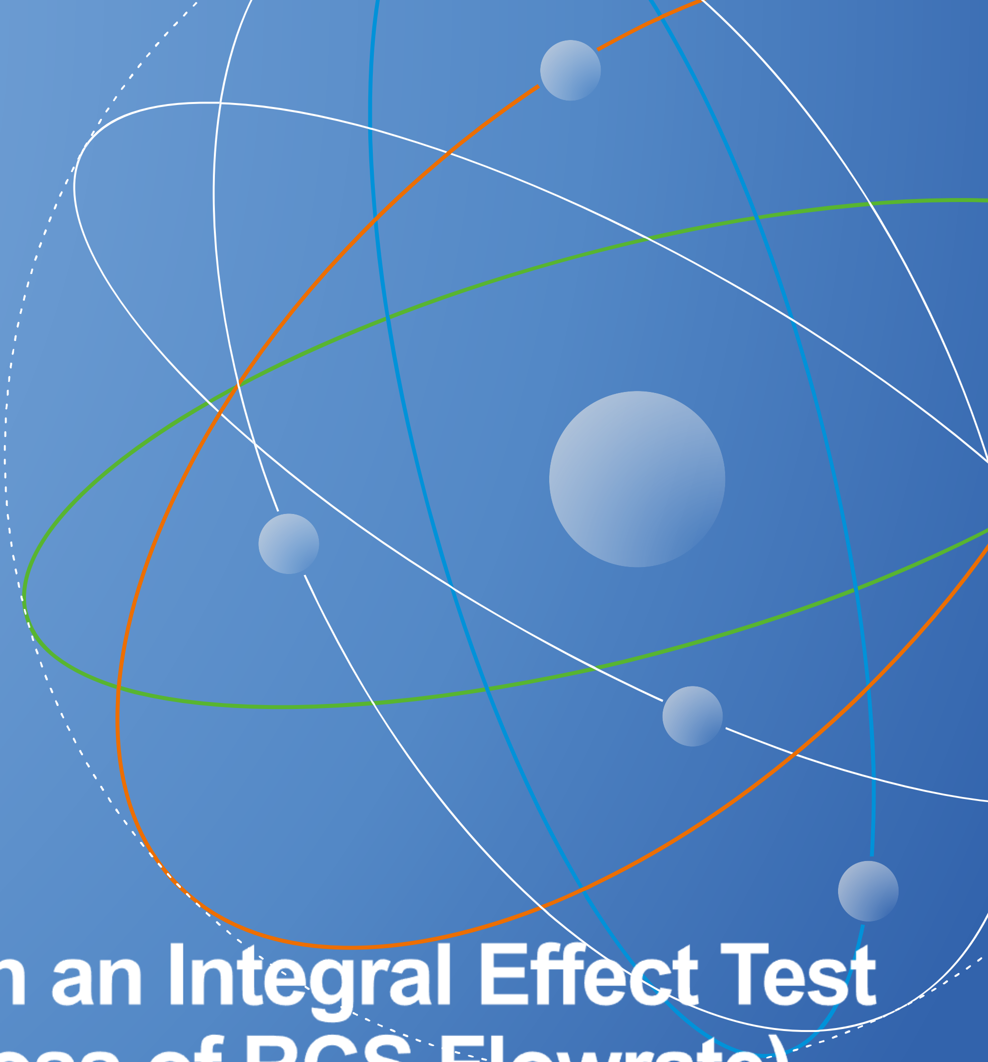
KOREA
ATOMIC
ENERGY
RESEARCH
INSTITUTE



MARS-KS Analysis on an Integral Effect Test of CLOF (Complete Loss of RCS Flowrate) for the SMART Design

Hyun-Sik Park, Jin-Hwa Yang, Byong-Guk Jeon, Hwang Bae

5/13/2024

KAERI Korea Atomic Energy Research Institute

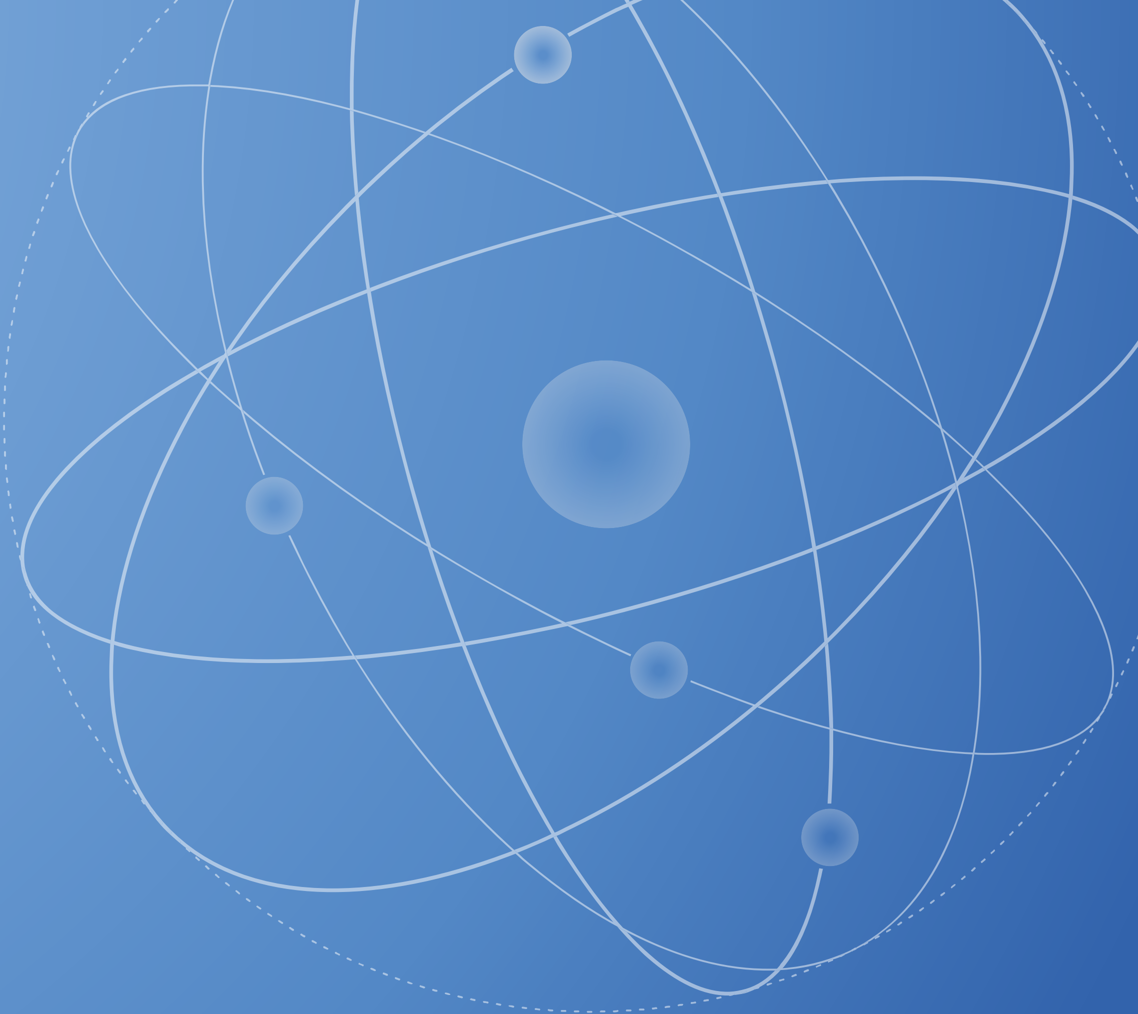
A nuclear research institute
reshaping the future based on
peoples trust

KAERI
Korea Atomic Energy Research Institute

CONTENTS

KAERI Korea Atomic Energy Research Institute

KOREA
ATOMIC
ENERGY
RESEARCH
INSTITUTE



01

Introduction

Introduction

- **A set of integral effect tests** were successfully performed to provide data to assess the capability of the system analysis code **for the SMART design using the SMART-ITL facility.**
- Among them there is **a complete loss of reactor coolant system (RCS) flow rate (CLOF) scenario.**
  - The steady-state conditions were achieved to satisfy initial test conditions presented in the test requirement, its boundary conditions were accurately simulated using the SMART-ITL facility.
  - The CLOF scenario for the SMART design was also reproduced properly.
- Previously **a similar test** was performed for the CLOF scenario with the **VISTA-ITL** facility and was analyzed using the best-estimate system analysis code of MARS-KS to provide a reasonable simulation results against the measured thermal-hydraulic data.
- In this paper, the test results from the SMART-ITL were analyzed using the MARS-KS code to assess its capability to simulate a CLOF scenario for the SMART design.

PIRTs for SMART

Cross Reference Matrix of Major Phenomena with High Importance for Selected Accident Scenarios for SMART (B.D. Chung, 2009)

Thermal-Hydraulic Phenomena	**Highest Importance Rank**	**Lowest Knowledge Level**	**Accident Scenarios**		
			MSLB	**CLOF (TLOF)**	SBLOCA
Critical Flow (Break)	5	5	●		●
Neutron Flux	5	5	●	●	●
Decay Heat	5	5	●	●	●
Variation of Gap Heat Conductance	5	4	●	●	●
Boiling Heat Transfer in Nuclear Fuel	5	4			●
Flow Mixing in Flow Mixing Head Assembly (FMHA)	5	3	●	●	●
Reactivity Feedback Effect in Reactor Core	5	5	●	●	
Variation of Multi-D Power Distribution in Core	5	5		●	
Pump Coast-down	5	4		●	●
Pressure/Level Increase/Decrease in Steam PRZ	5	5	●	●	
SI Pump Startup, Injection Characteristics	5	5			●
Convective Heat Transfer in Nuclear Fuel	4	5	●	●	
Phase Separation in the Upper Part of Reactor	4	4			●
SG Shell-side Heat Transfer (or Asymmetric Effect)	4	5	●		●
SG Tube-side Heat Transfer	4	3	●		●

Event Category for SMART100

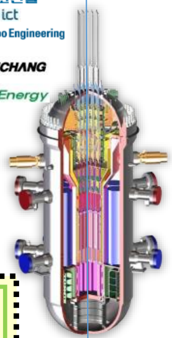
- **Representative Design Basis Events for Each Event Category (Y.J. Chung, 2012)**

Event category	**Representative event**
15.1 Increase in Heat Removal by the Secondary System	Main Steam Line Break (MSLB)
15.2 Decrease in Heat Removal by the Secondary System	Feedwater Line Break (FLB)
15.3 Decrease in Reactor Coolant System Flow Rate	Complete Loss of Reactor Coolant Flow (CLOF, or TLOF)
15.4 Reactivity and Power Distribution Anomalies	Control Rod Assembly Ejection Accident (REA)
15.5 Increase in Reactor Coolant Inventory	Pressurizer Level Control System Malfunction (PLCSMF)
15.6 Decrease in Reactor Coolant Inventory	Small-Break Loss-of-Coolant Accident (SBLOCA)

SMART Validation Test Program using SMART-ITL

Standard Design Approval (SDA) | **Safety Enhancement Research (SER)** | **Pre-Project Engineering (PPE)** | **SMART100 Standard Design Approval (SDA)** | **SMART FOAK Plants**

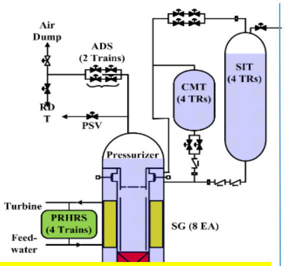
KAERI Korea Atomic Energy Research Institute
KEPCO, 한국수력원자력(주), KEPCO E&C, KEPCO NF, STX Heavy Industries, DSME DAEWOO SHIPBUILDING & MARINE ENGINEERING CO.,LTD., DAEWOO E&C, POSCO, 포스코건설, 포스코ICT, Daewoo Engineering, SEG SAMCHANG, 일진Energy



VISTA-ITL (Small-Scale IET)
- SBLOCA, CLOF
- PRHRS performance 10

SMART-ITL Construction

Commissioning Tests 8



PSS Validation (PRHRS, PSIS)

1st Phase Tests
- PSS Concept Verification
- CMT, SIT, ADS 14
- VISTA-ITL counterpart
- Characterization 6

PSS (1-Train)
- PSS Train Effects 5

PSS (2-Train)

SMART = سمارت

DBA (w/ 4-Train PSS)
- Full Train PSS Tests-SBLOCA (5)
- SRTs: SBLOCA, CLOF, FLB (3), SGTR, CRAW, NC, TLOSHR (6) 14

SP 3

- PSIS
- PRHRS

OM, SG
- Operation & Maintenance
- SG Concept Verification 5

55 tests finished
- SDA: 8 items
- SER: 25 items
- PPE: 22 items

PSS: Passive Safety System
DBA: Design Basis Accident
SP: System Performance
OM: Operation & Maintenance
SDCA: Standard Design Change Approval

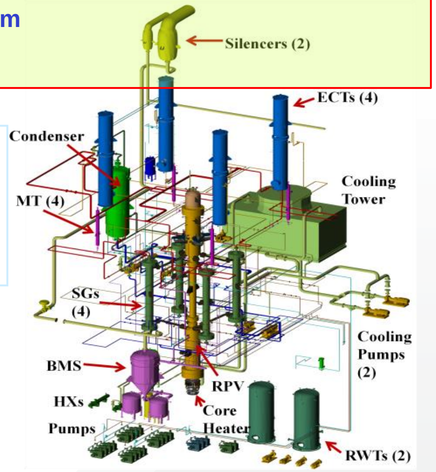
Future Items

SDA Support

Licensing Issues Resolution
- Safety Analysis
- Fluid System Design
- Others

Severe Accidents
- Beyond DBA Tests

PSA Concerns
- AM Measures
- EOP Development



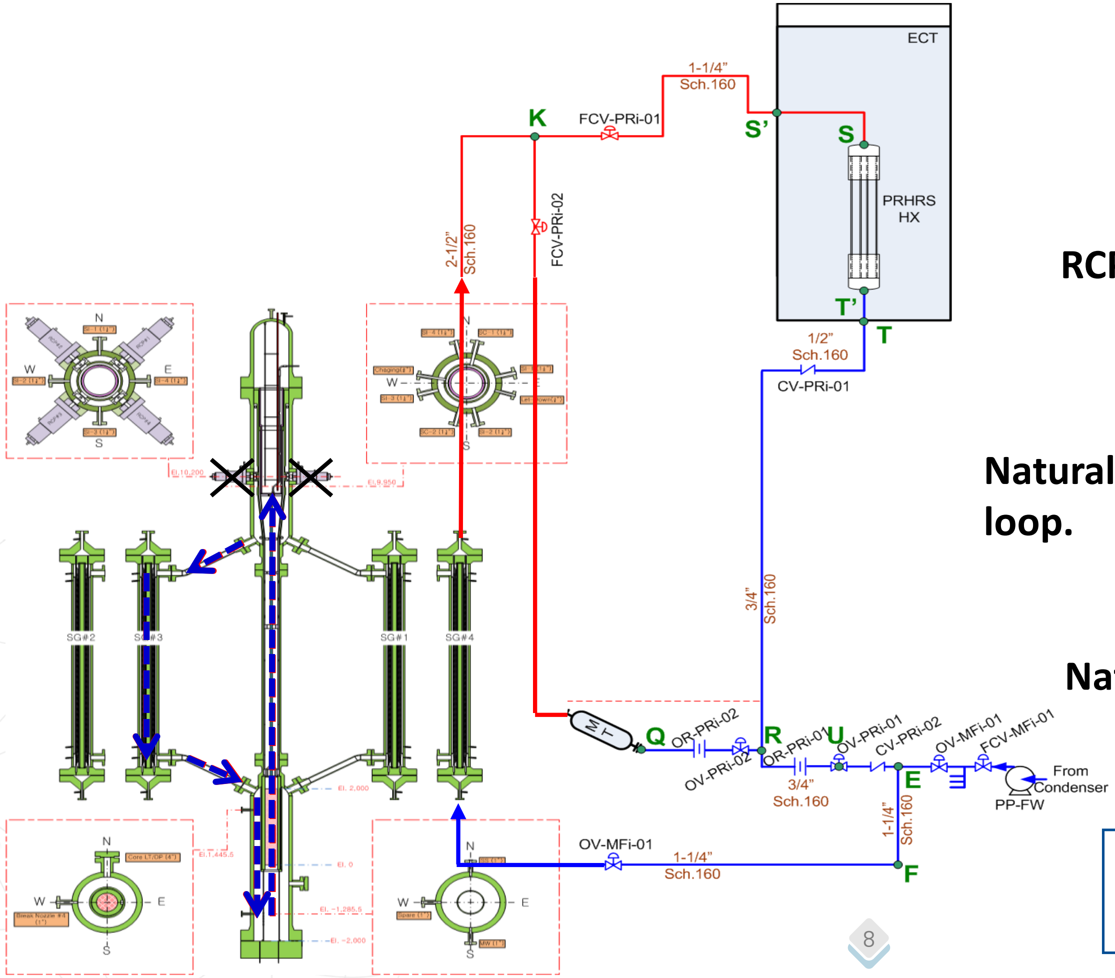
09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

Fukushima ('11.3.11)
SMART SDA Issued ('12.7.4)
SMART PPE Project ('15.12.~)
SISTA (2017~)
SISTA1 (2018~20)
SMART100 DCA ('19.1.1~)
SISTA2 (2021~23)
Now

Introduction

CLOF Scenario in SMART100

Progress of CLOF scenario



Steady-state operation

RCPs stop due to emergency power loss.

Natural Circulation occurs in the primary loop.

Natural Circulation starts in PRHRS also.

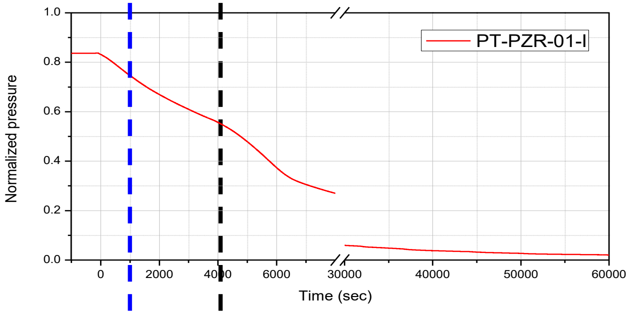
Single-phase NC (in RCS) & Two-phase NC (in Secondary Loop)

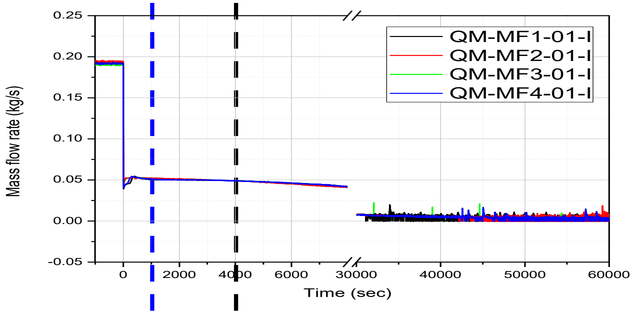
Introduction

CLOF-01 Test: Transient Data

Progress of CLOF scenario (J.H. Yang, 2018)

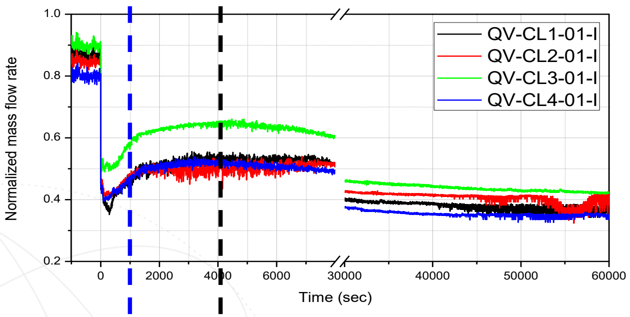
PZR pres.

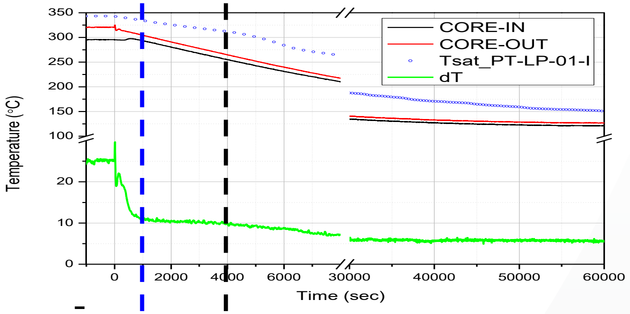




FW flowrate

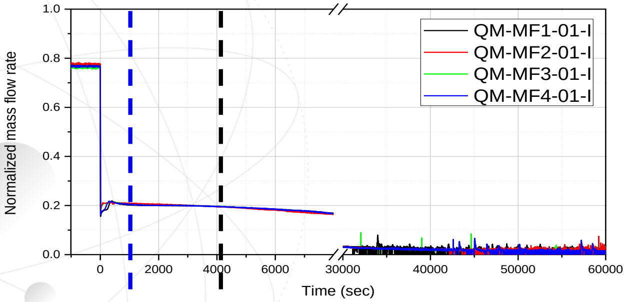
RCS flowrate

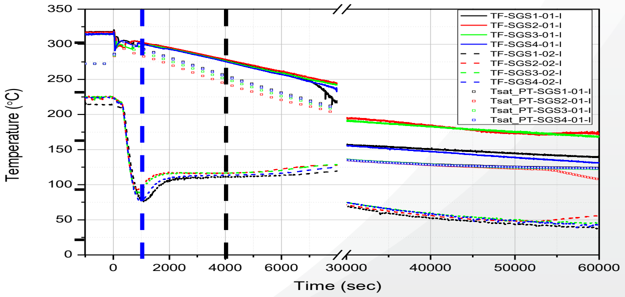




RCS fluid temp.

FW flowrate

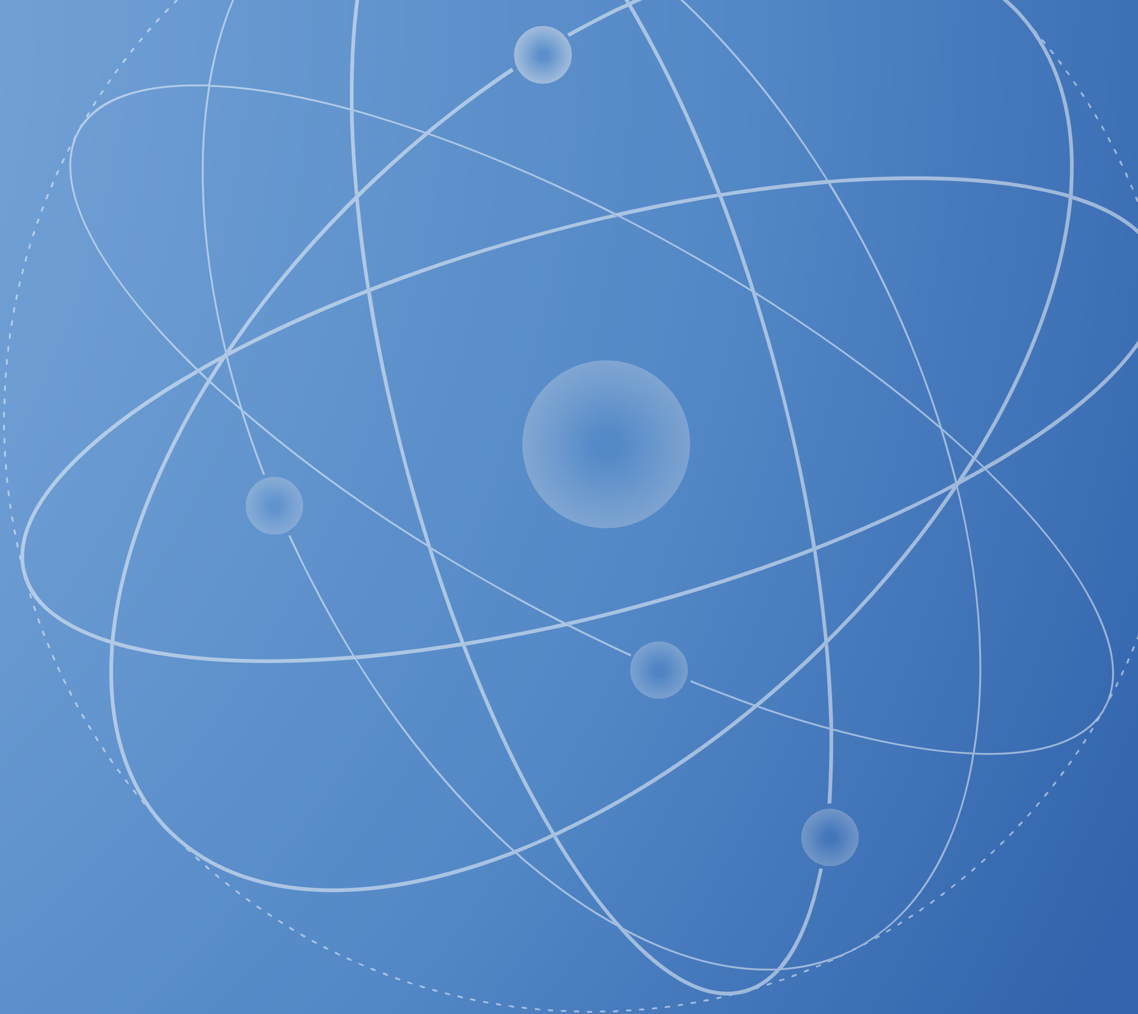




Steam/ FW fluid temp.

KAERI Korea Atomic Energy Research Institute

KOREA
ATOMIC
ENERGY
RESEARCH
INSTITUTE



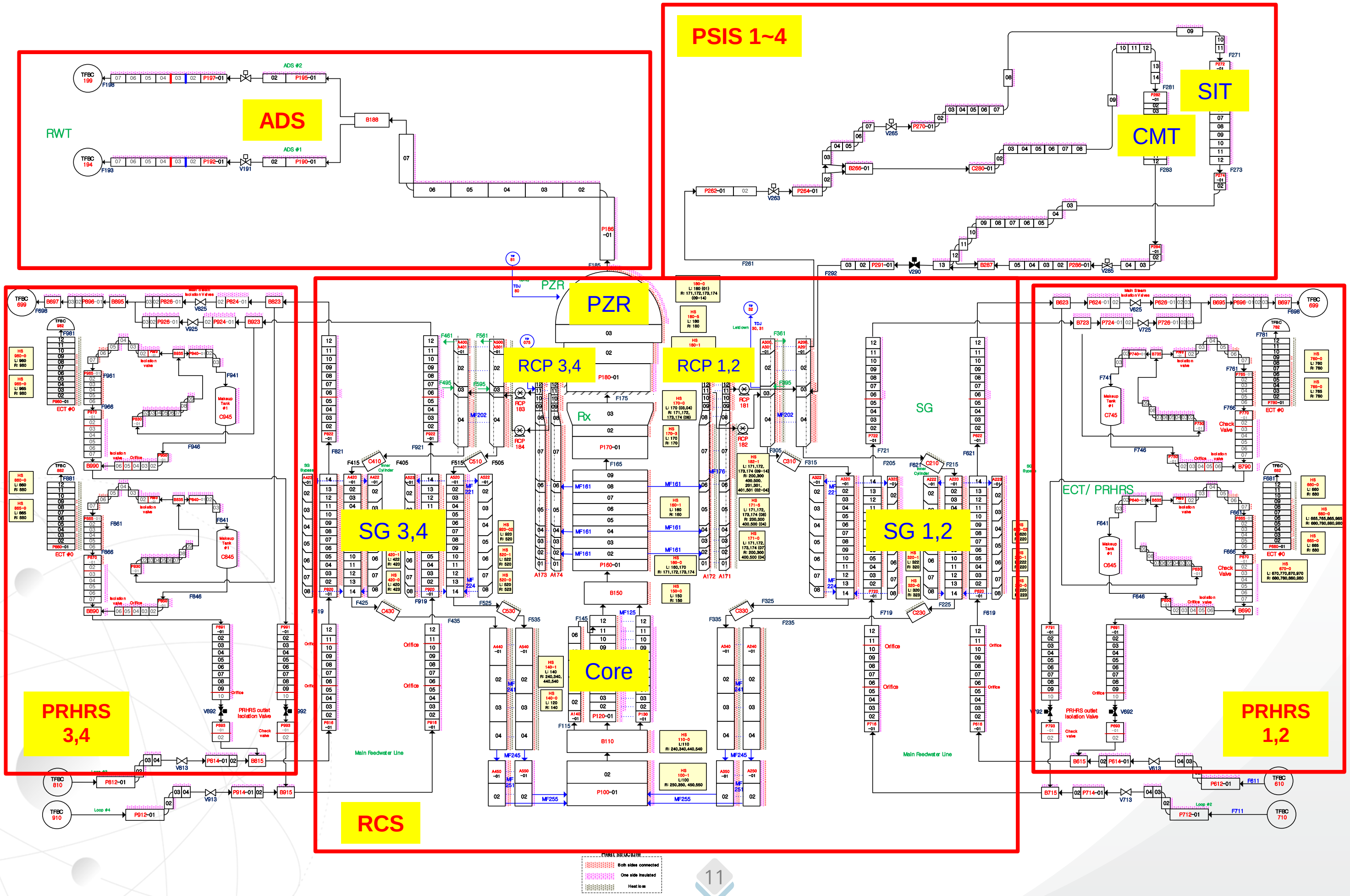
02

Simulation Results on the CLOF Test

Simulation Results on the CLOF Test

Nodalization and Input Preparation

MARS-KS nodalization for the SMART-ITL: Overview

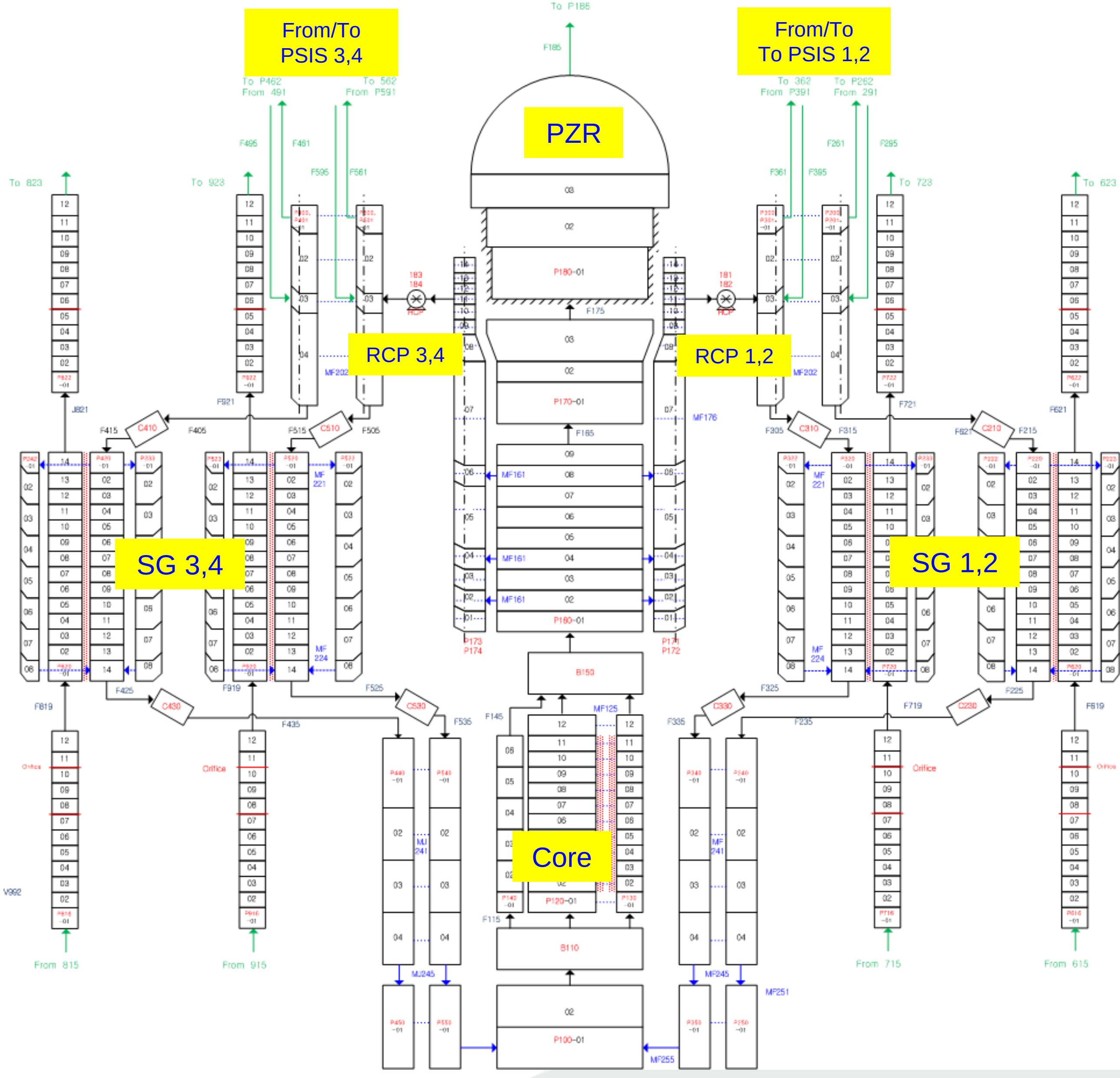


Korea Atomic Energy Research Institute

Simulation Results on the CLOF Test

Nodalization and Input Preparation

- MARS-KS nodalization for the SMART-ITL: RCS

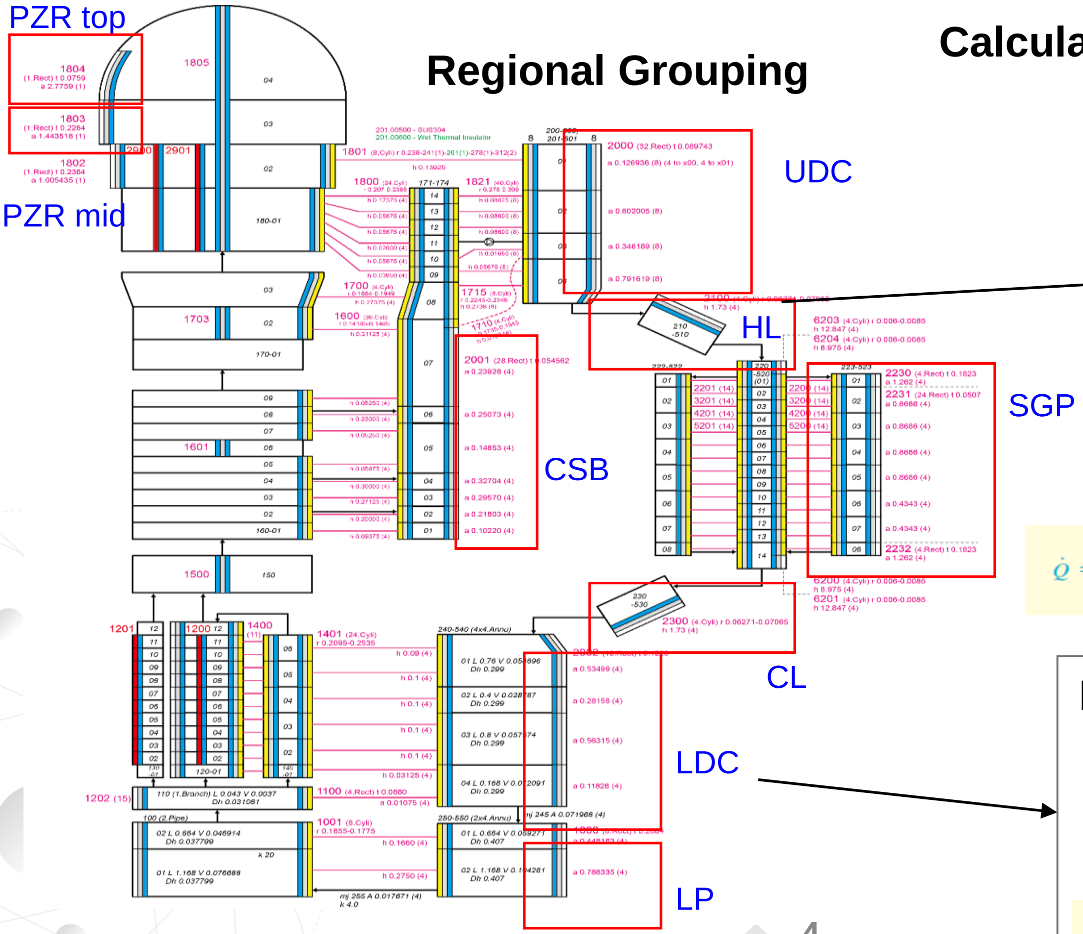


Simulation Results on the CLOF Test

Nodalization and Input Preparation

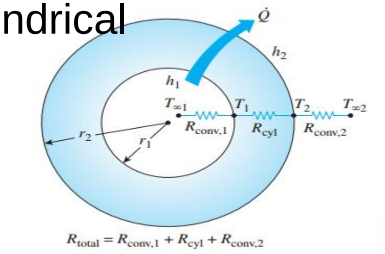
Estimation of Heat Loss Coefficient

Regional Grouping



Calculation of Heat Loss Coefficient

Cylindrical



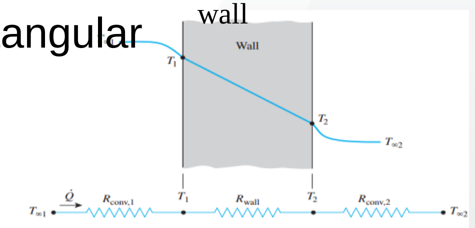
$$R_{\mathrm{total}} = R_{\mathrm{conv,\,1}} + R_{\mathrm{cyl}} + R_{\mathrm{conv,\,2}} = \frac{1}{(2\pi r_1 L)h_1} + \frac{\ln(r_2/r_1)}{2\pi L k} + \frac{1}{(2\pi r_2 L)h_2}$$

$$\dot{Q} = \frac{T_{\infty 1} - T_{\infty 2}}{R_{\mathrm{total}}} \quad \mathrm{(W)}$$

Parameters

- h_1 : fluid HTC
- h_2 : ambient HTC
- k : conductivity for pipe wall

Rectangular



$$R_{\mathrm{total}} = R_{\mathrm{conv,\,1}} + R_{\mathrm{wall}} + R_{\mathrm{conv,\,2}} = \frac{1}{h_1 A} + \frac{L}{kA} + \frac{1}{h_2 A} \quad \mathrm{(K/W)}$$

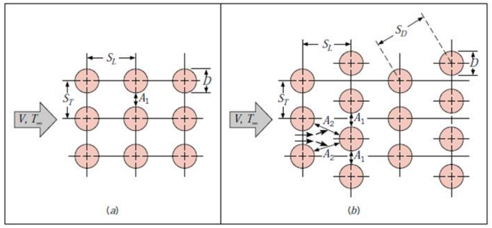
Simulation Results on the CLOF Test

Nodalization and Input Preparation

Heat Structure - Helical Coiled SG

- Left/Right BC: Table 9.16-1, Card 501 / Table 9.17-1, Card 601
- Word 3: Convection Boundary Type (Left: Tube; Right: Shell)

Word 3	Geometry Type
1, 100, 101	Default
114	**Helical S/G tube side (set Dc/di on 801/901 card Word 10)**
135	Helical S/G shell side (set P/D on 801/901 card Word 10)
160	**Zukauskas heat transfer correlation for staggered bundle cross flow shell side**
161	Zukauskas heat transfer correlation for staggered and finned bundle cross flow shell side
162	Zukauskas heat transfer correlation for in-lined bundle cross flow shell side



Tube arrangement in a bank:
(a) in-lined, (b) **staggered**

- Word 10: Rod or tube pitch-to-diameter ratio. The default is 1.1;
  - (Dc/di): Helical Circle Diameter-to-Tube Inner Diameter Ratio
- Modified in MARS-KS 2.0 version (Consulted by Dr. C. W. Choi (2021.6.))

Simulation Results on the CLOF Test

Steady-State Calculation Results: ICs / BCs / Heat Balance

Brief setting of initial / boundary values (from measurement values)

- Pressure : Pressurizer & Steam line
- Temperature : Core inlet-outlet & SGP inlet-outlet
- Flow rate : RCP RPM (Measured at cold leg), Feedwater pump (FW line)
- Level : Pressurizer
- Heater power : Core (Average & Hot)
- Heat Loss (HTC of Heat Structure) : Sectional estimation
  - CL, RPV(UDC+LDC), PZR, PSIS (PBL), PRHRS (ECT)

Heat Balance between RCS and Secondary System

- Core power & FW flowrate
- Achieve constant temperatures adjusting heat loss (using HTC of heat structure)

Reactor Coolant System Parameters

- PZR water level: control using letdown and spray control variables (initial value: @C180)
- PZR pressure and temperature: PZR heaters
- Temp. diff. of Core/SGP inlet & outlet: RCS flow rate adjusting RCP RPM

Secondary System Parameters

- Steam & FW line pressures
  - SGS inlet : K factor of junction @C619, C719, C819, and C919
  - SGS outlet : Steam line boundary (@TDBC 698)
- Feedwater line (SGS inlet) flowrate using FW pumps
- Feedwater line (SGS inlet) temperature @C610, C710, C810, and C910

Simulation Results on the CLOF Test

Steady-State Calculation Results: Optimization

SS calculation with MARS-KS 1.4 ('17~'18)

Cases	Calculation Conditions
ⓞ	Previous Calculation
①	RCP spec. / Actual RPM (SMART-ITL pump (Canned Motor) spec. & Heat loss distribution in RCS)
②	RCP spec. / Modified RPM
③	RCP spec. / Modified RPM + heat loss location (Lower DC→CL)
④	③ + HTC optimization (CL: 206.5 & PZR: 5 & HL & wall: 2)
⑤	④ + SMART-ITL Homologous Curve
⑥=SS1	④ + SMART-ITL Homologous Curve + tuned loss coefficient (from F103: SBLOCA case)

SS calculation with MARS-KS 2.0 ('23~'24)

Cases	Calculation Conditions
⑥=SS1	Previous Calculation
⑦	⑥ + RCP RPM tuning (to fit initial RCS flowrate)
⑧	⑦ + PZR backup heater limit (15.0 MPa, PZR pressure)
⑨=SS2	⑧ + Core power tuning
⑩=SS2c2f4	⑨ + HCSG=114(tube), 160(shell); PZR(15.05)+Table 123(HTC=140); RPM=1.0

Simulation Results on the CLOF Test

Steady-State Calculation Results

- Comparison of the major parameters under a steady state condition

Parameter	Target value	Test Data	MARS Cal.	Error (%)
Power, MW	1.49	1.67	1.67	0.02%
1st Flowrate, kg/s	10.233	11.624	11.622	-0.02%
PZR pres., MPa	15.00	15.05	15.05	0.00%
PZR fluid Temp., ℃	342.2	340.4	340.8	0.11%
SG 1st inlet Temp., ℃	320.9	320.6	320.6	-0.01%
SG 1st outlet Temp., ℃	295.5	298.1	296.0	-0.70%
F.W. flow-rate, kg/s	0.778	0.769	0.768	-0.13%
SG 2nd inlet pres., MPa	6.71	5.71	5.67	-0.68%
SG 2nd inlet Temp., ℃	230.0	230.2	230.0	-0.09%
SG 2nd outlet pres., MPa	5.62	5.62	5.63	0.13%
SG 2nd outlet temp., ℃	≧ 301.4	314.7	320.5	1.84%
SG 2nd superheat, ℃	≧ 30.0	43.3	49.1	+5.8℃

Simulation Results on the CLOF Test

Sequence of Events for the CLOF Scenario

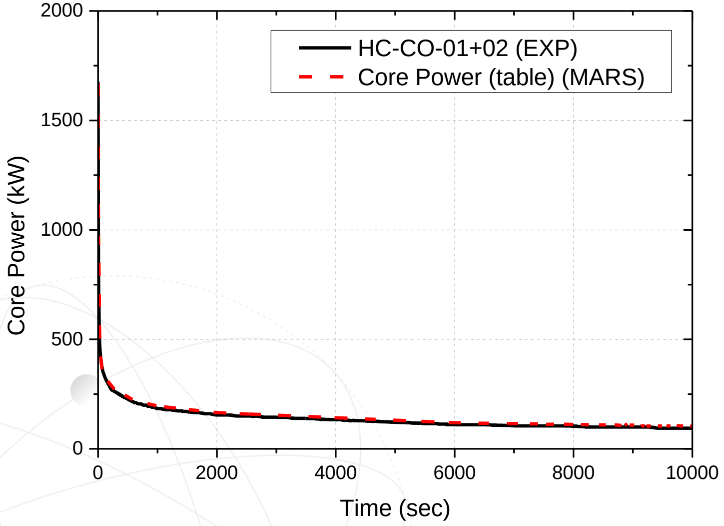
Comparison of a major sequence of a CLOF test

Event	SMART	SMART-ITL -Test (s)	SMART-ITL -Simulation (s)
Transient initiation	RCP coast-down	0	0
Trip signal	RPS (or HPP)	0.37	0.38
Reactor trip signal & FW stop	RPS + 1.1 s	1.47	1.48
PRHR actuation signal (PRHRAS) & CMTAS	RPS + 1.1 s	1.47	1.48
Control rod insert	RPS + 1.6 s	1.97	1.98
CMT Isolation Valve open	RPS + 2.2 s	2.57	2.58
PRHRS IV open	PRHRAS + 5.0 s	6.47	6.48
MSIV/FIV close	PRHRAS + 5.0 s	6.47	6.48
Test end	$T_{RCS} < 215^{o}C$ (or less than 36 hours)	8,120	9,495

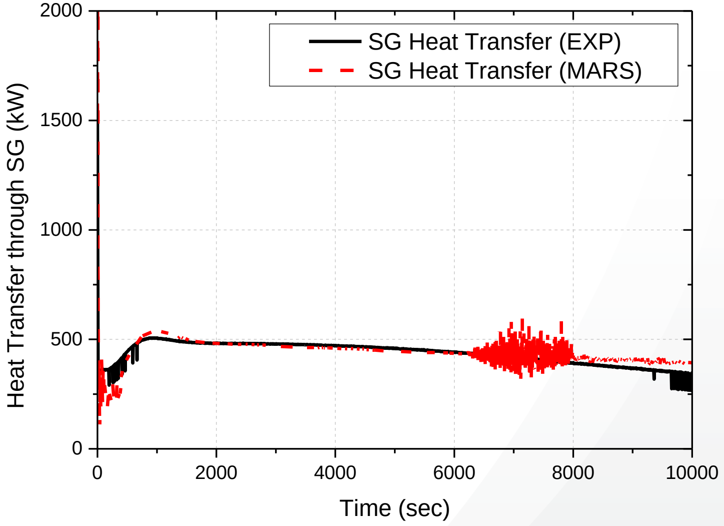
Simulation Results on the CLOF Test

Transient Calculation Results

- **The core power is well simulated. (Boundary Condition)**
- **The heat balance through SG is reasonable.**
  - Some fluctuation is observed between 6,000~8,000 s and thereafter the heat transfer is more active than the test data.



Core Power

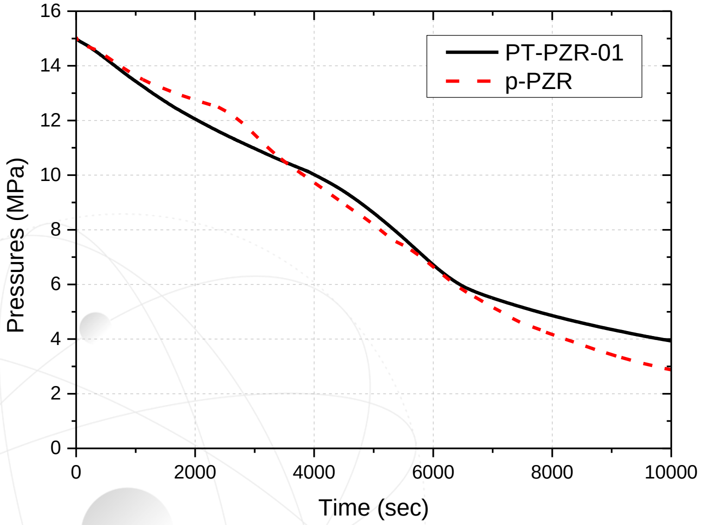


Heat Balance through SG

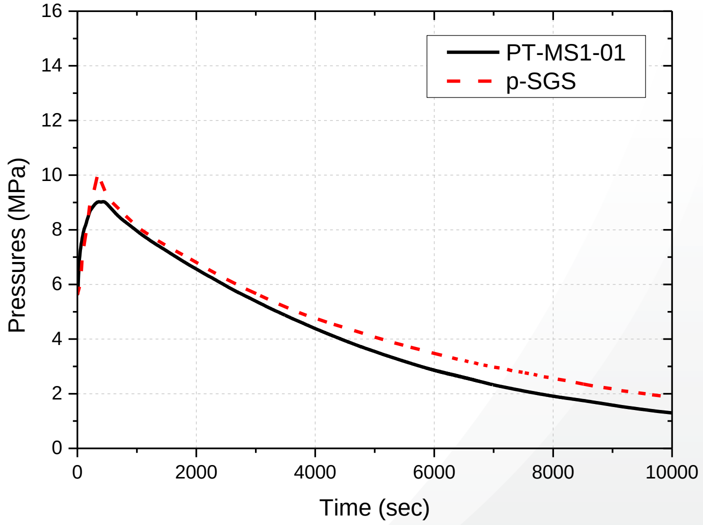
Simulation Results on the CLOF Test

Transient Calculation Results

- **Pressurizer pressure is well simulated in general but is under-predicted in the later phase.**
  - It is noted that the heat transfer characteristics between primary and secondary system is changed between 4,000~6,000 s in the test data.
  - The decrease rate of RCS pressure tends to reduce until 3,000 s but thereafter it turns to be steeper. It becomes slower after 6,000 s.
- **Secondary system pressure is well simulated.**
  - Its peak pressure is a little higher.



Pressure @ Pressurizer



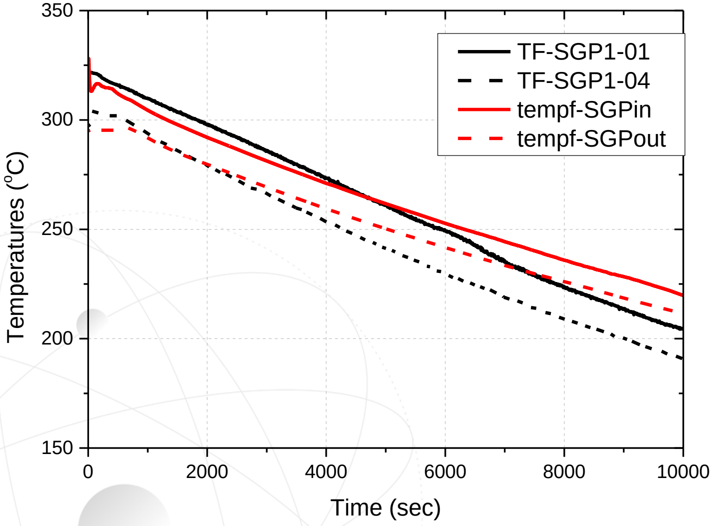
Pressure @ SG Secondary

Simulation Results on the CLOF Test

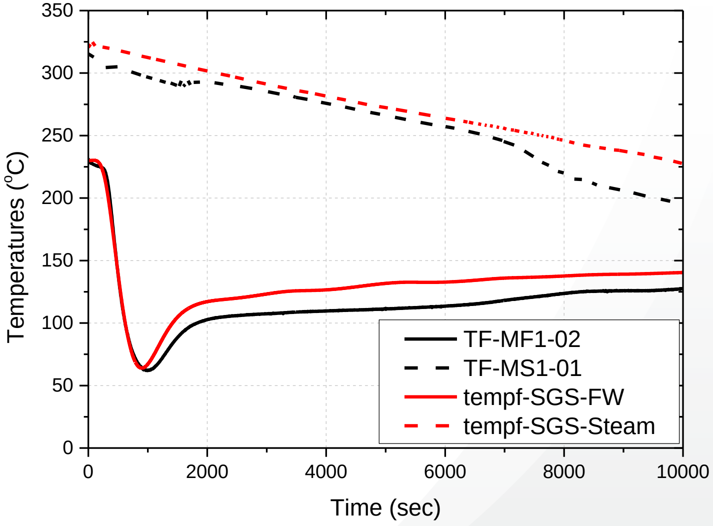
Transient Calculation Results

Fluid temperatures both in the primary and secondary sides of SG show the similar trends.

- The primary side temperatures decrease a little slowly in the MARS calculation. It keeps higher temperatures after 4,000 s.
- The recovered FW temperature is higher in the MARS calculation due to its high temperature in the primary side.



Temperature @ SG Primary

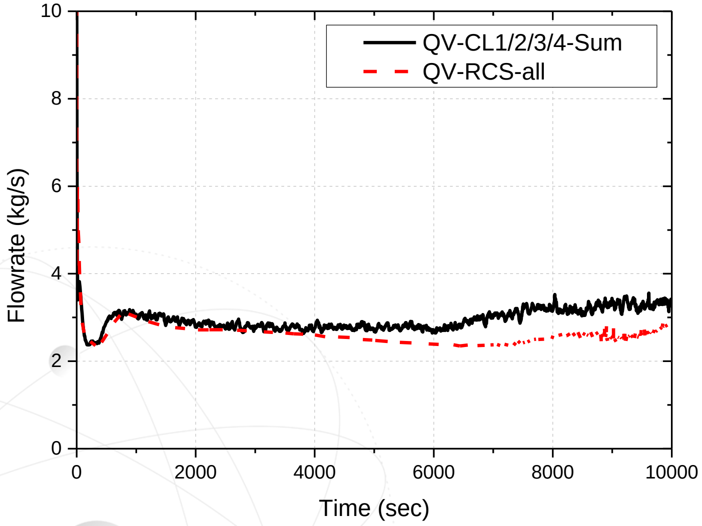


Temperature @ SG Secondary

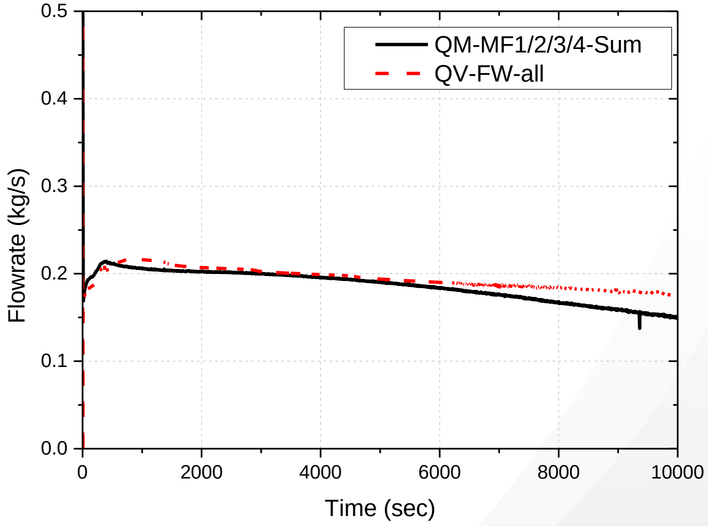
Simulation Results on the CLOF Test

Transient Calculation Results

- **The MARS code predicts lower mass flow rate than the test data in the primary loop of RCS.**
  - It predicts the mass flow rate in RCS very well until 4,000 s but thereafter the under-prediction increases with the maximum difference of about 26% and the difference at 10,000 s is about 16%.
- **The MARS code predicts higher mass flow rate that the test data in the secondary loop of FW-SG-MS-PRHRS.**
  - It predicts the mass flow rate in PRHRS very well until 4,000 s but thereafter it over-predicts the test data. The maximum difference is about 14% at 10,000 s.



Mass flow rate @ RCS (CL)

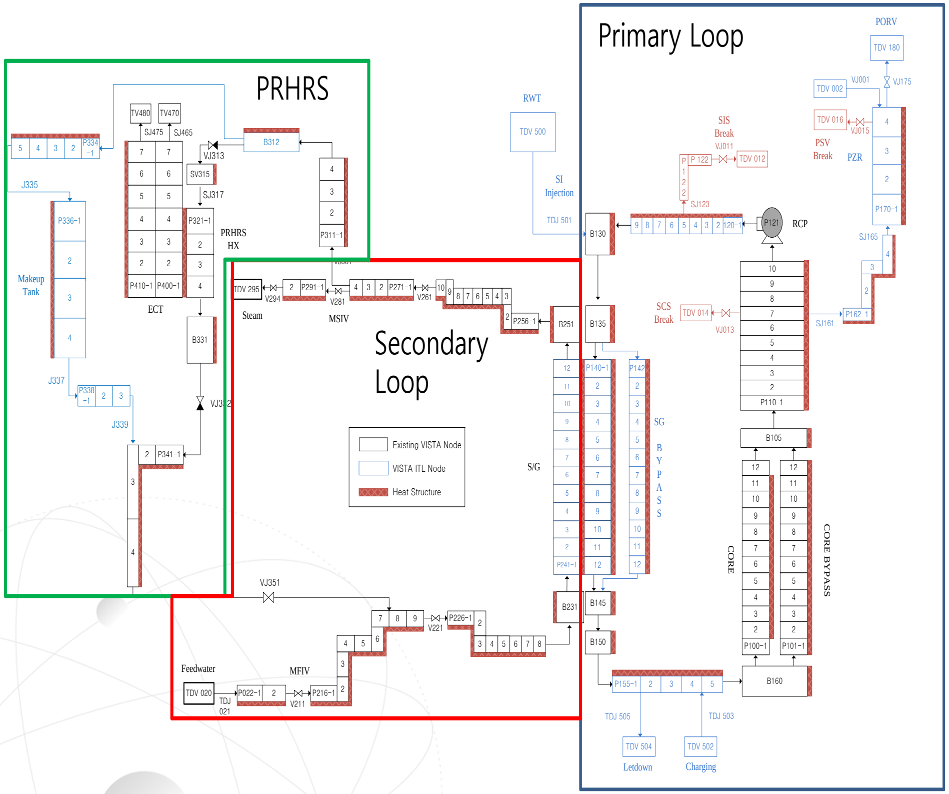


Mass flow rate @ Main FW

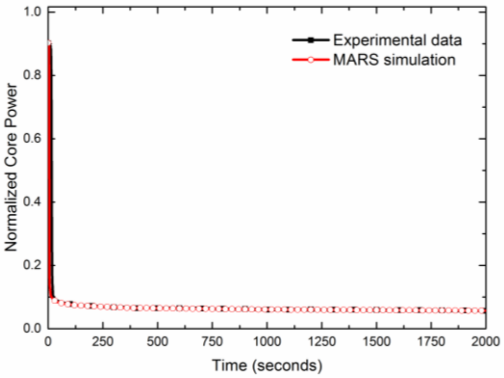
Simulation Results on the CLOF Test

Transient Calculation Results (Ref: VISTA-ITL, 2017)

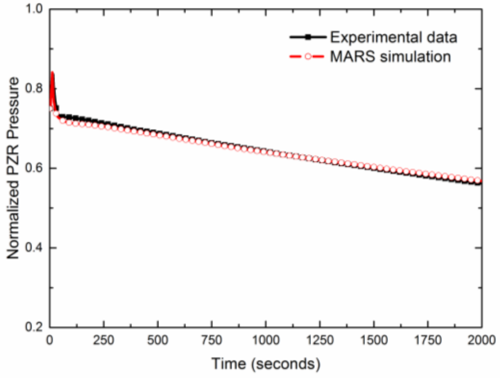
- It is similarly observed during the CLOF test using VISTA-ITL.



MARS-KS nodalization for the VISTA-ITL



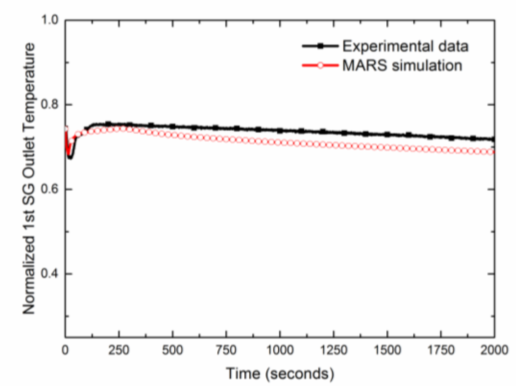
Core power



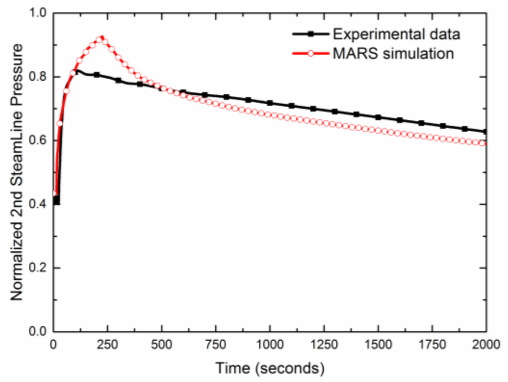
Pressurizer pressure

Simulation Results on the CLOF Test

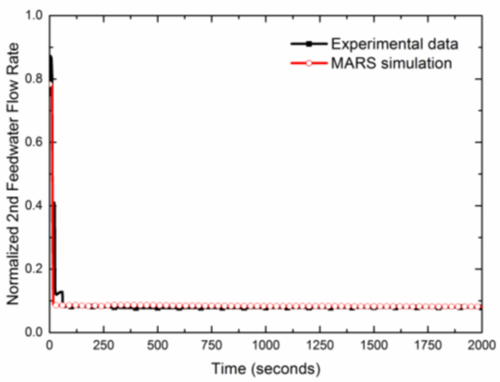
Transient Calculation Results (Ref: VISTA-ITL, 2017)



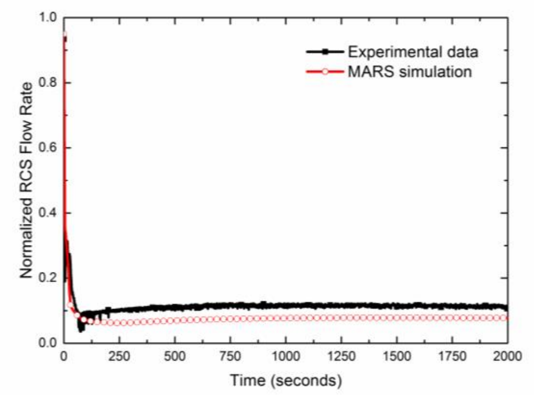
SG 1ry outlet temp.



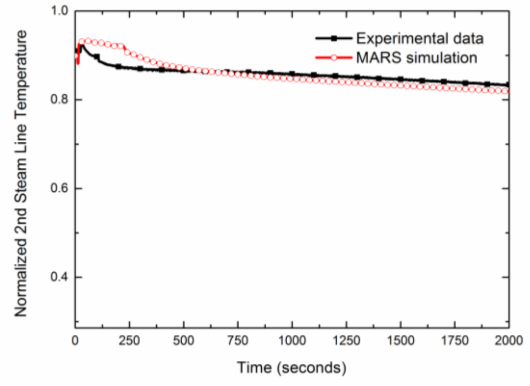
2ry system pressure



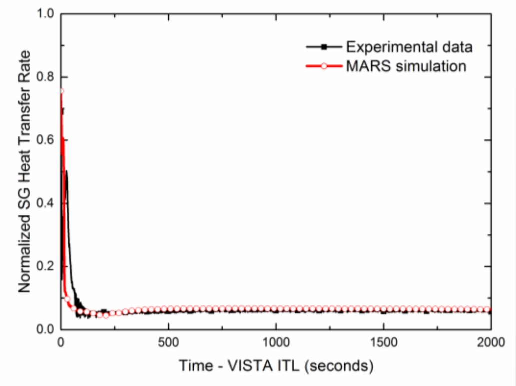
2ry system flowrate



RCS flowrate

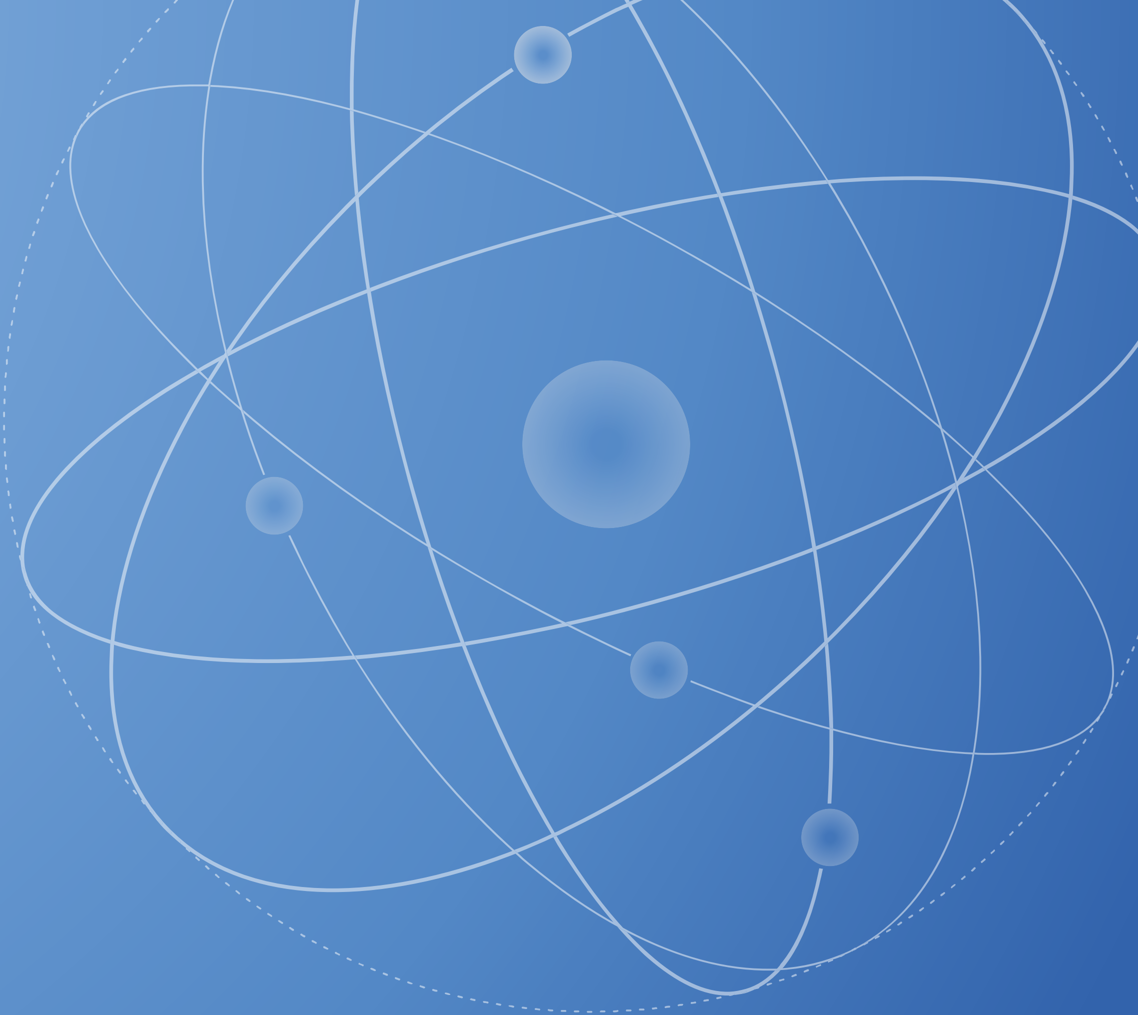


2ry system steam temp.



SG heat transfer

KOREA
ATOMIC
ENERGY
RESEARCH
INSTITUTE

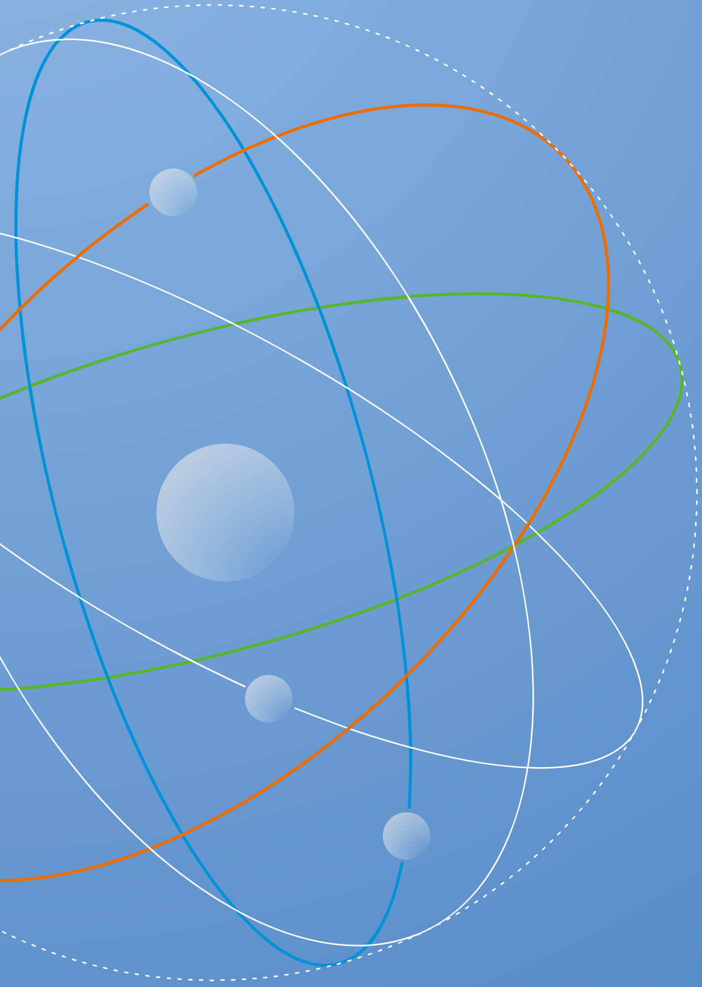


03

Conclusions

Conclusions

- An integral effect test for the CLOF scenario was successfully performed to provide data to assess the capability of the system analysis codes of MARS-KS for the SMART design.
- The CLOF test results were simulated using the MARS-KS code to assess the simulation capability for the CLOF scenario of the SMART design.
- In overall the measured thermal-hydraulic data from the test were properly simulated using the MARS-KS code.
- However, there are still some discrepancy between the test and simulation results such as higher RCS temperatures, difference of flow rates in the later phase, etc.
- It is estimated that more accurate simulation is possible with further consideration on the heat loss through the heat structure, flow resistance in the primary and secondary loops, heat transfer rate through HCSG, etc.



A nuclear research institute

reshaping the future based on **peoples trust**

THANK YOU

KAERI

Korea Atomic Energy
Research Institute