Development of Tornado PRA Methodology

Nuclear Risk Research Center
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Contents

1. Responding to Tornado Events
2. Tornado PRA Gaps and Efforts to Overcome Them
3. Tornado PRA Model Development
4. Tornado PRA R&D
   (1) Tornado Wind-Speed Hazard Assessment
   (2) Tornado Missile Hazard Assessment
   (3) Fragility Assessment
5. Future Actions

[Appendix] Roadmap

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1. Response to Tornado Events

- Tornado damage occurs every year in Japan, making protection against tornado-generated missiles an important issue for nuclear power plants.
- Steel plates, wire-mesh barriers, and other missile protection systems have been installed to meet the new regulatory requirements. These are deterministic measures for a design-basis tornado, yet the risk posed by tornadoes to an entire plant has not been fully assessed.
- In the United States where tornado damage is significant, high-wind PRA of tornadoes and hurricanes have been applied to nuclear power plants based on the EPRI High-Wind Risk Assessment Guidelines and other guidance. [1]
- In Japan, PRA methodologies need to be developed further to quantitatively assess tornado-induced accident scenarios and plant risk.

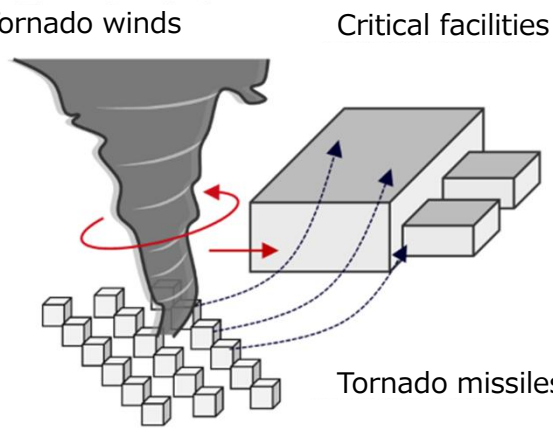
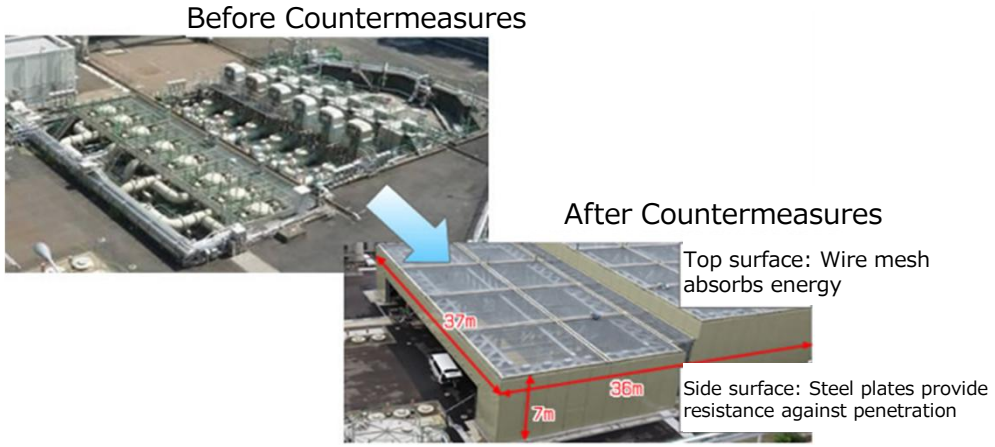


Illustration of Damage Caused by Tornado Missiles



Examples of Missile Protection Systems at Takahama Nuclear Power Station

2. Tornado PRA Gaps and Efforts to Overcome Them

■Gaps to Overcome

- Further development of tornado PRA methodologies was needed to quantitatively assess component damage and plant risk associated with low-frequency, high-consequence events exceeding the design-basis tornado wind speed.
- Japan-specific tornado characteristics as well as the protective effects of steel plates, wire-mesh barriers, and other missile protection systems needed to be considered, making direct application of U.S. methods difficult.

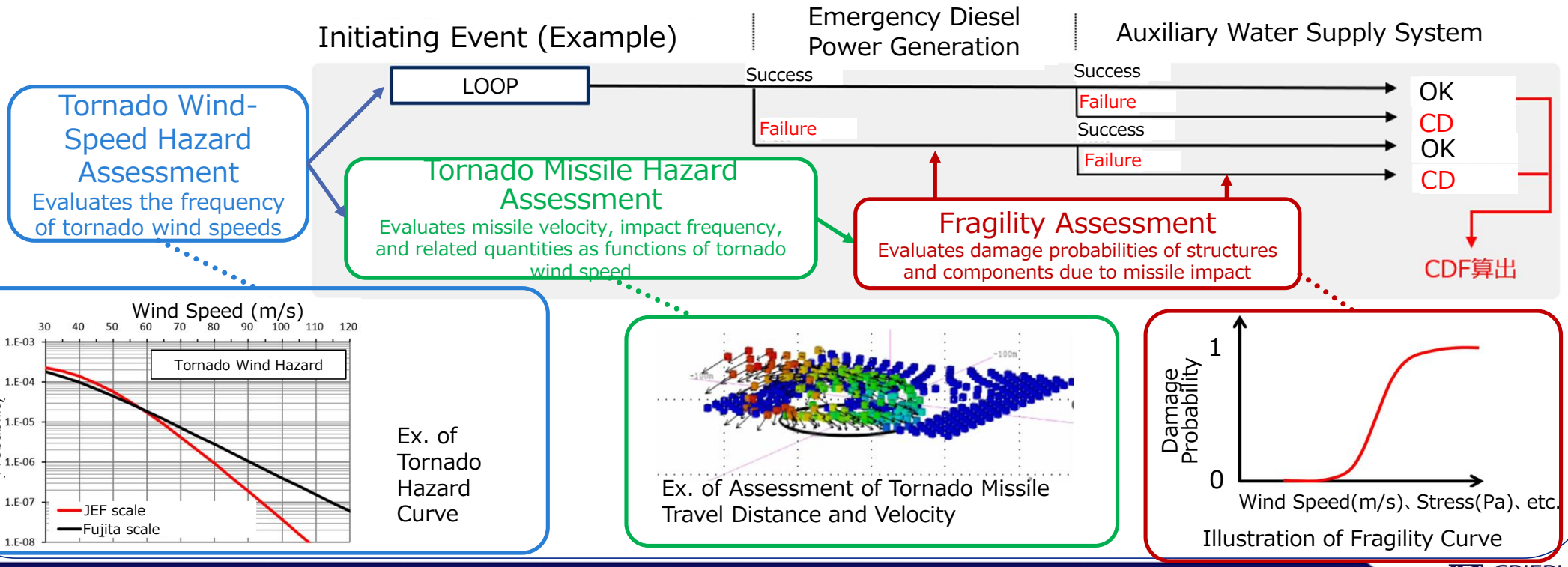
■Efforts to Overcome Gaps

- Integrate NRRC knowledge of tornado wind-speed hazard assessment, missile hazard assessment, and performance evaluation of missile protection systems to develop a Japan-specific tornado PRA methodology applicable to domestic nuclear power plants.

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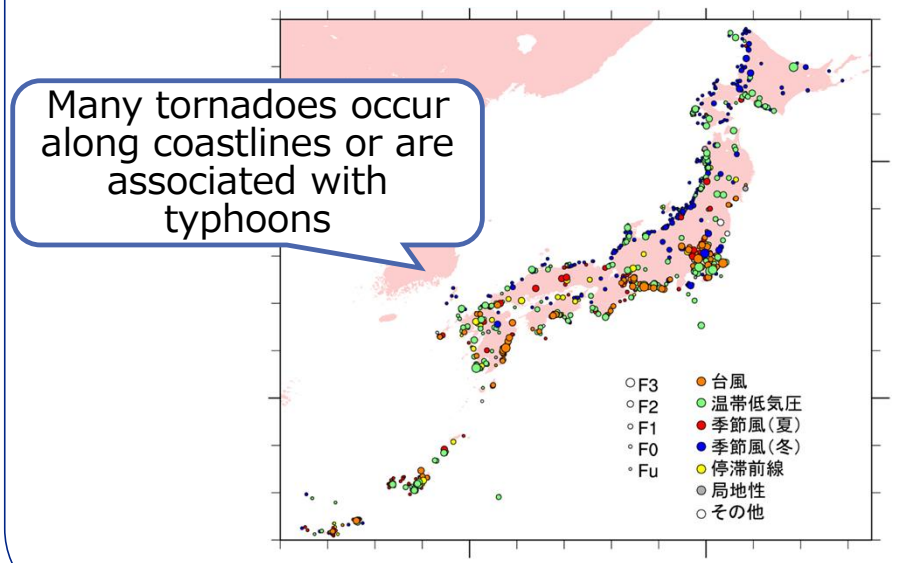
3. Tornado PRA Model Development

- The tornado PRA model is developed based on the internal-events PRA model and incorporates results of tornado wind-speed hazard, missile hazard, and fragility assessments into the selection of components to be modeled, initiating events, and component damage probabilities.[2]
- The model enables quantitative evaluation of tornado-induced accident scenarios and plant risk.

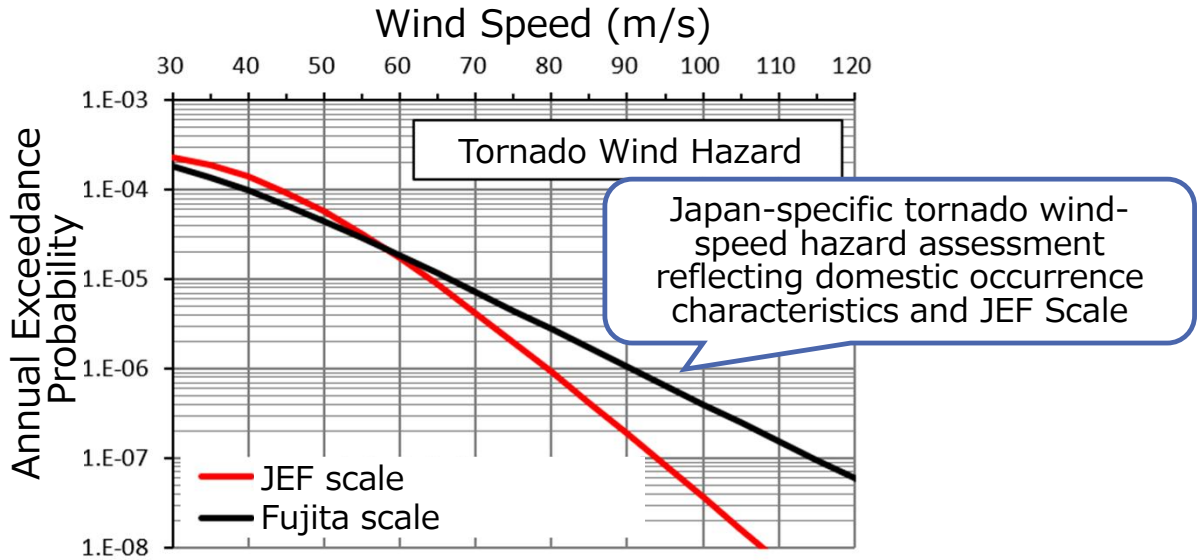


4. Tornado PRA R&D (1)
Tornado Wind-Speed Hazard Assessment

- Tornado occurrence in Japan differs from that in the United States as they frequently occur near coastlines, and many events along the Pacific coast are associated with typhoons.
- In addition to developing tornado wind-speed hazard curves that account for tornado occurrence characteristics in Japan, we developed an assessment tool (TOWLA-CL) that incorporates the Japanese Enhanced Fujita (JEF) Scale and accounts for uncertainties in observational data.[3-5]



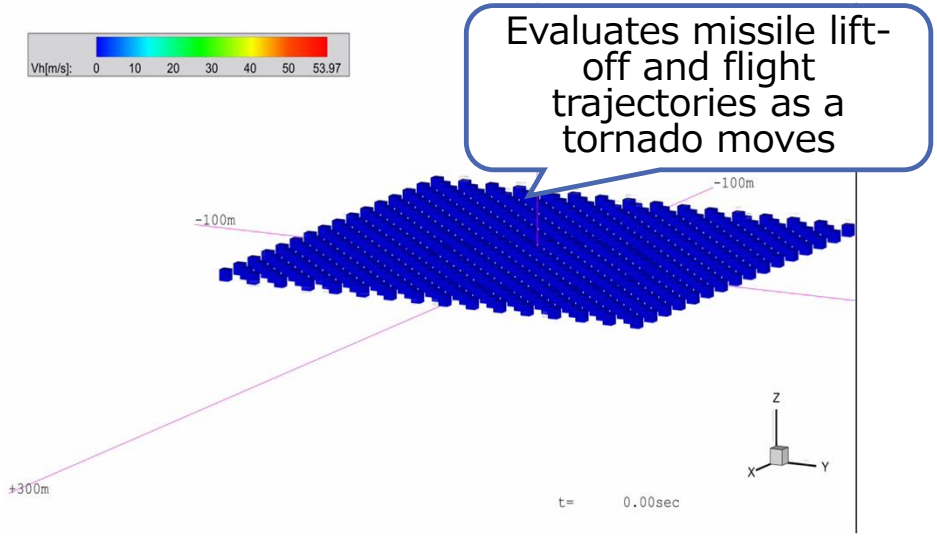
Tornado Distribution and Causal Factors



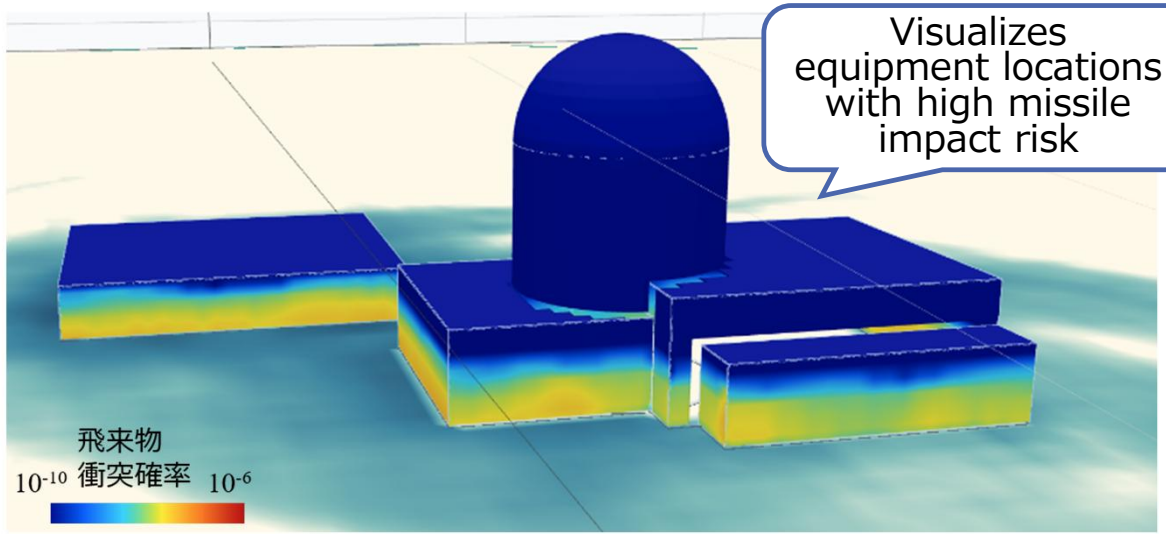
Example Tornado Wind-Speed Hazard Assessment

4. Tornado PRA R&D (2)
Tornado Missile Hazard Assessment

- TONBOS was developed to evaluate tornado wind fields and missile motion.[6]
- Extensions to TONBOS made it possible to acquire detailed impact information, including missile impact location, time, and velocity.[7-9]
- This impact information enables missile hazard assessments, including impact probabilities for structures and components.



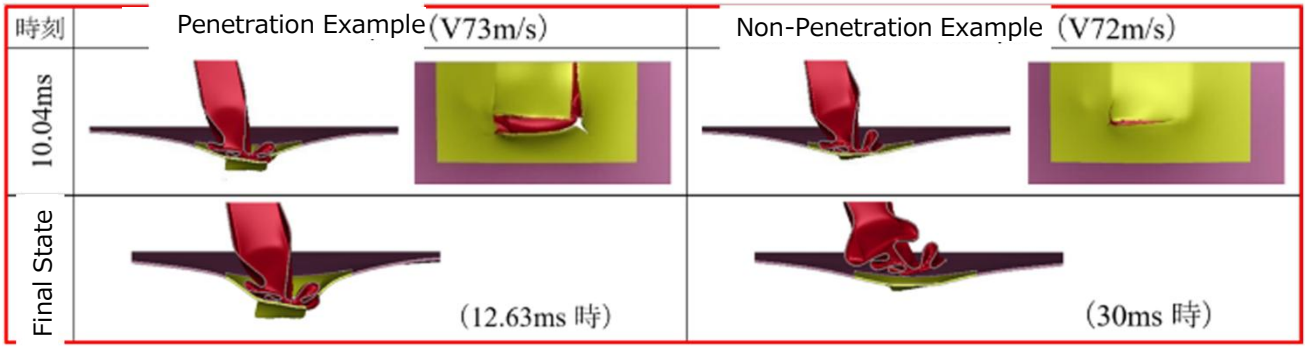
Ex. of Evaluation of Dispersal Distance and Speed of Tornado Missiles



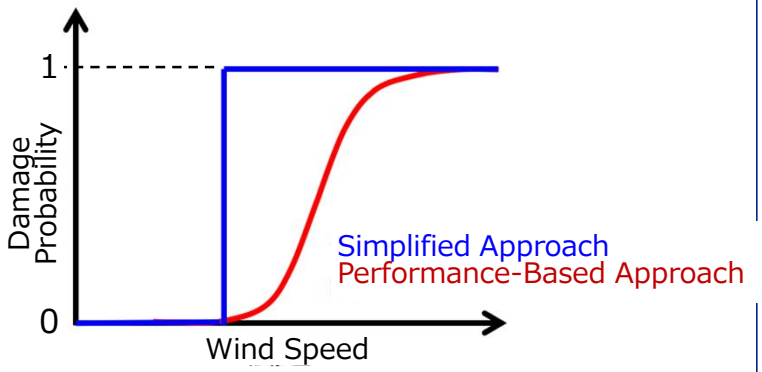
Ex. of Missile Impact Probabilities for Structures

4. Tornado PRA R&D (3) Fragility Assessment

- Current fragility assessments used in tornado PRA employ a simplified and conservative assumption that damage occurs when the tornado wind speed exceeds the design-basis tornado wind speed.
- Impact resistance of missile protection systems has been evaluated with impact tests. Numerical simulation techniques that reproduce test results now enable evaluation under a wide range of conditions. [10,11]
- Using numerical simulation results, we are evaluating uncertainties associated with missile impact and developing a fragility assessment method that accounts for the performance of missile protection systems.



Ex. of Numerical Assessment of Steel-Plate Impact Resistance



Incorporating missile impact assessment results into wind-speed-based fragility curves

5. Future Actions

Current Achievements

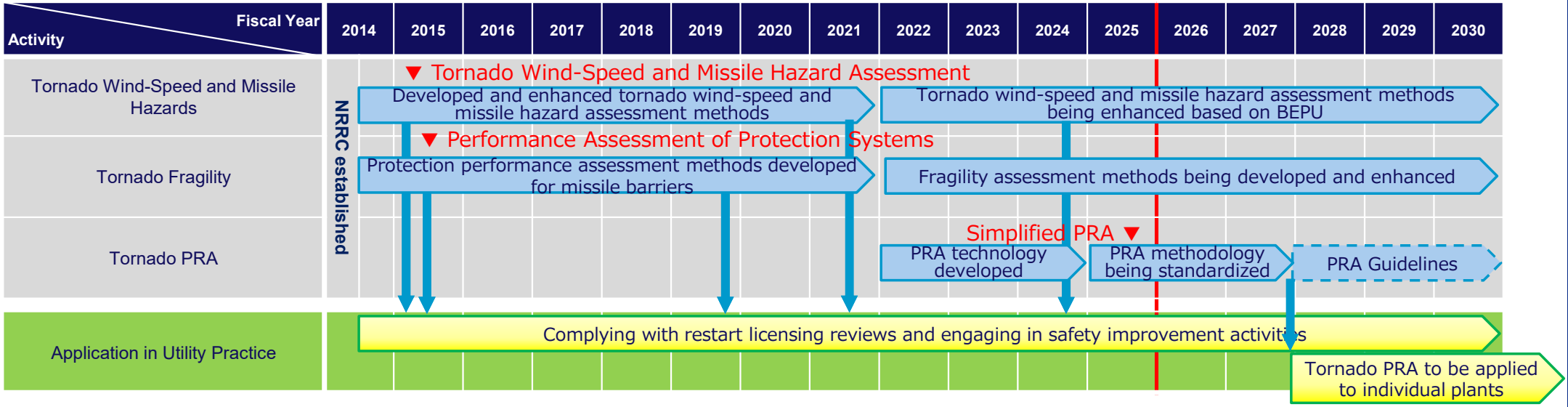
- Established a tornado wind-speed hazard assessment method reflecting Japan-specific tornado occurrence characteristics.
- Developed tools to evaluate tornado-induced missile lift-off and flight behavior, as well as methods for assessing missile impact on structures and components.
- Established techniques for evaluating impact resistance of missile protection systems specific to Japanese nuclear power plants using missile impact tests and numerical simulations that accurately reproduce test results.

Future Actions

- Develop a fragility assessment method reflecting the performance of missile protection systems to improve damage-probability assessments for structures and components.
- Conduct a trial application of the Tornado PRA based on actual plant data and develop a Japan-specific Tornado PRA methodology.

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[Appendix] Roadmap



[Appendix] References

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[2]Hattori Y., Murakami T., Fujiwara K., Nohara D., Namba K., Eguchi Y., Imai S. and Kunimasa T., A Tornado PRA Methodology with a Probabilistic Tornado Hazard Assessment, PSAM17&ASRAM2024, 2024.

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[5]Hirakuchi, H., Nohara, D., Sugimoto, S., Eguchi, Y., and Hattori, Y., Development of the TOWLA Tornado Wind-Speed Hazard Model for Coastal Nuclear Power Plants, CRIEPI Report O15005, 2016.

[6]Eguchi, Y., Sugimoto, S., Hattori, Y., and Hirakuchi, H., Development of TONBOS for Tornado-Induced Object Lift-Off and Flight Analysis, CRIEPI Report N14002, 2014.

[7]Murakami, T., Eguchi, Y., Fujiwara, K., and Hattori, Y., Development of the TONBOS-MIE Tornado Missile Impact Assessment Tool, CRIEPI Report NR24004, 2025.

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[9]Eguchi, Y. and Hattori, Y., Development of the Probabilistic High-Wind Missile Analysis Code TONBOS-pro, CRIEPI Report O20004, 2021.

[10]Namba, K. and Sata, D., Study on the Perforation Resistance of Steel Plates Subjected to Tornado Missile Impact: Basic Investigation of BRL Formula Applicability, CRIEPI Report O19003, 2020.

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Development of Volcano PRA Methodology

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Contents

1. Plant Response and Mitigation of Volcanic Ash-Fall
2. Volcanic Ash-Fall PRA Gaps & Efforts to Overcome Them
3. Countries' Guidelines & Volcanic Ash-Fall PRA Case Studies
4. Volcanic Ash-Fall PRA Model Construction
5. R&D progress
   (1) Selection of SSCs to Model
   (2) Improvement of Hazard Accuracy
6. Future Actions

[Appendix] Roadmap

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1. Plant Response and Mitigation of Volcanic Ash-Fall

◆Volcanic ash-fall is the sole event reaching every NPP in Japan.

➢ Volcanic ash-fall events tend to last longer than other external events

◆Plant facility responses and mitigation measures

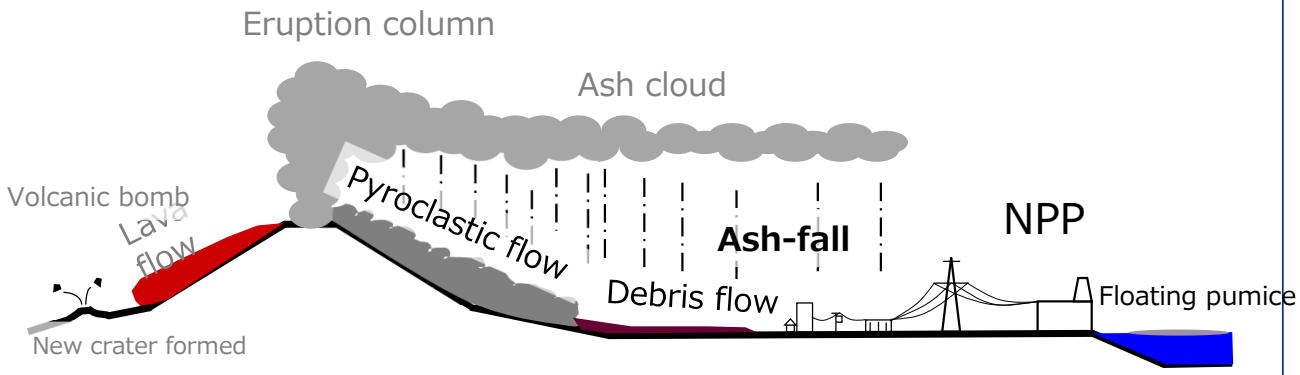
➢ Volcanic ash-fall event responses are operational engagement rather than leaving the facilities unattended

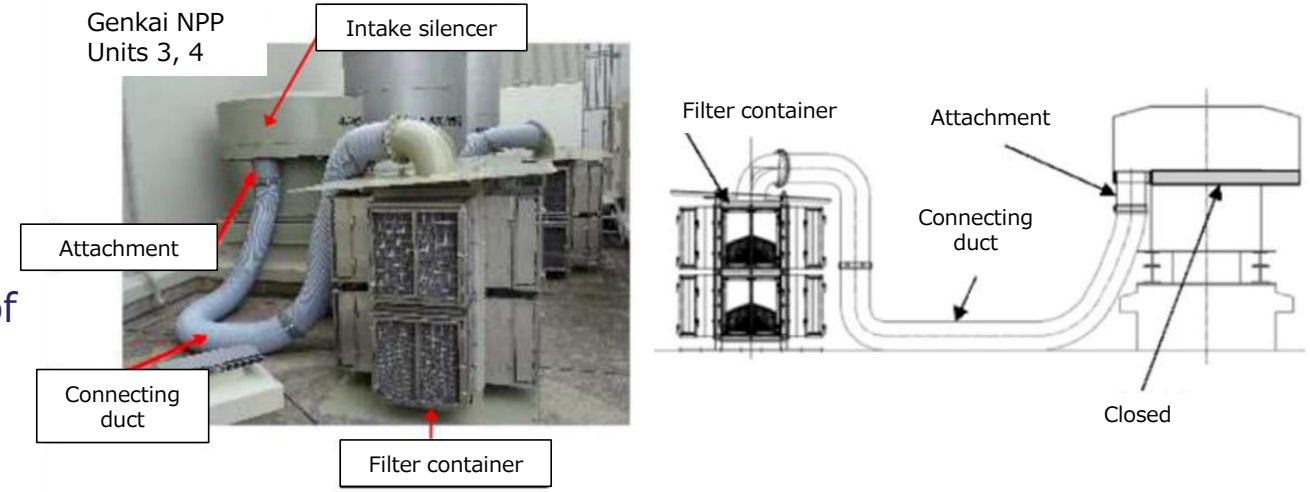
- Increase in building roof load

→ Volcanic ash-fall is removed

- Blockage of air intake filters due to loss of off-site power and operation of emergency diesel generators

→ Pre-filters installed and filters replaced and cleaned





Example of Pre-Filter for Air Intake Facility at NPP [1]

2. Volcanic Ash-Fall PRA Gaps & Efforts to Overcome Them

■ Background

- Volcanic ash-fall substantially affects air intake facilities of emergency diesel generators and other equipment.
- New regulatory requirements anticipate events where volcanic ash accumulates quickly in short time and mandates assessment and installment of mitigation measures for NNPs.
- To identify residual risks for volcanic ash-fall, it is necessary to conduct risk assessments that include long duration events.
- Volcanic ash-fall PRA lacks precedence both in Japan and abroad.

■ Gaps to Overcome

- No quantitative risk assessments have been conducted of NPPs that focus on volcanic ash-fall events.

■ Efforts to Overcome Gaps

- Construct volcanic ash-fall PRA model and draft guidelines.
- Update volcanic ash-fall database to improve accuracy of hazard assessments.

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3. Countries' Guidelines & Volcanic Ash-Fall PRA Case Studies

- **Japan and IAEA standards & guidelines**
  - PRA not specified
- **U.S NRC Volcano Guide RG 4.26** [2]
  - Specifies PRA and SSHAC, but does not provide details about assessment methods
  - Alternative path available using engineering analysis of equipment countermeasures
  - Formation of new crater is the key topic when reviewing sites for new plants
- **Volcanic Ash-Fall PRA of FBR plant**[3]
  - Assessment of multiple cooling facilities.
- **NRA Study of Volcanic Ash-Fall & Other External Event PRAs**[4]
  - Mitigation operations or extended duration of volcanic ash-fall events not evaluated.

→**Lack of case studies or guides for volcanic ash-fall PRA, so must start with selection of facilities to include in PRA model.**

Standards/ Guidelines	Hazard Assessment Method	Hazard Level of Impact Assessment	Comments
IAEA SSG-21 TECDOC-1795 TECDOC-2113*	Probabilistic & deterministic	Not specified	*Focus on volcanic ash-fall, including effects on SSCs, regulatory guides, and mitigation measures.
JEAG 4625 (Japan Electric Association Guide) Japan	Deterministic*	DBE	*Volcanic ash-fall hazard curve to be included as supplement in the next revision.
NRA Volcano Assessment Guide Japan	Deterministic	DBE*	*Some SA facility assessment conducted in operational safety programs.
NRC RG 4.26 U.S.	Probabilistic & Deterministic (SSHAC, PRA)*	DBE & BDBE	*Alternative path available for engineering analysis.

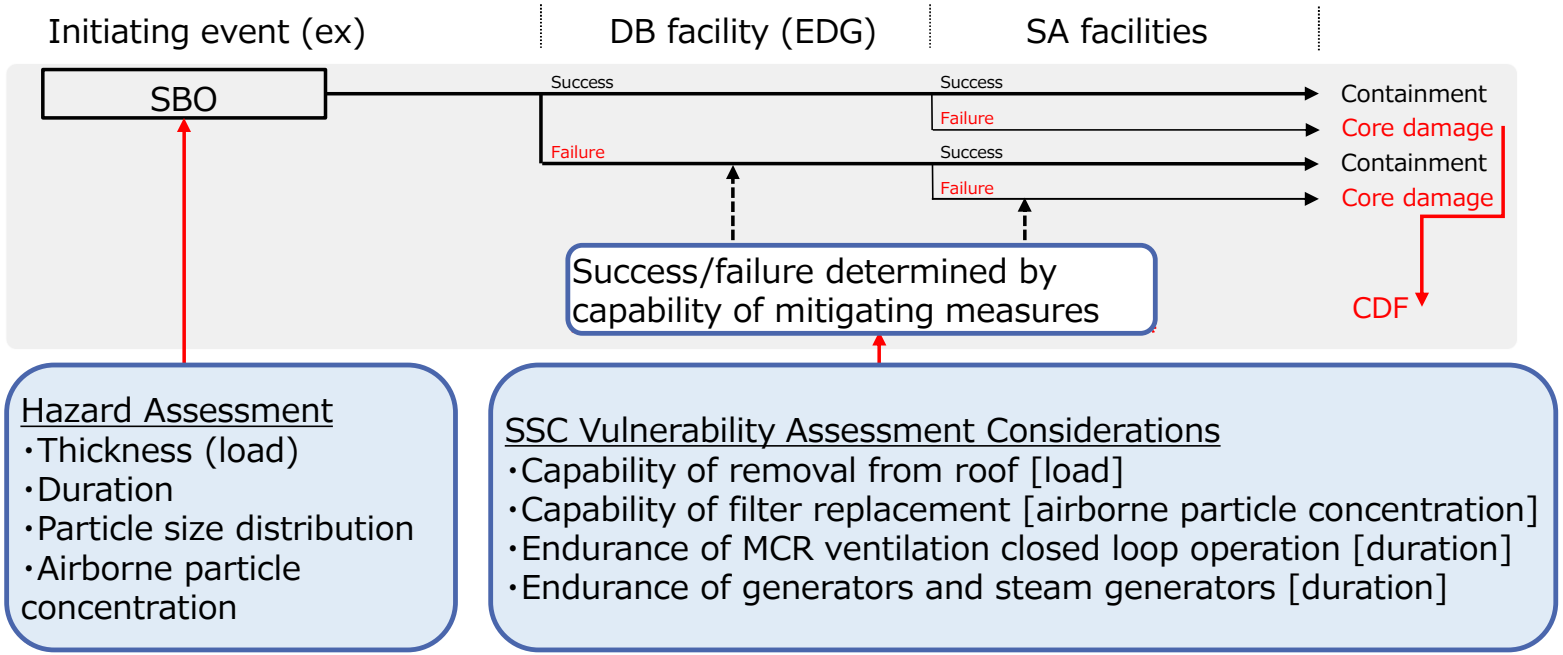
State of hazard assessment in guideline documents

4. Volcanic Ash-Fall PRA Model Construction

◆Volcanic ash-fall related considerations (hazard and vulnerability assessments) are incorporated to the internal event PRA model.

➢ Each facility responds differently to volcanic ash-fall hazards

➢ Vulnerability assessment based on capability of mitigating measures is used along with fragility curves to consider the probability of equipment function loss



5. R&D Progress
(1) Selection of SSCs to Model

◆Select response facilities to be included in the PRA model

➢Refer to list of selected SSCs in present license application documents

- Mitigation measures installed to counter high-particle concentration events
- SA facilities are used for events surpassing design basis

→We anticipate SSCs for managing extended duration of volcanic ash-fall events are most likely to be selected.

Included in License application

SSCs	Characteristics of ash-fall event	Response to DB event	Assessment criteria for DB event	Response to beyond DB event	Assessment criteria for beyond DB event
Building roofs	Thickness (load)	(Unnecessary)	Building code	Removal	Operational capability
EDG	Airborne particle concentration	Filter exchange	Capability of operation (24 hours)	Not included (Some plants) (Use SA facilities)	(Assess SA facilities)
	Duration	Operate	Amount of fuel (7days)		
SA facilities	Airborne particle concentration	(Not used)	(Not applicable)	Filter exchange	Operational capability
	Duration			Operate	Amount of fuel and water storage

Large particle concentration: included
Extended duration: not included

Status of SSCs for mitigation measures to counter beyond design events (conceptual diagram)

5. R&D Progress
(2) Improvement of Hazard Assessment Accuracy

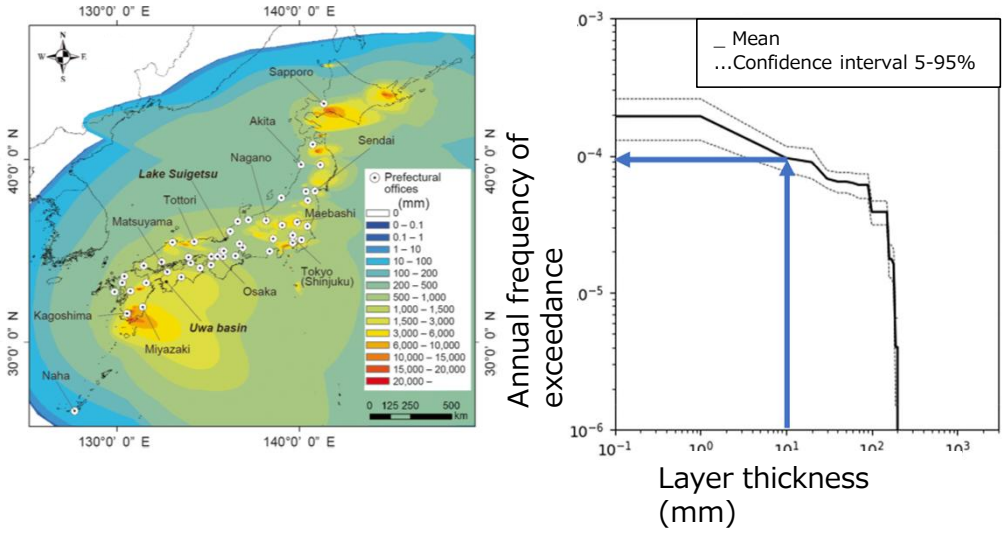
◆We have developed and released a volcanic ash-fall database and the online assessment tool for volcanic ash-fall layer thickness hazard.

➢List of volcanic ash-fall events and volcanic ash-fall thickness hazard curve obtainable by designating any coordinate in Japan.

→Tool used for volcanic ash-fall PRA.

◆To improve assessment accuracy, database is being updated by applying new interpolation method for ash-fall thickness

Access to the online tool



Distribution of Volcanic Ash-Fall in Japan and Hazard Curve [5]

6. Future Actions

➢Current Achievements

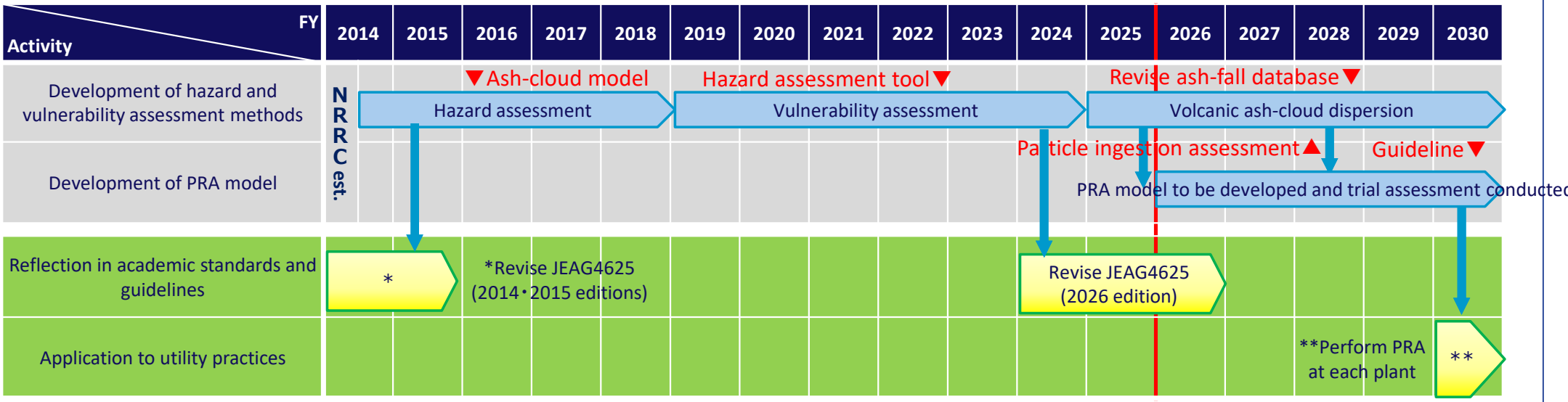
- Policy established for develop volcanic ash-fall PRA model.

➢Future Actions

- Construct PRA model, apply to an actual plant, to case study to conduct trial assessment.
- Draft guidelines incorporating trial assessment outcome.
- Publish papers and other publications detailing developed hazard and vulnerability assessment methods to make them available for application to safety improvement assessments.
- Incorporate developed assessment methods into PRA model.

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[Appendix] Roadmap



[Appendix] References

[1] IAEA, 2026, Volcanic tephra fallout hazard assessment and the associated design and operational considerations for nuclear installations. IAEA-TECDOC Series No. 2113.

[2] U.S. NRC, 2023, Volcanic hazards assessment for proposed nuclear power reactor sites, RG 4.26, Rev. 1.

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