Japan Atomic Energy Agency

Development of a Simulation-Based Dynamic PRA Methodology
（シミュレーションに基づく動的PRA 手法の開発）

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本件は、原子力規制庁から受託した「平成31年原子力施設等防災対策等委託費（動的レベル1確率論的リスク評価手法の開発）事業」の成果を含む。

Background

- Risk: An index to evaluate safety achievements and find weakness
- In Japan, risk-informed decision-making is being practiced to improve safety of nuclear power plants.

Probabilistic risk assessment (PRA):

$$\text{Risk} = \text{Frequency} \times \text{Consequence}$$

Role of JAEA

To contribute to improving the reliability of risk information, JAEA is making recommendations, providing tools for the sophistication of PRA methods, and applying them to JAEA facilities.

Implementations

JAEA is constructing an advanced PRA methodology, which is dynamic and simulation-based, and developing a simulation platform, with improvements on versatility and expandability for general-purposed applications.

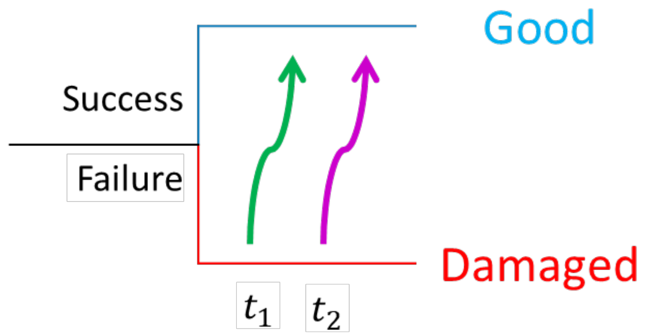
Dynamic PRA and its Advantages

Dynamic PRA: explicitly models system dynamics and its stochastic behaviors, employing deterministic simulations and probabilistic methods.

Classical PRA

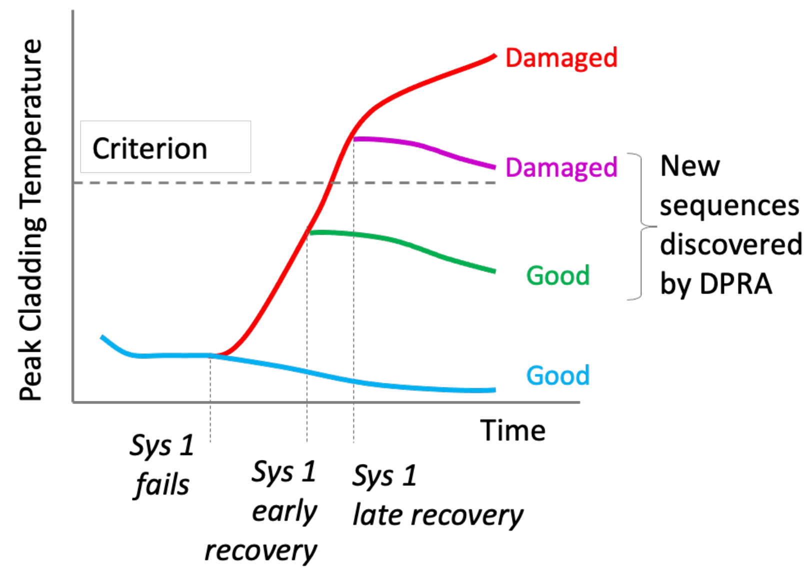
- Difficult to treat “timing” issues
- Plant-generic & scenario-independent failure probability

Initiating Event	System 1	Core Status



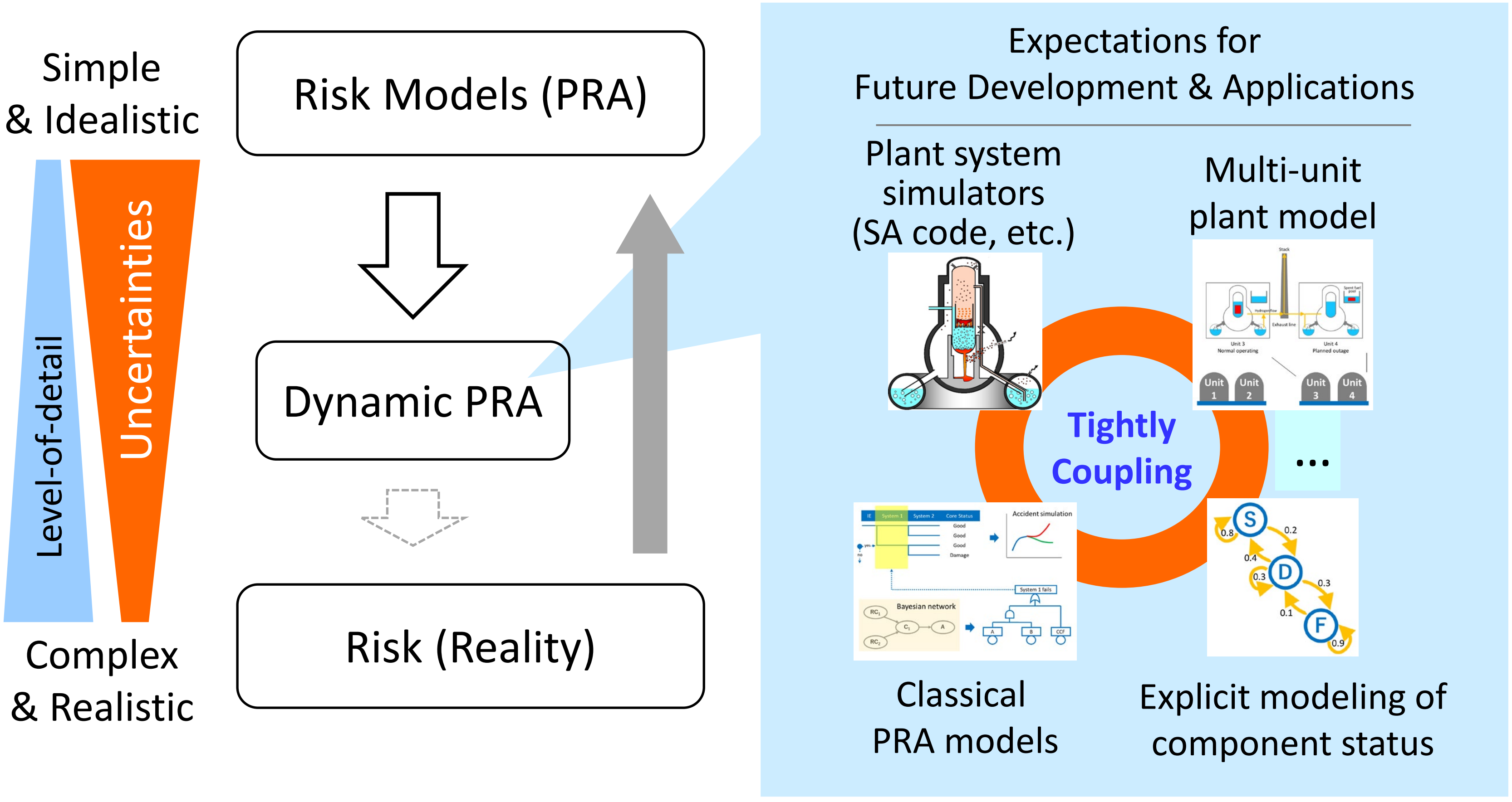
Dynamic PRA

- Use stochastic methods to treat “timing” issues
- Scenario-dependent failure modeling



Dynamic PRA Can Reduce PRA Uncertainties

Applying simulation approaches in general, DPRA improves the reliability of risk information by including more details and reducing uncertainties



DPRA Example: Evaluate Benefits of Accident Tolerant Fuel

LWRS (Light Water Reactor Sustainability) Program, INL/USDOE

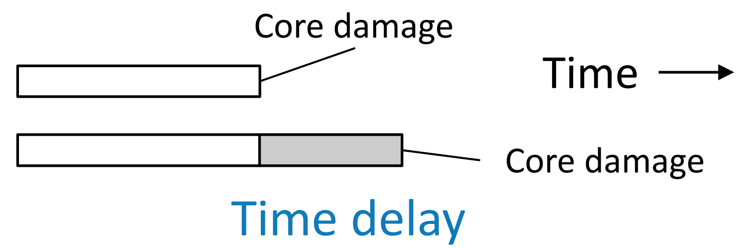
Accident Tolerant Fuel (ATF): new design of LWR fuel with improved resistance against severe accident conditions,

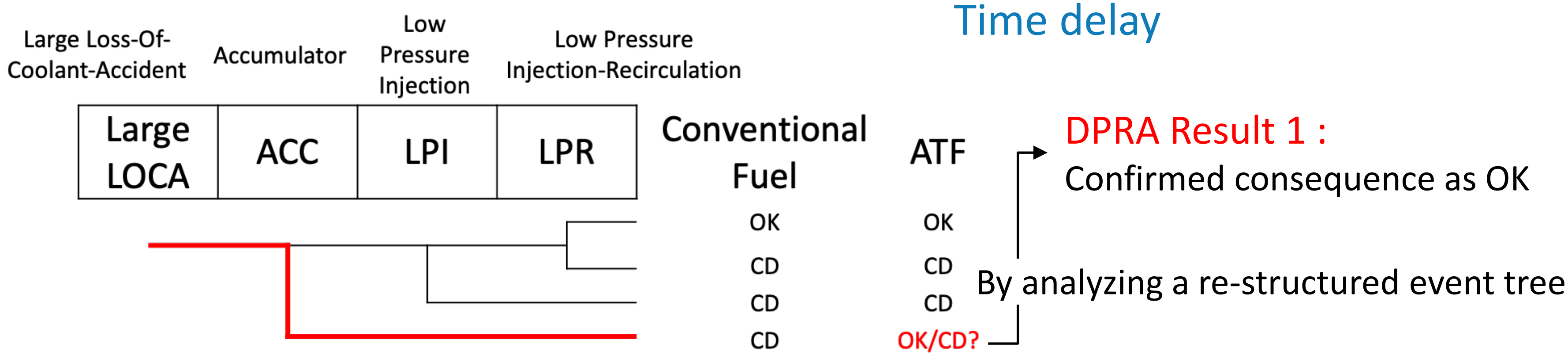
- enhanced fission product retentions
- enhanced fuel-thermo-physical and fuel-cladding properties

Comparison:

Conventional fuel (Zr cladding):

ATF (SiC, FeCrAl or other cladding materials):

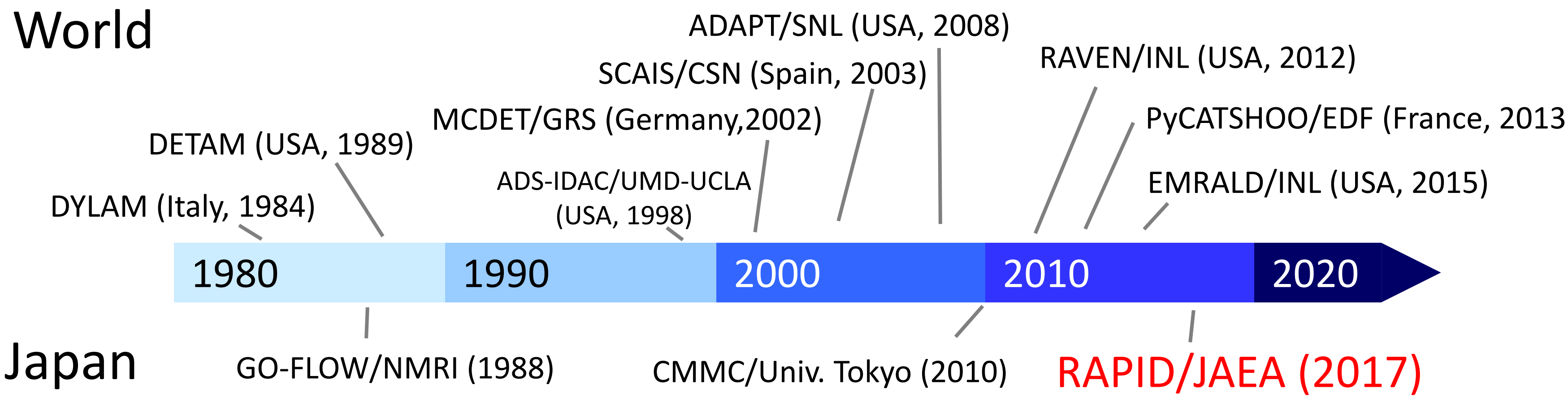




- DPRA Result 2: Quantified time delays of core damage and hydrogen production for core-damaged sequences

Reference: Mandelli, Accident tolerant fuels: a PRA comparison, IRUG Meeting (2019)

DPRA Research Status in- and outside of JAEA



Current Development Status at JAEA

	2017-2019	2020	2021	Future
Methodology	Established how to explicitly model system interactions			
Computational tool	Code design, Scenario generator	Sampling methods, Computational efficiency		
Applications	Level 1 DPRA of simplified accident scenarios	Level 1 DPRA of station blackout (SBO) accident		Specific applications: Level 2 DPRA, multi-unit DPRA, etc.

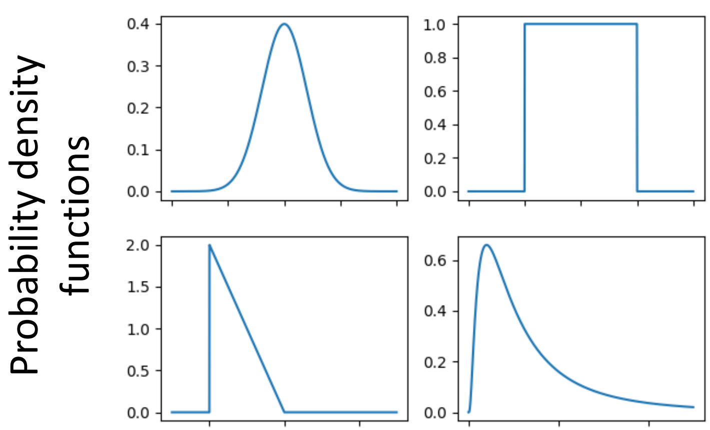
Now

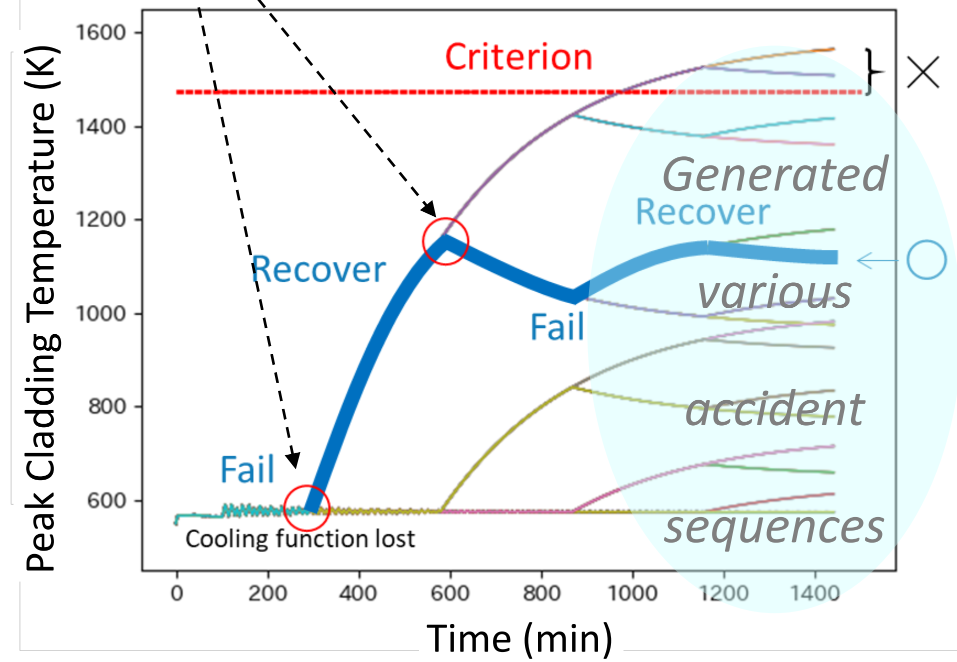
Typical Procedure of DPRA

1. Scenario generation by sampling methods → 2. Simulation with accident sequences branching → 3. Summarize simulation consequence and probabilities

Accident progression branching:

- Timing of failures,
- Timing of recoveries, …





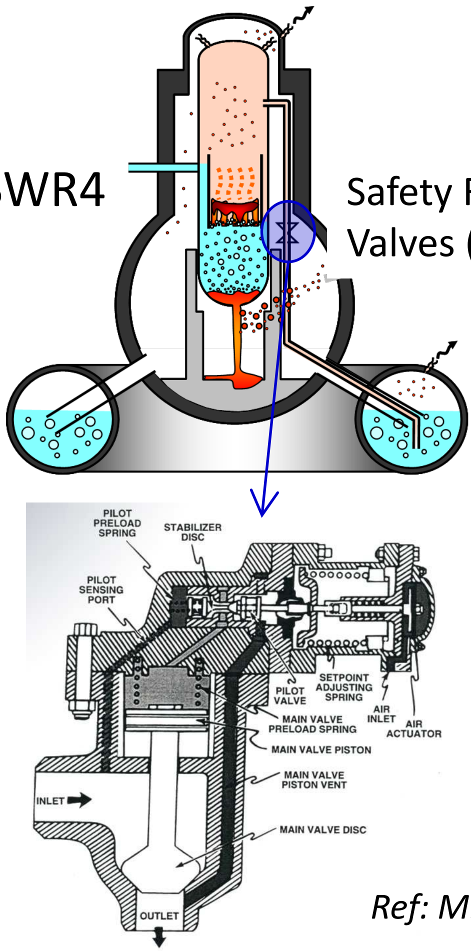
Problem: failure probabilities are simplified as independent from accident progression ▶ JAEA Solution: scenario-dependent failure modeling (**Interaction**)

Interactive SRV Failure Modeling by JAEA

1. Traditional simplified model: $prob = g(Number\ of\ Demands)$
2. But if considering Physics-of-Failure: SRVs seizure at open when operating at high gas temperature, $prob = f(Temperature)$

BWR4

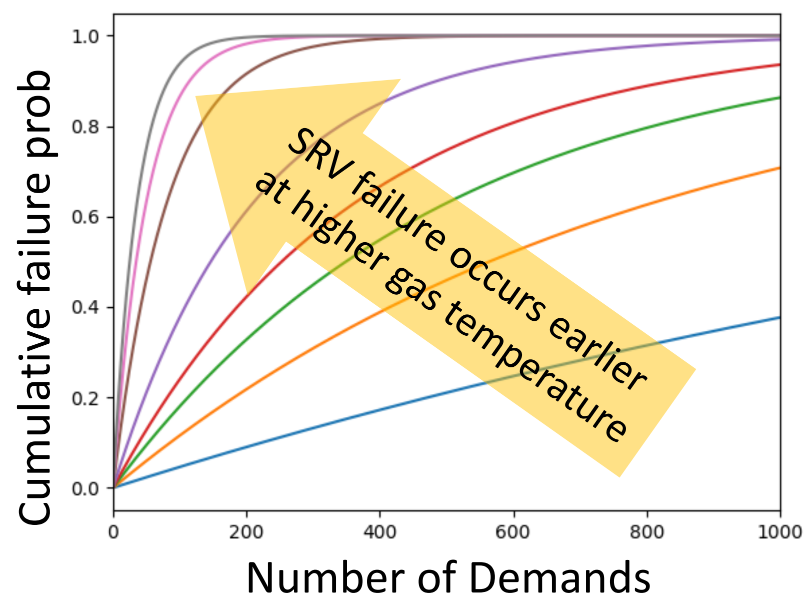
Safety Relief Valves (SRVs)



Realistic: scenario-dependent SRV failure models

$prob = F(Temperature, Number\ of\ Demands, Time)$

DPRA estimates failure probabilities using simulation

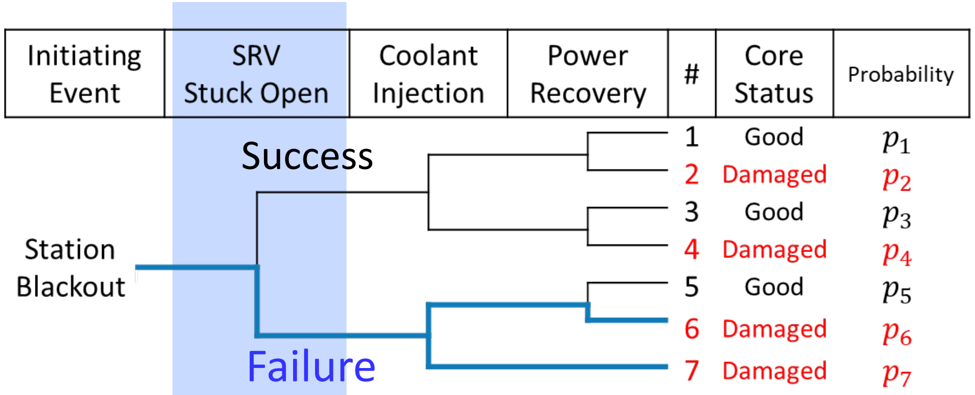


Ref: MELCOR Best Practices - An Accident Sequence Walkthrough, 2008 EMUG, Swiss

Comparison Between PRA and DPRA

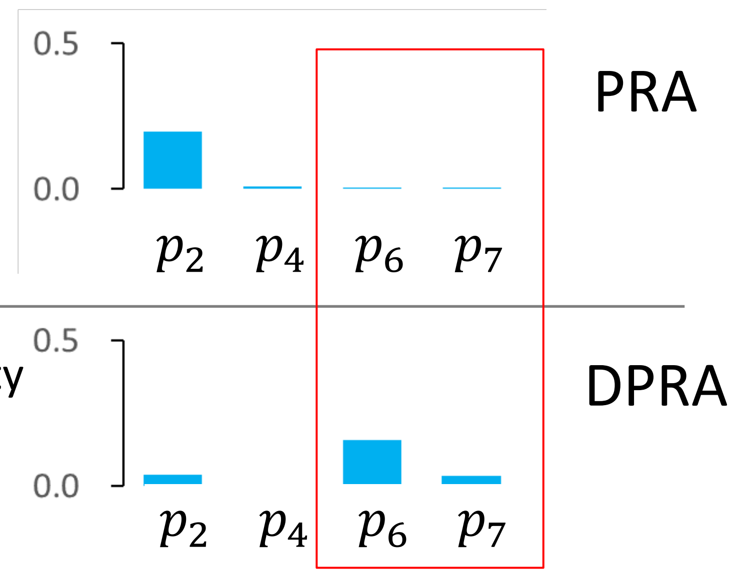
Ref: NUREG/CR-6928, Industry-average performance at US commercial NPPs

Simplified event tree for BWR Station Blackout



SRV stuck-open probability on demand (from generic database)

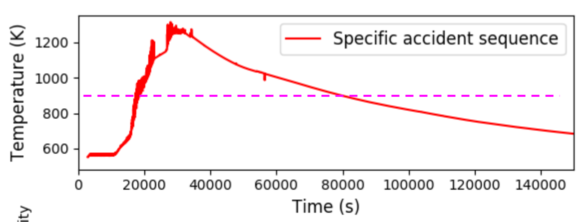
$\text{Prob}_{(\text{Failure})}$ ~ Beta(α:0.5, β:628.1)
mean: 7.95E-04



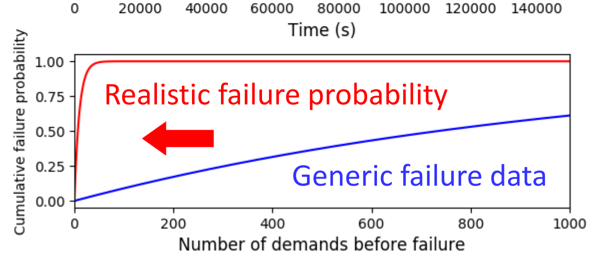
From: scenario-independent probability

To: scenario-dependent failure probability

Gas temperature in coolant system



SRV failure



SRV tends to fail with fewer open/close cycles ($p_{srv|SBO} > p_{srv}$), resulting in the change of CCDP distributions

DPRA may change PRA results

Development of JAEA Methodology for Dynamic PRA

Tightly coupling simulation, JAEA has established an integrated dynamic PRA framework.

Frequency

Probabilistic analysis

- Scenario generation
- Sampling
- Post data processing (Machine learning)
  - Surrogate model training
  - Classification, regression

Interaction Modeling

Consequence

Deterministic analysis

- System analysis using simulations
- Plant operations
- Source term analysis

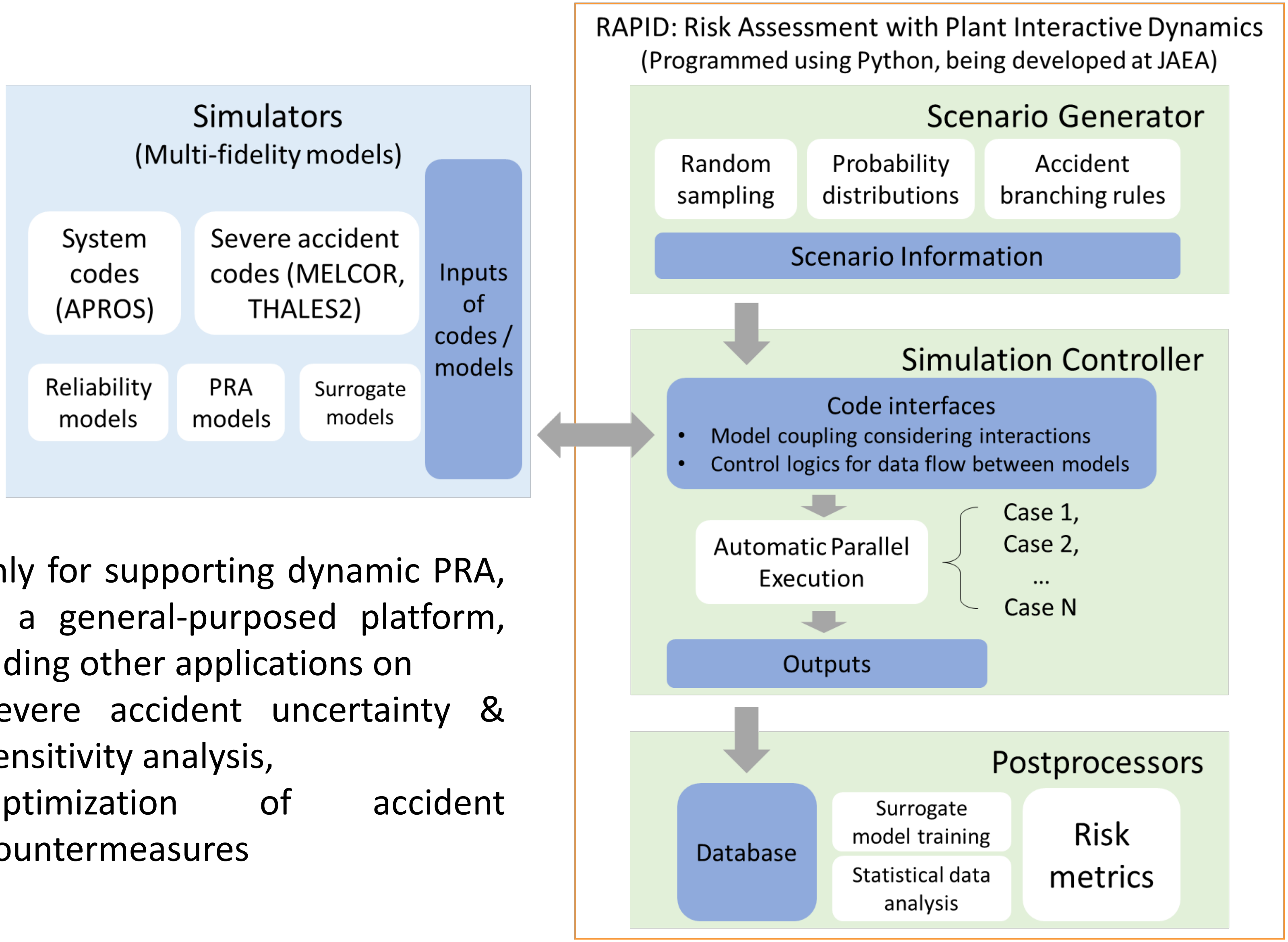
SA codes, System codes, …

Occurrence probabilities, Accident consequences, Risk

Simulation-based Risk-Informed Decision Making (RIDM)

The method refers to the RISMC (LWRS, USDOE) approach developed at INL,
but with a unique accident scenario generation mechanism considering frequent simulation interactions

Design and Development of DPRA Tool (RAPID)

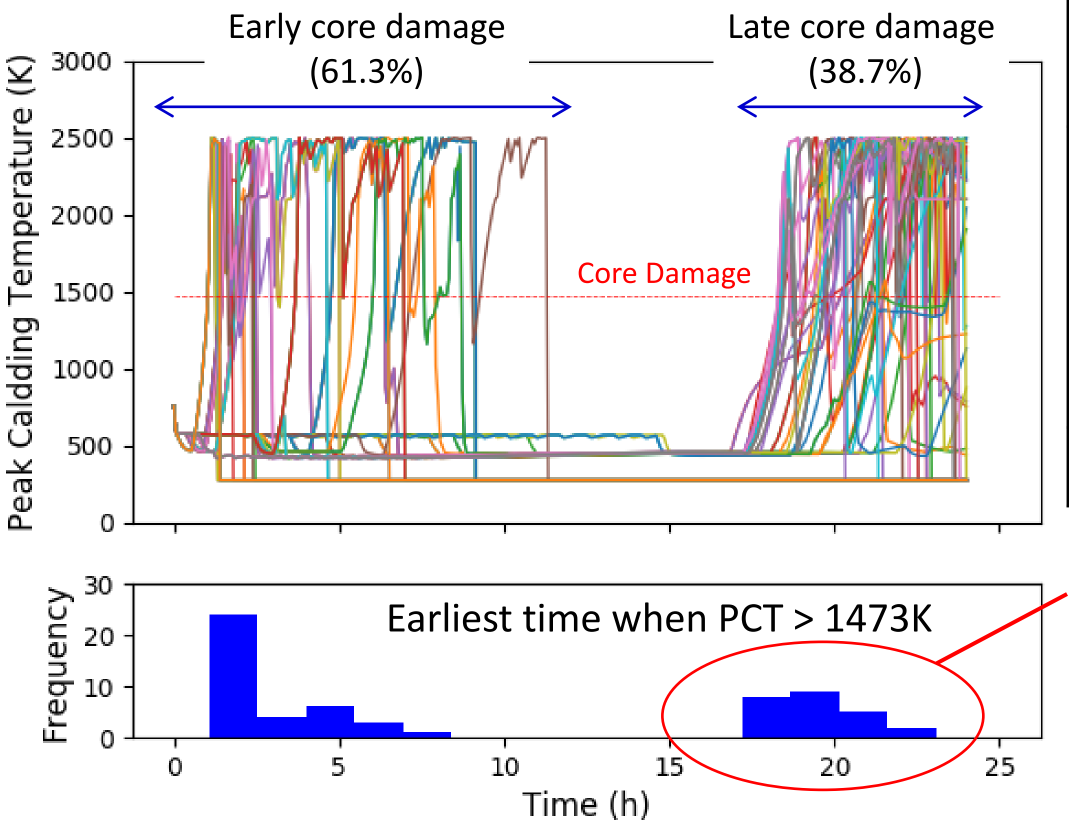


Mainly for supporting dynamic PRA, it is a general-purposed platform, including other applications on

- Severe accident uncertainty & sensitivity analysis,
- Optimization of accident countermeasures

Preliminary Dynamic PRA using THALES2 & RAPID

Sequences of Station Blackout (SBO) with core damage



Uncertain systems and factors Monte Carlo sampling with the consideration of system interactions	
EDG	Recovery time
DC	Depletion time
SRV	Fail to close (Thermal seizure failure, etc.) and open area
Pump	Seal failure rate and leak area
Others: RCIC, HPCS, Depressurization, LPCI.	

Low-pressure coolant injection system became unavailable because of high S/C water temperature, which can be avoided by recovering residual heat removal system.

Probabilistic and deterministic simulations are successfully integrated within DPRA, as well as the explicit modeling of "timing" differences for accident mitigation actions.

Conclusions and Future Work

Conclusions

- Dynamic PRA has shown advantages over PRA
- JAEA has established a simulation-based methodology and a computational platform (RAPID) of dynamic PRA:
  - Integrated deterministic and probabilistic analyses,
  - Tightly coupled heterogeneous models and tools (system codes, PRA models, reliability models, …)
  - Systematic treatment including (1) advanced sampling methods, (2) scenario generation, (3) uncertainty propagation, (4) phenomena simulation, (5) statistical data analysis including surrogate model training

Future work

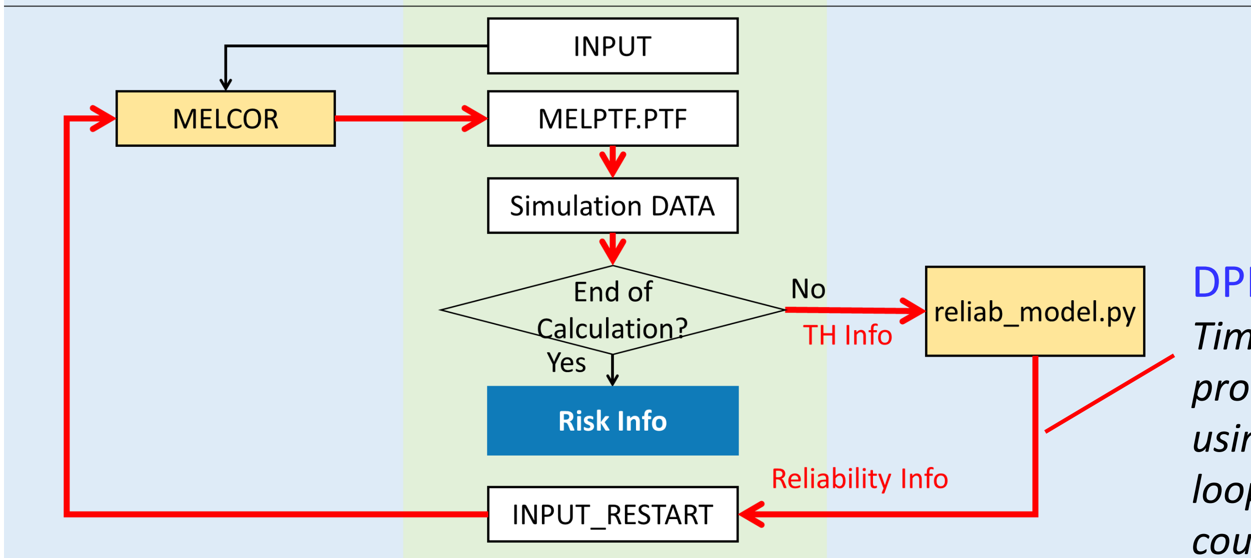
- Development of RAPID is still ongoing, especially in terms of a general-purposed platform.
- Also trying to make it useful for other PRA applications (for example, multi-unit PRA, HRA, external event PRA, …) and uncertainty analysis.

Ongoing Level 2 Dynamic PRA using MELCOR2.2 & RAPID

More precise source term uncertainty quantification using dynamic PRA

- A large number of parallel executions of MELCOR2.2-RAPID on JAEA supercomputers

Deterministic Simulation	DPRA Simulation Platform	Probabilistic Simulation
MELCOR 2.2	**RAPID**	**Reliability analysis module**
• Thermal-hydraulics, • Core status, • Source term, …	• Generate scenarios, • Control simulations, • Manage model interactions & process data, …	Options for model selection, e.g. • Physics of failure, • Markov model, • Failure probabilities, …



DPRA Advantage:

Time-dependent failure probability is explicitly treated using the interactive feedback loop with a discrete-time coupling scheme

Development of Support Techniques for DPRA

(1) Sequence clustering:

DPRA : Simulation data mining using machine learning

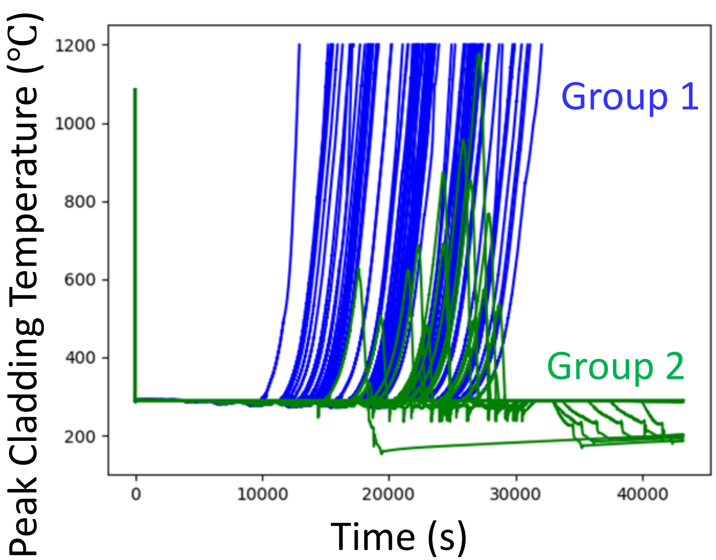
Advantage:

Automatic

No need to find representatives

Rule-based (less subjective)

RAPID-Apros (VTT-Fortum, Finland)



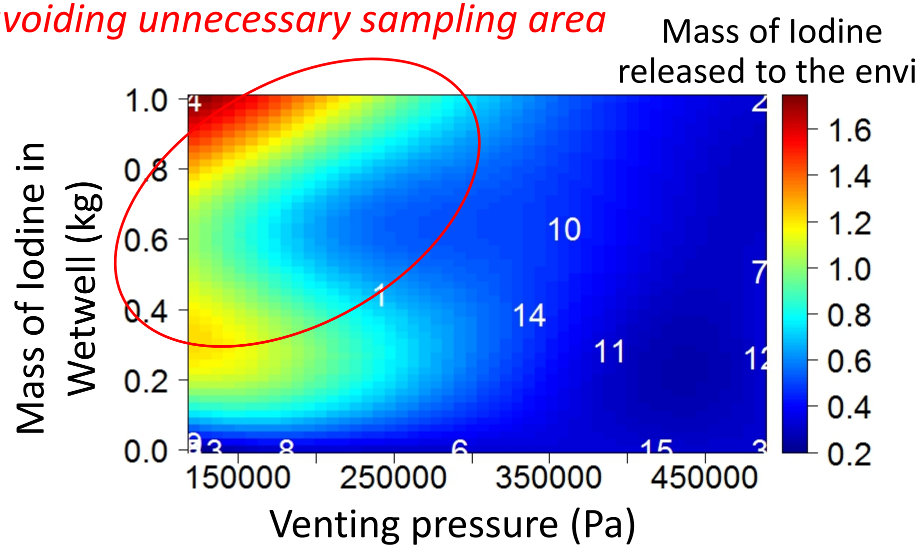
(2) Sampling and uncertainty propagation:

DPRA: Advanced sampling techniques, e.g. Surrogate-based adaptive sampling

Advantage: more efficient, combining high-fidelity simulator + low-fidelity surrogate

Global Optimization of BWR Containment-Venting Operations

Largely saved computational cost by avoiding unnecessary sampling area



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