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Analysis of a MSLB-induced Steam Generator Tube Rupture Accident for APR1400

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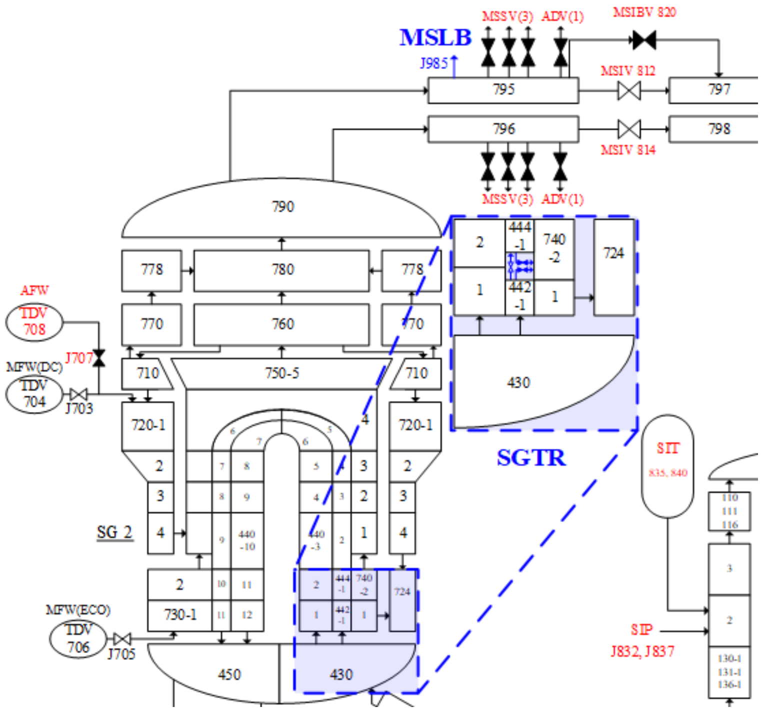
CONTENTS

1 INTRODUCTION

What is MSLB-SGTR?

- Main Steam Line Break (MSLB)
  - Guillotine **break in the main steam line** (MSL)
  - Steam leak out of the system → rapid **SG depressurization**
  - Break location is **inside the containment**
  - Steam generator **water level decrease** → dry out
- Steam Generator Tube Rupture (SGTR)
  - Assumed **rupture in a single U-tube** of steam generator
  - **Coolant** and radioactive materials released from **RCS to secondary side of SG**
- Main Steam Line Break induced Steam Generator Tube Rupture
  - Combines **MSLB and SGTR occurring together**
  - **Multiple-failure scenario** combining two Design Basis Accidents (DBAs)
  - Design Extension Conditions (**DEC-A**) – without significant fuel degradation

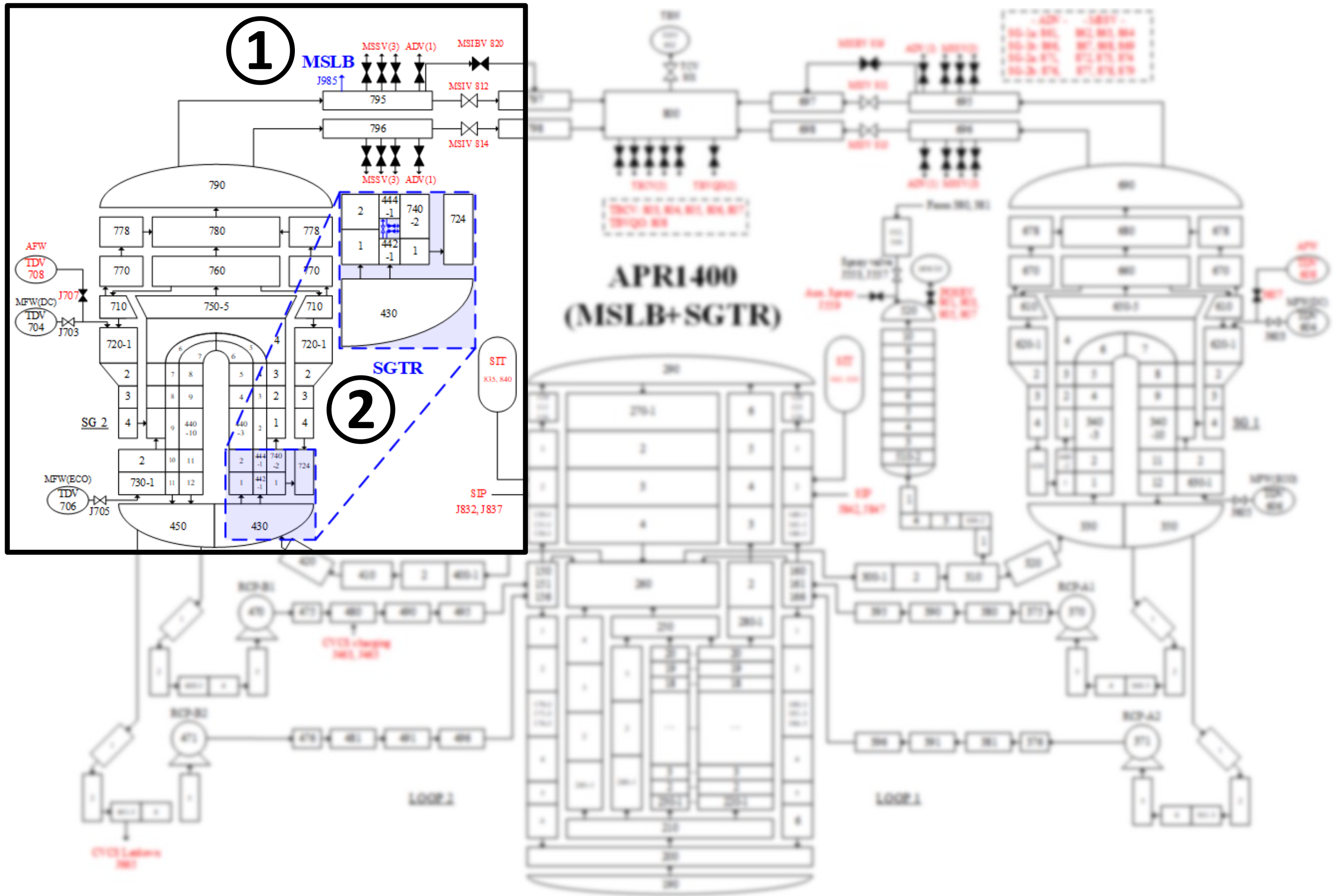


Research Scope

- Research goal – Conduct an accident analysis of **Main Steam Line Break induced Steam Generator Tube Rupture** (MSLB-SGTR) accident to **verify** that the safety systems together with appropriate operator actions can successfully **mitigate the accident** and ensure **plant cooldown conditions**
- Motivation – **research gap**, no previous studies found with focus on the MSLB-SGTR accident analysis
  - Experiment on MSLB-SGTR accident on ATLAS facility (scaled APR1400) published
  - **Importance** - several studies on DEC suggest investigation of MSLB-SGTR scenario
- Target plant – Korean **APR1400** plant with pressurized water reactor
- Used code – **RELAP5**/MOD3.3 TH system code
- Approach – **Best Estimate** analysis with **realistic assumptions**
  - Full power **nominal conditions**
  - **Offsite power is available** (no LOOP assumed)

2 METHODOLOGY

APR1400 plant model nodalization and steady-state parameters



Parameter	DCD	Model
Core power level, MWt	3983.0	3983.0
Pressurizer pressure, MPa	15.51	15.51
Pressurizer lever, %	52.8	50.01
Hot leg temperature, °C	323.9	324.6
Cold leg temperature, °C	290.6	291.7
Total RCS mass flow rate, kg/s	21000.0	20994.7
Steam generator pressure, MPa	6.89	6.57
Feed water flow rate per SG, kg/s	1130.57	1130.13
Steam flow rate per SG, kg/s	1130.56	1130.26
Steam generator water level, %	77.0	77.0

① Main Steam Line Break

② SG Tube Rupture

Safety systems and operator actions involved in the accident mitigation

Auxiliary Feed Water System (AFWS)

- Operate automatically when SG water level is below 20 % and stop with SG water level above 45 %
- Deliver feed water to the affected SG and provide cooling to RCS

Main Steam Isolation Bypass Valve (MSIBV)

- Allows steam flow from the unaffected SG to condenser
- Plant cooldown using the unaffected steam generator

Safety Injection Pump (SIP) with flow rate control

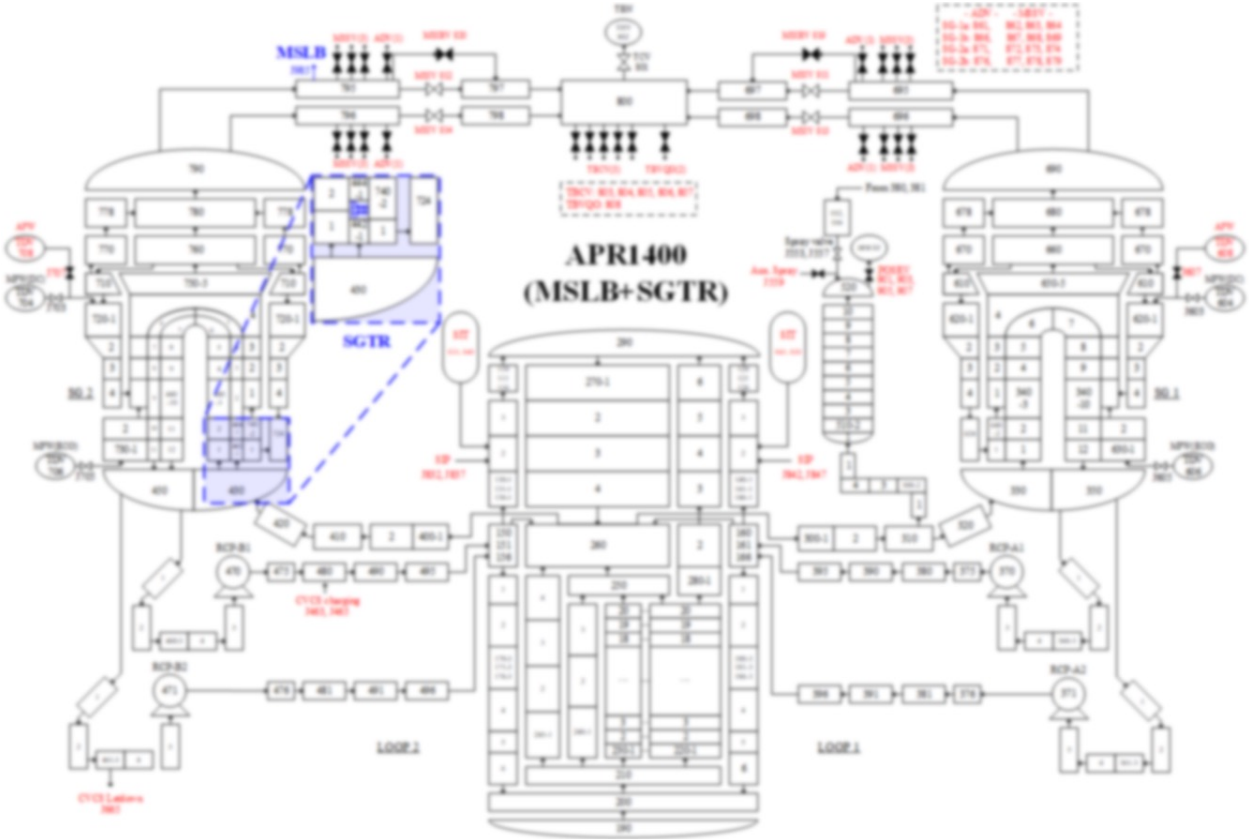
- Start operation by RCS pressure setpoint (~12.2 MPa for APR1400)
- Flow control after 30 minutes of accident initiation by operator

RCP shut down

- Assumed 1 RCP per loop (total 2) to shut down by operator

Pressurizer auxiliary spray

- Plays a major role in the plant cooldown and RCS depressurization
- Injection rate ~6.8 kg/s according to DCD of APR1400



Mitigation Strategy

Supplementation of RCS inventory

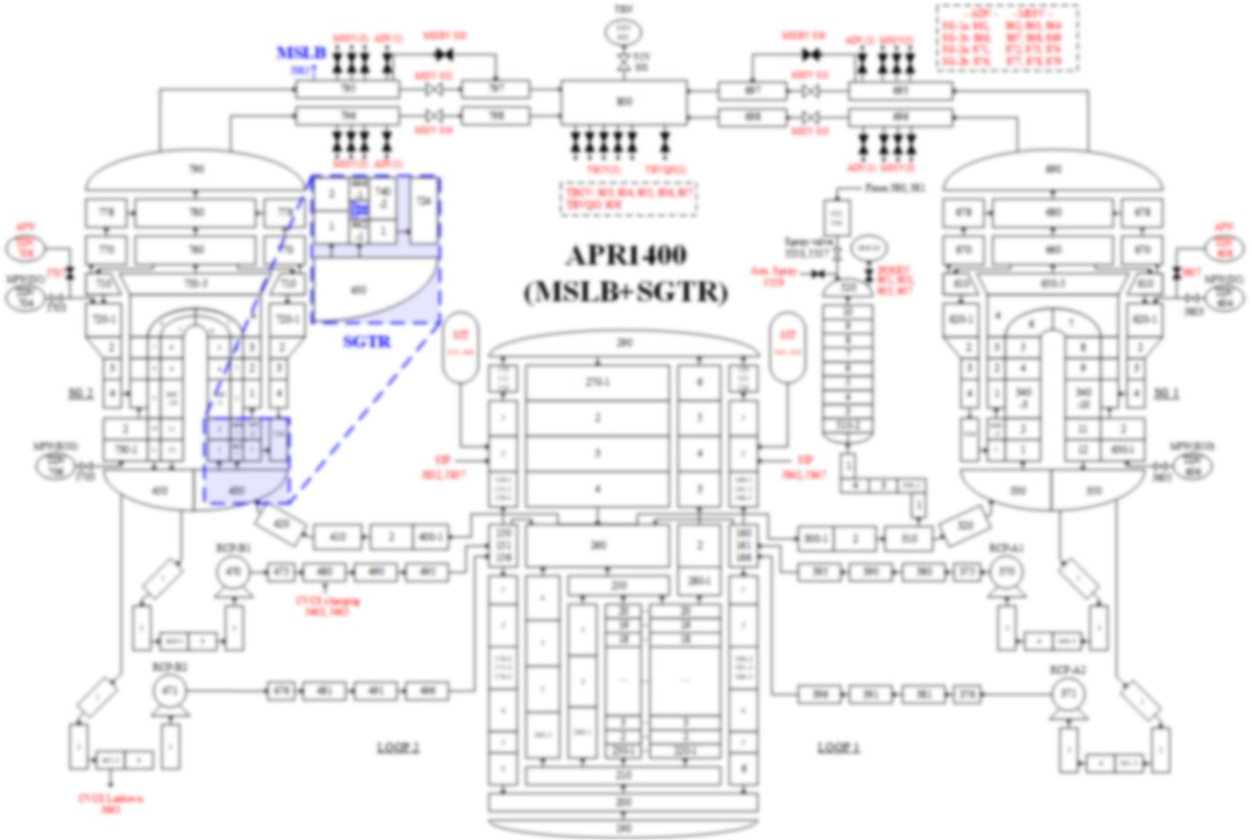
- RCS inventory decreases due to SGTR leakage to the secondary side
- To ensure RPV water level and prevent core uncovery
  - Water supply using Safety Injection Pumps (SIPs)
  - CVCS (charging/letdown) in operation to maintain PZR level

RCS Cooling

- Decay heat removal and cooling of the reactor core
  - Cooling by primary systems
    - Crucial function of PZR auxiliary spray to reach SCS entry conditions
    - Supported by SIP and RCP operation, manual control by operator
  - Cooling by heat transfer from primary to secondary side
    - Main cooling provided by affected SG via MSL break
    - Cooling by unaffected SG using MSIBV

SG Inventory Maintenance

- Feedwater delivery to affected SG by AFWS



3 ACCIDENT SCENARIO AND SEQUENCE OF EVENTS

Main Steam Line Break induced Steam Generator Tube Rupture

① Break on the Main Steam Line (28 inch break)

- Double ended rupture on the MSL

② Decrease of pressure and water level in affected SG

- Steam leaks through break in MSL and is discharged to containment

③ Reactor and Turbine trip (MSIV trip, SG isolation)

- Decay heat generation, SG isolation and turbine trip (MSIV close)

④ SGTR occurs when affected SG dries out

- SG dries out and pressure rapidly decreases
- Highest pressure difference between primary and secondary side
- SGTR occurs on hot-leg side upstream of the affected SG

⑤ SIP and AFWS operation

- AFWS delivers feed water to the affected SG
- Unaffected SG water level is maintained constant
- RCS inventory maintained by SIP operation

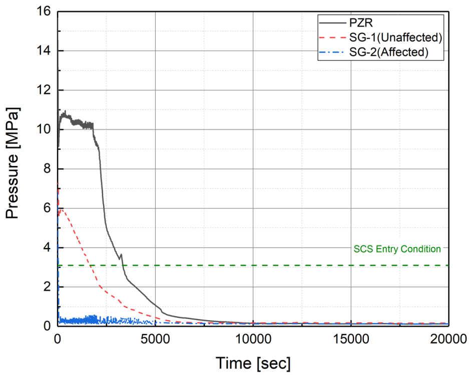
⑥ Operator action after 30 minutes assumed

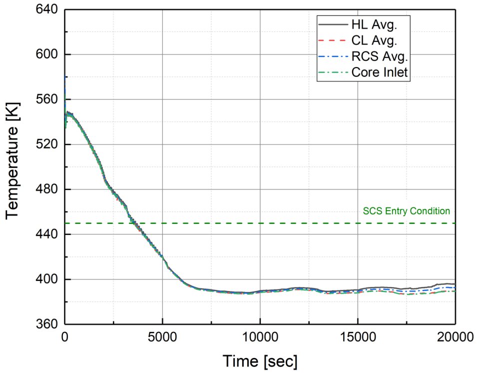
- Stop RCP, turn on PRZ spray, decrease SIP flow rate
- Determine the best strategy for successful plant cooldown

⬤ Simulation goal – reach SCS entry conditions

- RCS pressure ~3.1 MPa and temperature 176.7 °C / 449.85 K

Time	Event
0 s	Break on MSL occurs
1.46 s	Low SG Pressure Setpoint
2.63 s	Reactor Trip Signal
2.83 s	Turbine Trip
10.62 s	Low SG Water Level Setpoint
23.15 s	SIP Setpoint
35.10 s	SGTR occurrence - affected SG dry out (WL < 10 %)
63.16 s	SIP Start operation (40 s delay)
86.94 s	AFWS Start operation in affected SG
1800 s	Two RCPs (one per loop) shut down (operator action)
1800 s	PRZ Spray turned on (operator action)
3550 s	SCS Entry condition reached (T < 449.85 K)





4 ANALYSIS RESULTS

Analysis results 1/2

Core Power

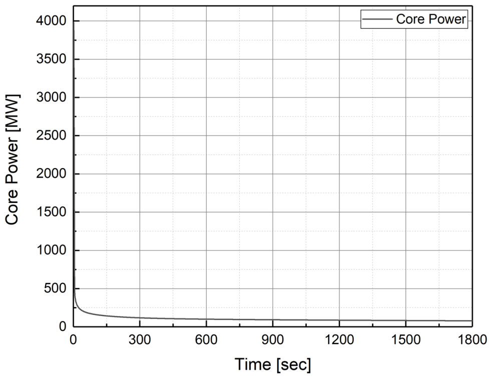
- Drops immediately with reactor trip (2.63 s) and follows decay heat curve

RCS Pressure

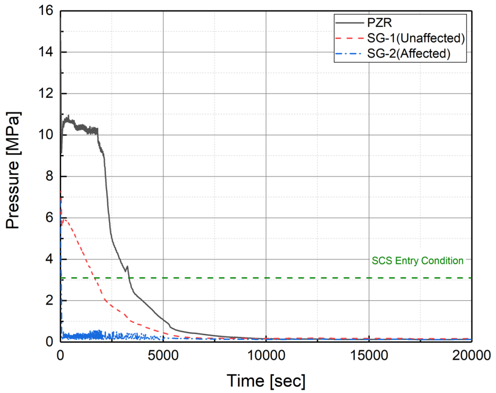
- Initial drop after reactor trip and SGTR occurrence remains around 10-11 MPa
- Decreases significantly with two RCPs shut down (1800 s) as operator action

SG Pressure

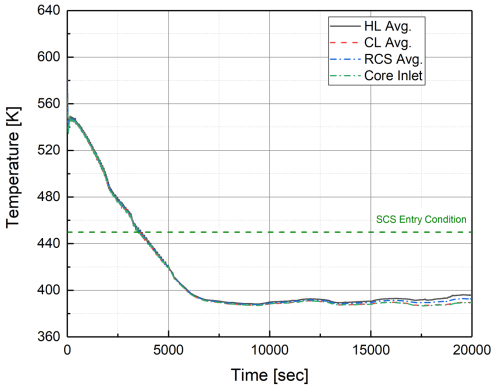
- Affected SG – rapid depressurization due to MSLB
- Unaffected SG – after initial pressure drop with reactor trip decreases with the plant cooldown



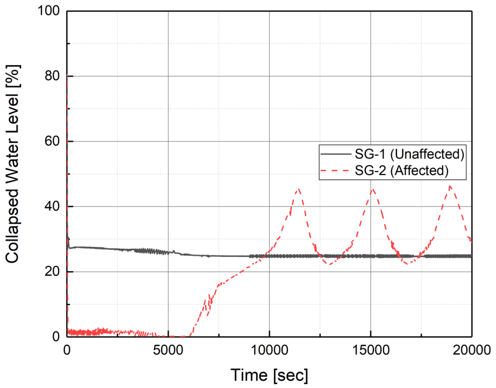
Core Power (MW_t)



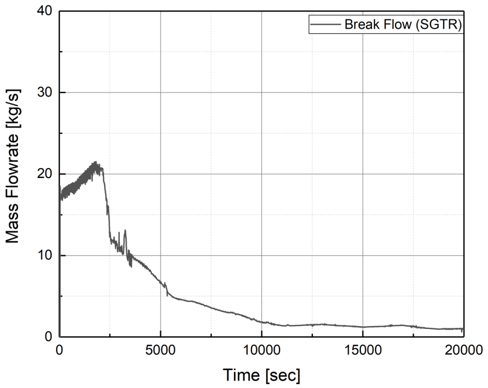
RCS & SG Pressure (MPa)



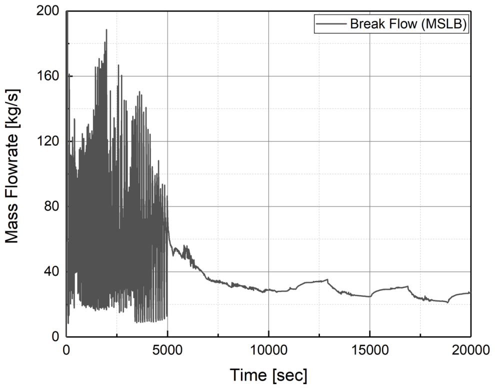
RCS Temperature (°C)



SG Water Levels (%)



SGTR break flow rate (kg/s)



MSLB break flow rate (kg/s)

Analysis of a MSLB-induced Steam Generator Tube Rupture Accident for APR1400

Analysis results 2/2

RCS Temperature

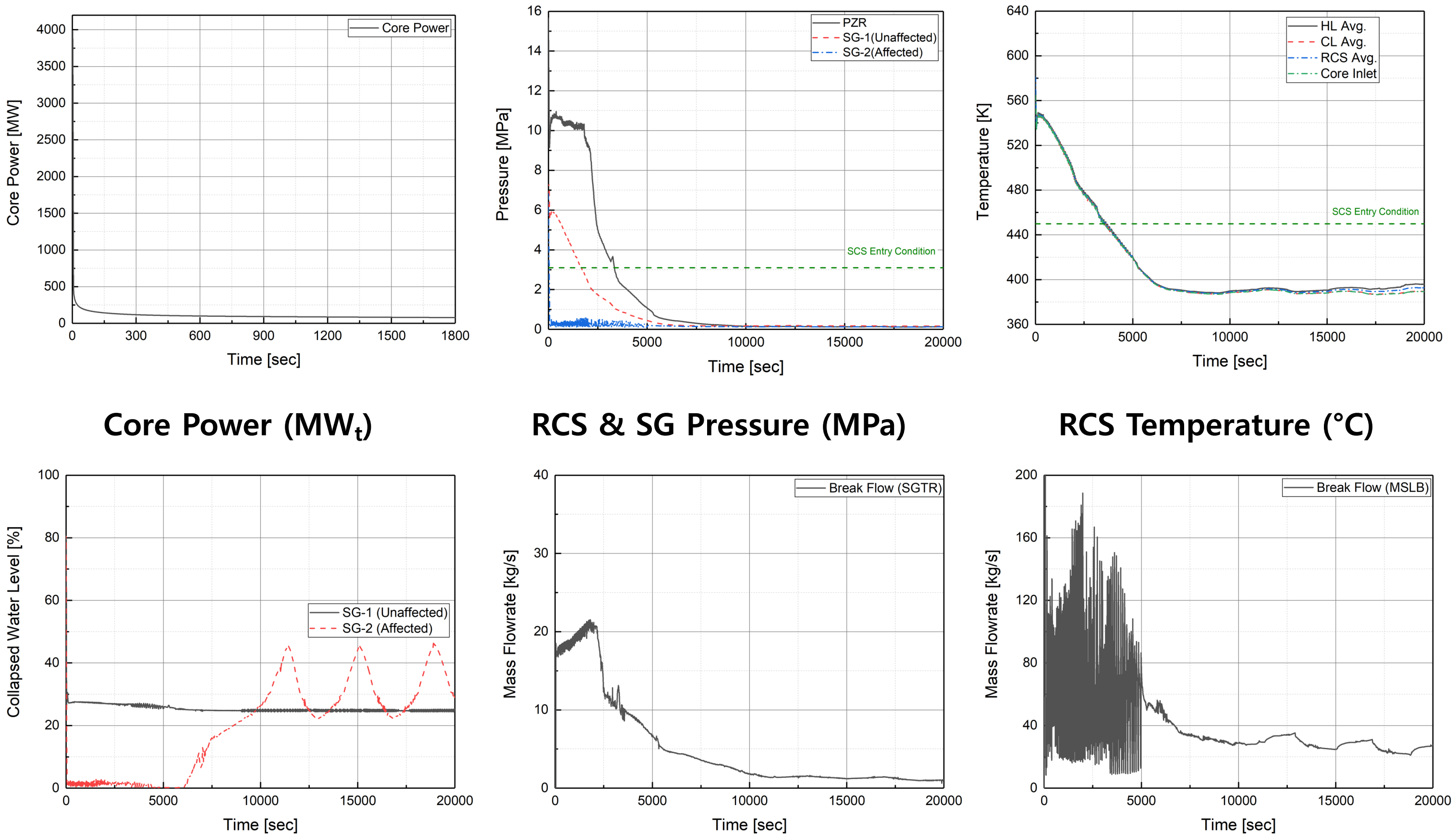
- Gradually decreases with reactor trip
- SCS entry condition (176.7 °C) at 3550 s
- After ~6800 s temperature stabilizes

SG Water levels

- Affected SG – inventory is depleted and SG dries out with MSLB occurrence
- After RCS temperature reaches steady value, water level increases due to operation of AFWS
- Unaffected SG – water level is constant

Break Flows

- **SGTR** – decreases with RCP shut down
- **MSLB** – initially high and oscillations due to constant AFW flow, then with increased SG water level stabilizes



Core Power (MW_t)   RCS & SG Pressure (MPa)   RCS Temperature (°C)

SG Water Levels (%)   SGTR break flow rate (kg/s)   MSLB break flow rate (kg/s)

5 CONCLUSION AND FUTURE WORK

Conclusion and future work

- Research scope – Simulation of **MSLB-SGTR** accident following **DEC-A** safety analysis methodology performed using **RELAP5/MOD3.3** system code for Korean **APR1400** plant
- Research goal reached – **successful accident mitigation** and **plant cooldown** have been verified
  - Results of the analysis presented, **SCS entry conditions reached at 3550 s**
  - Main strategy for plant cooldown – **AFWS and PZR auxiliary spray operation**
  - Analysis gives insight into **mitigation strategy** and impact of operator actions
- Final conclusion – This accident **does not lead to core damage** when appropriate **operator actions** are conducted and available **safety and control systems** are in operation
- Future work consist of further **sensitivity analysis**
  - Related with **operator actions** (SIP, RCP, ADV, AFWS, PZR auxiliary spray operation)
  - Related with **plant status** (MSLB break size, number of ruptured U-tubes in SG)

Acknowledgement

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20208540000020)

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THANK YOU!

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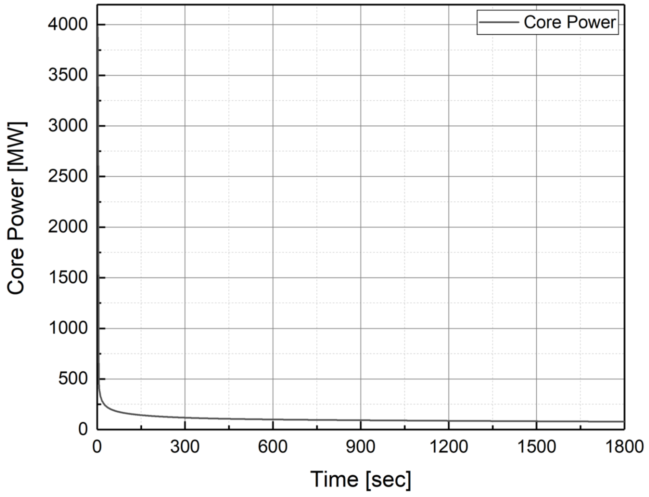
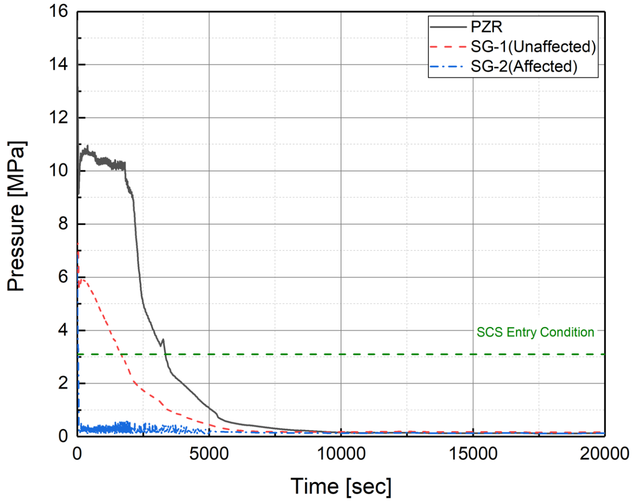
A APPENDIX

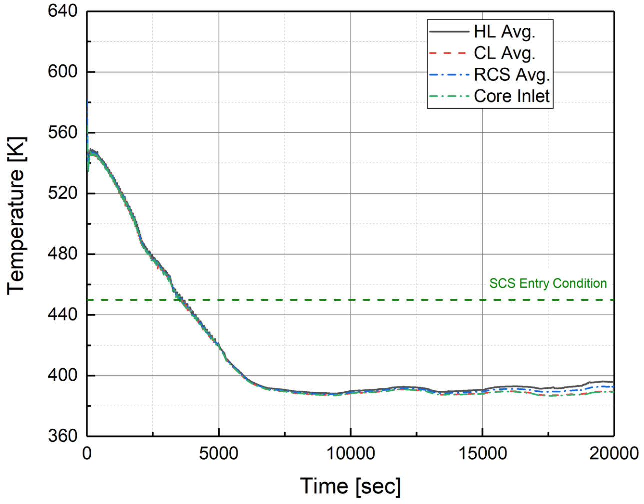
Analysis results 1/2



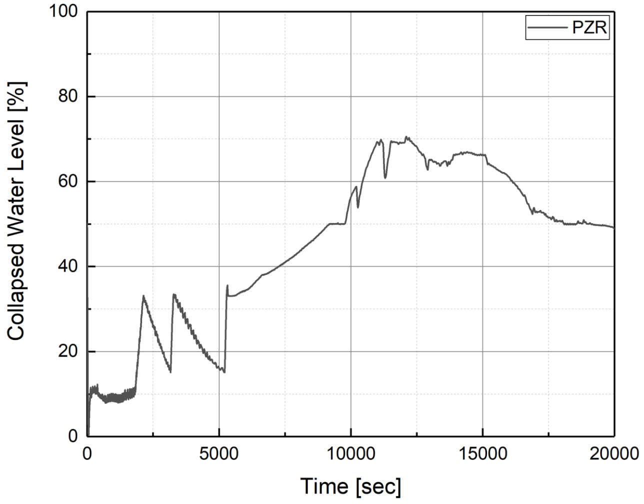
Core Power (MW)



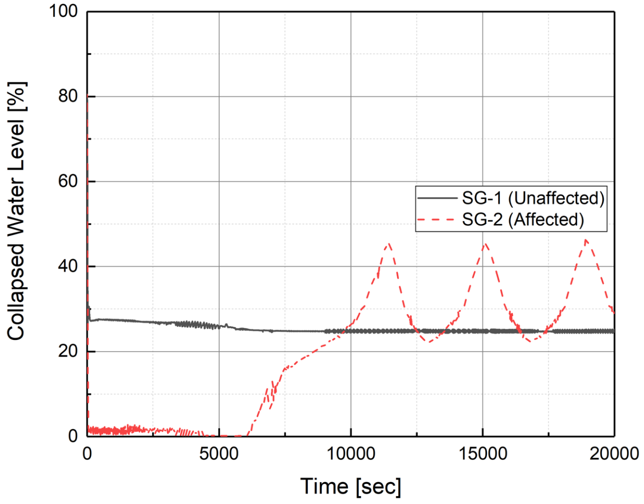
RCS & SG Pressures (MPa)



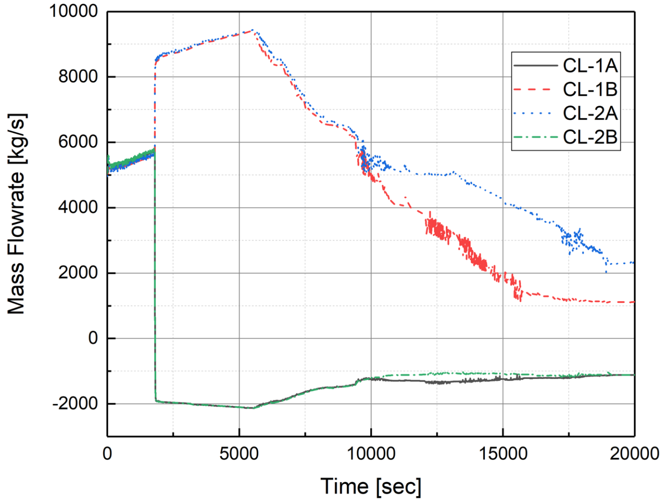
RCS Temperatures (°C)



PZR Water Level (%)

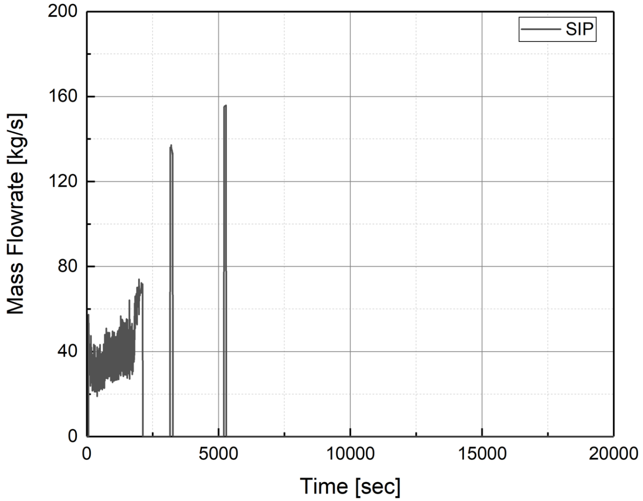


SG Water Levels (%)

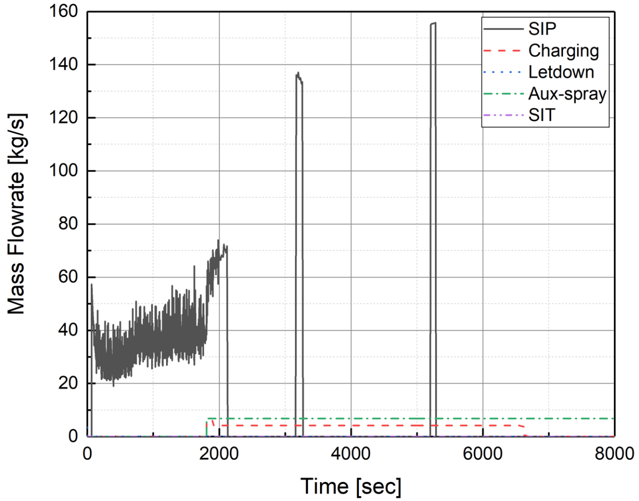


Cold Leg Temperatures (°C)

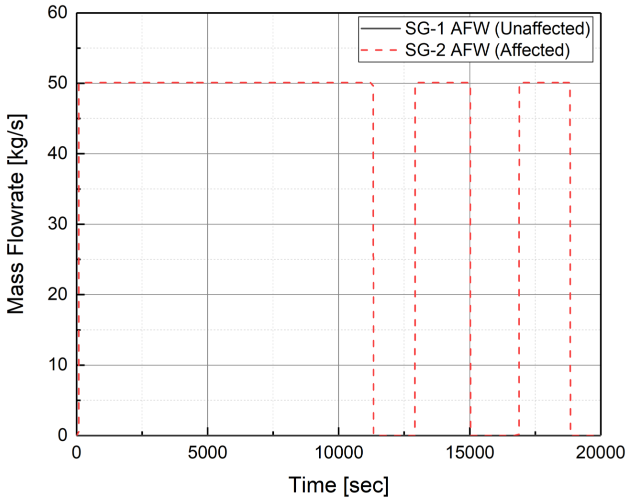
Analysis results 2/2



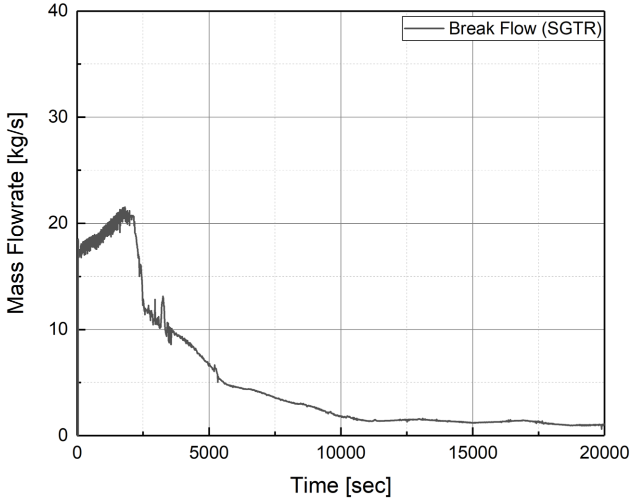
SIP Mass Flow Rate (kg/s)



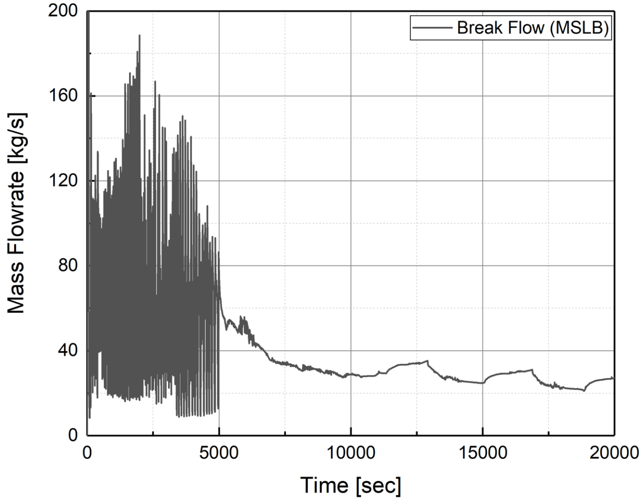
CVCS Mass Flow Rates (kg/s)



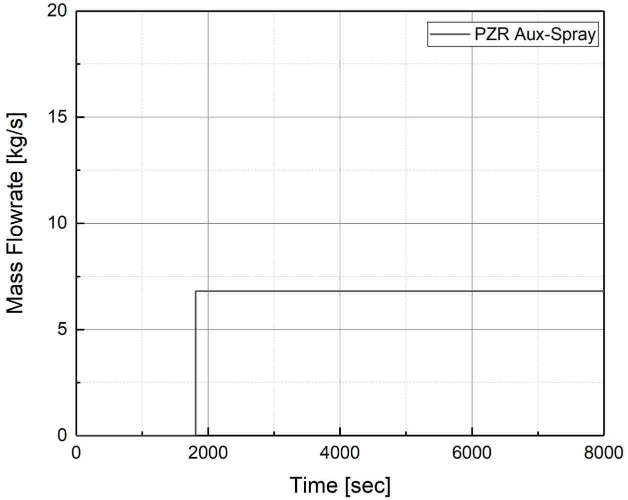
AFWS Mass Flow Rates (kg/s)



SGTR Break Mass Flow Rate (kg/s)



MSLB Break Mass Flow Rate (kg/s)



PZR Spray Mass Flow Rate (kg/s)