Preliminary Single-code Analysis of Mass and Energy Release and Containment Vessel Response in i-SMR during Postulated LOCA and MSLB Using SPACE Code

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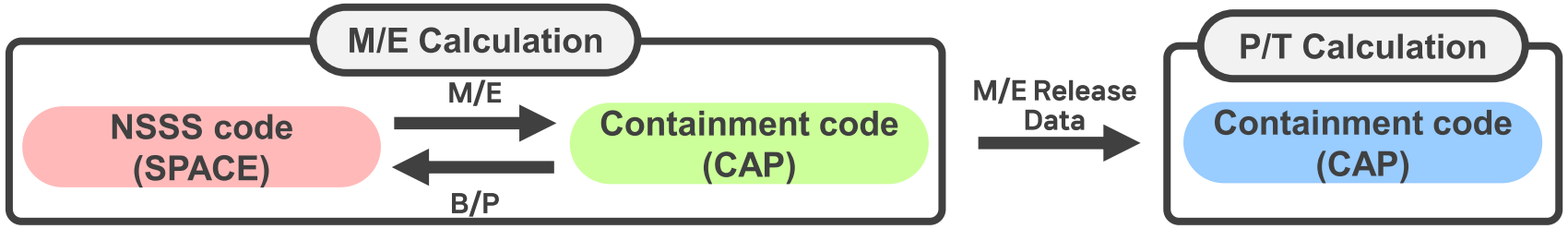
OUTLINE

1. Overview
2. Analysis Methodology
3. Analysis Results
4. Concluding Remarks

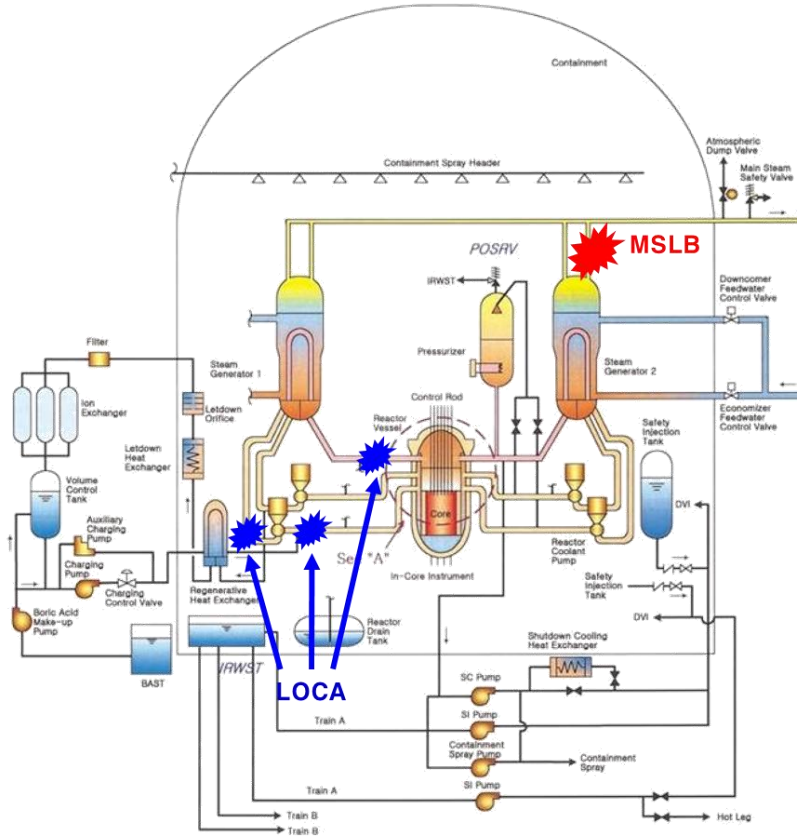
1. Overview

Mass and Energy (M/E) Release & Containment Response Analyses

- **Reactor Containment**
  - Final physical barrier against radioactive release (Defense-in-depth)
  - Withstand pressure and temperature (P/T) from any design basis accidents
- **M/E Release Analysis**
  - Providing boundary condition for containment P/T evaluation
  - Loss-of-coolant accident (LOCA) and main steam line break (MSLB) for PWRs.
- **Containment Response Analysis**
  - Predicting containment P/T using M/E release data
  - For containment functional design, equipment environmental qualification (EEQ)



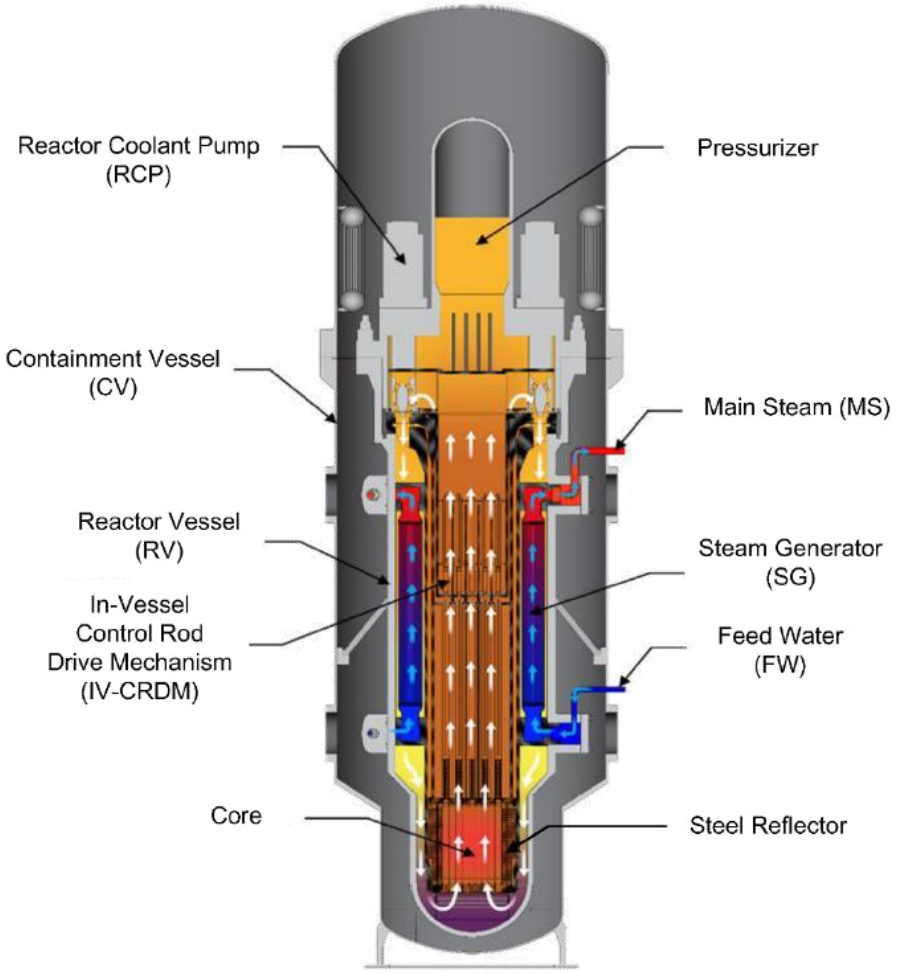
[Fig. M/E – P/T Analysis Schematic Diagram]



[Fig. Typical Break Locations of LOCA and MSLB in PWR]

Design Characteristics of Innovative Small Modular Reactor (i-SMR)

- **Integral type PWR**
  - Reactor power: 520 MWt / 170 MWe
- **Containment Vessel (CV)**
  - Steel pressure vessel, vacuum condition
  - High design pressure : 5.0 MPa (725 psia) (APR1400 0.52 MPa (60 psig))
- **Helical-coiled Steam Generator (HCSG)**
  - No steam separator, low inventory
- **Passive Emergency Core Cooling System (PECCS)**
  - Emergency Depressurization Valve (EDV)
  - Emergency Recirculation Valve (ERV)
- **Passive Auxiliary Feedwater System (PAFS)**
- **Passive Containment Cooling System (PCCS)**
- **Emergency Cooling Tank (ECT)**

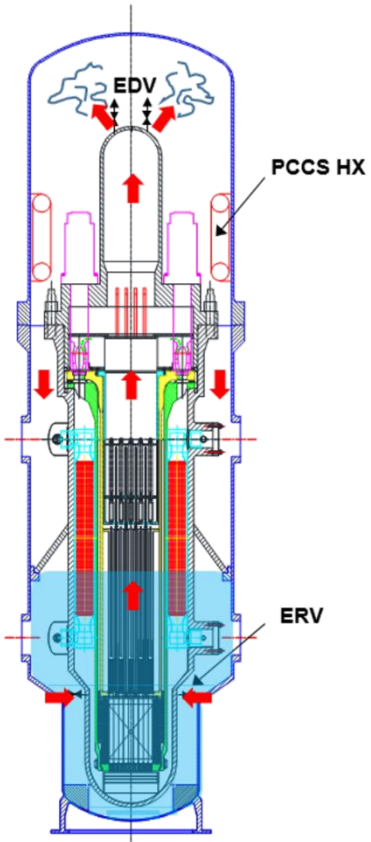


[Fig. i-SMR Design Configuration]

01 Overview

M/E Release and CV Response Analyses of i-SMR

- **Primary-side Pipe Rupture**
  - Large break LOCA (LBLOCA) is fundamentally eliminated in i-SMR
  - Small break LOCA (**SBLOCA**) : Charging Line Break (**CLB**), Letdown Line Break (**LLB**)
  - Inadvertent opening of PECCS (**IOPECCS**) : Inadvertent Opening of EDV or ERV (**IOEDV**, **IOERV**)
- **Secondary-side Pipe Rupture**
  - Main steam line break (**MSLB**) inside CV, feedwater line break (FWLB) inside CV



[Fig. i-SMR LOCA]

Today's Presentation Topic

- **Preliminary Study on M/E Release and CV Response of i-SMR**
  - LOCA and MSLB scenarios of i-SMR were analyzed using SPACE code.

Single-code Analysis

- The i-SMR standard design employs a two-step approach (M/E release (SPACE) → CV response (CAP)).
- In this study, a one-through analysis of M/E release and CV response was performed for preliminary evaluation.

2. Analysis Methodology

02 Analysis Methodology

Analysis Procedures

- **SPACE Modeling of i-SMR NSSS and CV**

  - The standard input deck for i-SMR has been jointly developed by KEPCO E&C, KHNP, KEPCO NF, and FNC.

  - The SPACE ver. 3.3.1 modified by KAERI for i-SMR safety analysis was used.

- **Steady-state Calculation**

  - M/E basedeck, modified from standard input deck to maximize M/E release and CV response, was used.

  - Initial operating conditions of i-SMR were calculated.

- **M/E Release and CV Response Calculations**

  - Casedecks for simulating LOCA and MSLB were used.

[Fig. Single-code Approach of M/E Release and CV Response Analyses Using SPACE Code]

[Fig. i-SMR Node Configuration]

02 Analysis Methodology

SPACE Modeling of i-SMR Primary Side & CV

- **Reactor Vessel (RV)**
  - Reactor core ([redacted])
  - RV downcomer ([redacted]), RCP 4 ea
  - Pressurizer, safety relief valves 2ea (PSRVs)
  - HCSG primary side (Helical shell/tube model, [redacted])
- **PECCS**
  - EDV 3ea (at the top of the pressurizer)
  - ERV 2ea (at the RV downcomer)
  - Low riser level signal + SOPM actuation
- **CV**
  - Vacuum state
  - [redacted]

[Fig. i-SMR Primary Side & CV Node Configuration]

02 Analysis Methodology

SPACE Modeling of i-SMR Secondary Side

- **Main Steam & Feedwater System**
  - HCSG secondary side (Helical shell/tube model, [redacted])
  - Main steam line & header, serial MSIVs in one steam line
  - Feedwater line, serial FIVs in one feedwater line
- **PAFS (4-train)**
  - Improved PAFS condensation model
  - Startup valves operated by reactor trip signal
- **PCCS (4-train)**
  - High pressure condensation model

  [redacted]
- **ECT (2-train)**

[Fig. Schematics of i-SMR PAFS]

[Fig. i-SMR Secondary Side Node Configuration]

Major Assumptions & Initial Conditions

- All assumptions were chosen conservatively to maximize the M/E release and CV response results.

  - Volume expansion for NSSS [redacted] are assumed.

- Sensitivity studies were performed to determine parameters.

[Table. Major Assumptions for M/E Release and CV Response Analyses of i-SMR]

Parameters	Assumptions				
Initiating event	• LOCA: CLB inside CV, LLB inside CV, IOEDV, IOERV • MSLB inside CV				
Initial operating conditions	Core Power	[redacted]	[redacted]	[redacted]	[redacted]
	103%	[redacted]	[redacted]	[redacted]	[redacted]
Break size	Maximum [redacted]				
Critical flow model	Henry-Fauske (Sub-cooled) / Moody (Two phase)				
Decay heat	1979 ANS Standard + [redacted]				
Turbine trip	At break				
AC power	• LOCA: Loss at break • MSLB: Available				
DC power	Available				
Single failure	PAFS failure (no significant effect to results)				
Low riser level setpoint	Maximum in harsh environment				
SOPM setpoint	Nominal				

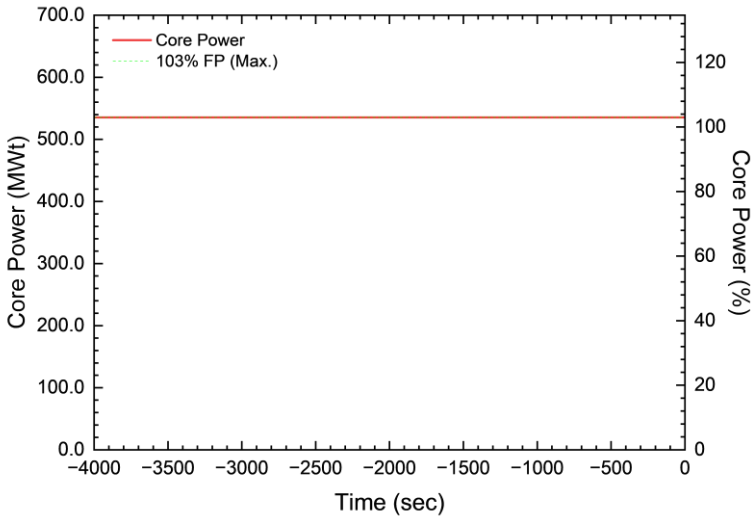
02 Analysis Methodology

Steady-state Calculations

- Steady-state calculation

  → <u>error rates of less than 0.001%</u>

  for each operating parameters
- Maximizing initial M/E inventory of NSSS (RCS, secondary side)



[Fig. Core Power]

3. Analysis Results

Event Sequence of LOCA (CLB) Analysis

- Reactor coolant is released into the CV
  → Pressurization of the CV.
- High containment pressure (HCP) signal
  → Reactor trip, CV isolation, PAFS actuation
- Riser water level decreases to the low riser level setpoint for PECCS actuation.
- Differential pressure (DP) between RV and CV reaches SOPM setpoint.
- Low Riser Level + SOPM → PECCS actuation
  - Opening the remaining EDVs and ERVs.
- RCS is cooled to a safe shutdown state through continued actuation of both the PAFS and the PECCS.

[Table. Event Sequence of LOCA (CLB) Analysis]

Time (sec)	Sequence of Event
[redacted]	• Break occurrence • Turbine trip • Loss of offsite power (AC power)
[redacted]	• CV pressure reaches the HCP setpoint
[redacted]	• HCP reactor trip signal
[redacted]	• Reactor trip breaker opening
[redacted]	• MSIVs and FIVs closure • PAFS actuation (Startup Valve Opening)
[redacted]	• Riser water level reaches low level setpoint
[redacted]	• Low riser level signal
[redacted]	• RV-CV DP reaches SOPM setpoint
[redacted]	• PECCS actuation (EDVs and ERVs opening)
[redacted]	• CV pressure reaches peak pressure (3.85 MPa)
[redacted]	• Safe shutdown state ([redacted])

Mass and Energy Release during LOCA (CLB)

- Reactor coolant is released into the CV though the break.
- **Heat transfer** from the reactor coolant to the CV through the **RV wall** occurs.

  - Discharge of coolant → loss of CV vacuum
- As the accident progresses, the M/E release rate gradually decreases.
- When the PECCS is actuated, **additional M/E is released** due to opening of **the remaining EDVs and ERVs**.

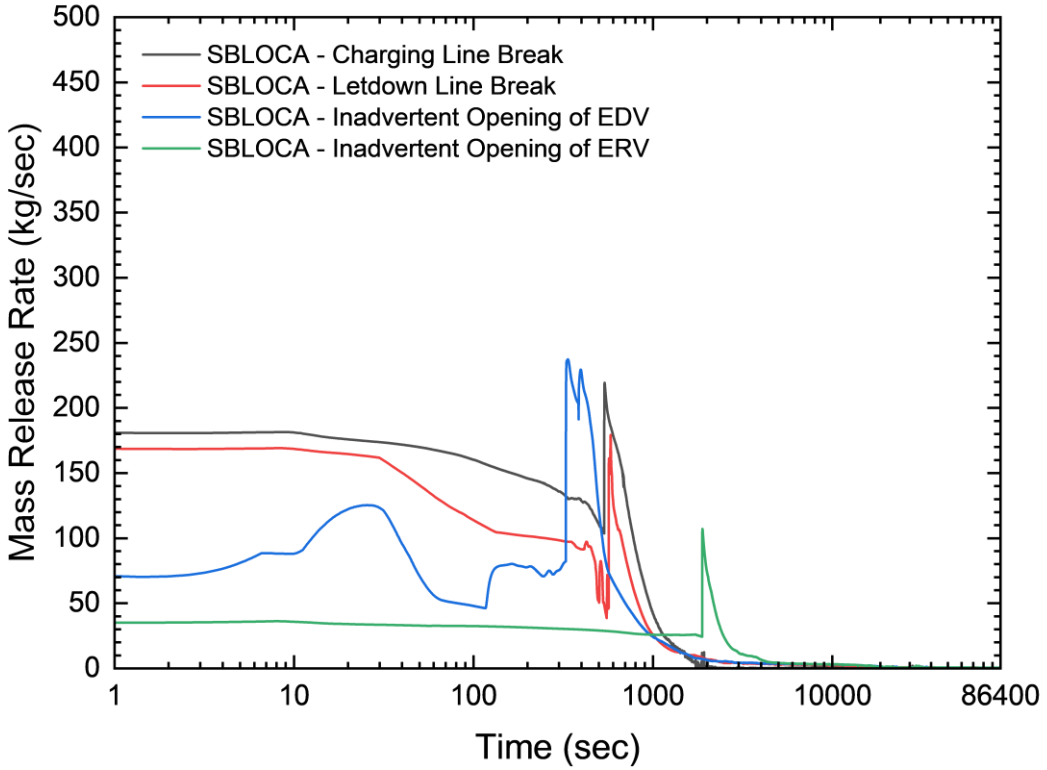
[Fig. Break Mass Release Rate during LOCA(CLB)]

[Fig. PECCS Mass Release Rate during LOCA(CLB)]

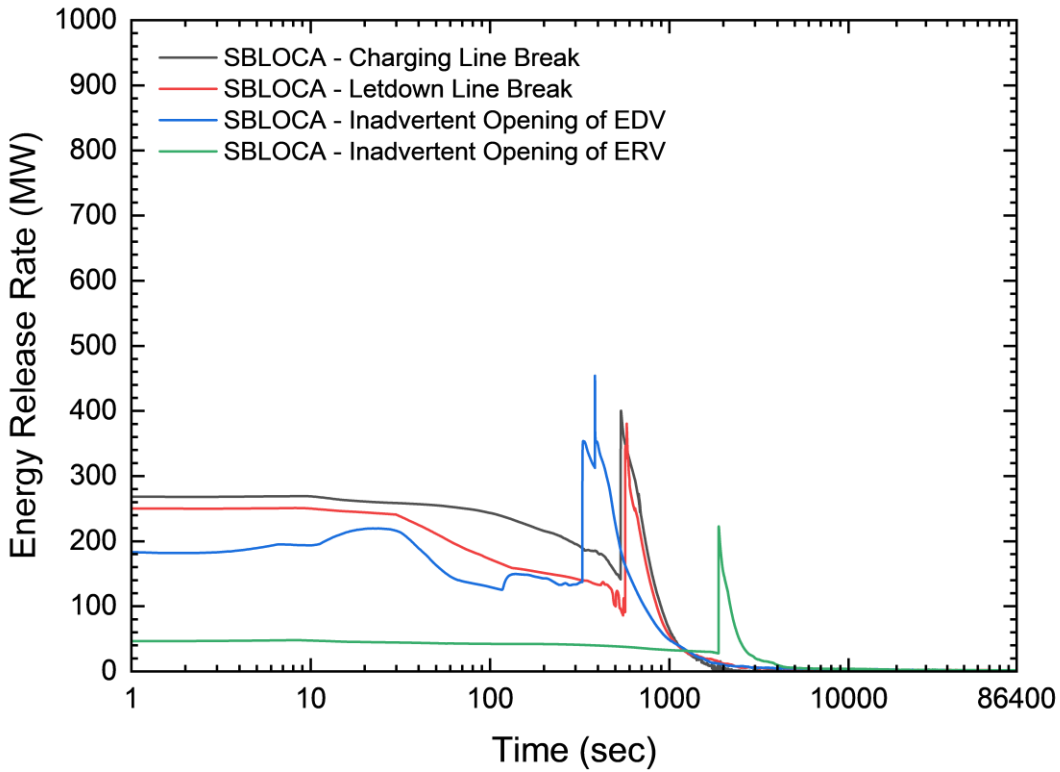
[Fig. Heat Transfer from RV to CV during LOCA(CLB)]

Mass and Energy Release during LOCA Scenarios

- Due to the lower elevation of charging line compared to letdown line, a higher M/E release rate is observed in **CLB**.
- During **IOEDV**, reactor coolant is discharged through the EDV as a two-phase mixture (EDVs at the top of the pressurizer).
- During **IOERV**, the liquid coolant is discharged through the ERV (connected to RV downcomer < normal RCS water level).



[Fig. Break and PECCS Mass Release Rate during LOCA]



[Fig. Break and PECCS Energy Release Rate during LOCA]

CV Response during LOCA Scenarios

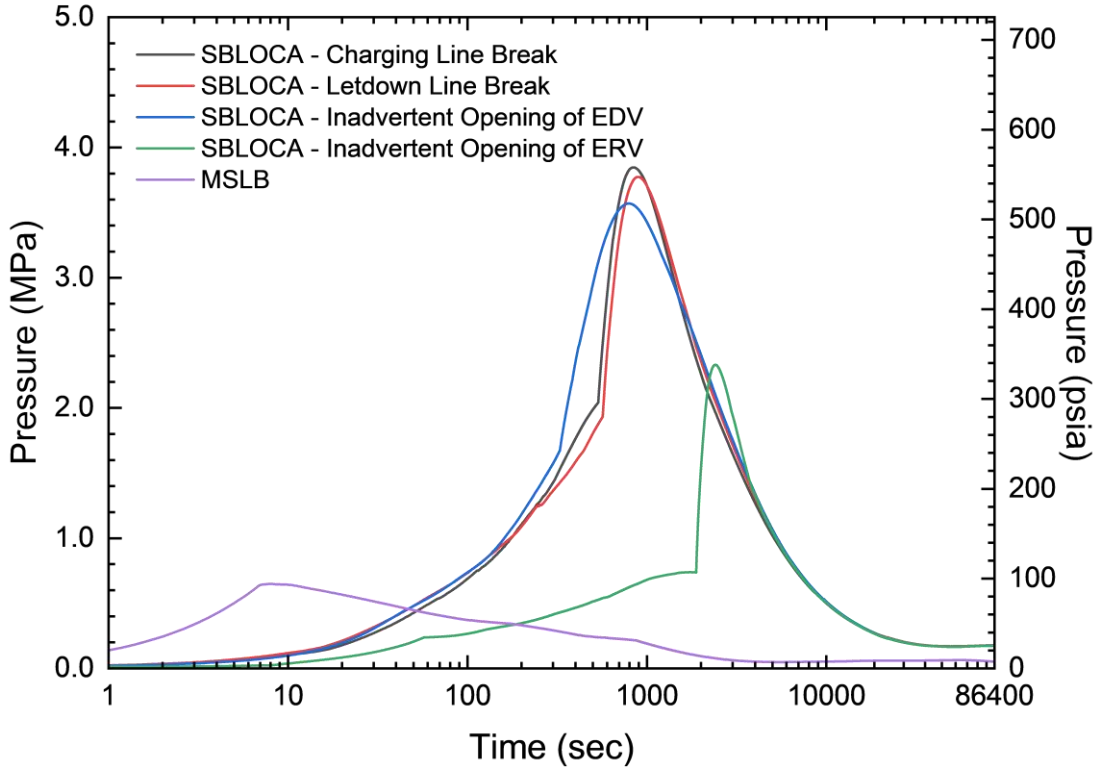
- M/E release → Loss of CV vacuum → **PCCS condensation** + **passive heat sink (PHS) condensation**
- Condensed water accumulates at the bottom of CV → CV water level increases
- PECCS actuation → **CV water is injected into the RV through the ERVs**
- M/E (Initiating events) → Additional M/E (PECCS actuation)

  → CV peak pressure (M/E release < PCCS + PHS cooling)

  - LOCA limiting scenarios : **CLB > LLB > IOEDV > IOERV**

[Fig. CV Peak Pressure and Relevant Reaching Time during LOCA]

Case	CV Peak Pressure, MPa	Reaching Time, sec		
		CV Peak Pressure	Low Riser Level	SOPM Setpoint
CLB	3.85	846.4	[redacted]	[redacted]
LLB	3.77	897.0	[redacted]	[redacted]
IOEDV	3.57	774.4	[redacted]	[redacted]
IOERV	2.33	2422.4	[redacted]	[redacted]



[Fig. CV Pressure during LOCA and MSLB]

Event Sequence of MSLB Analysis

- Superheated steam is released into the CV
  → CV pressurization, HCP reactor trip
  → CV isolation, PAFS actuation
- M/E release completely terminates at 11.2 seconds
  - Unlike the LOCA, the M/E release terminates within a short duration due to Limited inventory of the helical-coiled steam generator (HCSG)
- The RCS is then cooled down to a safe shutdown state solely by PAFS, without PECCS actuation.

[Table. Event Sequence of MSLB Analysis]

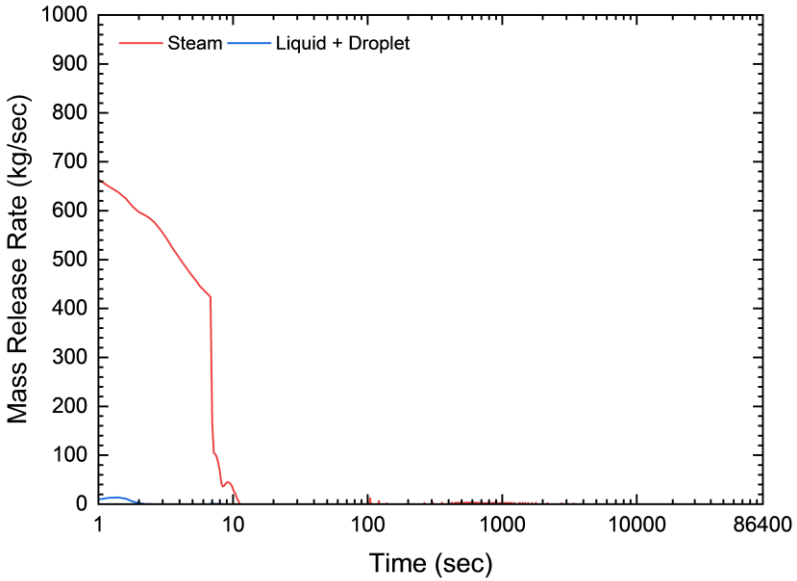
Time (sec)	Sequence of Event
[redacted]	• Break occurrence • Turbine trip
[redacted]	• CV pressure reaches the HCP setpoint
[redacted]	• HCP reactor trip signal
[redacted]	• Reactor trip breaker opening
[redacted]	• MSIVs and FIVs closure • PAFS Actuation (Startup Valve Opening)
[redacted]	• CV pressure reaches peak pressure (0.65 MPa)
[redacted]	• End of blowdown
[redacted]	• Safe shutdown state ([redacted])

M/E Release and CV Response during MSLB

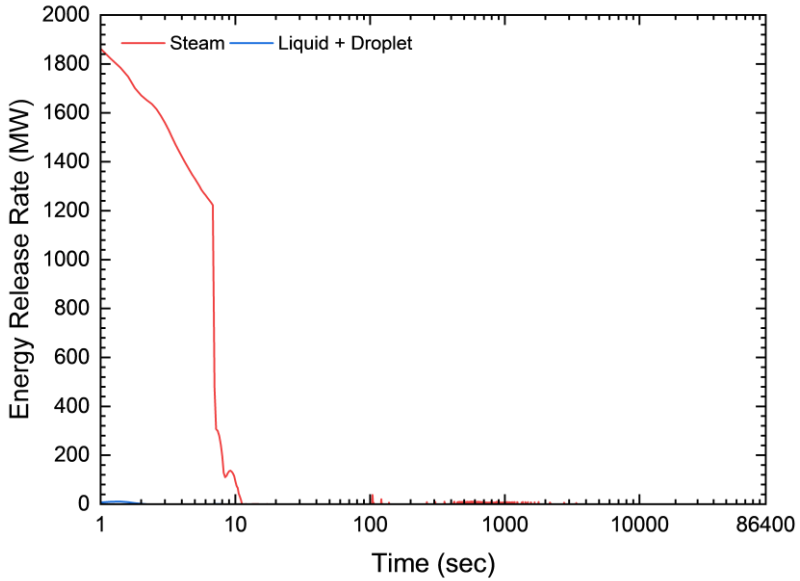
- In the very early phase, a significant amount of **superheated steam M/E is released through the break.**

  - Steam discharge occurs simultaneously from both the affected HCSG and the steam header.

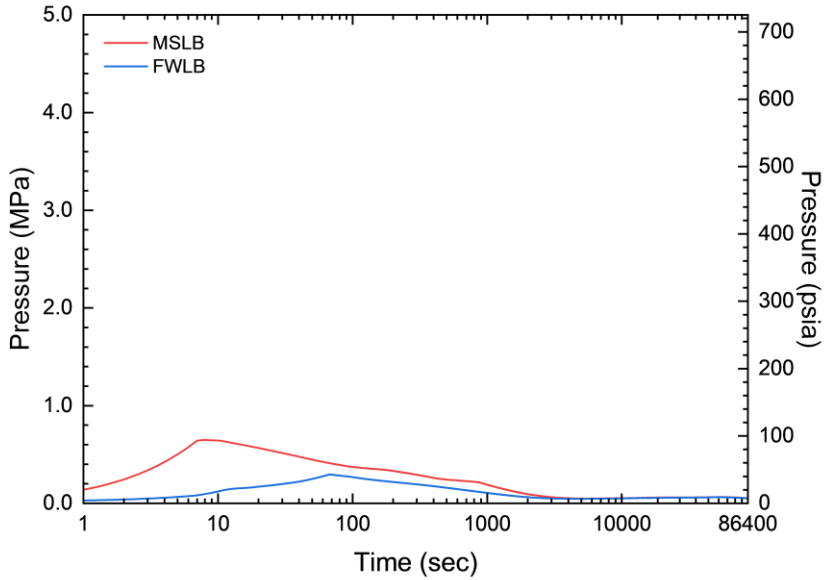
- Only a very small amount of **liquid and droplet entrainment was observed.**
- MSIV closure by HCP reactor trip → blocking steam release from the steam header → rapid decrease in M/E release rate.
- CV peak pressure of MSLB : 0.65 MPa



[Fig. Break Mass Release Rate during MSLB]



[Fig. Break Energy Release Rate during MSLB]



[Fig. CV Pressure during MSLB and FWLB]

Sensitivity Study – Single Failure

- **PAFS Startup Valve Single Failure**

  - LOCA (CLB): PAFS 4-train [redacted] → PAFS 3-train [redacted]

  - MSLB: PAFS 4-train [redacted] → PAFS 3-train [redacted]

[Fig. CV Pressure by Number of Operating PAFS Train during LOCA]

[Fig. CV Pressure by Number of Operating PAFS Train during MSLB]

Sensitivity Study – PECCS

- **PECCS – Low Riser Level Setpoint**

  - LOCA (CLB) : Max. setpoint [redacted] → Min. setpoint [redacted]

- **PECCS – SOPM Setpoint**

  - LOCA (LLB) : High setpoint [redacted] → Low setpoint [redacted]

- **PECCS – Number of EDVs**

  - LOCA (CLB): EDV 2 ea [redacted] → EDV 3 ea [redacted]

[redacted]

[Fig. CV Pressure by Low Riser Level Setpoint during LOCA]

[Fig. CV Pressure by SOPM Setpoint during LOCA]

[Fig. CV Pressure by Number of EDV during LOCA]

4. Concluding Remarks

04 Concluding Remarks

M/E Release and CV Response Analyses of i-SMR

- **LOCA**

  - Reaching CV peak pressure due to **additional M/E release by PECCS actuation** following initial M/E release.

  - The highest CV peak pressure was observed in the CLB, reaching 3.85 MPa (23% margin to acceptance criteria).

- **MSLB**

  - M/E release terminates within a short duration due to **small inventory of HCSG** (CV peak pressure 0.65 MPa)

Future Research

- **Development of M/E Release and CV Response Analyses**

  - Reliability of non-safety grade power (DC)

  - Development of two step analytical methodology (SPACE-CAP)

- **Preparation of i-SMR SDA Licensing Process**

  - Preparation of licensing documents (safety analysis report, technical report)

  - More sensitivity studies for answering the RAI

Thank you for your kind attention.

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