Development of Methodologies for Full-Scope PRA

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1. Introduction ~Aiming for Full-Scope PRA~

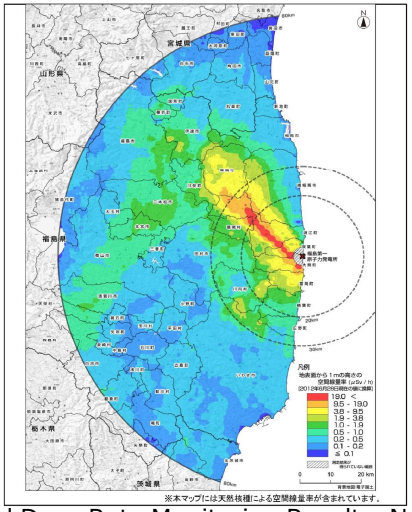
- NRRC anticipates operators' PRAs will "expand incrementally as PRA implementation methods mature*," and continues to develop PRA technologies to accommodate the broader scope of external events to be evaluated as well as to better suit plant operating conditions and site environments.
- In light of the Fukushima Daiichi Nuclear Power Station accident, we are establishing new evaluation methods and improving current approaches to address the following PRA types:

"Superposed earthquake and tsunami events*"	"Events occurring simultaneously at multiple units*"	"Events occurring in spent fuel storage pool/pit*"	Health & environmental impacts off-site
⇒ **Multi-hazard PRA**	⇒ **Multi-Unit PRA**	⇒ **SFP PRA**	⇒ **Level 3 PRA**
(pp. 4~6)	(pp. 7~9)	(pp. 10~12)	(pp. 13~15)

***Cited from Chapter 2, Section 3-1 (2) "Probabilistic Risk Assessment (PRA) (3)" of the NRA's "Operational Guide on Safety Improvement Assessments for Commercial Power Reactors"[1].**



Damage to Units 1~4 at Fukushima Daiichi Nuclear Power Station, March 19, 2011
(Source: Tokyo Electric Power Company Holdings[2])



Ex. of Spatial Dose Rate Monitoring Results, November 2012
(Reference: Ministry of the Environment (https://www.env.go.jp/content/900412677.pdf)[3])

2. ① Multi-Hazard PRA: Overview

- Multi-Hazard PRA evaluates the frequency of core damage and containment failure of a nuclear power plant when the impact of multiple hazards (multi-hazard events) superpose
  - **In the case of multi-hazard scenario superimposing earthquake and tsunami:** After an earthquake damages part of a facility, an earthquake-induced tsunami strikes, further damaging the plant and causing loss of function



Ex. of Earthquake Damage
(Damage to Switchyard Circuit breakers)
(Source: Tokyo Electric Power Company Holdings[4])



Tsunami Striking After Earthquake
(Source: Tokyo Electric Power Company Holdings[5])

Photographs of Fukushima Daiichi Nuclear Power Station Accident

2. ② Multi-Hazard PRA: Gaps & Efforts to Overcoming them

■ Background

- Japan: AESJ's tsunami PRA standard[6] addresses earthquake-induced tsunamis.
  - It specifies general evaluation items (indicating what to assess) taking into consideration earthquakes and tsunami superimposition.
- IAEA: Although a standard framework for multi-hazard PRA has been gradually developed in technical documents and other materials since 2011, no actual PRA examples anywhere in the world take into account superposed earthquakes and tsunami.

■ Gaps to Overcome

- Practical PRA methodology (indicating how to assess) for nuclear power plants taking into consideration earthquakes and tsunami superposition has not been established.

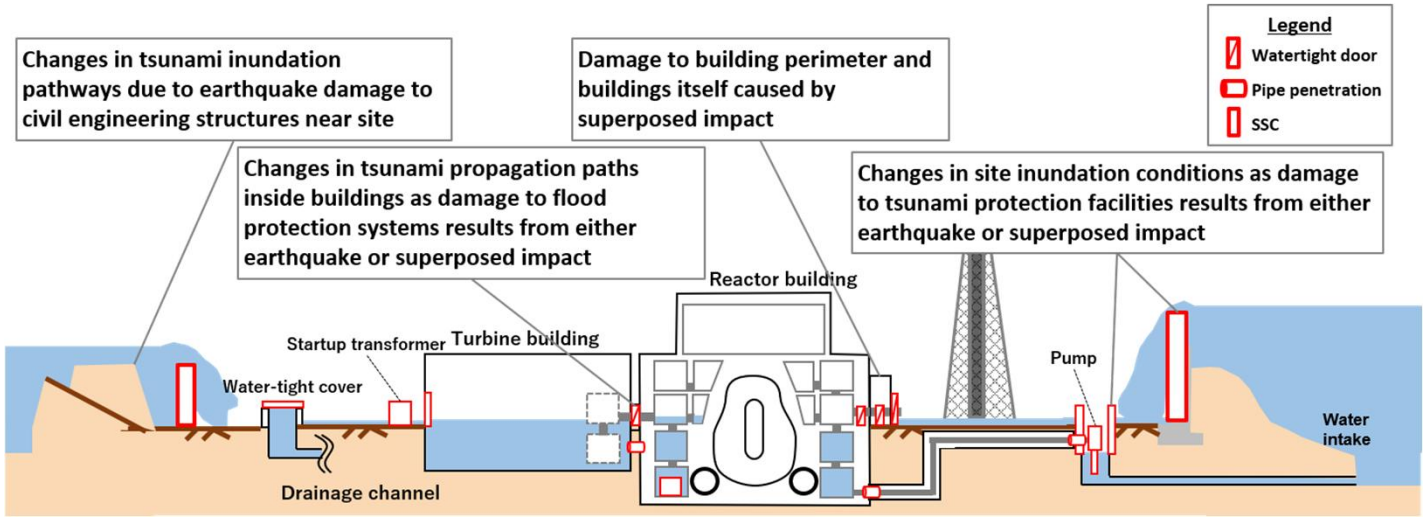
■ Efforts to Overcome Gaps

- Develop the technical basis necessary for multi-hazard PRA addressing superposed earthquake and tsunami events
  - Scenario analysis as well as hazard and fragility assessments of superposed earthquake and tsunami events
  - Conduct a coherent Level 1 through Level 2 PRA for superposed earthquake and tsunami events

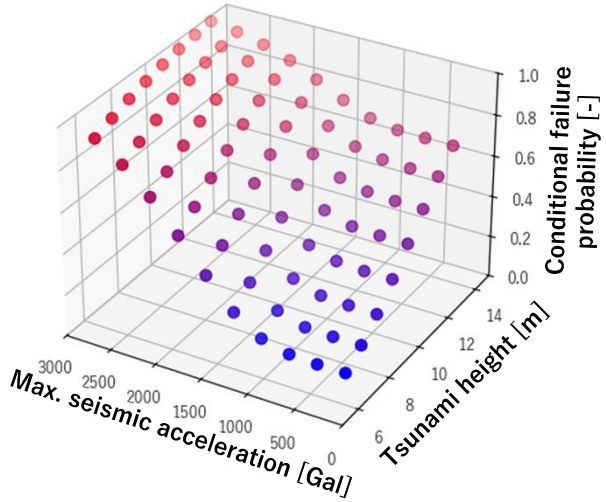
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2. ③ Multi-Hazard PRA: R&D Progress

- Examples presented of analyses of superposed earthquake and tsunami scenarios for NPP (left diagram)
  - Events identified that are associated with tsunami propagation in safety-significant buildings and the impact on accident mitigation
- Methods and approaches developed for evaluating superposed earthquake and tsunami hazards and fragility
  - Probability evaluated of hazards occurring with consideration given to correlation between seismic motion intensity and tsunami height at target sites
  - As seismic motion intensity and tsunami height increase, the superposition effect also increases the probability of component failure (right graph)



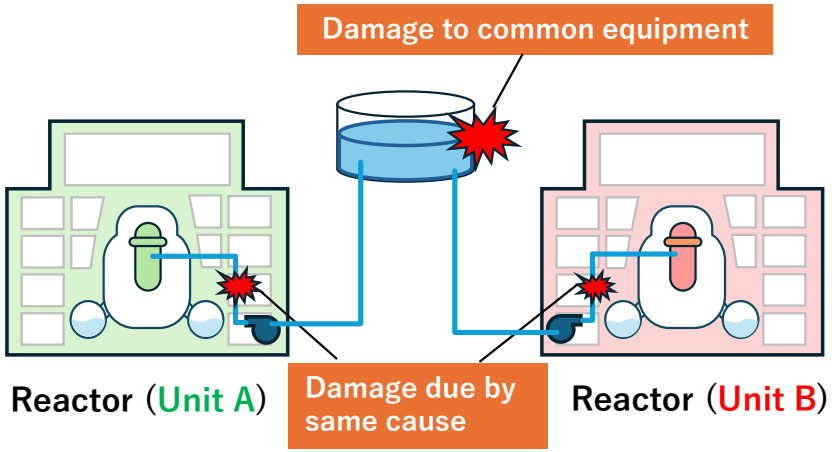
Ex. of Superposed Earthquake and Tsunami Scenarios Critical to Safety



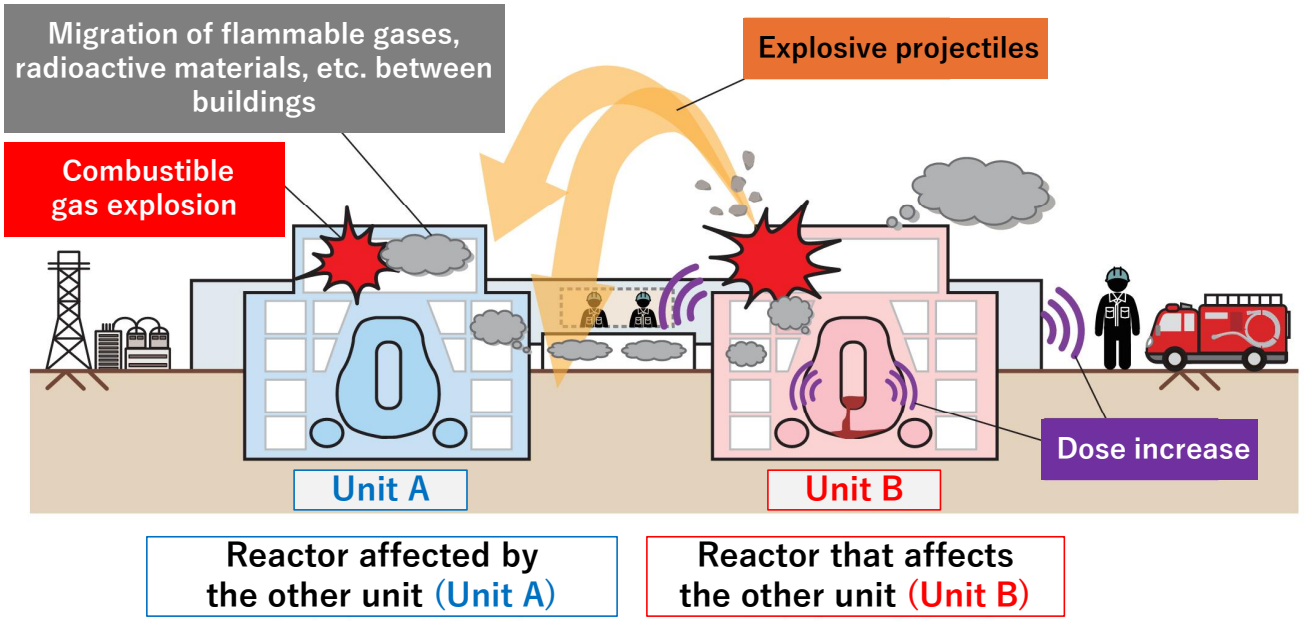
Ex. of Component Fragility Assessment Considering Seismic Motion Intensity and Tsunami Height[7]

3. ① Multi-Unit PRA: Overview

- Multi-Unit PRA evaluates the frequency and other characteristics of the cores of multiple units damaged simultaneously or sequentially when a single power plant comprises multiple reactors (multi-unit configuration)
  - This requires appropriate consideration of dependencies, interactions, etc. between/among units, rather than a simple summation of risks to individual units.



Damage to Common Equipment at Power Plant with Two Units or Single Factor Leading to Core Damage at Two Units



Core Damage in One Unit Affecting Other Unit at Power Plant with Two Units

Illustration of Events Considered in Multi-Unit PRA

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3. ② Multi-Unit PRA: Gaps & Efforts to Overcoming Them

■ Background

- No country, including Japan and the U.S., has currently established a multi-unit PRA (MUPRA) methodology that is regarded as an industry standard or approach.
- IAEA: Although the IAEA has published technical documents comprehensively and systematically summarizing MUPRA methodology (2019:[8]; 2023:[9]) since 2011, no specific assessment methods for their implementation have been consolidated.

■ Gaps to Overcome

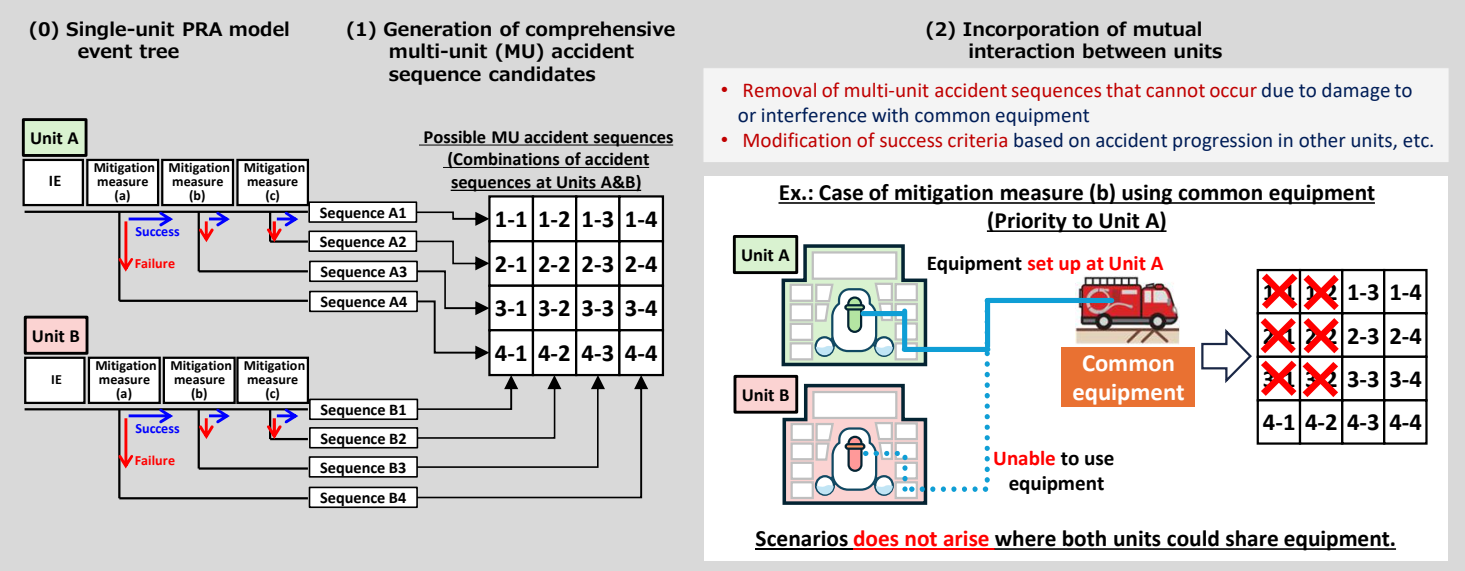
- No methodology for the specifically implementing MUPRA has been established

■ Efforts to Overcome Gaps

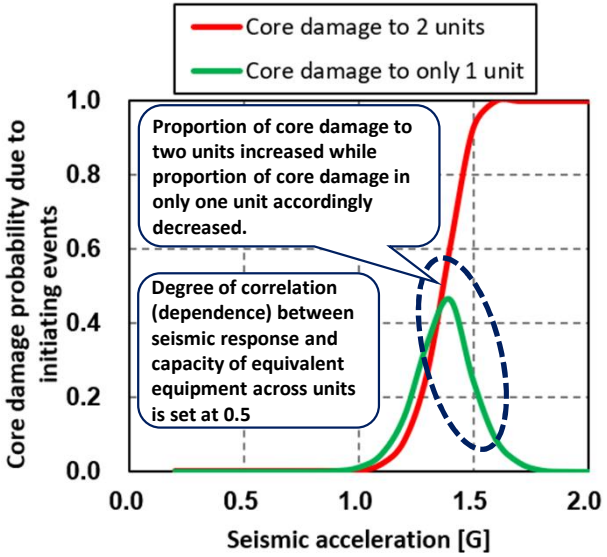
- Develop the MUPRA methodology and related elemental technologies
  - Develop methodologies for Level 1 internal events MUPRA, Level 1 seismic MUPRA, and Level 2 MUPRA

3. ③ Multi-Unit PRA: R&D Progress

- **Level 1 MUPRA methodology developed for internal events based on single-unit PRA model**
  - Procedures developed for constructing multi-unit accident sequences applicable to various hazards (left diagram)
    - Method has no theoretical upper limit on the number of units, but, in practice, the limit would essentially be 3 units at present due computational resource and time restrictions.
- **Level 1 seismic MUPRA methodology developed**
  - Case study conducted of level 1 seismic MUPRA considering inter-unit component failure dependencies (right diagram)



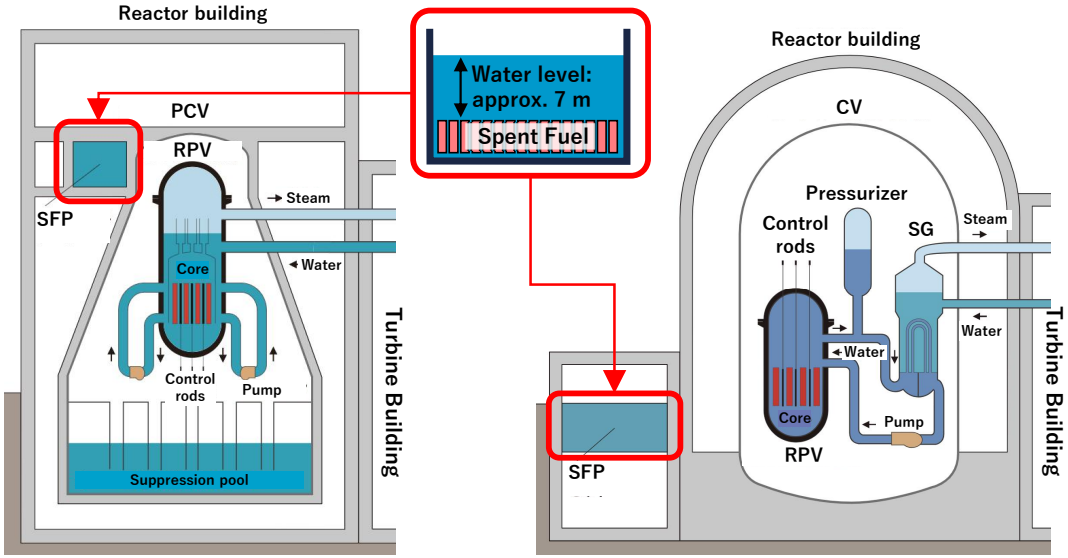
Procedures for Constructing MUPRA Accident Sequences [10]



Ex. of Evaluating of Core Damage Probability of Two Units with an Earthquake

4. ① Spent Fuel Pool/Pit (SFP) PRA: Overview

- Spent Fuel Pool/Pit (SFP) PRA assesses the frequency of damage to spent fuel in SFP during an accident and any subsequent release of radioactive materials
- Since the SFP is outside the containment vessel, fuel damage or melting in the SFP results in the release of radioactive materials into the reactor building
- Primary cause of fuel damage is the loss of cooling function due to a drop in SFP water level (evaporation or outflow)
  - Cooling system shutdown (pump failure, loss of power), cooling system pipe damage, pool/pit damage, etc.



Relative Positions of Reactor Building and SFP in BWR (left) and PWR (right)
(Created using data from JAERO (Japan Atomic Energy Cultural Foundation) [11])

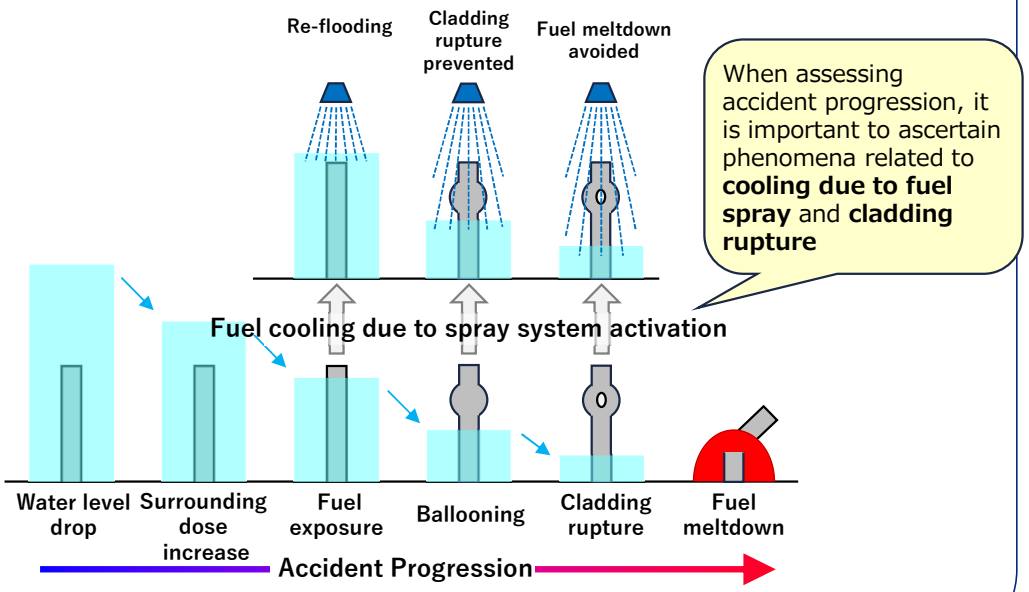


Illustration of Fuel Damage Process From Drop in Water Level in SFP

4. ② SFP PRA: Gaps & Efforts to Overcoming Them

■ Background

- Japan: Evaluation items are specified in AESJ standard[12] , but no evaluations have yet been conducted of actual reactors.
- U.S.: NRC and EPRI have developed an SFP PRA methodology[13,14], which uses the SFP water level [fuel top + 3 ft] as an indicator to conservatively assess fuel damage.
- IAEA: Revised edition of the PRA Guide (SSG-3)[15] recommends assessments using multiple sources for both the core and the SFP

■ Gaps to Overcome

- Phenomena have not necessarily been realistically evaluated as relates to cooling due to fuel spraying and cladding rupture as accident progresses following a drop in SFP water level.

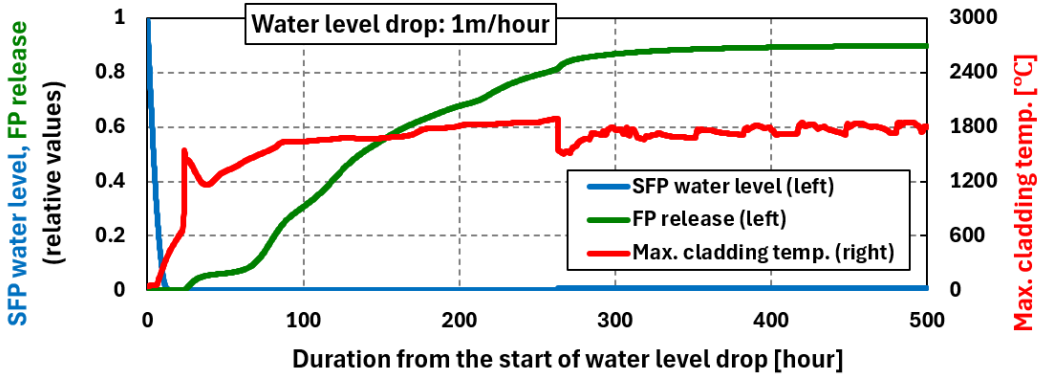
■ Efforts to Overcome Gaps

- Empirically verify the following SFP fuel effects and behaviors and propose an evaluation model
  - Effects of spraying to cool fuel
  - Conditions of fuel cladding rupture by water level drop

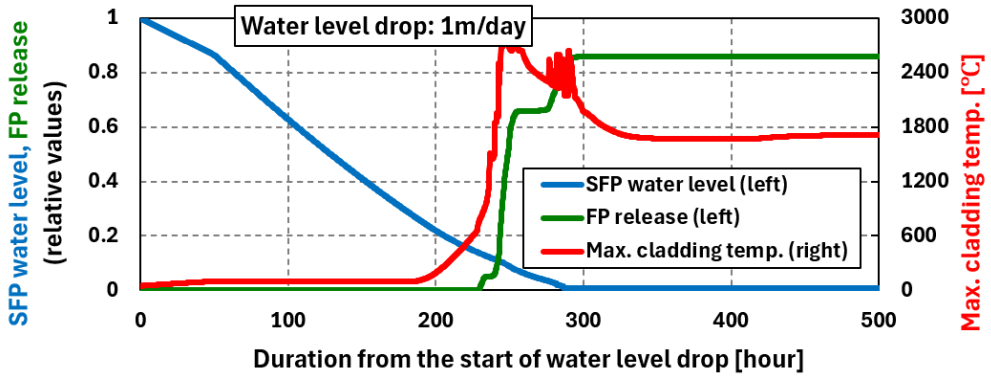
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4. ③ SFP PRA: R&D Progress

- Models evaluating SFP fuel spray cooling performance and cladding rupture developed based on empirical data, and both models incorporated into and implemented in severe accident analysis code MAAP, making them available to plant operators.
- Accident progression analyses using MAAP has made it possible to realistically evaluate maximum cladding temperature and amount of radioactive material released as a function of the rate of SFP water level drop (diagram)
  - Able to be used to quantitatively assess time margin available for accident prevention and mitigation measures



(a) Case of High SFP Water Level Drop Rate



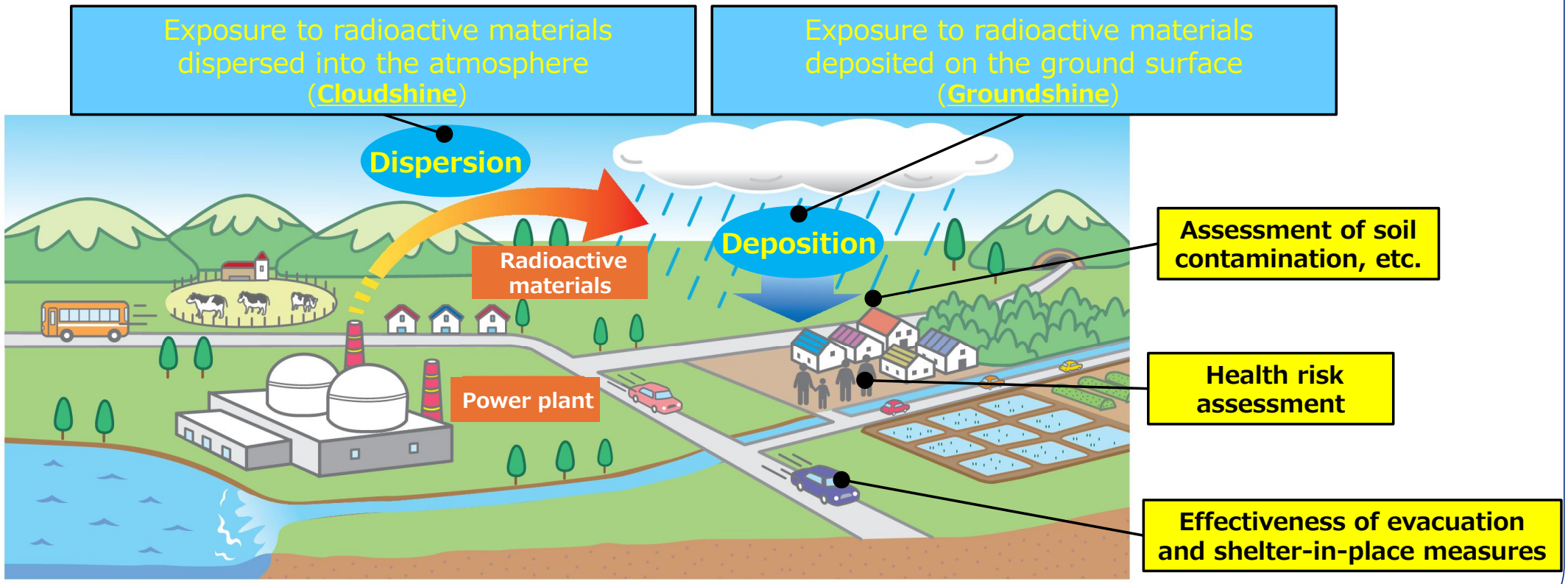
(b) Case of Low SFP Water Level Drop Rate

Evaluation Examples with Different SFP Water Level Drop Rates

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5. ① Level 3 PRA: Overview

- Level 3 PRA assesses health risks, contamination, and other environmental impact caused by radioactive materials released from power plants into the environment



Major Events Assessed in Level 3 PRA

5. ② Level 3 PRA: Gaps & Efforts to Overcoming Them

■ Background

- Japan: Although evaluation items specified in the AESJ standard[16], no evaluations yet conducted on actual reactors
- U.S.: NRC conducting Level 3 PRA research project[17] since 2007; ASME/ANS Level 3 PRA standard published in 2025[18]; however, no evaluation yet for regulatory compliance.
- U.K.: Criteria for health risks equivalent to Level 3 established as regulatory requirements in 2006, and actual reactors evaluated
- IAEA: Plans to issue safety guide for Level 3 PRA in 2029
- Technology needed to evaluate risk reduction effect of protective measures, including evacuation and shelter-in-place, to implement Level 3 PRA in Japan.

■ Gaps to Overcome

- Although Level 3 PRA codes developed, appropriate method suitable for Japan context has not been established, so no assessments could be performed.

■ Efforts to Overcome Gaps

- Develop Level 3 PRA methodology based on the circumstances in Japan that takes into account protective actions and other social initiatives.
  - Set up virtual model plant reflecting circumstances in Japan and conduct trial Level 3 PRA

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5. ③ Level 3 PRA: R&D Progress

- Set up virtual model plant reflecting circumstances in Japan and conduct trial level 3 PRA
  - Virtual model plant established that utilizes Japan land use conditions, meteorological data, protective measures, etc.
  - Radioactive material release conditions (source terms) verified to significantly impact health risk assessments (left diagram)
  - Importance confirmed of assessing soil contamination and long-term evacuation of residents (right diagram)
  - Going forward, trial results using virtual model plant will be compiled and standard operating procedures developed for Level 3 PRA (FY2026)

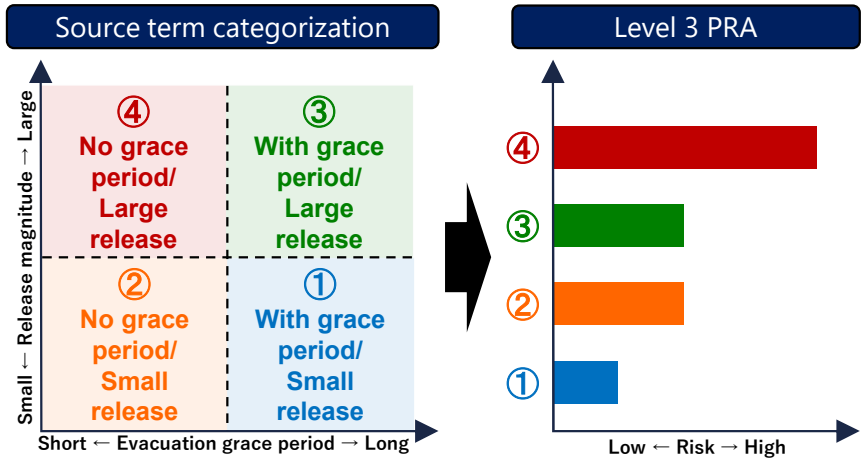
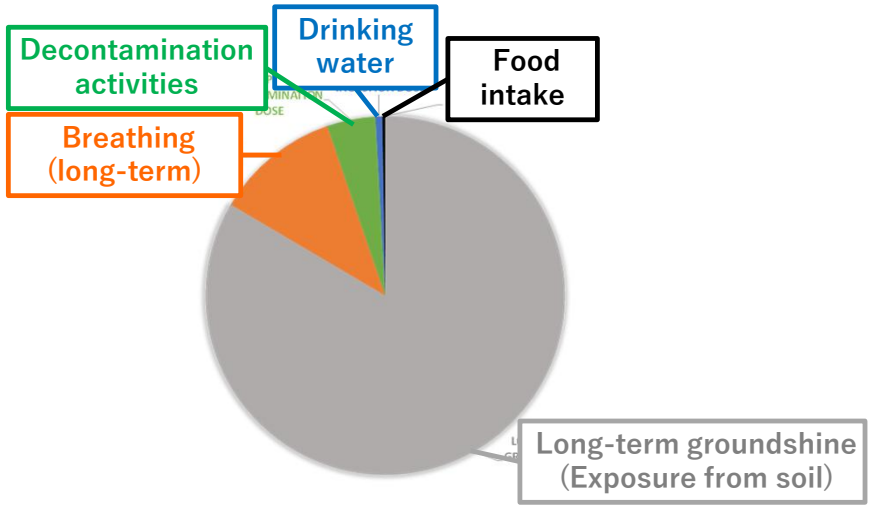


Illustration of Source Term Classification and Level 3 PRA Risk Assessment Based on Residents' Evacuation Lead Time and Scale of Radioactive Material Release



Ex. of Exposure Dose Assessments According to Exposure Pathway

6. Future Actions

- **Multi-Hazard PRA (Earthquake and Tsunami Superposition)**: To date, basic evaluation methods have been established for hazards, fragility, and accident sequences related to earthquake and tsunami superposition. Going forward, coherent earthquake and tsunami superposition PRA from Level 1 through Level 2 will be conducted.

- **Multi-Unit PRA:** To date, methodologies have been established for Level 1 internal events and Level 1 seismic MUPRA. Going forward, Level 2 MUPRA methodologies will be developed.

- **SFP-PRA:** To date, evaluation models have been developed for spray cooling of fuel in SFP and cladding rupture. Going forward, trial evaluations will be conducted using a model plant.

- **Level 3 PRA:** Input parameters will continue to be refined for Level 3 PRA code WinMACCS taking into account domestic circumstances and Level 3 PRA implementation procedures established based on preliminary evaluations of virtual model plant.

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[Appendix] References

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