Internal Fire PRA Methodology and Internal Flooding PRA Methodology Development and Plant Applications

Nuclear Risk Research Center

Motomu SUZUKI

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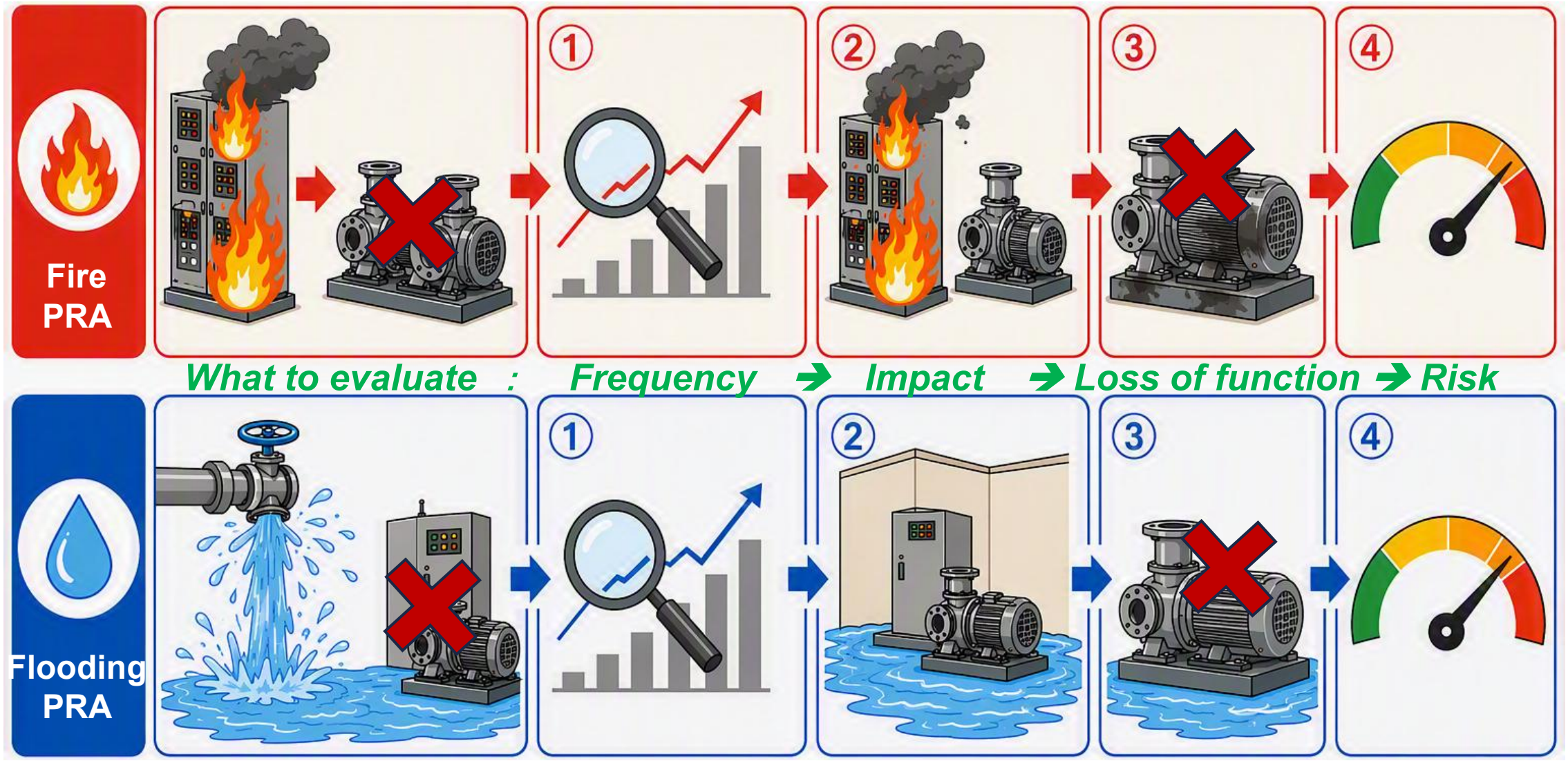
CRIEPI Central Research Institute of Electric Power Industry

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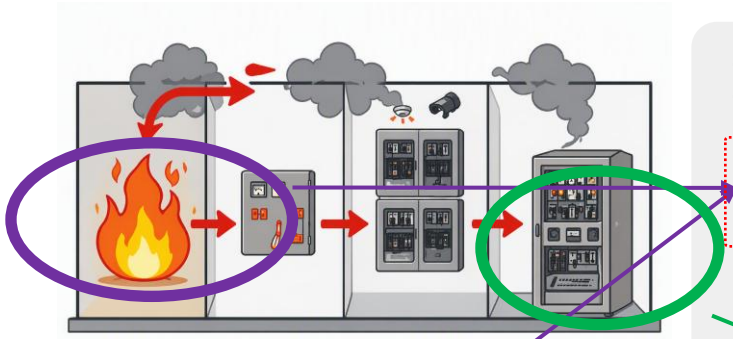
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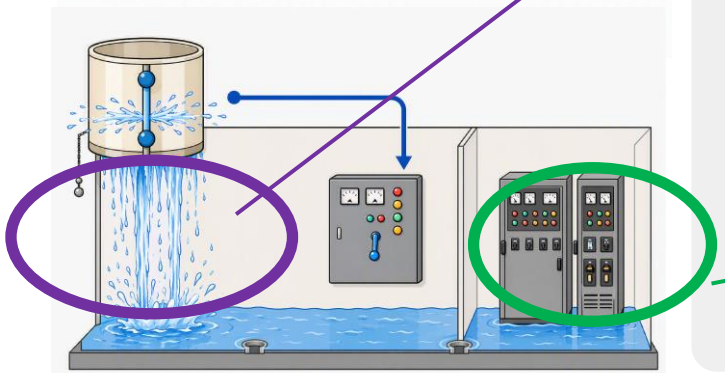
1. Internal Fire/Flooding PRA Overview

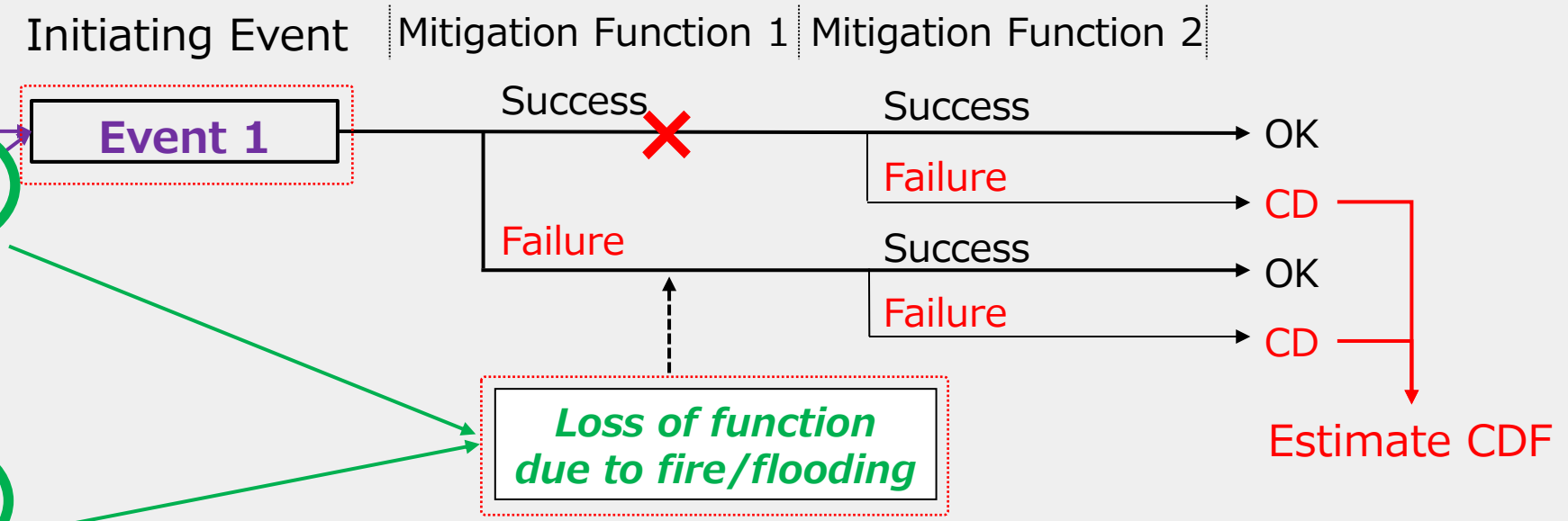


2. Internal Fire/Flooding PRA Model Structure

- Internal fire & flooding PRA models are based on the internal event PRA model and incorporate considerations specific to fire events (fire damage and HRA) and flooding events (submersion due to inundation, water exposure from spray, steam effects, and HRA), respectively.
- Fire occurrence frequency is based on fire incident data, and flooding frequency on pipe rupture frequency data.







3. Internal Fire/Flooding PRA Background & Gaps

■Background

- International findings recognize internal fire and flooding to be relatively high-risk events at NPPs.
- In the U.S., in addition to the ANS PRA implementation standards[1], industry has issued guidelines (Internal Flooding PRA[2]: 2009; Internal Fire PRA[3]: 2012).
- In Japan, AESJ issued implementation guidelines (Internal Flooding PRA[4]: 2012; Internal Fire PRA[5]: 2014).
- Practical methodologies have yet to mature in Japan.

■Gaps to Overcome

- No guidelines, relevant data, insights, or practical methods had been developed to conduct effective and efficient PRAs for internal fires and flooding that reflected the conditions at domestic plants.

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4. Efforts to Overcome Internal Fire PRA Gaps

- **Develop internal fire PRA guide**
  - Draft guide for internal fire PRA at domestic NPPs ⇒【Research Result (1)】
- **Consolidate internal fire frequency**
  - To use parameters based on domestic data to perform evaluations, we collected data from domestic NPPs to estimate fire frequency. ⇒【Research Result (2)】
- **Develop methods for conducting practical evaluations**
  - Develop fire models ⇒【Research Result (3)】
  - Gather data from fire tests
- **Conduct evaluations based on actual plant data**
  - Evaluate based on actual plant data to gain insight for guide feedback ⇒【Ongoing】
- **Update internal fire PRA Guide** ⇒【Next Steps】

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5. Research Result (1) PRA Implementation Guide Development

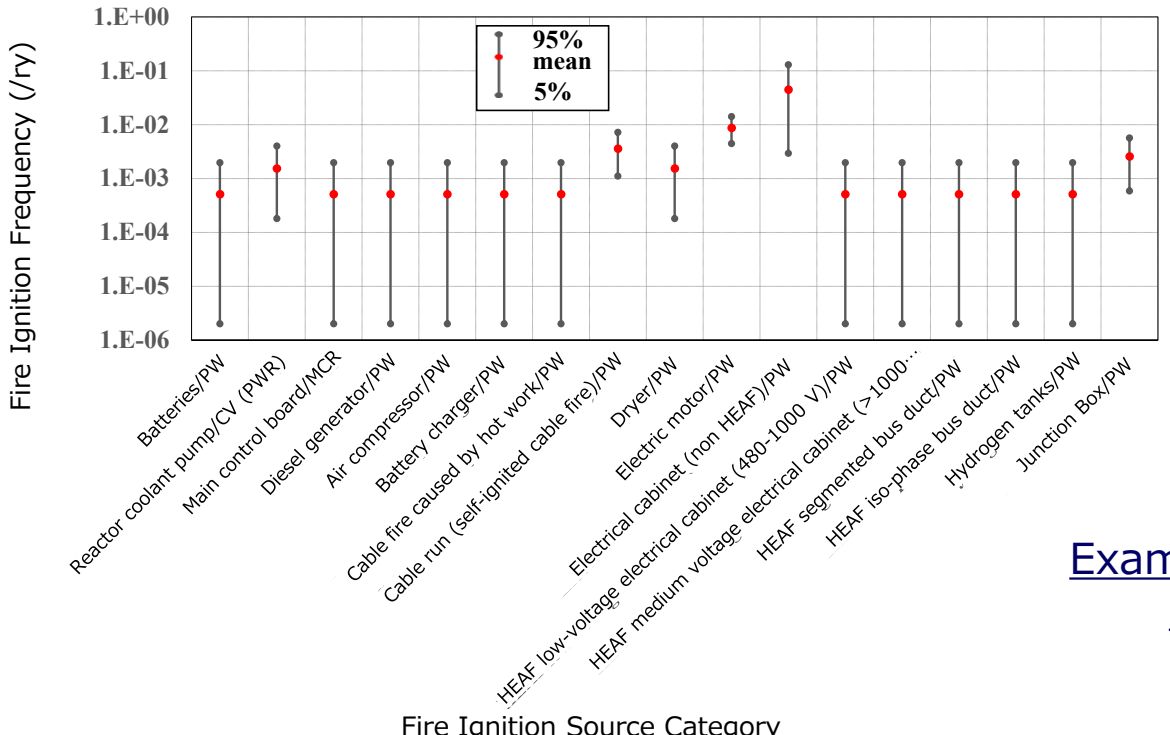
- **Draft internal fire PRA guide[6] to support effective and efficient implementation of fire PRAs at domestic NPPs**
  - Practical fire PRA guide based on the U.S. Comprehensive Fire PRA Guide (NUREG/CR-6850) and incorporating the latest technical insights available at time of publication

Phase A **Construct Plant Response Model and Scenarios**	**Task 1: Plant Response Model for Fire PRA** **Task 2: Define Fire Compartments** **Task 3: Analyze Human Reliability** **Task 4: Create Fire PRA Equipment List** **Task 5: Analyze Circuits and Identify Cables** **Task 6: Perform Qualitative Screening (Optional)** **Task 7: Set Initial HEP Values (Optional)** **Task 8: Assess Fire Ignition Frequencies** **Task 9: Verify Assessment and Model Data and Perform Full Compartment Burn Analysis**
Phase B **Fire Risk Quantification**	**Task 10: Analyze Main Control Room** **Task 11: Analyze Structural Steel Failure** **Task 12: Analyze Multi-Compartments** **Task 13: Identify Risk Significant Scenarios** **Task 14: Perform Fire Modeling** **Task 15: Perform Detailed Human Reliability Analysis** **Task 16: Analyze Circuit Failure Mode Likelihood** **Task 17: Determine Need for Detailed Analysis** **Task 18: Quantify Fire Risk** **Task 19: Analyze Uncertainty and Sensitivity** **Task 20: Document Fire PRA**

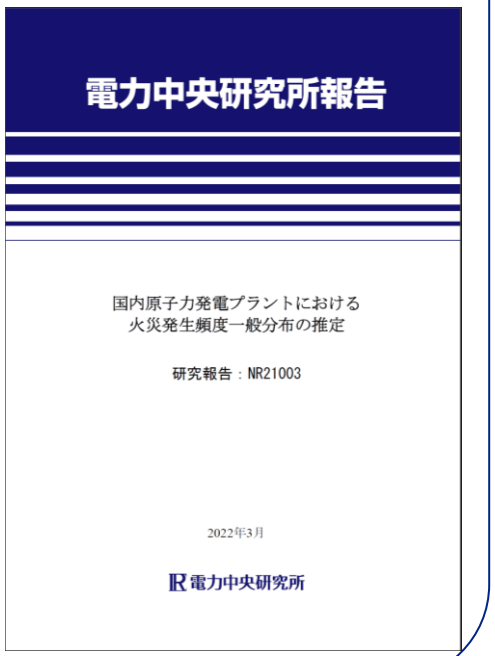


5. Research Result (2) Generic Fire Ignition Frequency Distribution Compilation

- **Publication of generic fire ignition frequency distribution based on domestic data[7]**
  - Collected and analyzed information on fire incidents at domestic NPPs
  - Quantified generic fire ignition frequency distribution applicable to internal fire PRA during power operation
  - Confirmed no significant difference from application of method developed by EPRI



PW: Plant-Wide
CV: Containment Vessel
MCR: Main Control Room
RwB: Radioactive Waste Building
TA: Transformer Area
TB: Turbine Building

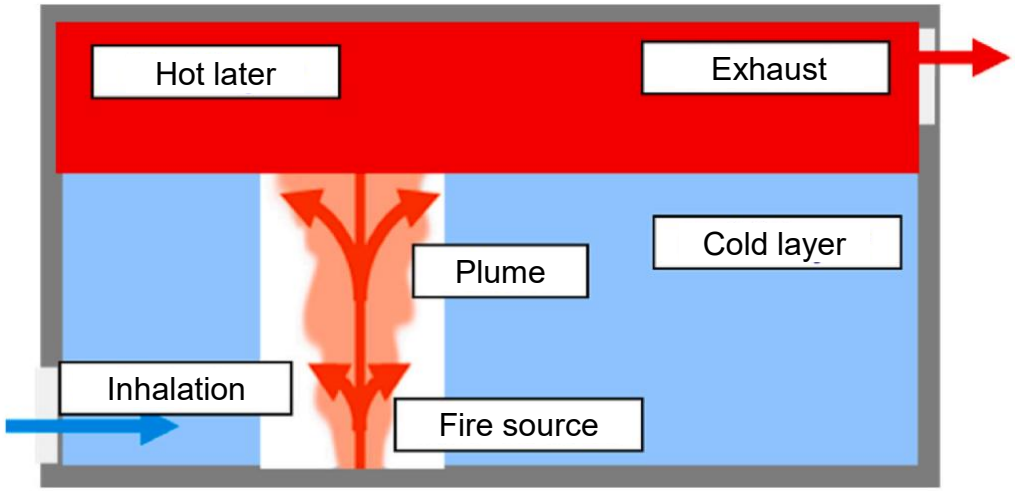


Example of Generic Fire Ignition Frequency Distribution

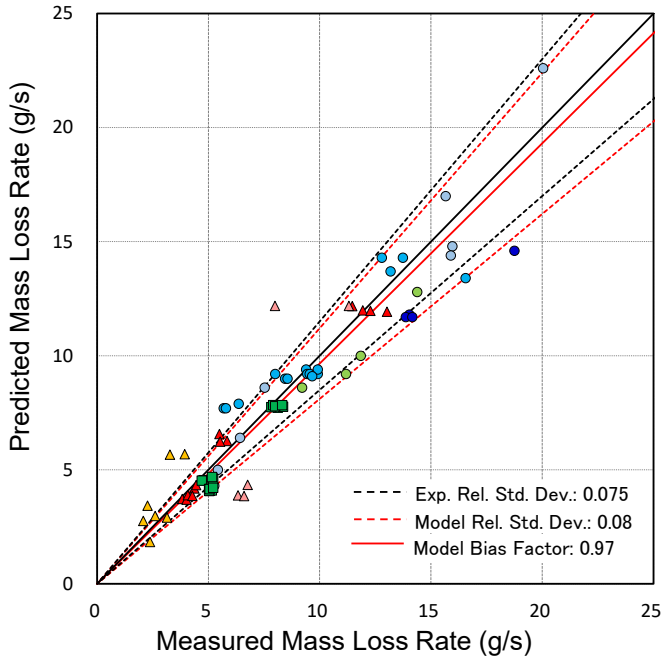
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5. Research Result (3) Development of Assessment Methods Required for PRA

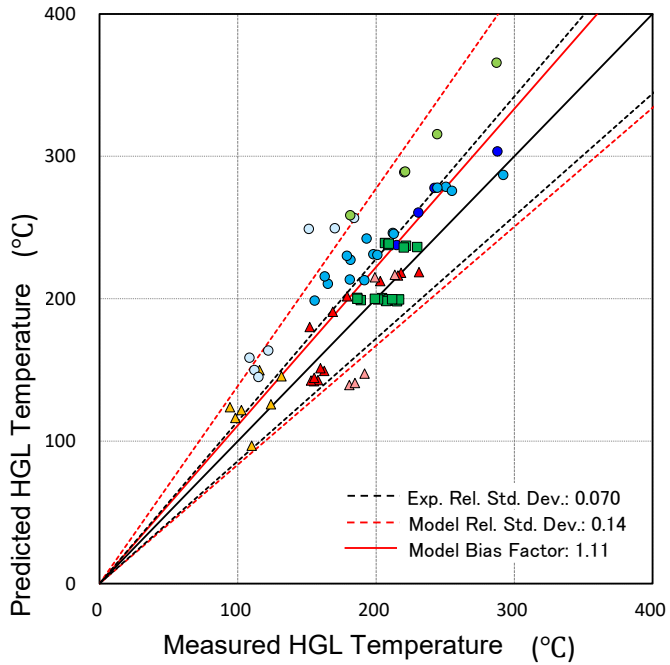
- **Development of BRI2-CRIEPI for predicting fire propagation under ventilation restrictions in mechanical air conditioning systems at NPPs[8]**
  - Adoption of two-layer zone model enables rapid fire progression prediction
  - Extensive V&V based on fire tests conducted by OECD, NEA, and other organizations carried out



Conceptual Diagram of Two-Layer Zone Model Code



Mass Loss Rate (MLR)

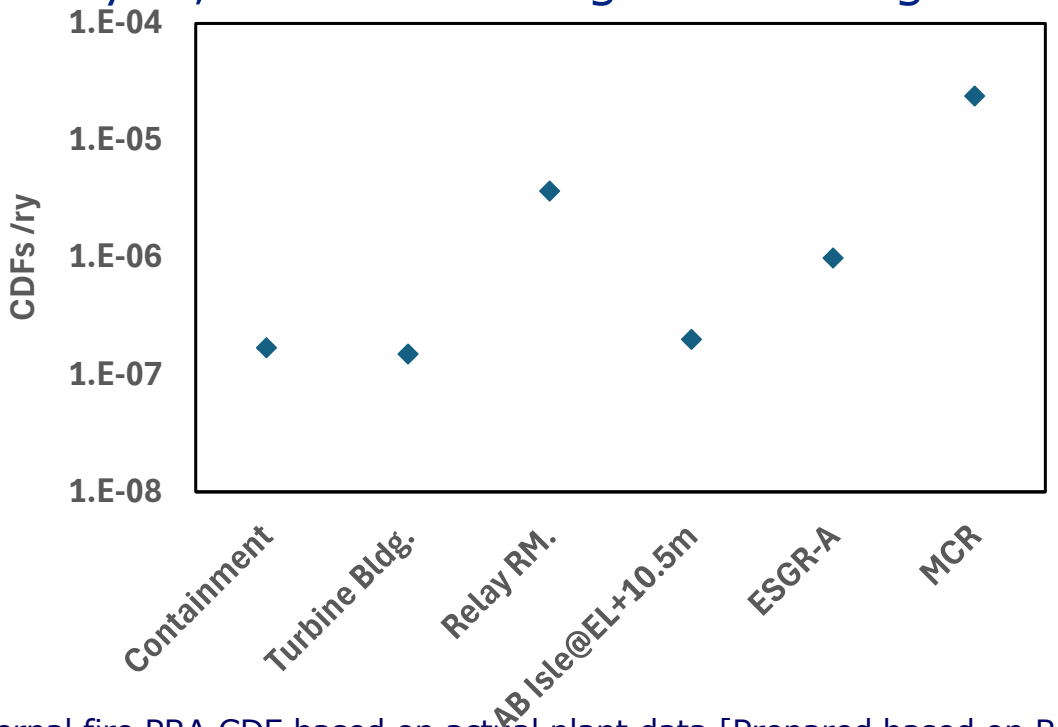


Hot Gass Layer (HGL) Temperature

BRI2-CRIEPI V&V Results[9]

5. Research Result (4) Actual Plant Data Evaluations

- **Using developed internal fire PRA guide, we are currently conducting an internal fire PRA based on actual plant data[10]**
  - Assessment tasks arranged into two stages: full burn assumption analysis and detailed analysis
  - Major fire sources and fire scenarios identified based on CDF quantified in detailed analysis, and derive insights for the guide



Internal fire PRA CDF based on actual plant data [Prepared based on Ref. 10]

***Full-burn assumption analysis:**
Analysis based on assumption that all cables and equipment inside a fire compartment are damaged by a fire that occurs within that compartment.

****Detailed Analysis:**
Detailed analysis takes into account the location and heat release rate of a fire occurring in a fire compartment, as well as the location characteristics of the affected cables and equipment.

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6. Internal Fire PRA Current Achievements & Future Actions

■Current Achievements

- Guide developed for conducting internal fire PRA, and framework for conducting internal fire PRA is being consolidated.
- It has also been confirmed that the resources required to perform internal fire PRA are substantial, posing a challenge.

■Future Actions

- Update next internal fire PRA guide (~FY2029)
  - Reflect applied results from actual plants and latest findings from Japan and abroad
- Review efficiency improvements based on insights from evaluations grounded in actual plant data (~FY2029)
  - Based on implementation results, incorporate omissions or excesses into guide in next revision.

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7. Efforts to Overcome Internal Flooding PRA Gaps

- **Conduct evaluation based on actual plant data**
  - Conduct evaluation based on actual plant data to gain insight for guide development ⇒【Research Result (1)】
- **Develop methods for conducting practical evaluations**
  - Methods for evaluating success or failure of operations performed by worker specific to overflow events ⇒【Research Result (2)】
  - Methods for evaluating the impact and extent to which water overflow within building affects surrounding equipment ⇒【Research Result (3)】
  - Methods for evaluating watertight performance of doors between compartments within a building
  - Methods for evaluating water levels in compartments of a building due to propagation of water overflow
- **Develop internal flooding PRA Guide**
  - Guide drafted for conducting internal flooding PRA at domestic NPPS ⇒【Research Result (4)】
  - Apply PRA Guide to actual plants ⇒【Future action】
- **Consolidate internal flooding frequency**
  - Estimate flooding frequency by collecting domestic data to conduct evaluations using parameters based on domestic events ⇒【Future action】

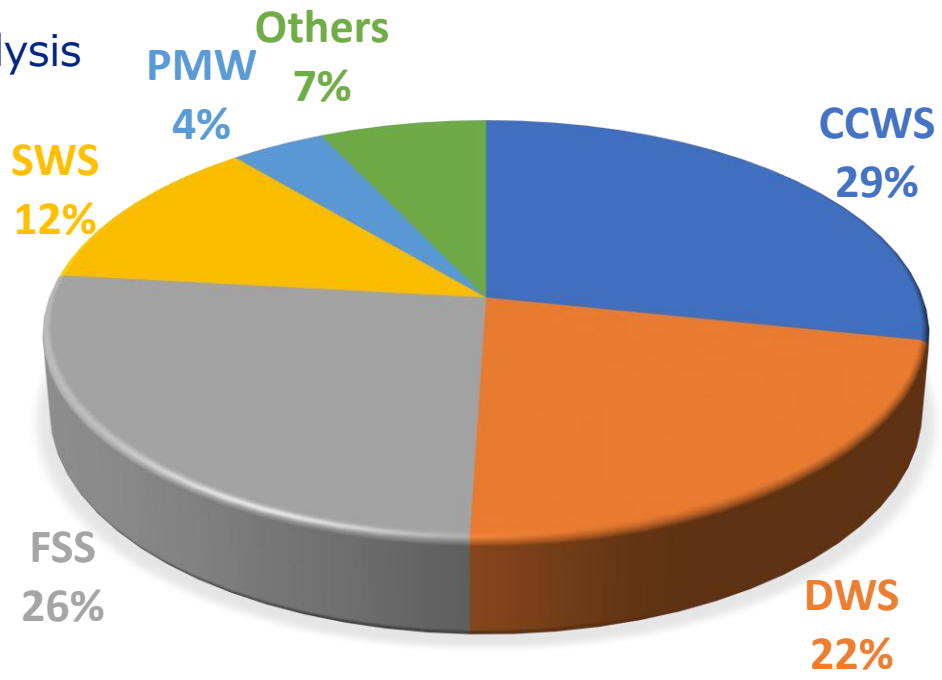
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8. Research Result (1) Actual Plant Data Evaluations for Guide Development

- **Conducted evaluation based on actual reactor data to gain insight for development of PRA guide on internal flooding[11]**
  - Conducted internal flooding PRA, referencing U.S. methodologies and flooding frequencies and using data from actual domestic NPPs
  - Organized evaluation tasks into three stages: qualitative analysis, screening analysis, and detailed analysis
  - Identified flooding sources and scenarios that significantly contribute to CDF quantified in the detailed analysis, and incorporated these findings into guide

- **Lessons Learned for guide development**

A) Exhaustively conduct walkdowns to ascertain information about “plant as-is”
B) HRA for flood isolation and safe plant shutdown
C) Screening analysis to improve IF-PRA efficiency
D) Comprehensive identification of flood sources
E) Realistic flood propagation paths
F) ZOI of spray scenarios



Contribution of overflow sources to CDF based on internal flooding

8. Research Result (2) Development of Assessment Methods Required for PRA (A)

- **HRA methodology developed for specific response procedures during internal flooding incidents**
  - Utilizing findings from our detailed human reliability assessment[12] based on narrative intelligence, we evaluated operators' cognitive and diagnostic tasks in response to internal water leakage events—specifically unique response operations (e.g., water leakage shutdown procedures)—as well as execution tasks involved in these events, ranging from developing water leakage shutdown procedures to actually operating valves and other actions.
  - HFE estimated for specific operational procedures

Procedure for Stopping Flooding

① Recognition/Assessment of Possibility of Flooding
② Identification of Location of Flooding
③ Preparation of Operating Procedures for Stopping Flooding
④ Operation/Execution to Stop Flooding

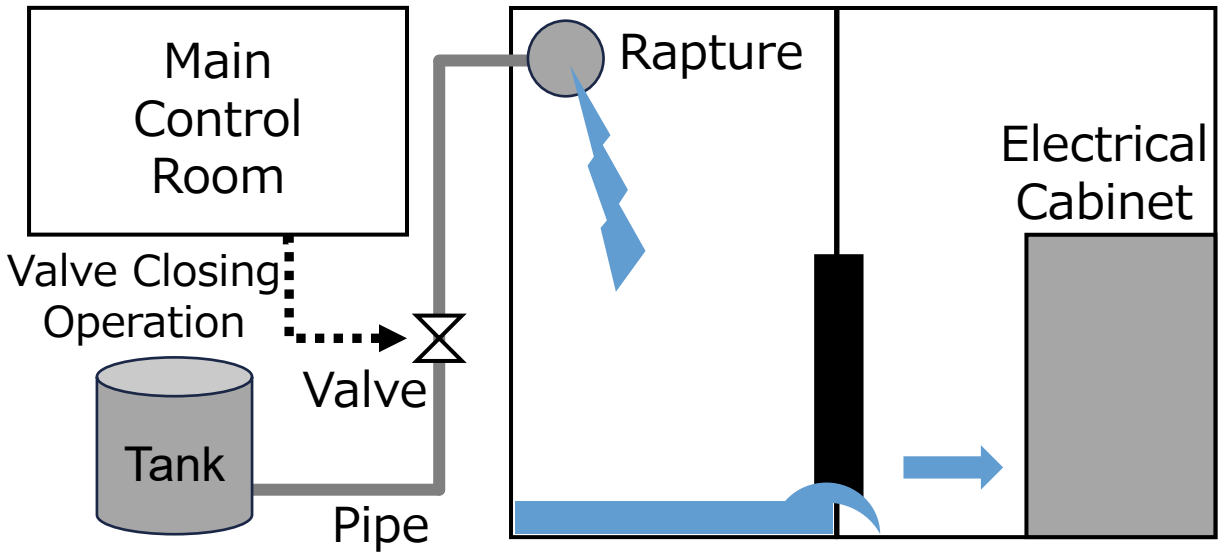
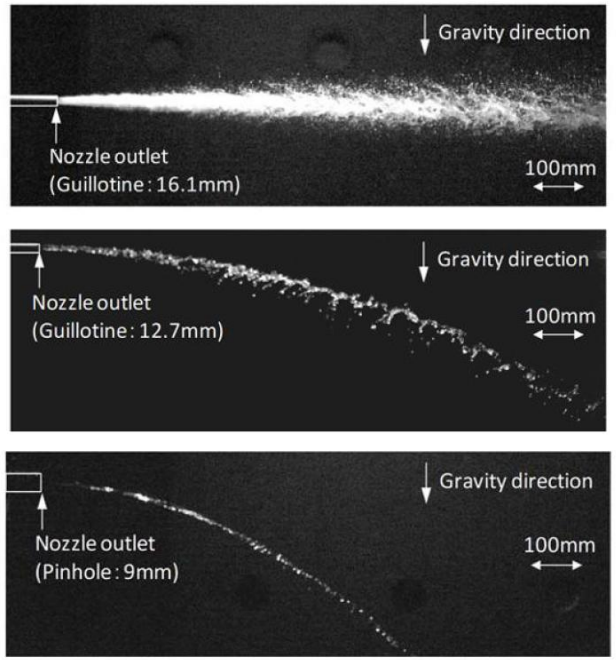


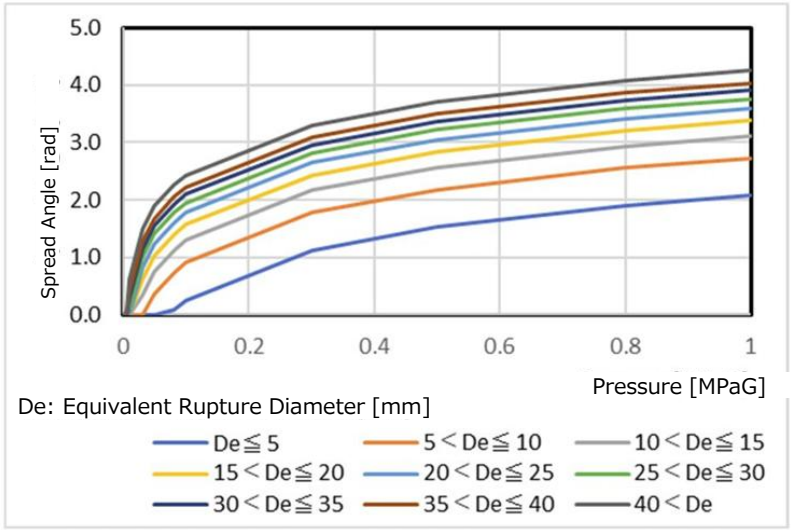
Illustration of Internal Water Leakage and Procedures to Stop Leaks[12]

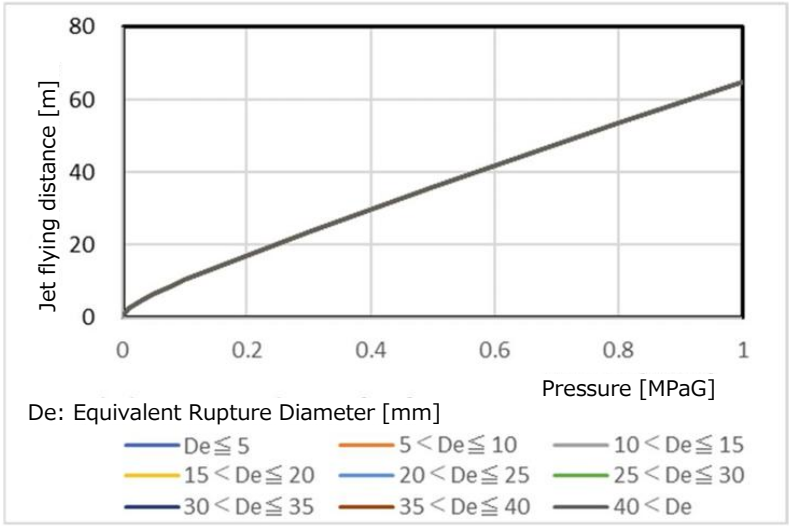
8. Research Result (2) Development of Assessment Methods Required for PRA (B)

- **Consolidation of Evaluating Method for Impact Area of Flooding based on Water Jet Experiments**
  - Water jet experiments conducted using nozzles that simulated pinhole and guillotine ruptures, and equations proposed to estimate jet spread angle and reach distance based on visual flow analysis.
  - This method utilized to realistically evaluate the area impacted by water spray caused by flooding on the loss of function of equipment as considered in PRA.



Visualizations of Water Jet Experiments[13]





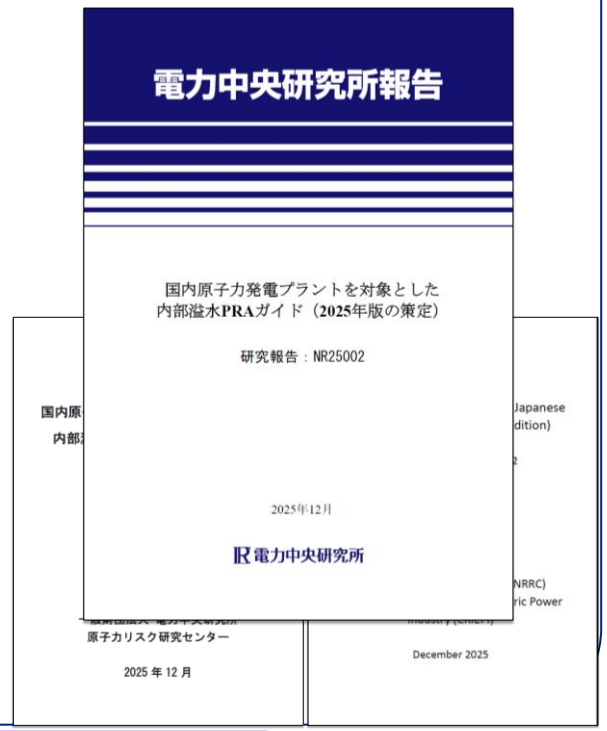
Quick Reference Chart for Area Impacted by Spray Caused by Flooding[14]

8. Research Result (4) Drafting of PRA Implementation Guide

- **Publication of Internal Flooding PRA Guide (2025 Edition)[15]**
  - Structure constructed of report text and guide (Japanese and English versions)
  - Feedback incorporated from the model plant evaluation [Research Result (1)]
  - Methodologies incorporated for conducting more realistic assessments [Research Result (2)]
  - International practical insight reflected following the U.S. expert review of internal flooding PRA

Main Components of Internal Flooding PRA Implementation Guide

Phase A: Qualitative Analysis Develop and screen scenarios based on conservative assumptions	Task 1: Definition of Plant Boundaries, Flood Areas, and SSCs (Structures, Systems and Components) Task 2: Internal Flooding Scenarios Task 3: Plant Walkdown Task 4: Qualitative Screening
Phase B: Quantitative Analysis Conduct detailed analysis of scenarios not screened out in Phase A	Task 5: Internal Flooding Propagation Event Tree Task 6: Internal Flooding Scenario Frequencies and Flooding Rates Task 7: Equipment Damage Probability Task 8: Internal Flooding Damage States Characterization Task 9: Plant Response Model for Internal Flooding PRA Task10: Analysis of Operator Action Task11: Risk Quantification Task12: Reduction in Conservatism Task13: Uncertainty Analysis and Sensitivity Analysis Task14: Internal Flooding Final Report



9. Internal Flooding PRA Current Achievements & Future Actions

■Current Achievements

- Referring to the Internal Flooding PRA Implementation Guide made it possible for utilities to effectively and efficiently conduct high-quality internal flooding PRA analyses that reflect specific conditions of their individual plants.

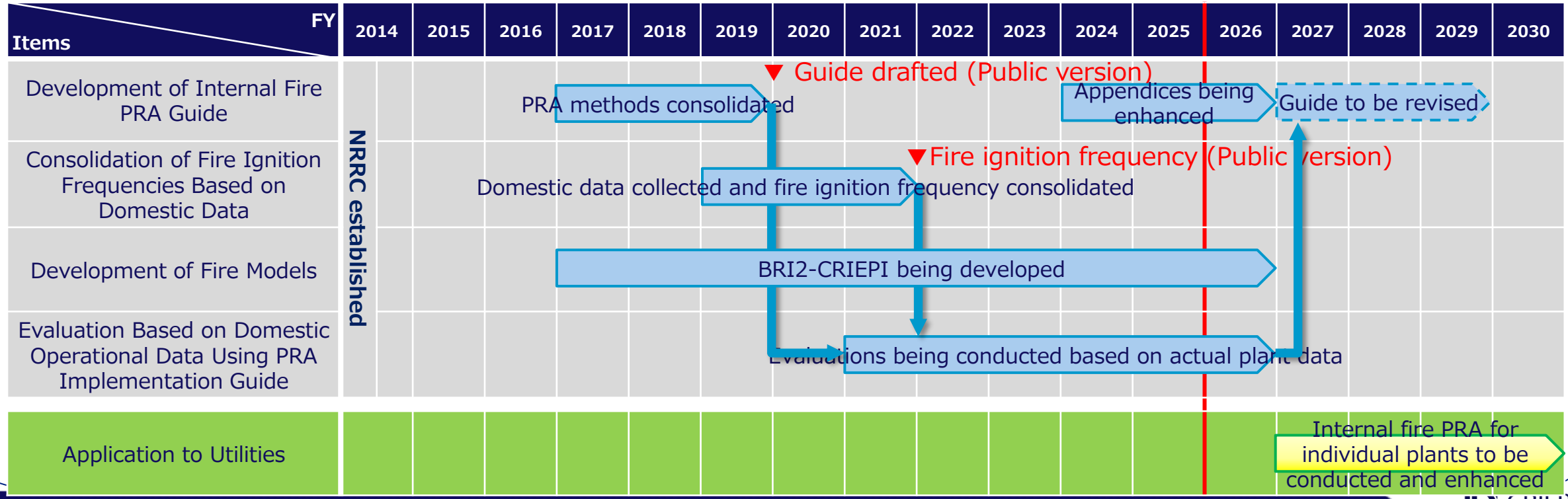
■Future Actions

- Establish flooding frequency based on latest domestic data (~2027)
  - Plan to continue regularly collecting domestic data and update the frequency of overflow incidents
- Verify applicability of guide (2025 Edition) at actual plants (~2029)
  - Based on implementation results, incorporate guide omissions or excesses into the next revised edition.
- Revise next internal flooding PRA (~2029)
  - Reflects application results from actual and individual plants, as well as the latest findings from Japan and abroad

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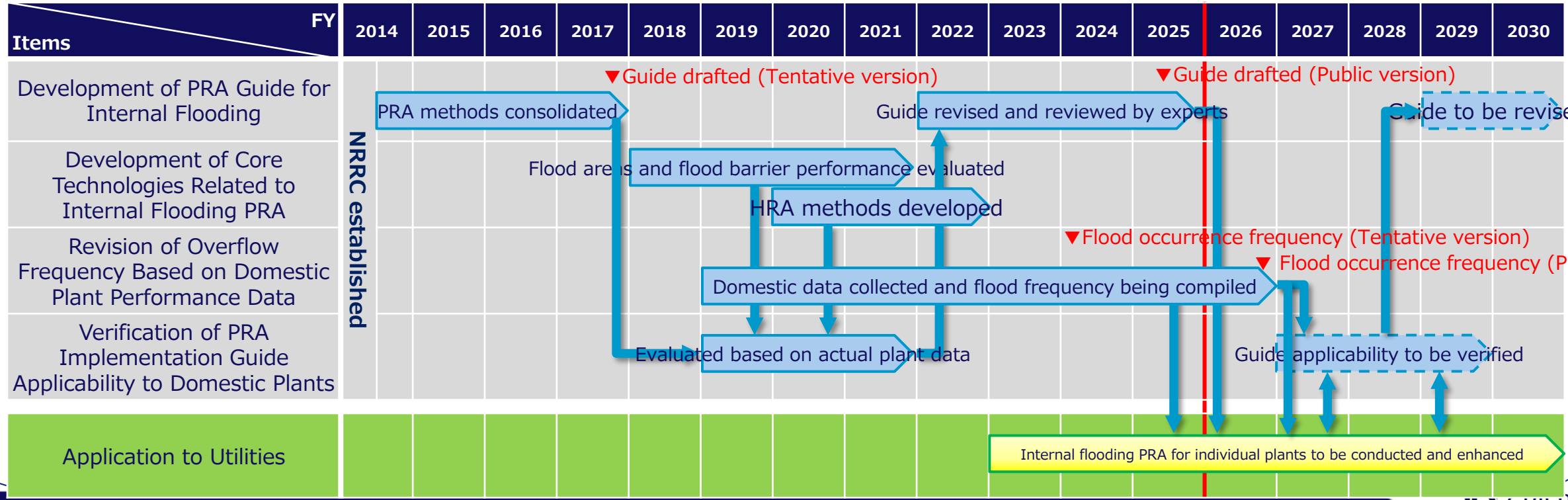
[Appendix] Progress in Overcoming Gaps

- Insights acquired for developing guide through qualitative and detailed analyses using domestic plants
- Evaluation methods developed for various individual elements to enable more realistic assessments



[Appendix] Progress in Overcoming Gaps

- Insights acquired for developing guide through qualitative and detailed analyses using domestic plants
- Evaluation methods developed for various individual elements to enable more realistic assessments
- PRA guide drafted for internal flooding that meets international standards
  - NRRC's research findings and the latest domestic and international insights reflected and guide published in Dec. 2025 following review by international experts



[Appendix] Status of Initiatives

Gaps to Overcome	Description	Progress
Guidelines and other documents for conducting internal flooding PRA not yet consolidated in Japan	Evaluate based on actual plant data to develop guide	Completed in FY2021
	Develop methods for conducting practical evaluations	Completed in FY2022
	Develop internal flooding PRA guide	Completed in FY2025
	Estimate flooding frequency based on domestic plant data	Ongoing through FY2026
	Verify guide's applicability at actual plants	Ongoing through FY2030
Guidelines and other documents for conducting internal fire PRA not yet consolidated in Japan	Develop internal fire PRA guide	Completed in FY2019
	Estimate fire ignition frequency based on domestic plant data	Ongoing through FY2027
	Develop methods for conducting practical evaluations	Ongoing through FY2026
	Evaluate based on actual plant data to develop guide	Ongoing through FY2026
	Revise guide	Ongoing through FY2029

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[Appendix] References

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