Analysis of Thermal–Hydraulic Behavior during Loss-of-Coolant Accidents in PWR Plants for Pressurized Thermal Shock Assessment

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PSAM 18 | Pittsburgh, Pennsylvania | July 2026

Contents

1. INTRODUCTION

2. TRACE ANALYSIS OF A 4-LOOP PWR PLANT

3. RESULTS AND DISCUSSION
   - CL 5-inch break with the HPI-available case
   - CL 5-inch break with the HPI-unavailable Case

4. CONCLUSIONS

Contents

1. INTRODUCTION

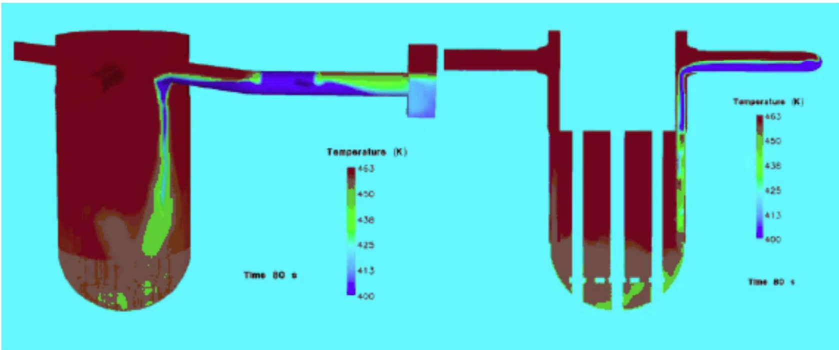
2. TRACE ANALYSIS OF A 4-LOOP PWR PLANT

3. RESULTS AND DISCUSSION
   - CL 5-inch break with the HPI-available case
   - CL 5-inch break with the HPI-unavailable Case

4. CONCLUSIONS

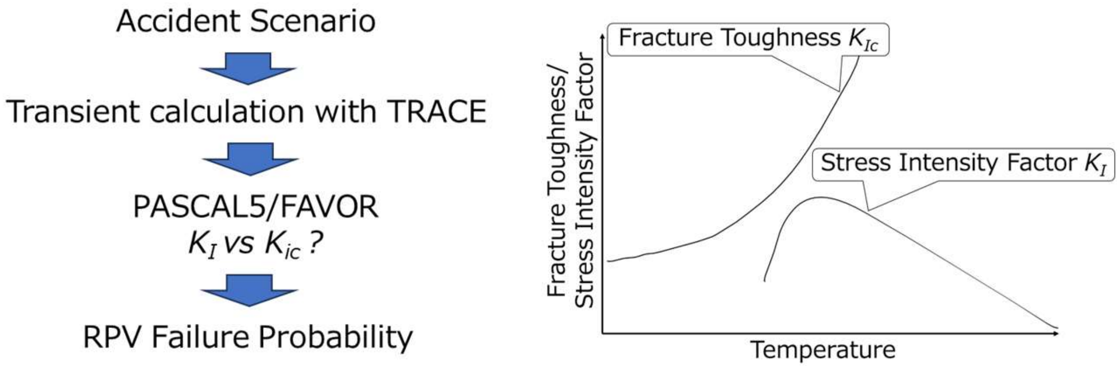
Pressurized Thermal Shock (PTS)

- Progressive neutron irradiation embrittlement of the reactor pressure vessel (RPV) makes maintaining its structural integrity an increasingly important nuclear safety issue during long-term operation.
- In Japan, long-term operation (>40 years) of NPPs is increasing and evaluating pressurized thermal shock (PTS) has become increasingly important.
- PTS occurs when ECCS injection rapidly cools the RPV inner wall during a loss-of-coolant-accident (LOCA).
- Rapid cooling under pressure generates high tensile stresses near the RPV inner surface.
- Traditionally, PTS has been evaluated using deterministic fracture mechanics under conservative assumptions in Japan.
- However, efforts have been made to enhance PTS assessment by applying probabilistic fracture mechanics (PFM) recently.



Vessel and fluid temperatures with ECC injection

NEA/CSNI/R(2014)11, 2015

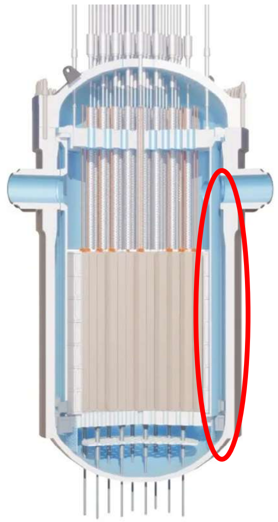


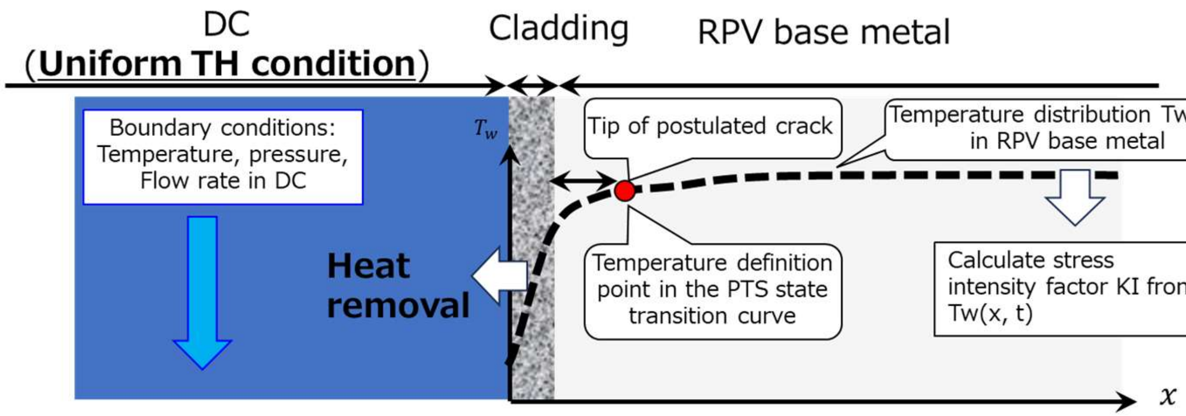
PTS assessment process

Background of this study

Overview of PTS assessment using PFM

PTS assessment requires transient temperature distributions of the RPV inner wall to evaluate crack growth. PFM is a methodology that calculates the probability of RPV failure by accounting for various uncertainties.
Current PTS assessments assume spatially uniform DC conditions and do not account for the spatial non-uniformity of actual DC thermal-hydraulic behavior.





Focus of this study

We investigate spatial non-uniformity in DC TH behavior to evaluate its impact on PTS assessment.

Abbreviations:
DC = Downcomer
TH = Thermal-Hydraulic

*https://www.energyencyclopedia.com/en/free-downloads/images/npp-pwr-reactor-140#&gid=1&pid=1

Contents

1. INTRODUCTION

2. TRACE ANALYSIS OF A 4-LOOP PWR PLANT

3. RESULTS AND DISCUSSION
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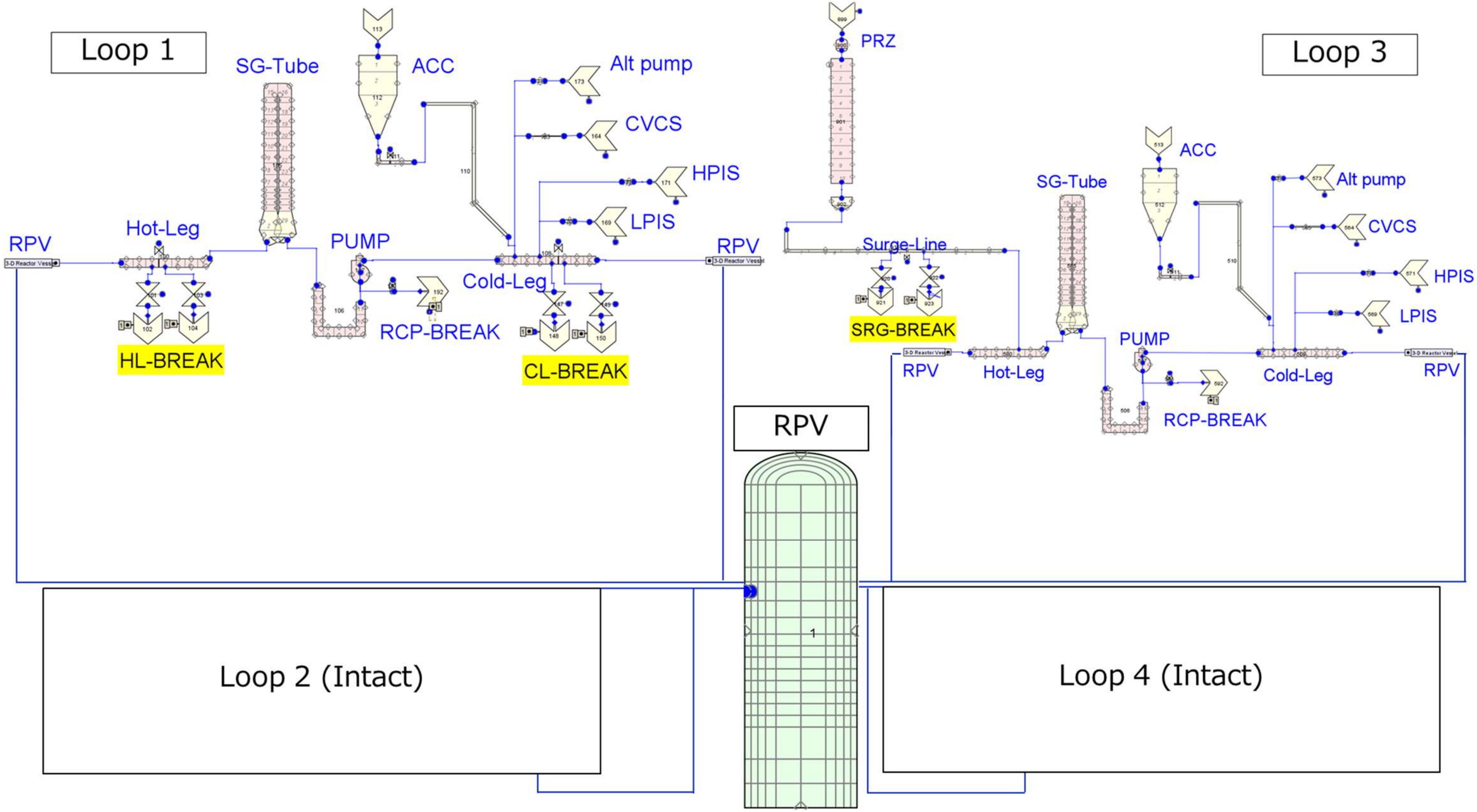
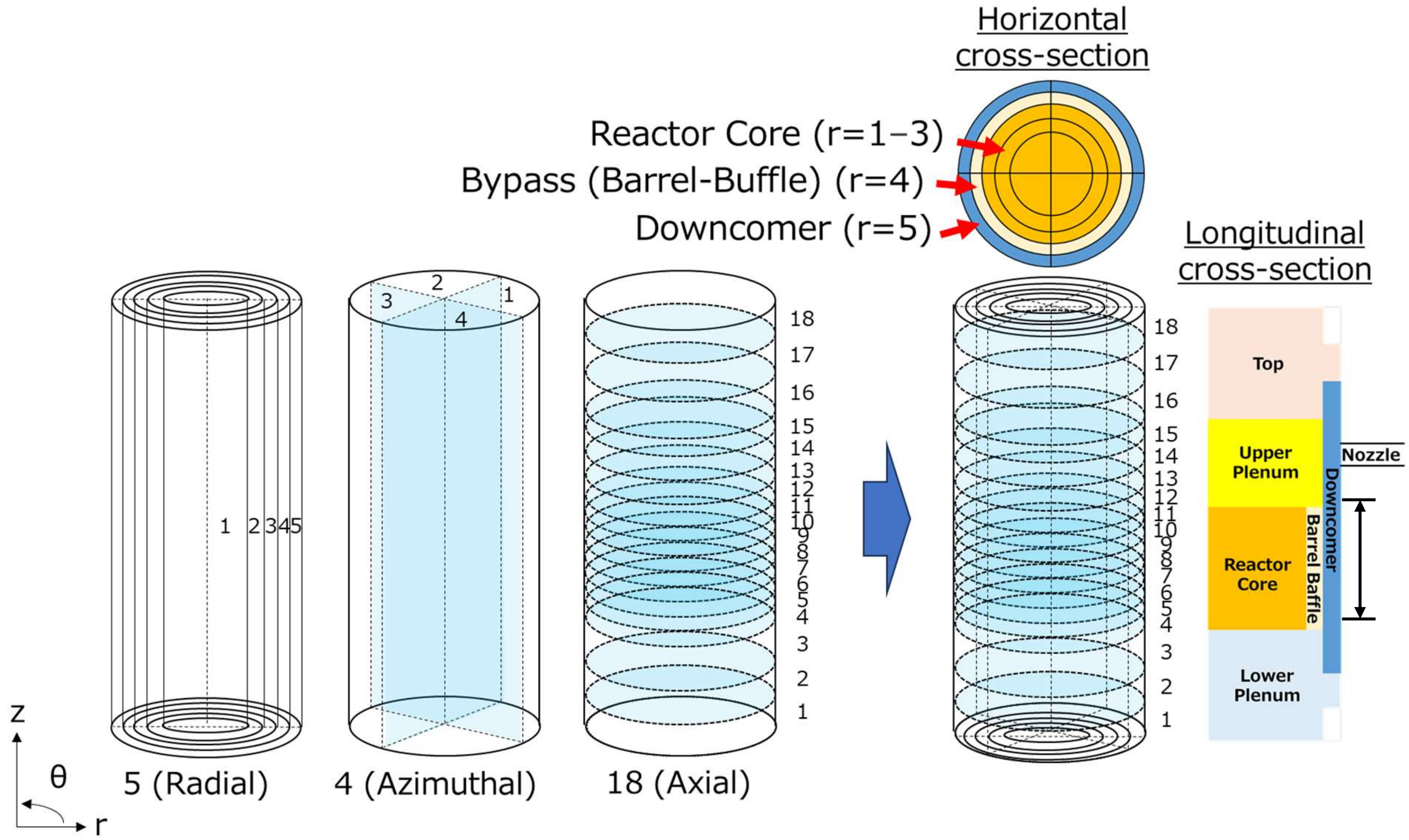
   - CL 5-inch break with the HPI-unavailable Case

4. CONCLUSIONS

Analytical Model:
TRACE 4-Loop PWR Plant model

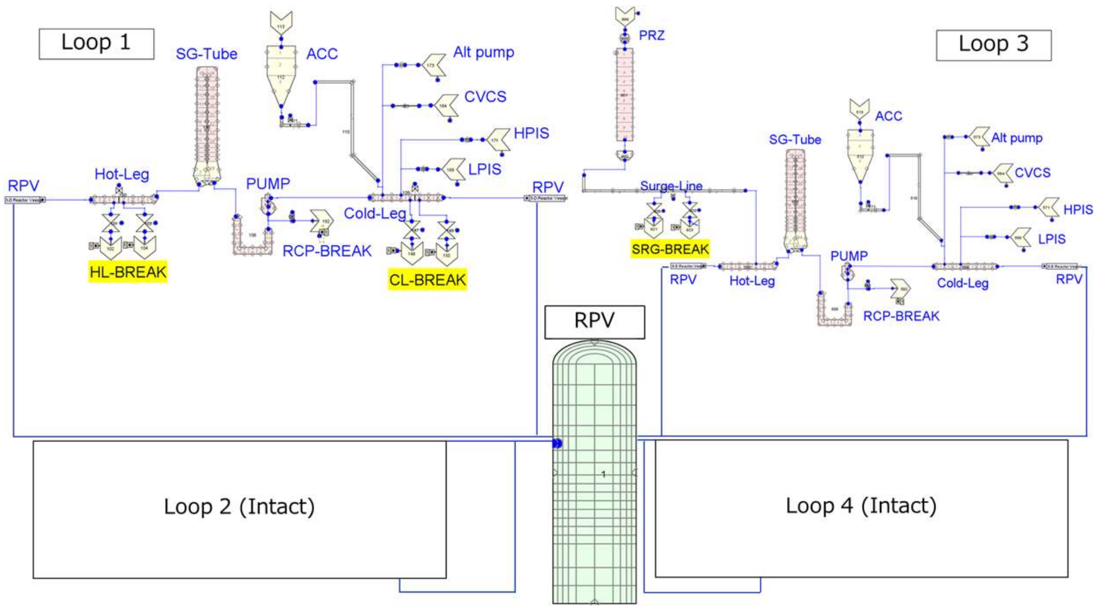


Analytical Model:
RPV and DC Beltline Nodalization



- RPV is divided into 5 radial, 4 azimuthal, and 18 axial segments
- DC is located in the outermost radial region
- Beltline region corresponds to z = 4–11
- Nozzle elevation corresponds to z = 14

Analytical conditions:



Node Diagram of TRACE Analytical Model of 4-loop PWR

Break location	Break size (inch)	ECCS condition
CL	1,5,10	HPI available /unavailable
HL	1,5,10	HPI available /unavailable
SRG	1,5,10	HPI available /unavailable

LOCA scenarios

- For the plant TH analysis under LOCA conditions, a 4-loop PWR analysis model using the TRACE code was employed.
- Selected LOCA scenarios: **CL 5-inch** break LOCA with **high-pressure injection system (HPI) available/unavailable** case

Contents

1. INTRODUCTION

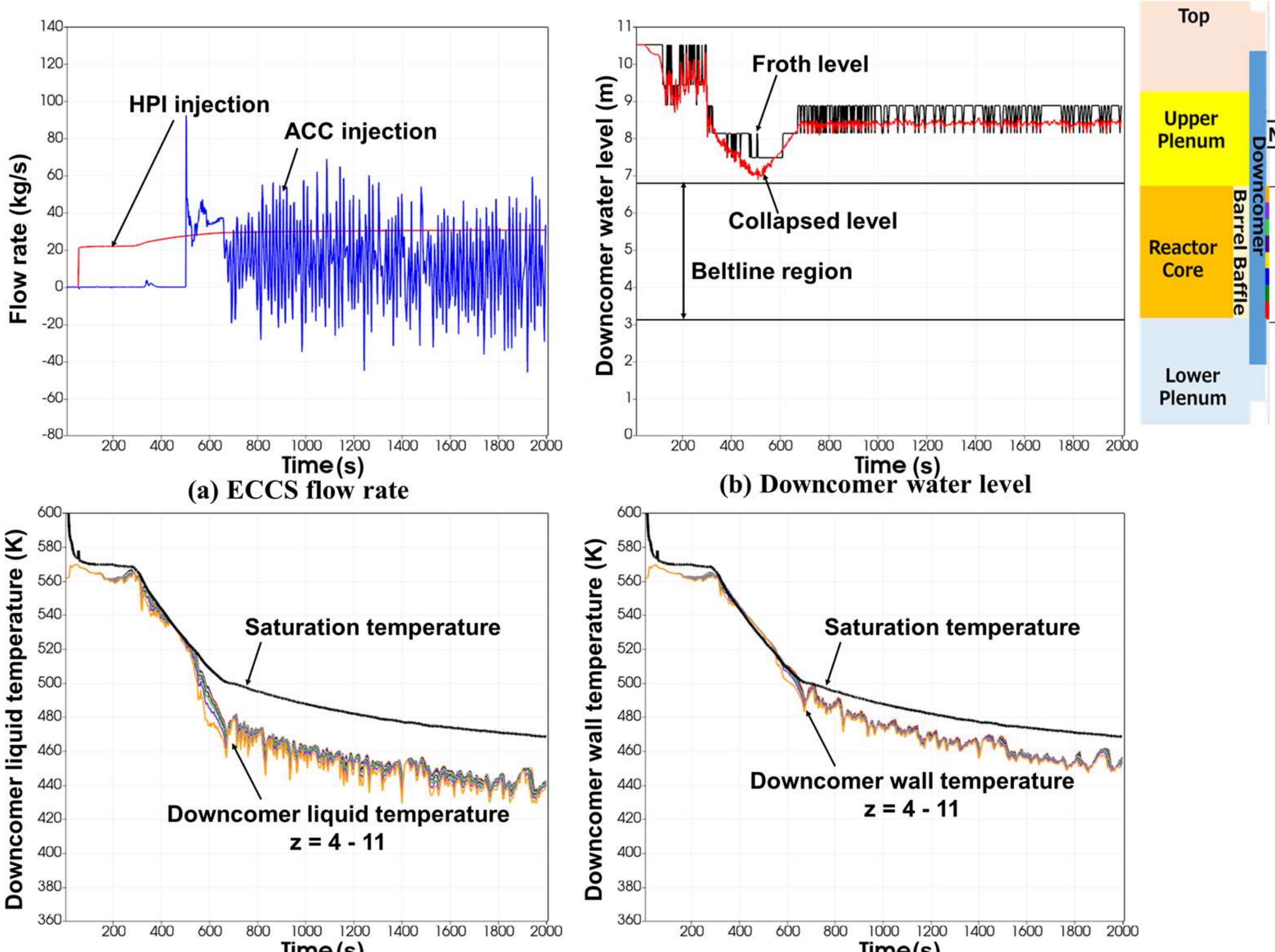
2. TRACE ANALYSIS OF A 4-LOOP PWR PLANT

3. RESULTS AND DISCUSSION

- **CL 5-inch break with the HPI-available case**
- CL 5-inch break with the HPI-unavailable Case

4. CONCLUSIONS

CL 5-inch Break with the HPI-available case (1/2): ECCS flow rate, DC water level, DC liquid temperature, and DC wall temperature



(a) ECCS flow rate

(b) Downcomer water level

(c) Downcomer liquid temperature and saturation temperature

(d) Downcomer wall temperature and saturation temperature

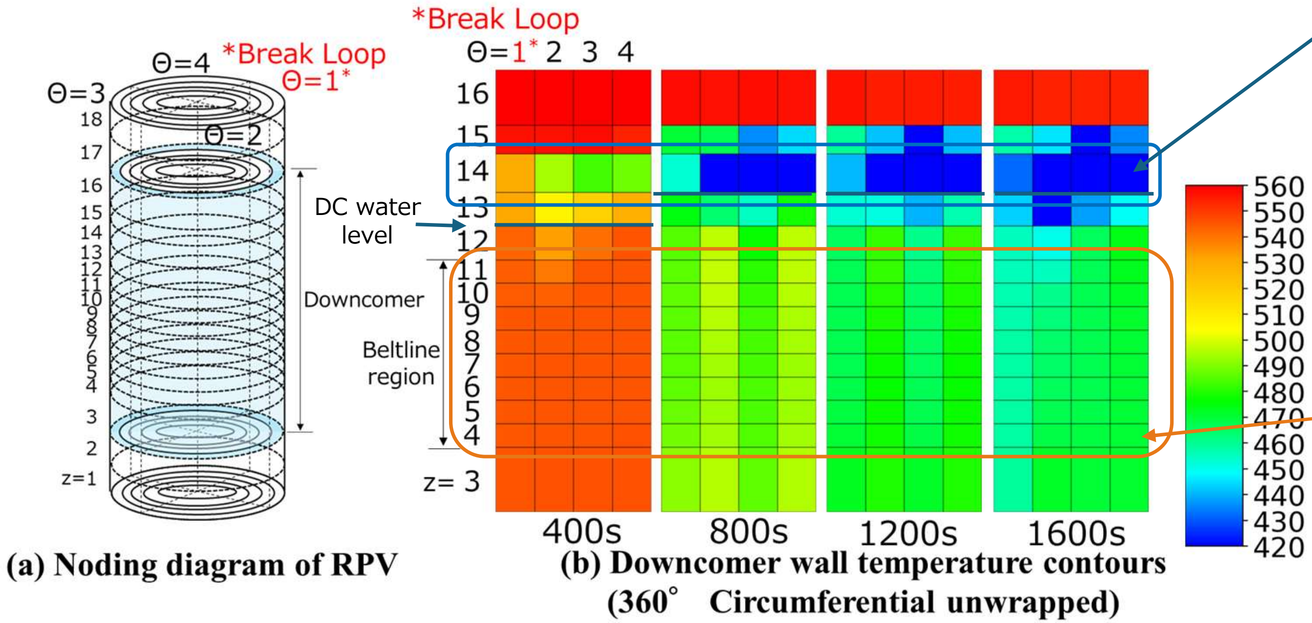
Results for the CL 5-inch break under the HPI-available case

Main observations

- HPI starts at about 30 s, and ACC starts around 500 s after the break.
- DC water level does not decrease to the beltline region.
- Beltline region remains flooded throughout the transient.
- DC wall temperature decreases monotonically with liquid temperature.

Cooling mode: Flooded-wall cooling

CL 5-inch Break LOCA the HPI-available Case (2/2): Azimuthal Differences in the DC Wall Temperature



Wall temperature distribution for the HPI-available case

Nozzle elevation (z=14)

・Azimuthal differences are observed at nozzle elevation.
・Broken-loop wall temperature is higher due to delayed cooling.
・Difference is attributed to ECCS discharge from the break opening.

Beltline region (z=4-11)

・No considerable azimuthal differences are identified in the beltline region.
・HPI maintains DC water level and supports flooded-wall cooling behavior.
・Azimuthal non-uniformity is limited in the beltline region.

Nozzle-level azimuthal differences appear, but beltline azimuthal non-uniformity remains limited.

Contents

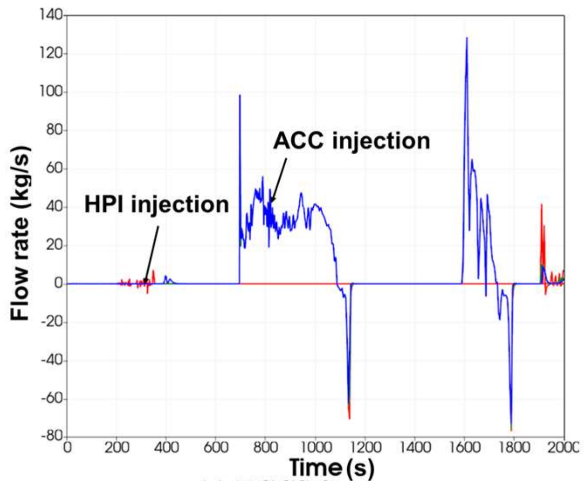
1. INTRODUCTION

2. TRACE ANALYSIS OF A 4-LOOP PWR PLANT

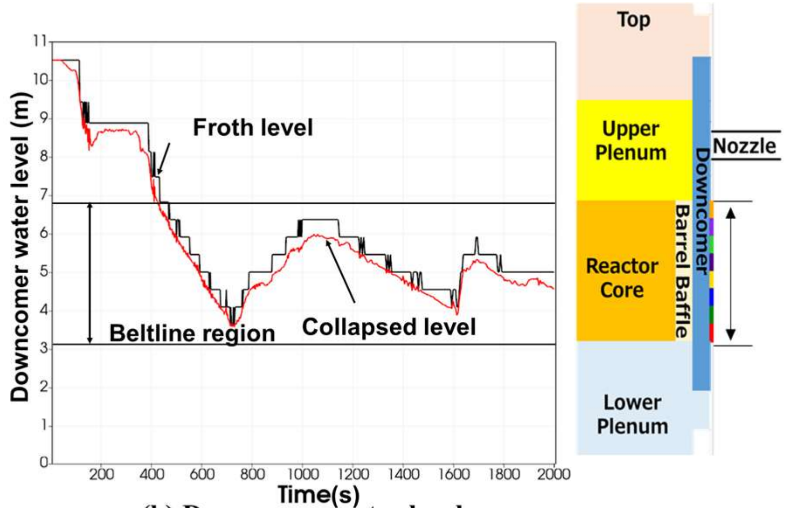
3. **RESULTS AND DISCUSSION**
   - CL 5-inch break with the HPI-available case
   - **CL 5-inch break with the HPI-unavailable Case**

4. CONCLUSIONS

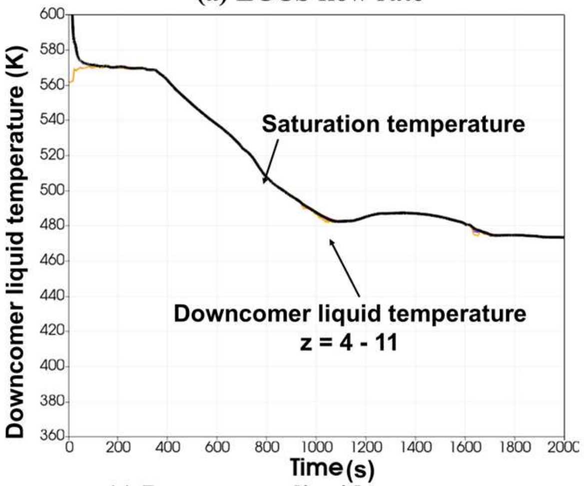
CL 5-inch Break with the HPI unavailable case (1/4): ECCS flow rate, DC water level, DC liquid temperature, and DC wall temperature



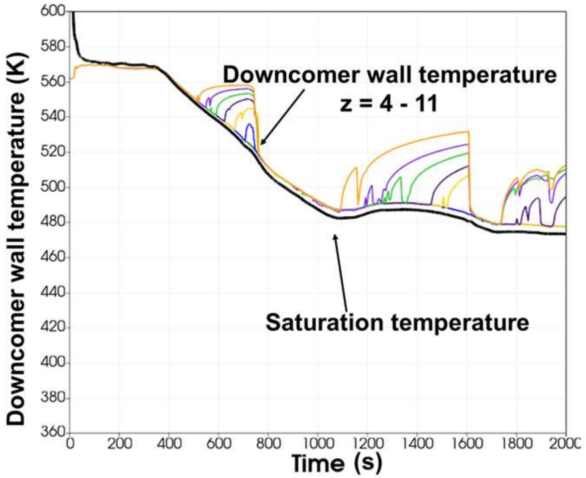
(a) ECCS flow rate



(b) Downcomer water level



(c) Downcomer liquid temperature and saturation temperature



(d) Downcomer wall temperature and saturation temperature

Results for the CL 5-inch break with the HPI-unavailable case

Main observations

・No HPI injection; ACC injection occurred in two peaks.

・DC water level decreases to the lower beltline region.

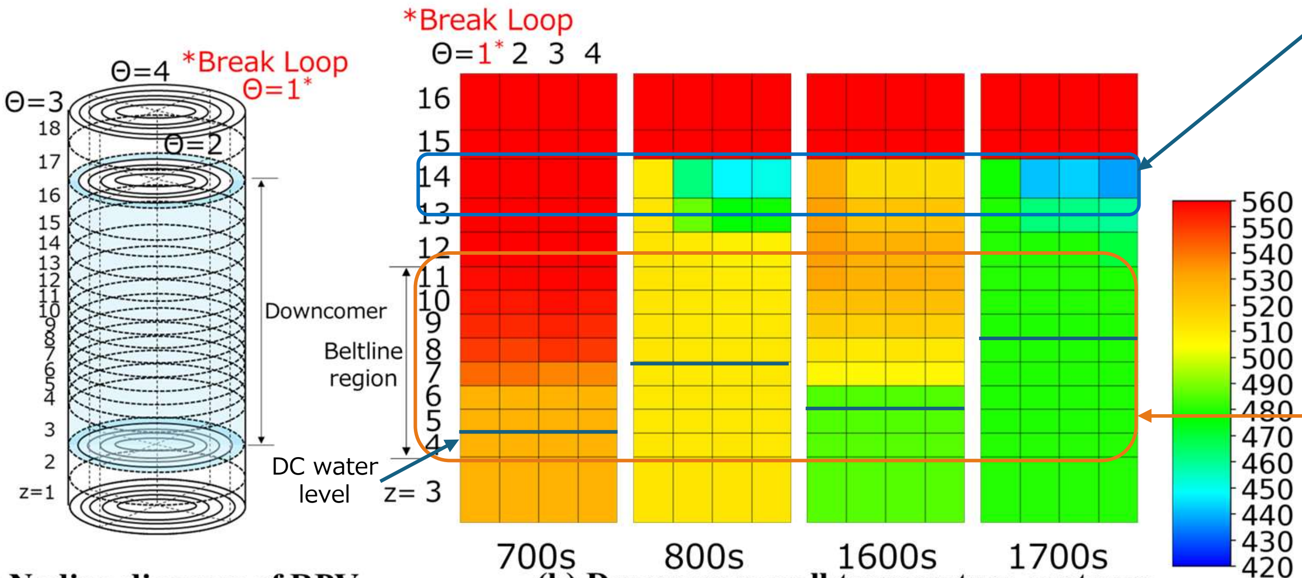
・Upper beltline wall becomes exposed.

・Wall temperature rises above saturation after exposure.

・Rapid cooling occurs twice in correspondence with ACC inflow.

Cooling mode: Re-wetting after wall exposure

CL 5-inch Break with the HPI Unavailable Case (2/4): Azimuthal Differences in the DC Wall Temperature



(a) Noding diagram of RPV

(b) Downcomer wall temperature contours (360° Circumferential unwrapped)

Wall temperature distribution for the HPI-unavailable case

Nozzle elevation (z=14)

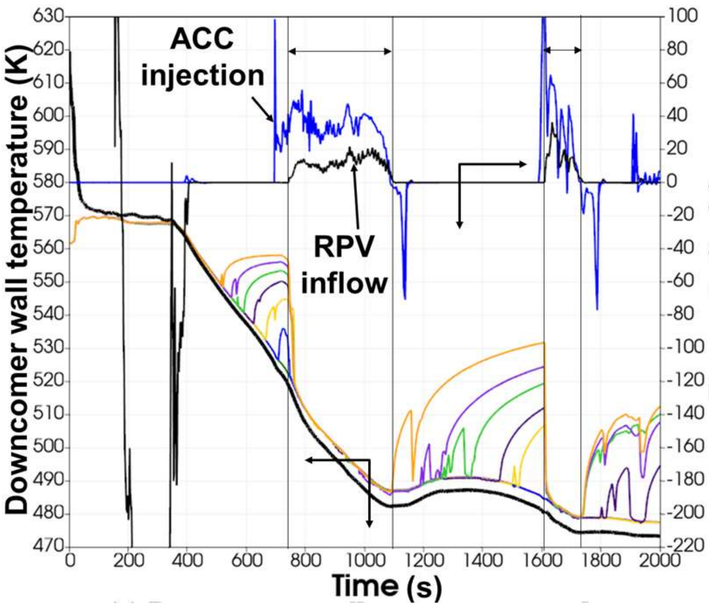
・Azimuthal differences are observed at nozzle elevation.
・Broken-loop wall temperature is higher due to delayed cooling.
・The difference is attributed to ECCS discharge from the break.

Beltline region (z=4-11)

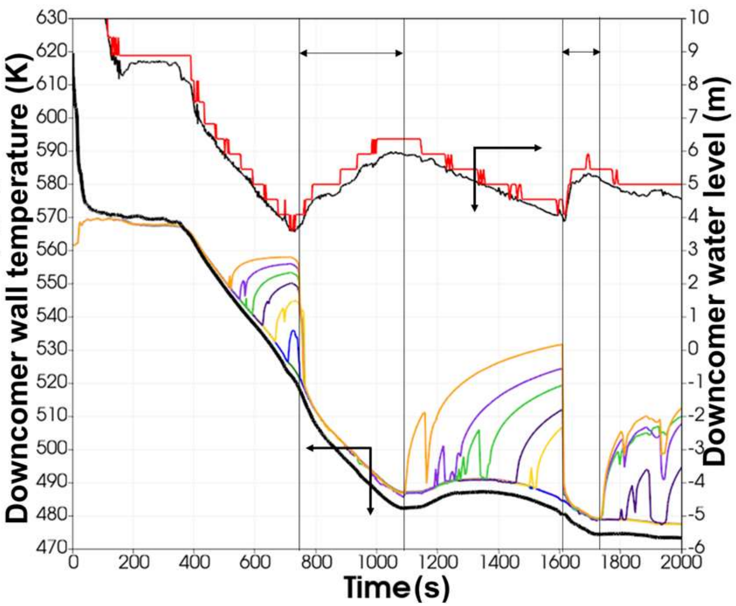
・No considerable azimuthal differences are identified in the beltline region.
・Axial temperature differences are observed.
・Axial behavior is associated with water-level variation and wall. exposure

Nozzle-level azimuthal differences appear as well, beltline behavior is governed mainly by axial cooling-mode differences rather than azimuthal non-uniformity.

CL 5-inch Break with the HPI-unavailable Case (3/4)
(a)DC wall temperature vs ECCS flow rate – RPV inflow rate
(b)DC wall temperature vs DC water level



(a) DC wall temperature vs ECCS flow rate – RPV inflow rate



(b)DC wall temperature vs DC water level

Main observations

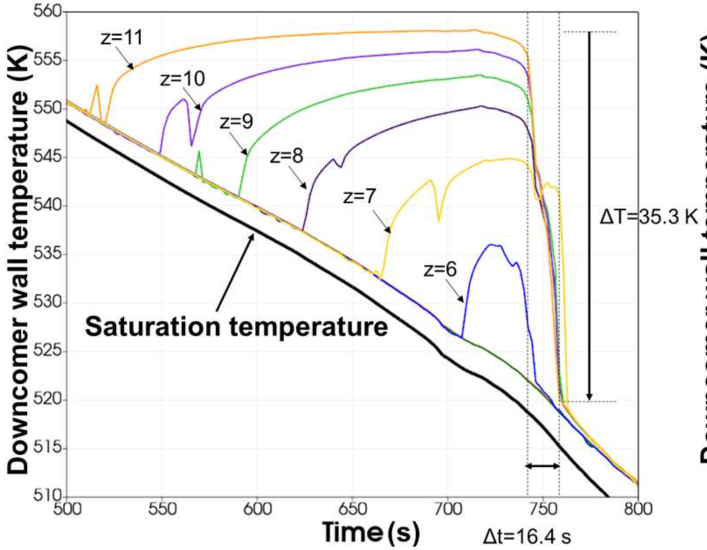
・Rapid cooling of DC wall nearly coincides with RPV inflow.

・It does not simply coincide with ACC injection into CL.

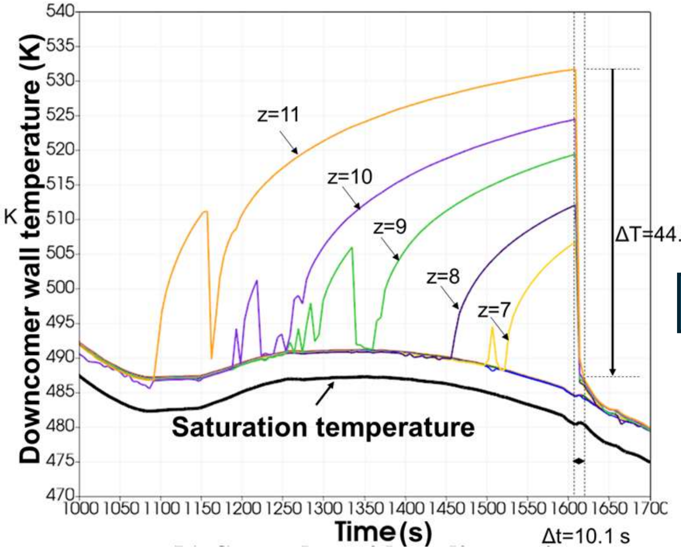
・Wall temperature remains near saturation during RPV inflow.

Rapid cooling is governed by the arrival of ACC water into the RPV/DC region.

CL 5-inch Break with the HPI-unavailable Case (4/4)
Cooling Rate of the DC wall-temperature at rapid cooling points

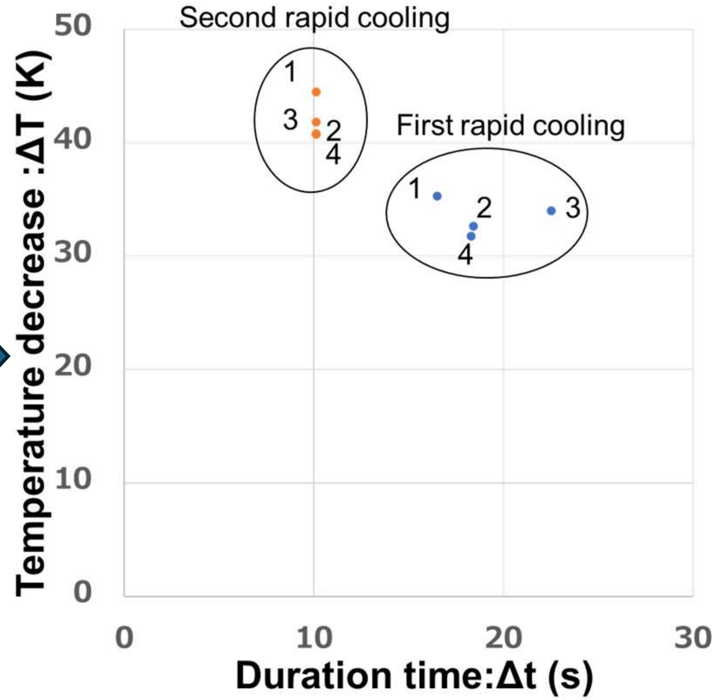


First rapid cooling point



Second rapid cooling point

Temperature transient in the broken loop (Loop 1)



Decreasing rate of DC wall temperature in belt-line of Loop 1 - 4

Quantitative findings

- Broken loop, first rapid cooling: 35.3 K over 16.5 s, corresponding to 2.14 K/s
- Broken loop, second rapid cooling: 44.5 K over 10.1 s, corresponding to 4.39 K/s
- Across all loops, repeated 30–50 K temperature drops occur with cooling rates up to approximately 4 K/s

Contents

1. INTRODUCTION

2. TRACE ANALYSIS OF A 4-LOOP PWR PLANT

3. RESULTS AND DISCUSSION
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    - CL 5-inch break with the HPI-unavailable Case

4. CONCLUSIONS

Conclusions

1. Even under the same 5-inch CL break condition, HPI availability significantly affects DC water level and wall cooling behavior.
2. In the HPI-unavailable case, the DC water level decreased to the lower beltline region, resulting in wall exposure before followed by rapid re-cooling during ACC inflow.
3. Azimuthal temperature differences are pronounced near the nozzle elevation but limited in the DC beltline region both in HPI available/unavailable case.
4. When HPI is unavailable, a cooling mode is identified in which ACC injection water directly flows into the exposed DC beltline region wall (z = 6–11), inducing rapid cooling with temperature decreases of 30–50 K observed multiple times, with cooling rates of up to approximately 4 K/s.

- Conventional PTS assessments generally assume uniform TH conditions in the DC beltline region. However, accident progression may create spatially non-uniform cooling conditions through water level changes, wall exposure, and rewetting representing a potential source of TH uncertainty.
- The DC during such exposure events showed that the observed rapid cooling behavior could be quantified.
- The study results indicate that the DC wall cooling behavior varies depending on the ECCS operating conditions.
- When applying PFM to PTS assessment using TH analysis results for individual LOCA scenarios as inputs, the branching associated with ECCS operating modes needs to be explicitly considered.