


Sequence Classification of the Best Estimated Risk Metrics

The risk triplet including sequences (scenarios), probabilities, and consequences.

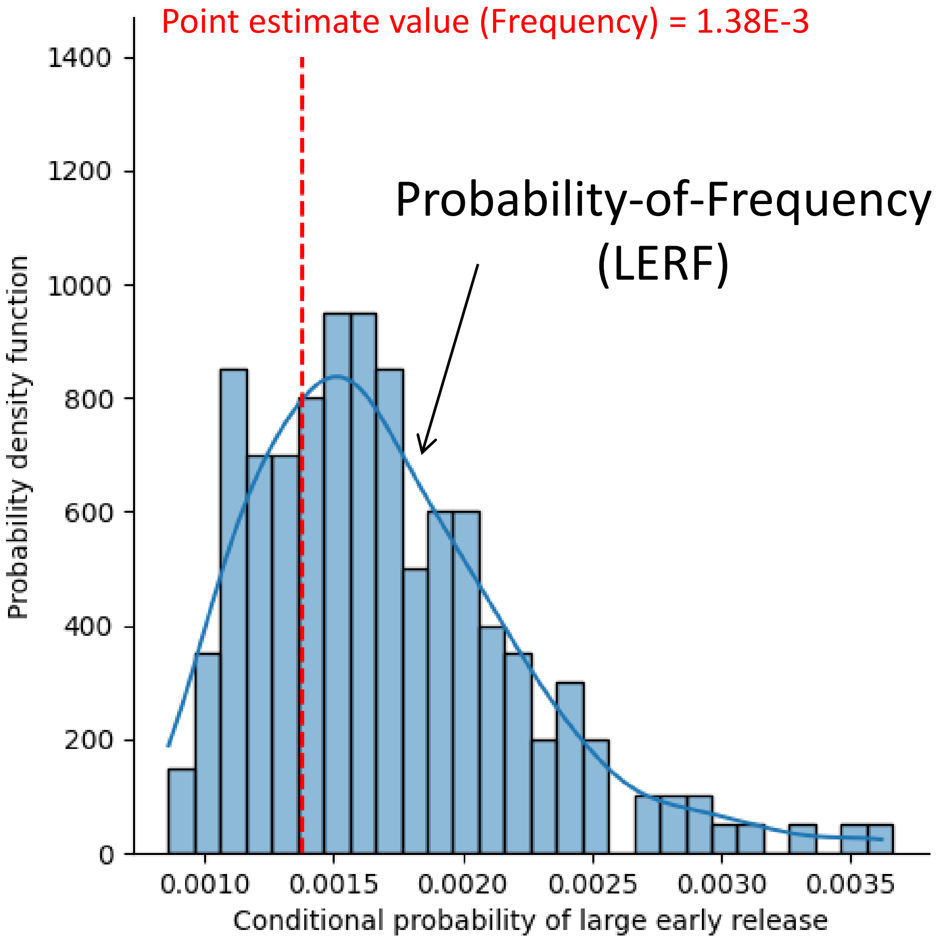


Feedback from dynamic PRA to static PRA:
- Improved the completeness of PRA models (green)
- Merged less-realistic branches after considering time (blue)



Risk Metrics	Point Estimate Results
CCDP (conditional core damage probability)	1.40E-2
Conditional probability of LER (large early release)	1.38E-3

Preliminary Uncertainty Analysis Results of Level 2 PRA



With the treatment of aleatory uncertainty (inner Monte Carlo loop) and epistemic uncertainty (outer Monte Carlo loop), dynamic PRA can

- Provide a more integrated estimation of the probability density function of risk metrics
- Combine Level 1 and 2 PRAs, e.g. for LERF estimation

Expectation: within the dynamic PRA framework, the dependency between failure modeling and accident progression can be better treated, so such model uncertainties can be avoided.

Uncertainty Analysis Comparison Between PRA and Dynamic PRA

		PRA	**Dynamic PRA**
Method of frequency estimation (Aleatory uncertainty)		Boolean-Logic-based	Simulation-based (Monte Carlo)
Epistemic uncertainty types	Examples of parameter uncertainty	Frequencies of initiating events, branching probabilities, …	Parameters of probability distributions
	Examples of model uncertainty	ET/FT structure, failure model of sub-systems, …	Mathematical form of probability distributions, reliability modeling, …
	Completeness	Treated by Defense-in-Depth and the maintenance of safety margin	
Method for uncertainty propagation		Monte Carlo	Two-stage nested Monte Carlo
Result visualization		Probability distribution of frequencies, risk curves, …	

Conclusions of Dynamic PRA Uncertainty Analysis

- The two-nested Monte Carlo approach has been implemented in JAEA’s dynamic PRA tool, as the result, effectiveness of quantifying aleatory and epistemic uncertainty has been confirmed.
- To alleviate the computational cost of dynamic PRA, multi-fidelity simulations have been applied by flexibly selecting between deterministic accident codes and machine learning models.
- The dynamic PRA can provide a more integrated Level 1&2 PRA.
- In future, we plan to show that dynamic PRA has the advantages in reducing PRA epistemic uncertainty by explicitly considering the dependencies between failure-of-physics and accident progression.

To PSAM16 organizers and attendees:

Thank you very much!