한국원자력학회 2022년도 춘계학술발표회
제주, 5월 19-20일, 2022
(제5분과 C)

Major Results from Validation Tests for SMART Passive Safety Injection System with the SMART-ITL Facility

(SMART 종합효과시험장치를 활용한 피동안전주입계통 검증시험의 주요 결과)

2022. 5. 19.

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2) SMART100 RAI for PSIS (SSAR-6.3)
3) Special Component Model for Safety Analysis Code

SMART Program (1/2)

- SMART is an Integral Type Reactor with Multiple Application of Electricity and Portable Water, etc.
  - Harmonizing Innovative Concept and Proven Technology for Regulatory License and Market/Public Acceptance.

Innovative Concept

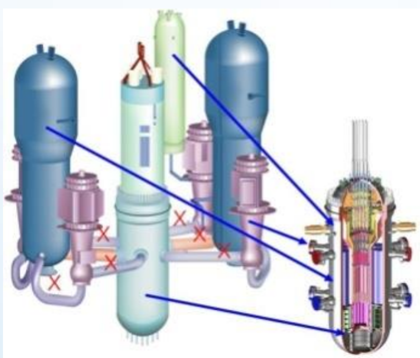
- All Primary Components in Reactor Vessel
- Passive Safety Systems
- Modularization for Field Installation and Maintenance
- Fully Digitalized Control System

Proven Technologies

- 17x17 UO_2 Proven Fuel Technology
- Large Dry Containment Building
- Control Rod Drive Mechanism
- Reactivity Control Concepts using Burnable Poison and Soluble Boron

Comprehensive Technology Validation

Systems, Component, and Design Tools have been fully Developed and Licensed



Development of an Integral Type Reactor, SMART

Separate Effect Tests | Integral Effect Tests | Component Development

Early Deployment of SMART (for a city with 100,000 population)

SMART Program (2/2)

❑ SMART Development (1997~2018)

* IET: Integral Effect Test
* ITL: Integral Test Loop

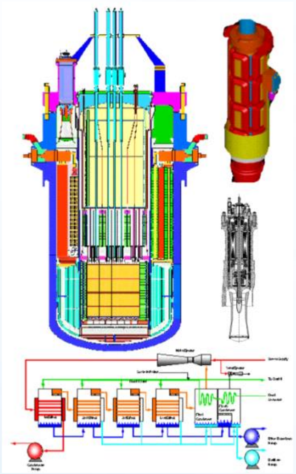
* SDA: Standard Design Approval
* PSS: Passive Safety System
* PPE: Pre-Project Engineering

Thermal-Hydraulic Validation Tests - IETs

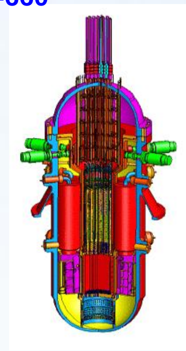
- VISTA Tests
- VISTA-ITL Tests
- SMART-ITL Construction
- SMART-ITL PSS Validation Tests
- SMART-ITL Tests for SMART-PPE

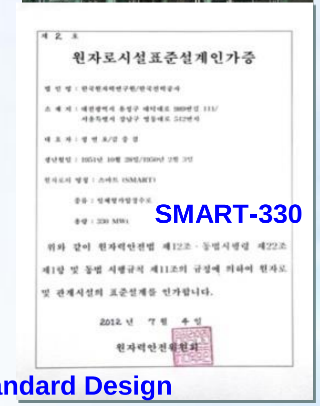
1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018

- **Conceptual Design**
- **Basic Design**
- **SMART-P (65MWt) Design and Licensing**
- Pre-Project Service
- Design Optimization
- **SMART Standard Design Approval**
- **Safety Enhancement Research for SMART Construction**
- **SMART Pre-Project Eng. (PPE) Project**



SMART -660

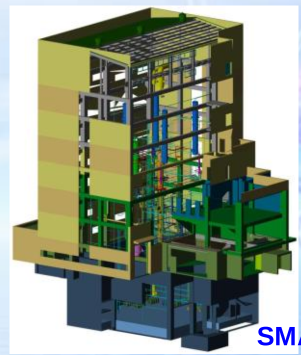




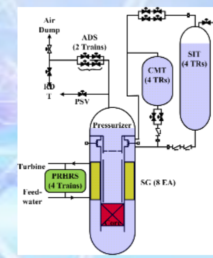
Standard Design Certificate for SMART

Business for SMART Construction

- **Foreign Cooperation**: Saudi Arabia, UK, Moldova, Malaysia, etc.
- **SPC** : Business for SMART Export



SMART-ITL



SMART-PSS

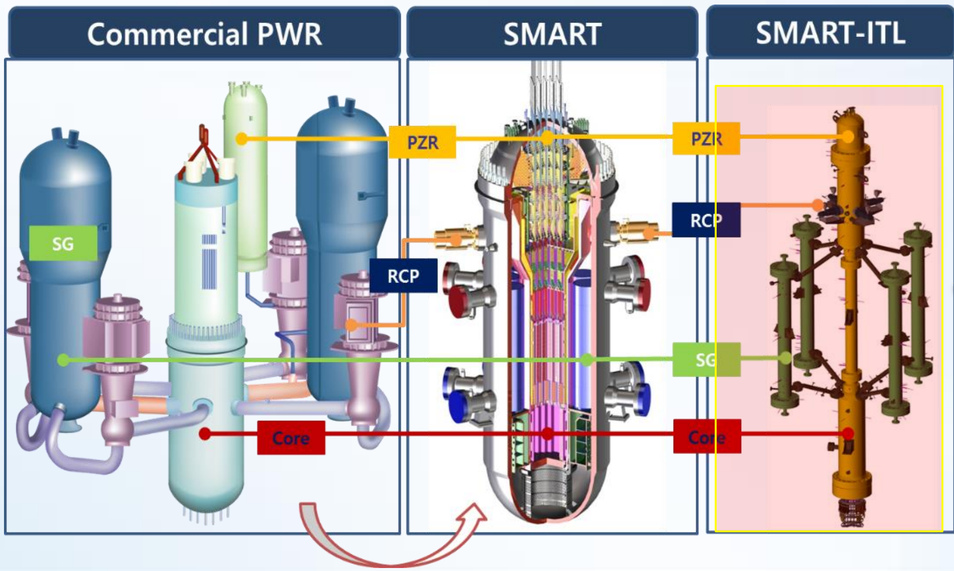
Total 1,500 MY and ~300 M$ are invested.

Standard Design Approval @ 2012. 7. 4. (SMART-330)

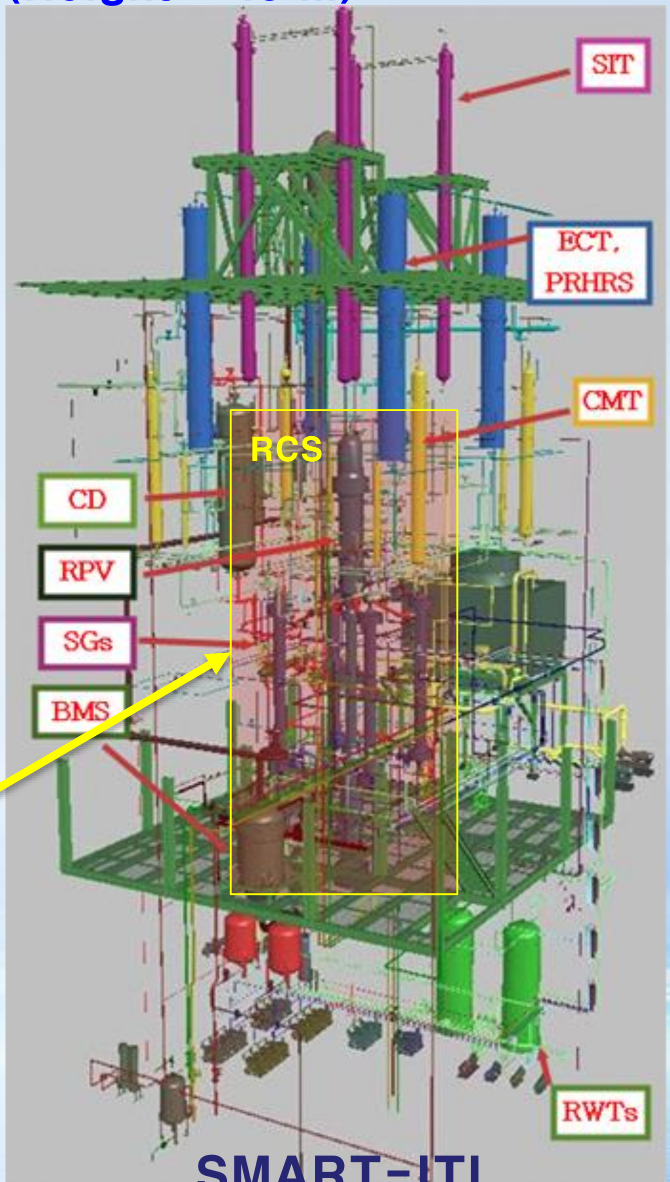
Standard Design Change Approval @ 2019~2022 (SMART100, Collaboration with KHNP, KACARE)

SMART-ITL Program (1/3)

- SMART-ITL (Integral Test Loop), alias FESTA
  - Reference Plant: SMART100
    - Core power : 365 MWth
    - Design press. & temp. : 17.0 MPa / 350 °C
    - Mass flow rate in core : 2,507 kg/s
  - Volume Scaling Methodology: 1/1-H, 1/7-D



(Height ~ 45 m)



SMART-ITL

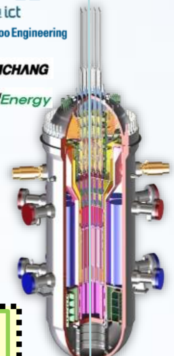
SMART-ITL Program (2/3)

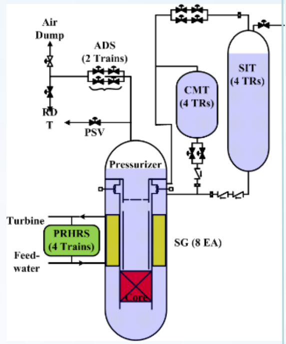
❑ SMART Validation with SMART-ITL

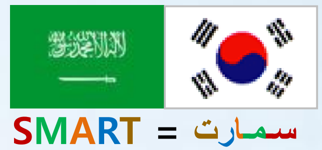
* SMART SDCA (2019~2022)
* i-SMR: Innovative SMR (2021~2028)

Standard Design Approval (SDA)	Safety Enhancement Research (SER)	Pre-Project Engineering (PPE)	Standard Design Change Approval (SDCA)	SMART FOAK Plants

Korea Atomic Energy Research Institute (KAERI)







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

10

SMART-ITL Construction

Commissioning Tests 8

1st Phase Tests
- VISTA-ITL counterpart
- Characterization

6

PSS (1-Train)
- PSS Concept Verification
- CMT, SIT, ADS

14

PSS (2-Train)
- PSS Train Effects

5

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

14

SP
- PSIS
- PRHRS

3

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

Under Planning

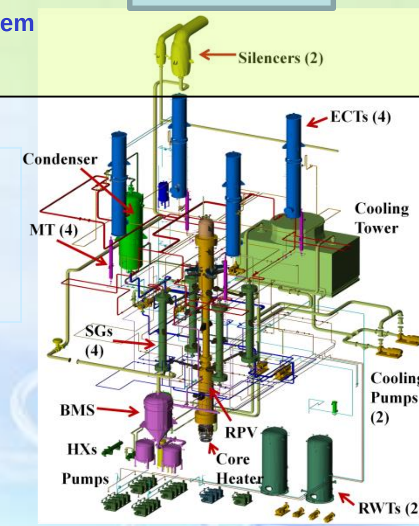
SDCA Support

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

Severe Accidents
- Beyond DBA Tests

PSA Concerns
- AM Measures
- EOP Development

i-SMR



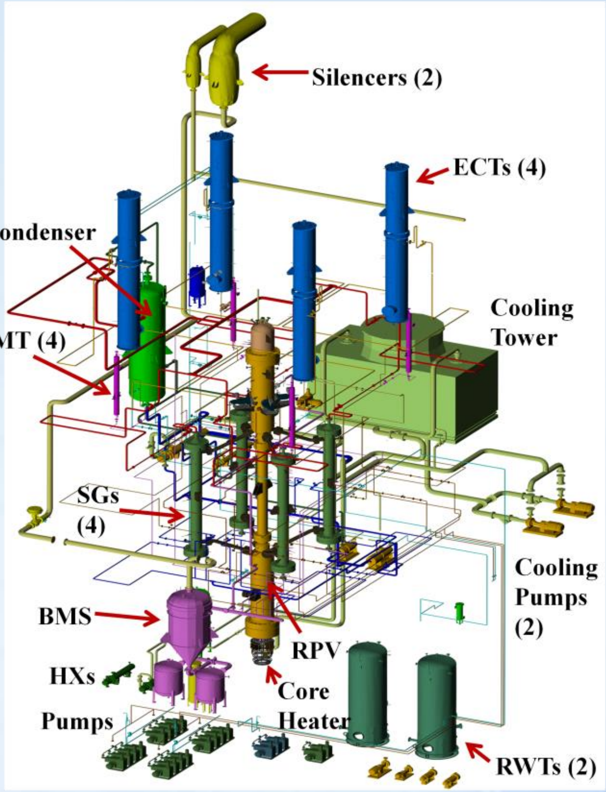
09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

- Fukushima ('11.3.11)
- SMART SDA Issued ('12.7.4)
- SMART PPE Project ('15.12.1)
- SMART SDCA Project ('19.1.1)
- Now

❑ Design Characteristics

- **Design pressure & temp.**
  - 180 bar, 370°C
- **Maximum core heater power**
  - 2.0 MW (30% of scaled full power)
- **SG, PRHRS, PSIS : 4 Trains**
  - External SGs for proper instrumentation and easy maintenance
- **Major Components**
  - Primary/Secondary systems
  - PRHRS, SIS/SCS, Auxiliary systems
  - Break system, Break measuring system
- **Instruments : ~ 1,600**
  - Pressures, temperatures, flow rates, mass, power, etc.

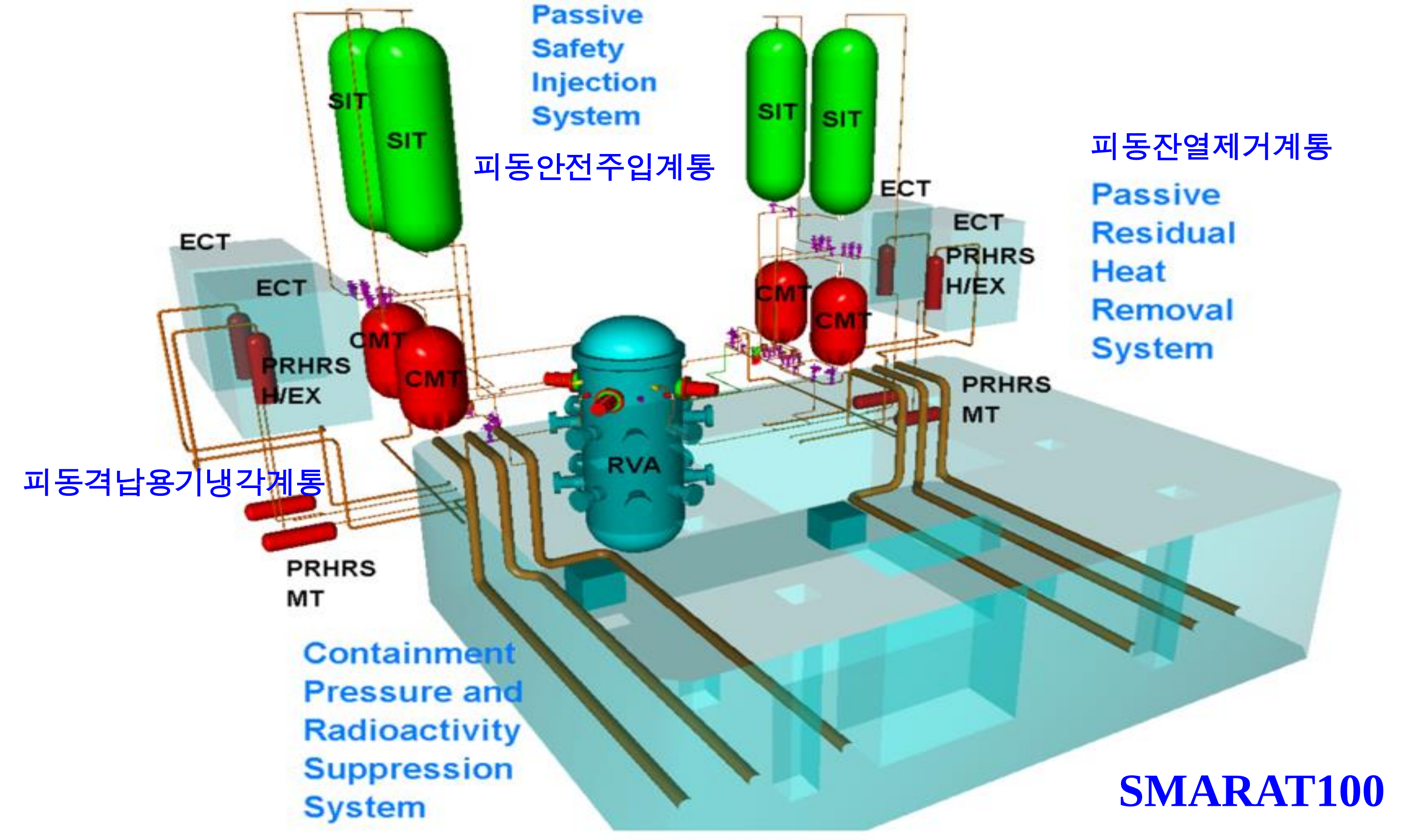
SMARAT-ITL Schematics



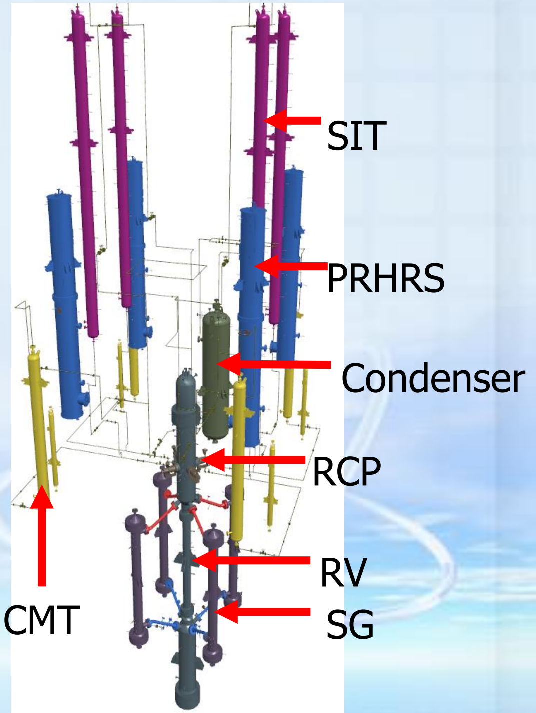
Control Room

Passive Safety Systems: SMART (1/3)

- PRHRS (Passive Residual Heat Removal System), PSIS (Passive Safety Injection System), ADS (Automatic Depressurization System) , PCCS (Passive Containment Cooling System, or CPRSS)



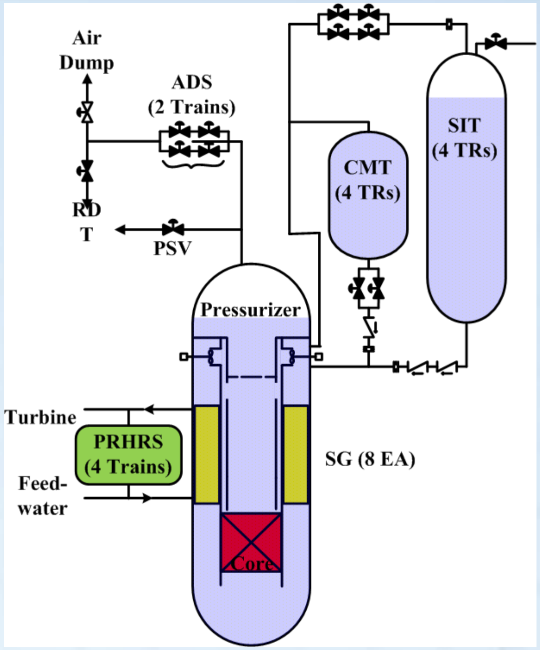
SMARAT-ITL



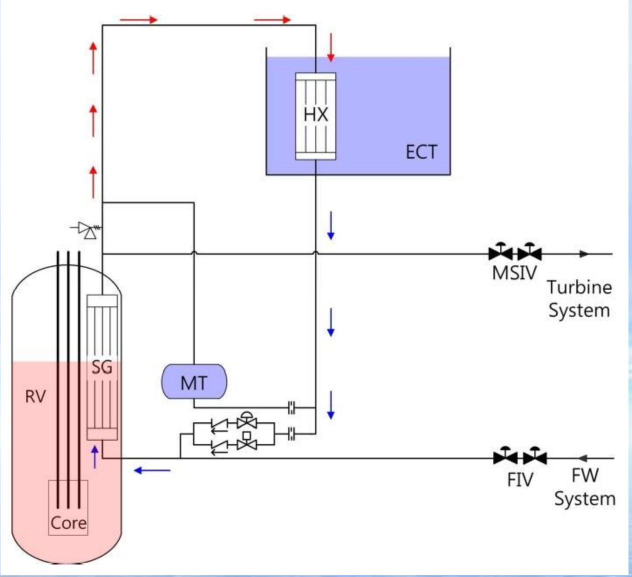
Passive Safety Systems: SMART (2/3)

- Passive Safety Injection System (PSIS)
  - 4 Core Makeup Tanks (CMTs)
  - 4 Safety Injection Tanks (SITs)
  - Pressure-Balanced lines (PBLs) : From RCP discharge to CMTs & SITs
  - Injection Lines (ILs) : To safety injection line
- Automatic Depressurization System (ADS)
  - 2-stage ADVs (ADV-1 & -2)
- Passive Residual Heat Removal System (PRHRS)
  - 4 Trains of PRHRS Heat eXchanger (PRHRS HX), Emergency Cooldown Tank (ECT) and Makeup Tank (MT)

PSIS & ADS



PRHRS

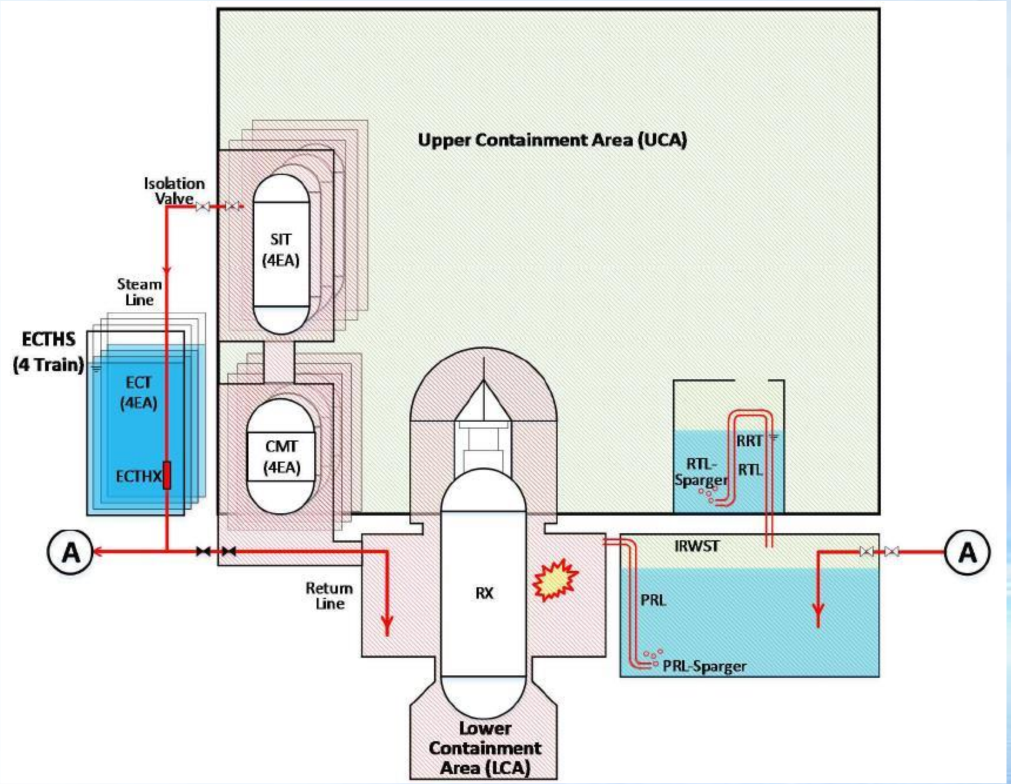


Passive Safety Systems: SMART (3/3)

- Containment Pressure and Radioactivity Suppression System (CPRSS)
  - Design to reduce LPZ (Low Population Zone)
  - Lesser radioactivity release
  - Major components
    - Lower Containment Area (LCA)
      - ✓ Encompassing RX, CMTs, SITs
    - Upper Containment Area (UCA)
      - ✓ Existing containment
    - IRWST, PRL, PRL sparger
    - RRT, RTL, RTL sparger
    - ECTHSs, ECTHXs
      - ✓ Using the PRHRS ECTs

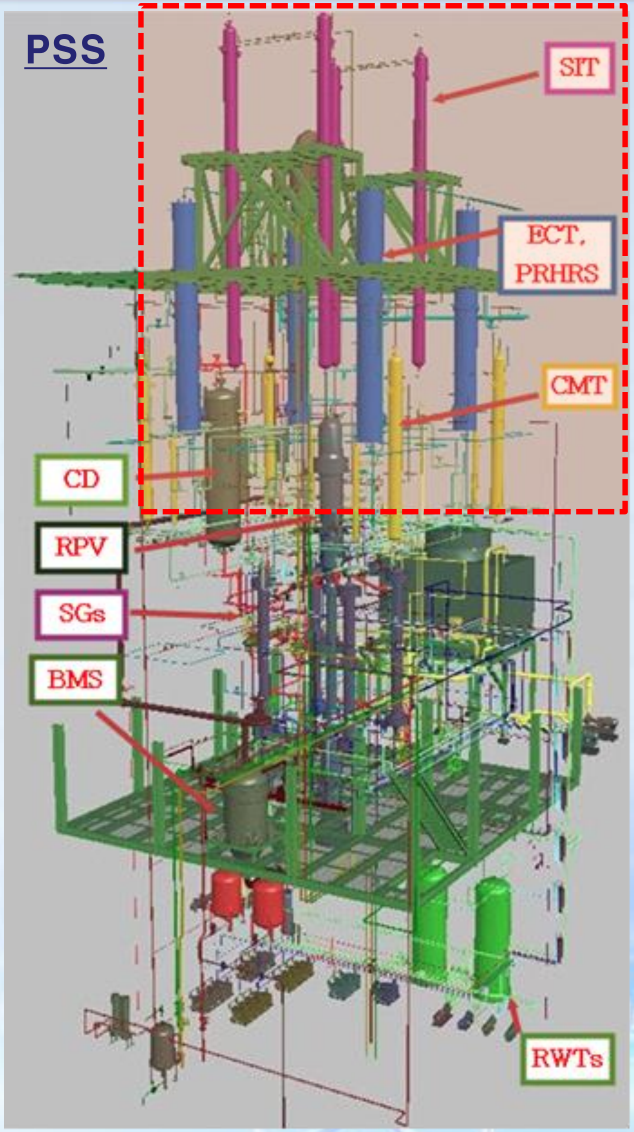
* IRWST: In-containment Refueling Water Storage Tank
* PRL: Pressure Relief Line
* RRT: Radioactive material Removal Tank
* RTL: Radioactive material Transport Line
* ECT: Emergency Cooldown Tank
* ECTHS: ECT Heat Removal System
* ECTHX: ECT Heat Exchanger

CPRSS



Validation Tests for SMART PSIS (1/7)

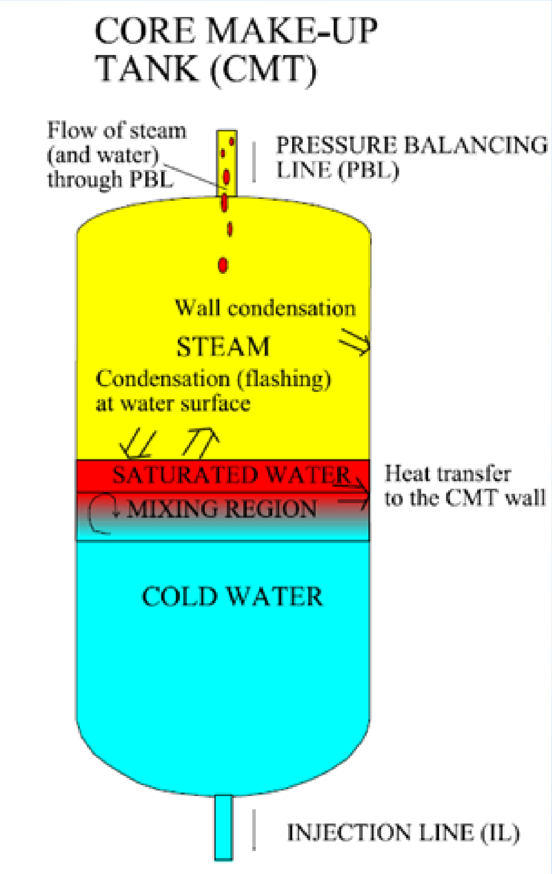
- Scaled-Down Facility for SMART PSS
  - SMART-ITL-PSS
- CMT and SIT for SMART-ITL
  - Based on volume scale methodology
  - Scale ratio of height, diameter: 1/1, 1/7
  - Scale ratio of the tank cross-section & volume : 1/49
- Test Objectives
  - To assess the performance of PSIS (CMT, SIT, ADS) together with PRHRS for SMART
  - To analyze the physical phenomena occurring inside of the tanks (CMT, SIT)
  - To provide data to assess the related models of safety analysis codes



SMART-ITL-PSS

Validation Tests for SMART PSIS (2/7)

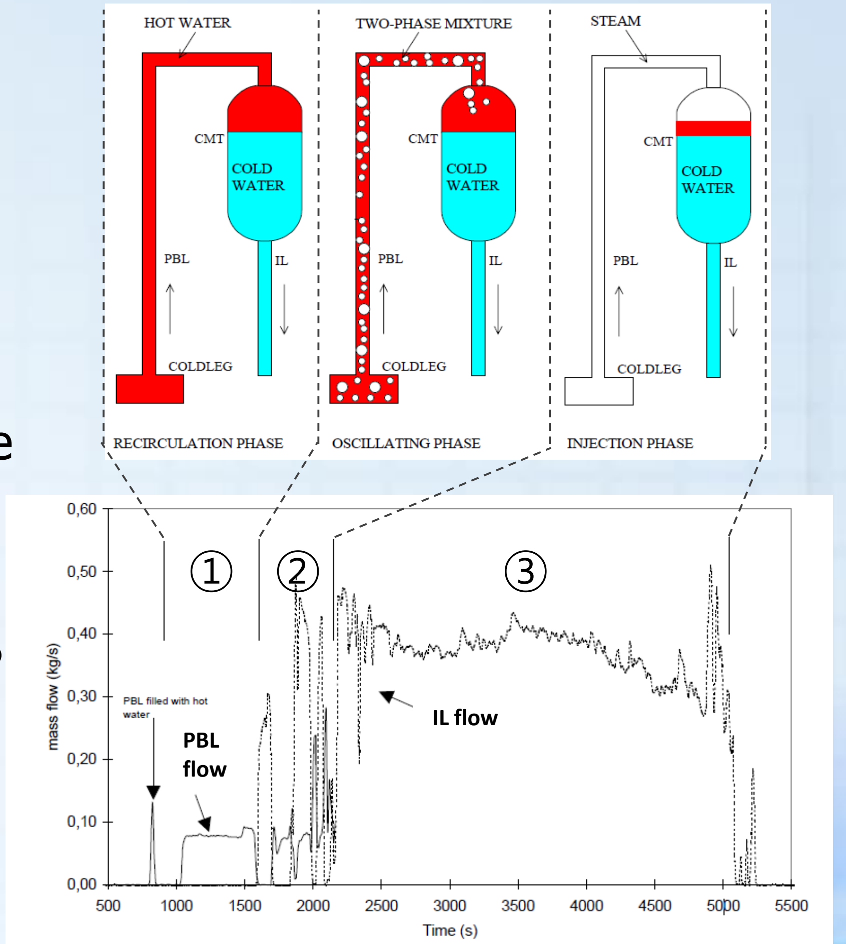
- Major Phenomena & Instrument
  - Flashing, direct contact condensation, wall condensation and injection flows are expected in CMT, SIT, PBL & IL pipes.
  - Appropriate thermocouples and flow meters have to be installed in the pipes and tanks.
- Expected Test Results & Application
  - Thermal-hydraulic performance of the PSIS
  - Performance of flow distributor (or sparger) nozzle geometry, break size and tank geometry
  - Assessment of the existing model for direct contact condensation occurring in PSIS (CMT, SIT & ADS)



Phenomena in the CMT during ECC injection

Validation Tests for SMART PSIS (3/7)

- CMT of AP600 (Tests using PACTEL)
  - Injection is delayed due to condensation.
  - With flow distributor, it functions properly.
- Operation Modes in PSIS
  - Recirculation Phase: 1-phase water (①)
    - The density difference between the PBL and the CMT creates the driving force.
  - Oscillating Phase: 2-phase flow (②)
    - When the cold leg water-level is close to the PB connection, the void is generated.
    - The density difference becomes larger.
  - Injection Phase: 1-phase steam (③)
    - Steam flows into CMT when the level near the PBL drops so much.
    - The stratified water is injected through IL.



Thermal-hydraulic Phenomena in CMT and PBL

Validation Tests for SMART PSIS (4/7)

- **SMART PSIS 1-train simulation tests using SMART-ITL**
  - SBLOCA Tests of SIS line break using SI Pump (~2014. 5.)
    - Tests using active pumps before installation of PSS
  - Differential pressure tests of PBL/IL (~2014. 6.)
    - Cold tests for Pressure Balancing Line (PBL) & Injection Line (IL)
    - Preliminary selection of orifice for CMT and SIT
  - Selection tests of Flow Distributor (~2014. 9)
    - Effects of FD existence, CMT Type & SIT / Break Size (2 & 0.4 inch)
  - CMT+SIT coupling test (~2014. 10)
    - CMT Type / Break Size / SIT Type (Pressure Balancing or Accumulator)
- **SMART PSIS 2-train validation tests (during 2015)**
- **SMART PSIS 4-train validation tests (during 2016)**
- **Technical support for SMART100 SDA (2019~present)**

Validation Tests for SMART PSIS (5/7)

❑ Test Matrix for 1-train simulation tests

Case	Break (inch)	CMT/SIT Type	Flow Distributor	Description	Test Group
S100	2	CMT #1-2	NA	No flow distributor	CMT #1-2 Tests (Half-height)
S102	2	CMT #1-2	Type B	Flow distributor (B)	
S103	2	CMT #1-2	Type A	Flow distributor (A)	
S104	2	CMT #1-2	Type C	Flow distributor (C)	
S101	2	CMT #1-1	Type A	Flow distributor (A)	CMT #1-1 Tests (Full-height)
S105	2	CMT #1-1	Type C	Flow distributor (C)	
S106	0.4	CMT #1-1	Type C	FD(C), Different size	
S107	2	SIT #1	Type C	SIT test	SIT#1 Test
S108	2	CMT #1-1, SIT #1	Type C	**Reference test**	CMT & SIT coupling test (Default: Back-pressure SIT)
S109	2	CMT #1-2, SIT #1	Type C	**Different CMT type**	
S110	0.4	CMT #1-1, SIT #1	Type C	**Different size**	
S201	2	CMT #1-1, SIT #1	Type C	**Pressurized SIT**	

Validation Tests for SMART PSIS (6/7)

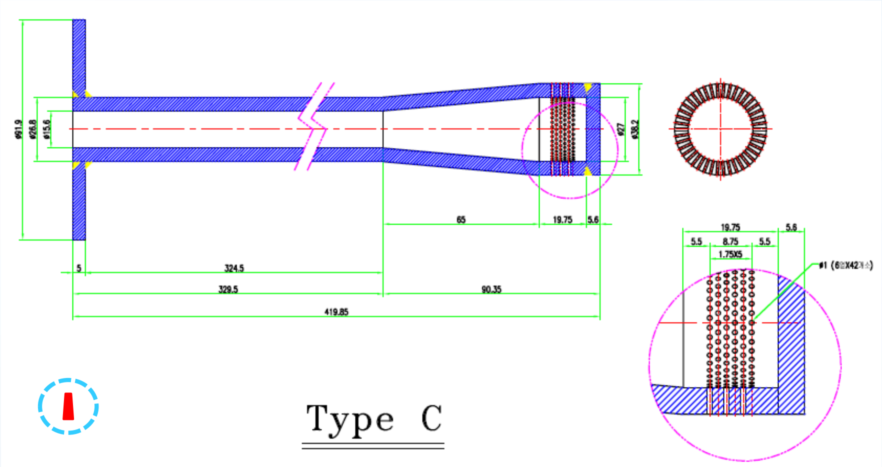
❑ Test Matrix for 4-train simulation tests including 1- & 2-trains

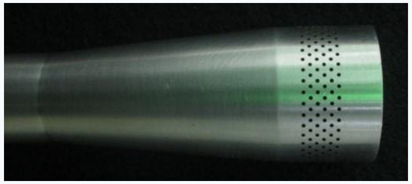
Cases (4-Train)	Break (inch)	CMT Trains	SIT Trains	Description	1-Train Test, ID	2-Train Test, ID
F101	2	#1, #2, #3	-	**CMT only**	S105	T101
F102	2	-	#1, #2, #3	**SIT only**	S107	T102
F103	**2**	#1, #2, #3	#1, #2, #3	**Reference case (SIS line break, 2 inch)**	S108	T103
F104	**0.4**	#1, #2, #3	#1, #2, #3	**Different Break size**	S110	T108
F301	2	#1, #2, #3	#1, #2, #3	**Break at PSV line**	S201	T201

Validation Tests for SMART PSIS (7/7)

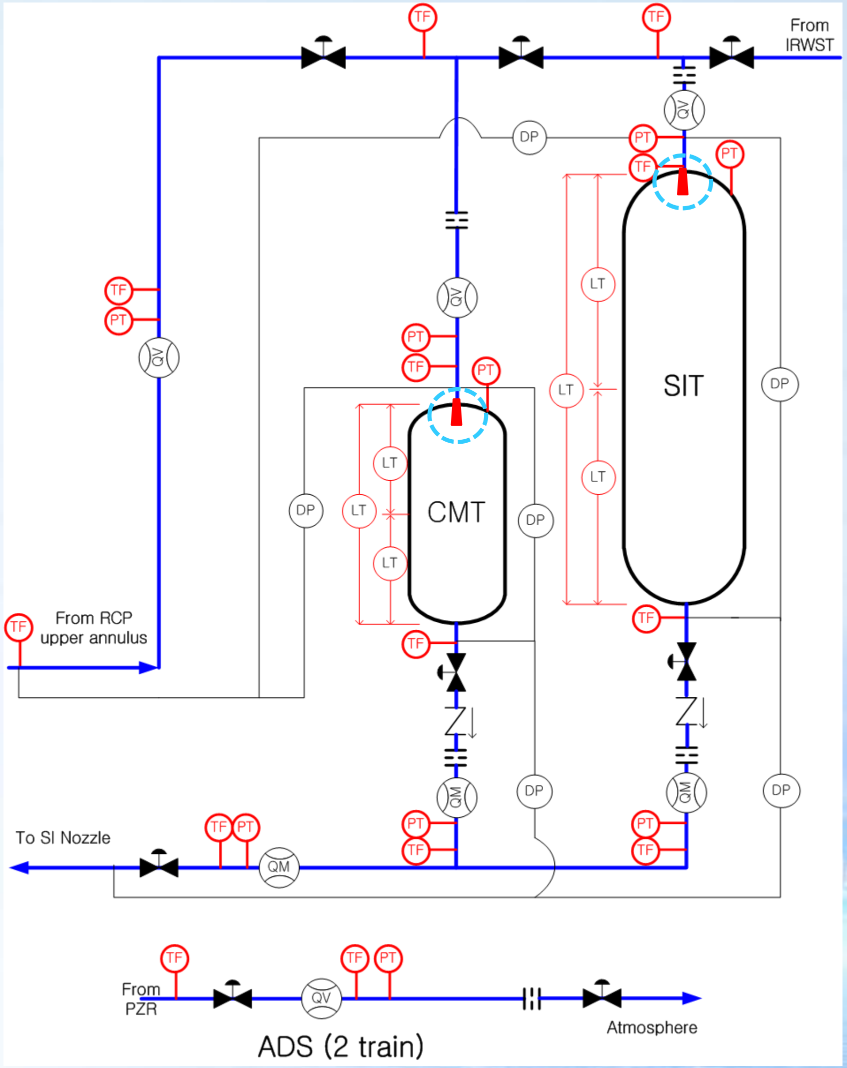
- Schematics and Flow Distributor

Flow distributor





PSIS Schematics



Major Results from 4-Train Validation Tests (1/9)

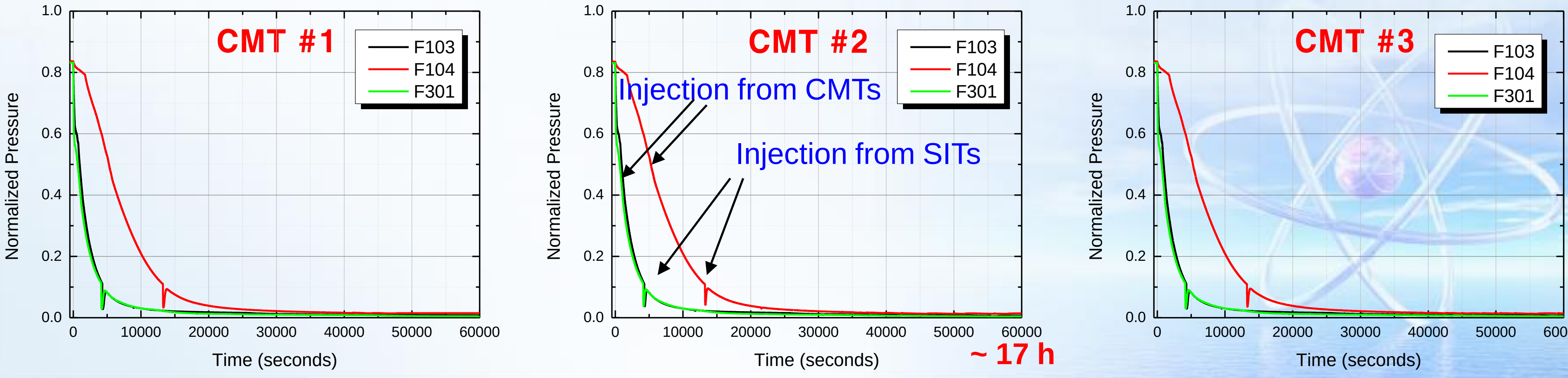
❑ Comparison of Major Sequence for the SBLOCA Tests

Group	Event	Trip Signal and Set-point	Time after break (s)			
			F 103	F 104	F 301	
Break, Trip, CMT	Break	-	0	0	0	
	LPP set-point	PZR Press = P_{LPP}	744	3,235	204	
	Reactor trip signal - Pump coastdown - CMT Act. Signal (CMTAS)	LPP+1.1 s	745	3,236	205	
	Reactor trip-curve start	LPP+1.6 s	746	3,237	206	
		LPP+4.1 s	-	-	-	
	CMT injection start	CMTAS+1.1s	747	3,238	206	
PRHRS	PRHR actuation signal	MSHP+1.1 s	-	-	-	
	PRHRS IV open	PRHRAS+5.0 s	754	3,245	214	
	FIV close, MSIV/ FW close	PRHRAS+5.0 s	755	3,245	215	
SIT	SIT injection signal (SITAS)	PZR Press = P_{SITAS}	4,282	13,231	4,127	
	SIT injection start	SITAS+1.1s	4,287	13,235	4,131	~ 1 h
ADS	ADS #1 open	CMT level < $L_{ADS\#1}$	25,569	-	24,093	~ 7 h
	ADS #2 open	SIT level < $L_{ADS\#2}$	-	-	-	
	Test stop	-	301,258	266,342	261,326	~ 73 h
			Reference	Different Break Size	Different Break Location	

Validation Tests for SMART PSIS (2/9)

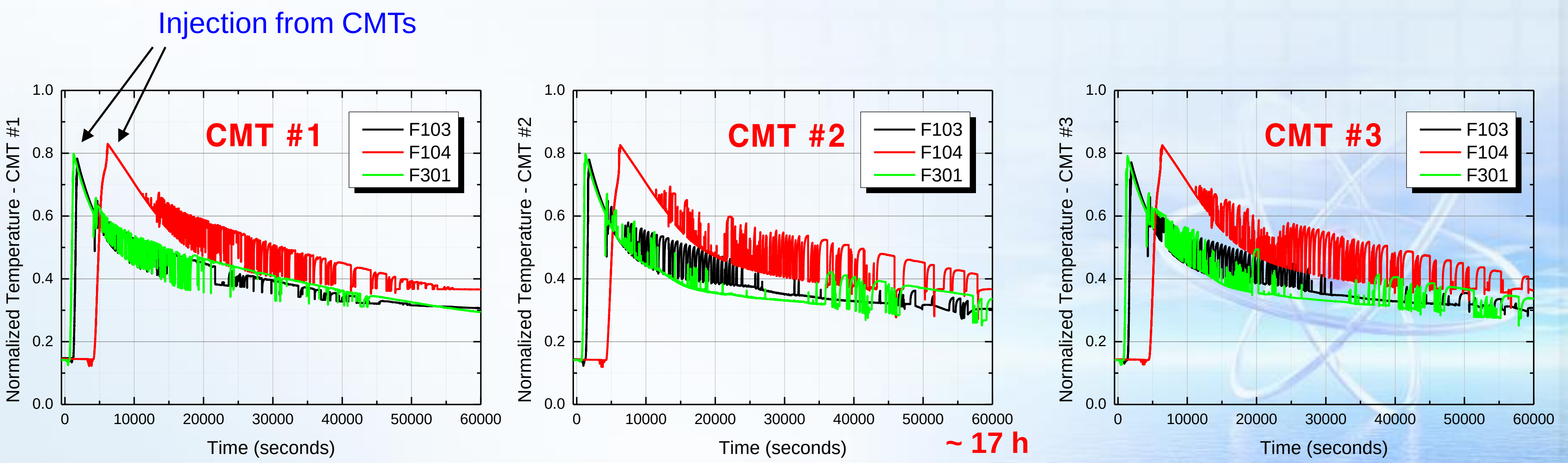
❑ Comparison of primary pressures (in CMTs)

- The primary pressures have similar trends during 2 inch break cases of F103 and F301, but it decreases very slowly during 0.4 inch break cases of F104. The pressure trend is very similar to that expected during the typical SBLOCA scenario.
- The pressure fluctuation around 4,300 seconds during the F103 test is due to the injection from SITs. The pressure trend in the F301 test behaves a little earlier than that in the F103 test since the break occurs on the PSV line.
- The pressure trend in the F104 test shows a slower transient due to its smaller break size and the SIT started to be injected around 12,000 seconds.
- The ADS #1 is actuated both in the F103 and F301 tests but not in the F104 test.



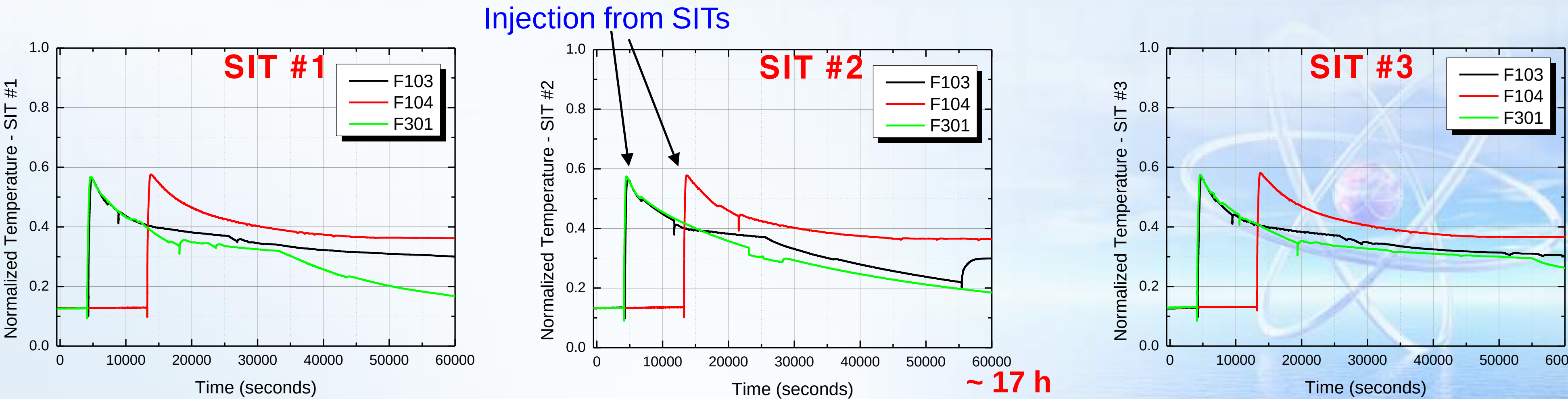
Validation Tests for SMART PSIS (3/9)

- Comparison of fluid temperatures in CMTs
  - The fluid temperatures in 3 CMTs have the similar trends during F103 and F301 after the injection is initiated from the CMTs.
  - They increase later and higher during the F104 test.



❑ Comparison of fluid temperatures in SITs

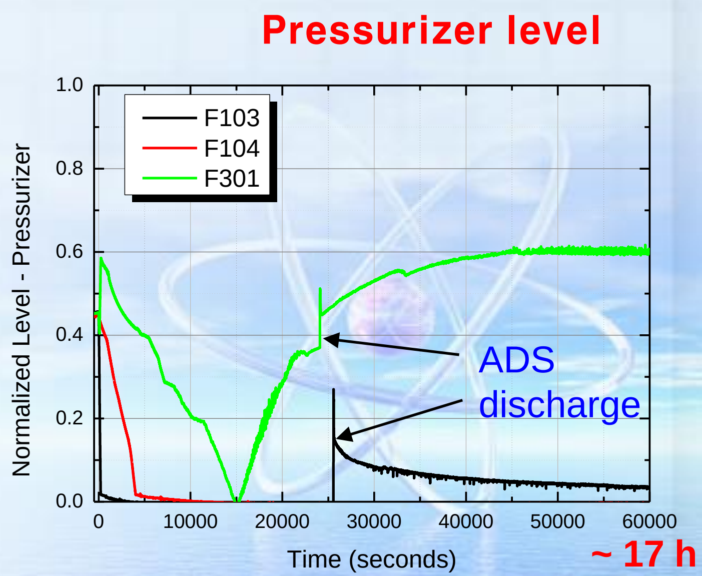
- The fluid temperatures in the SITs show different trends. After the PBL is connected to the SITs during F103, F104 and F301, <u>the temperatures increase abruptly with the SIT injection signal</u>.
- The injection time is earlier and rapider during F103 and F301 than F104. There is small difference between the F103 and F301 tests.
- The SIT fluid temperature decreases faster in F301 than in F103 after 13,000 seconds after the reactor trip. Temperature trends in CMT and SIT were also similar in three trains.



Validation Tests for SMART PSIS (5/9)

❑ Comparison of levels in Pressurizer

- PZR level decreases very rapidly as the break occurs in the F103 test.
  - At around 25,000 seconds it shows the recovery of level with the operation ADS #1 but it is estimated to be a fault signal affected by dynamic pressure caused by the ADS discharge.
  - In the F104 test, the pressurizer level is recovered around 130,000 seconds after the trip, which is not shown in this figure.
- As the PSV line is broken in the F301 test, the pressurizer level increases during the initial period and then decreases.
  - It begins to be recovered from around 15,000 seconds after the reactor trip.
  - It also shows a <u>level jump affected by dynamic pressure caused by the ADS discharge around 24,000 seconds.</u>



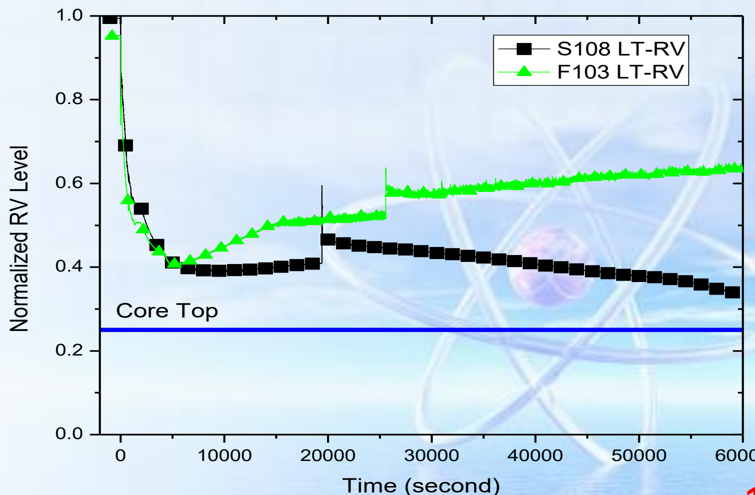
Validation Tests for SMART PSIS (6/9)

❑ Comparison of levels in RPV (F103 vs S108)

- The RV level in the F103 test is recovered during an earlier period compared with the S108 test. Furthermore, the RV water level remains much higher during the F103 test than during the S108 test during the entire test period.
  - In the S108 test, 1 trains of the PSIS are operated but the amount of injection is not enough for core recovery.
  - In the F103 test, 3 trains of the PSIS are operated independently and can increase the RV inventory the same amount as the addition of each train.

- It seems that 2 train of PSIS is enough for core recovery.
  - Single failure assumption is applied and 3 among 4 trains of PSIS are used to make up core inventory.
  - There is sufficient safety margin, which is estimated to be 50%.

RPV Levels (S108, F103)

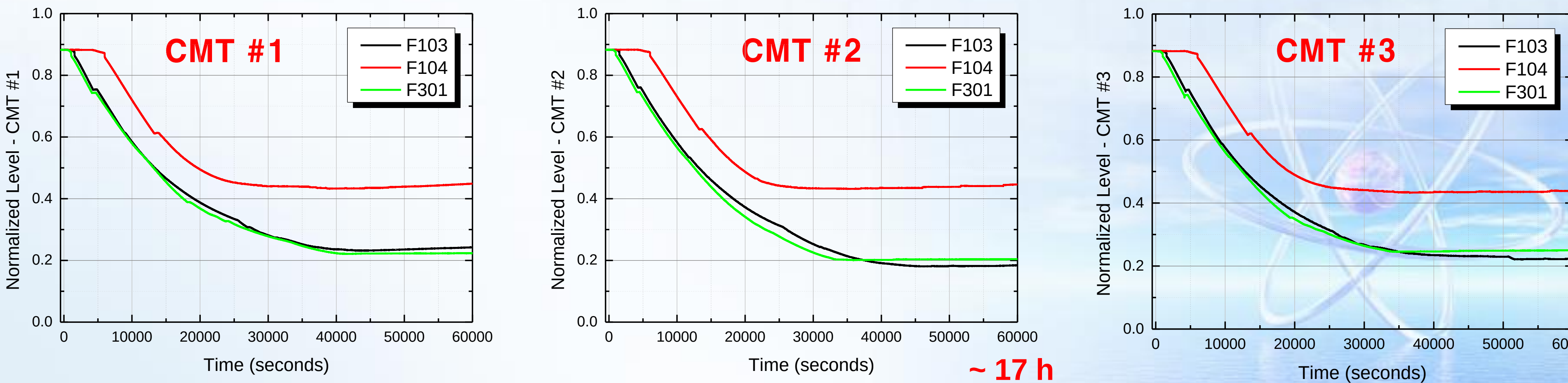


~ 17 h

Validation Tests for SMART PSIS (7/9)

❑ Comparison of levels in CMTs

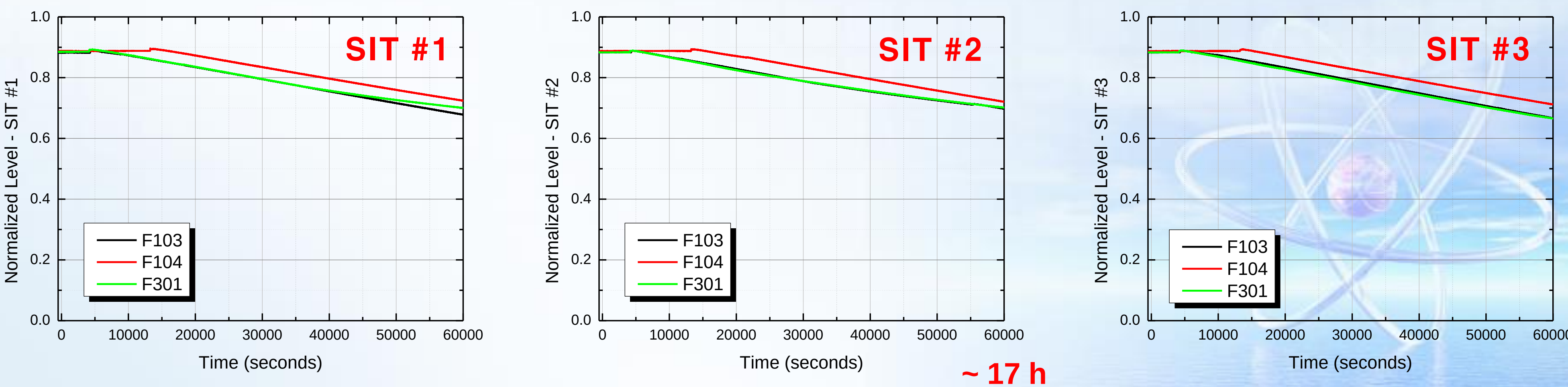
- The CMT level decreases as the CMT inventory is injected into the reactor pressure vessel.
  - The trends in the F103 and F301 tests are almost the same but the trend in the F104 test shows a delayed operation.
- In particular, the CMT levels are kept at certain levels without being emptied.
  - The final level is higher in F104 than those in F103 and F301.



Validation Tests for SMART PSIS (8/9)

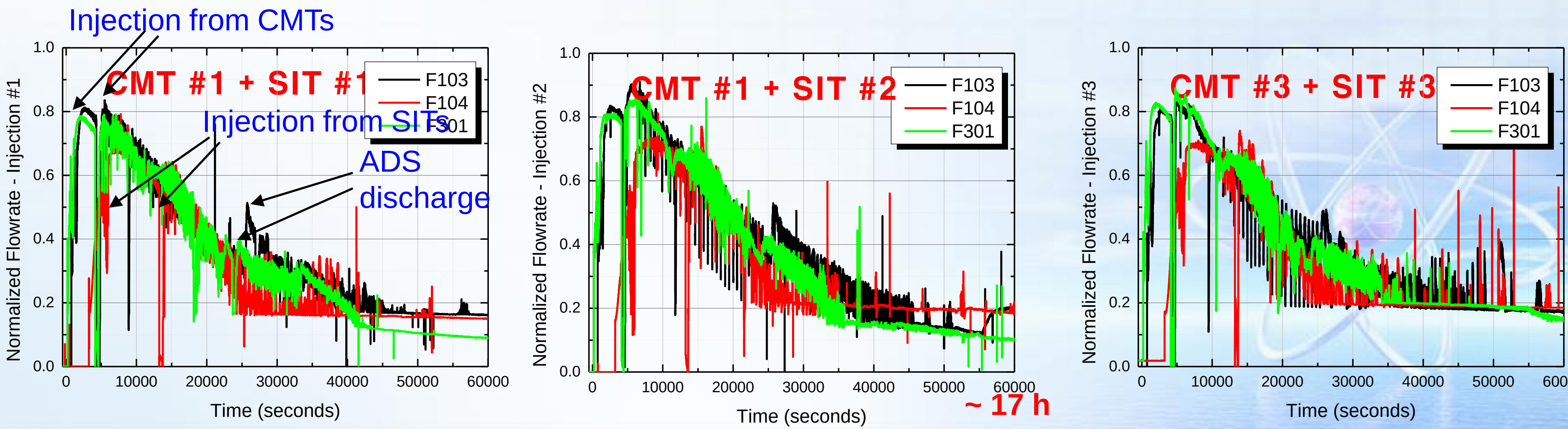
❑ Comparison of levels in SITs

- The SIT level decreases more slowly with the 0.4 inch break (F104) than with the 2 inch break (F103 & F301).
- Level trends in CMT and SIT were also similar in three trains.



❑ Comparison of injection flowrates

- The injected flow rates have similar trends during the 2 inch break cases of F103 and F301, but the injection is delayed during the F104 test.
  - The fluctuations in the F103, F301, F104 tests at around 4,300 s, 4,100 s, and 13,200 s, respectively, are due to the start of SIT injection.
- During the F103 and F301 tests, there was an abrupt increase in the injection flow rate at around 25,000 seconds with the actuation of ADS #1.
- Flowrates in injection line were also similar in three trains but the fluctuation time were different one another.



Summary

- A variety of thermal-hydraulic tests was performed to validate the performance of SMARS PSIS with the SMART-ITL facility.
  - SMART-ITL-PSS (1/1-height, 1/49-volume scale, full P & T conditions)
  - 1-, 2- and 4-train PSIS validation tests had been performed.
- Major results from SMART PSIS validation tests were summarized.
  - They included three kinds of SBLOCA tests, which are 2 inch SIS line break (F103), 0.4 inch SIS line break (F104) and 2 inch PSV line break (F301), using 4 trains of PSIS and PRHRS.
  - From the test results, it was estimated that the SMART PSIS had sufficient cooling capability to deal with the SBLOCA scenario of the SMART design together with PRHRS.
    - 2 trains of PSIS are enough for core recovery and it has about 50% margin.
  - During the SBLOCA scenario, the water inventory was well stratified thermally both in the CMTs and SITs, and the safety injection water from CMTs and SITs was injected efficiently into the RPV from the initial period, and cools down the RCS properly throughout the whole accident period.
- Test data was used to support SDA licensing for SMART100. (PSIS: SSAR-6.3)

Thank you for your attention!

Special Component Model for Safety Analysis Code

- ❑ Special component model = Special thermal-hydraulic component + Special heat structure model

- ❑ Special thermal-hydraulic component: Realistic calculation of the interfacial heat transfer
- ❑ Special heat structure model: Analytical calculation on the heat transfer from the hot steam to the cold tank wall

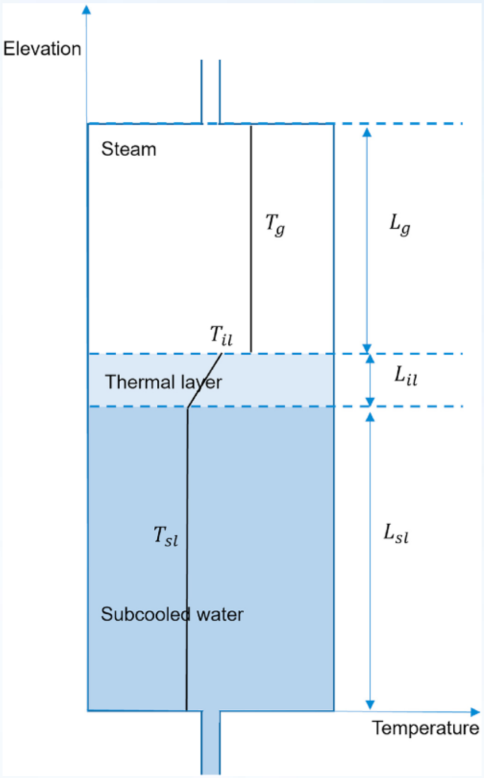


Fig. 13. Temperature distribution in the CMT and SIT.

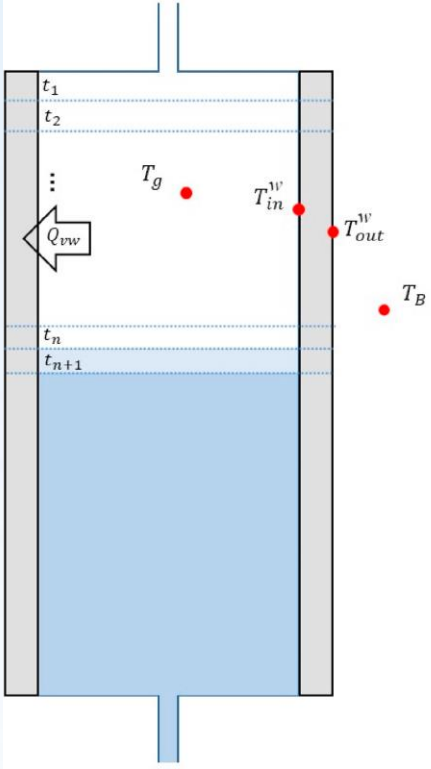


Fig. 14. Heat structure model.

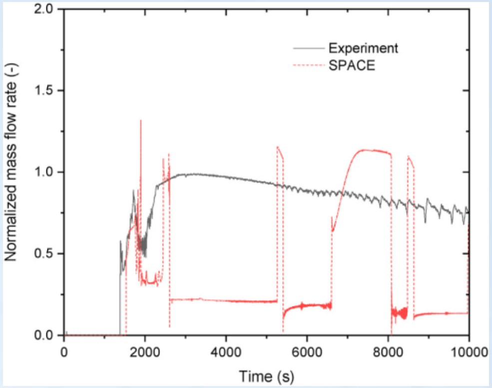


Fig. 7. CMT #1 injection flow rate of the F101 test (normalized).

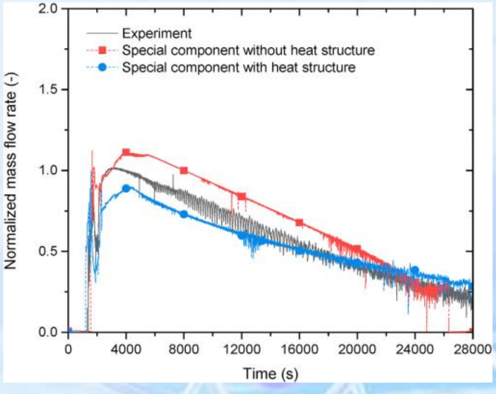


Fig. 16. Measured vs. calculated CMT #1 injection flow rate: F101 test.

- ❑ The model is assessed using the SMART-ITL PSIS test data. (F101)

Min-gi Kim, et al., Development of a special thermal-hydraulic component model for the core makeup tank, NET, 54, 1890-1901, 2022.

SMART100 RAI for PSIS (SSAR-6.3)

❑ SMART100 인허가 관련 질의 응답

- **1차 질의**(2021-10-25) 30**건 및 답변**(2022-03-22): **I-01~30 (R1, 30건)**
- **2차 질의**(2022-01-03) 20**건 및 답변**(2022-02-02): I-01~30 (R2, 20**건**)
- **3차 질의**(2022-03-04) 14**건 및 답변**(2022-04-03): I-08,09,26 (R2, 3**건**) & **II-01~11 (R1, 11건)**
- **3-2차 질의**(2022-04-01) 5**건 및 답변**(2022-05-01): I-07, 21, 23, 24, 29 (R3, 5**건**)
- **3-3차 질의**(2022-05-09) 4**건 및 답변**(2022-06-08): I-01, 18 (R3, 2**건**) II-03, 06 (R2, 2**건**)
- **질의 제목 (예)**

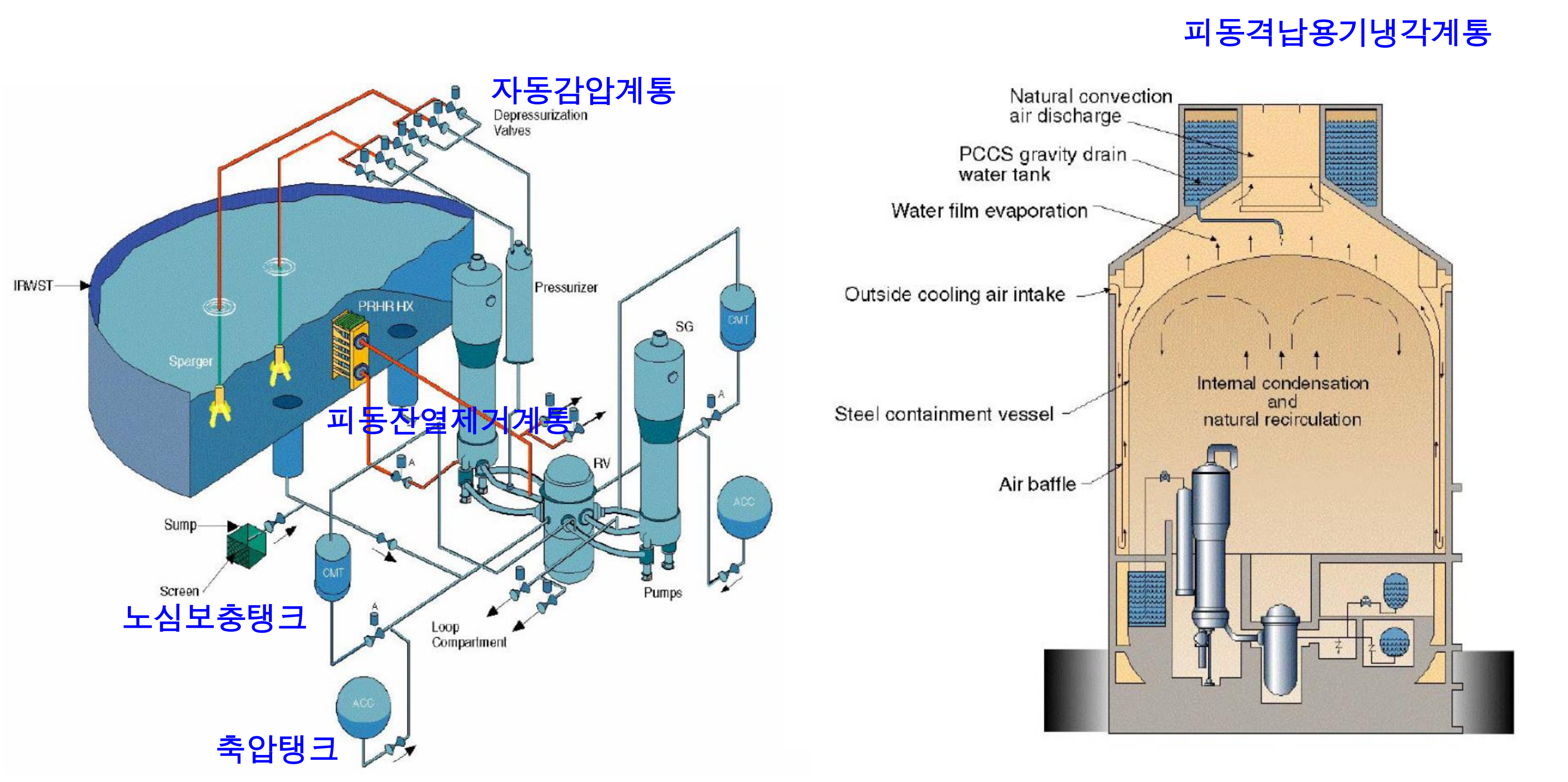
관리번호	질의 제목
SSAR-6.3-Ⅰ-07-3	격리밸브
SSAR-6.3-Ⅰ-21-3	피동안전주입계통의 공유
SSAR-6.3-Ⅰ-23-3	안전주입계통 밸브의 계측제어설비
SSAR-6.3-Ⅰ-24-3	가동중시험
SSAR-6.3-Ⅰ-29-3	TMI 후속조치

관리번호	질의 제목
SSAR-6.3-Ⅰ-01-3	안전주입탱크 재충수계통의 격납건물 외부 누설
SSAR-6.3-Ⅰ-18-3	장기냉각 계획의 적절성
SSAR-6.3-Ⅱ-03-2	노심보충탱크 설계
SSAR-6.3-Ⅱ-06-2	노심보충탱크 가변설정치

Passive Safety Systems: AP1000

- PRHRS (Passive Residual Heat Removal System), PCCS (Passive Containment Cooling System), CMT (Core Makeup Tank), ACC (Accumulator), ADS (Automatic Depressurization System)

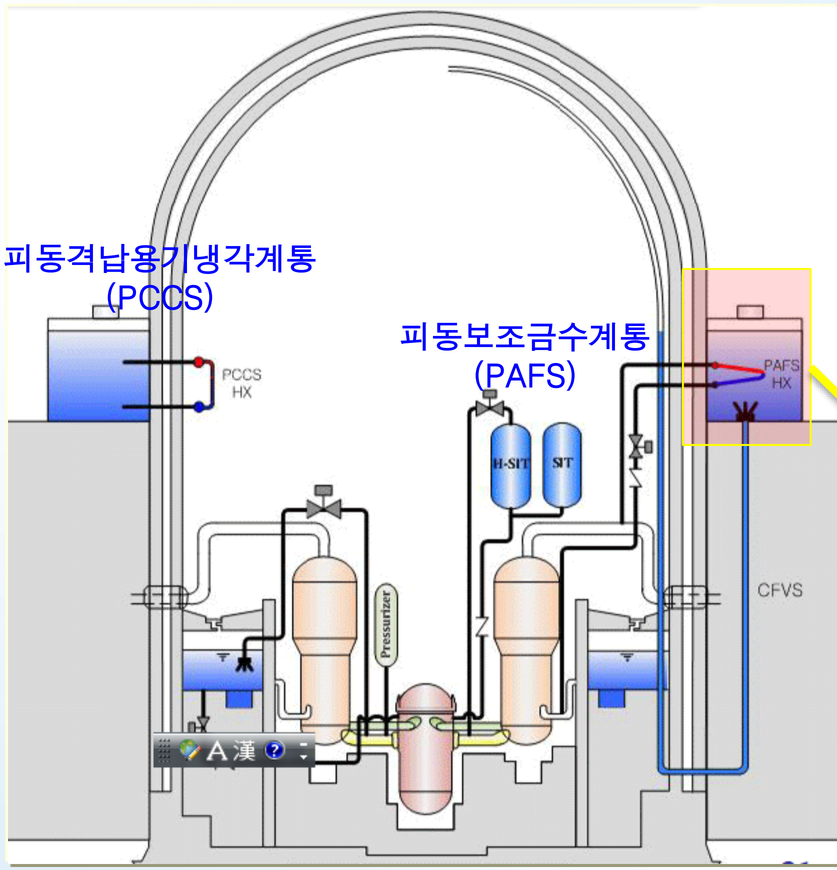
AP1000 PASSIVE SAFEY SYSTEM



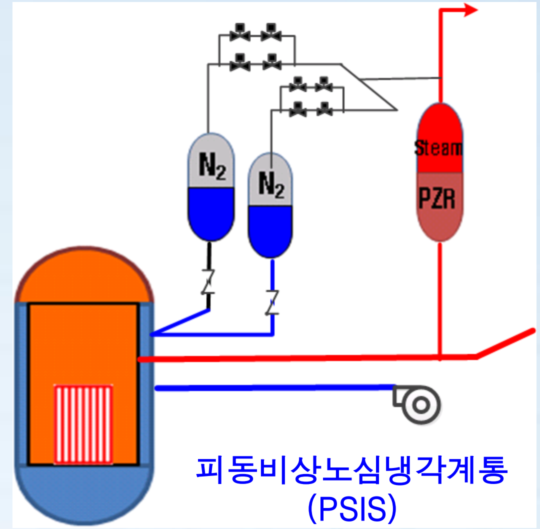
PASSIVE CONTAINMENT COOLING SYSTEM

Passive Safety Systems: APR+, IPOWER

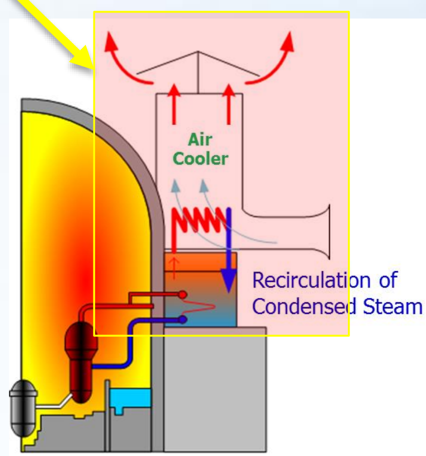
- PAFS (Passive Auxiliary Feedwater System), PCCS (Passive Containment Cooling System)



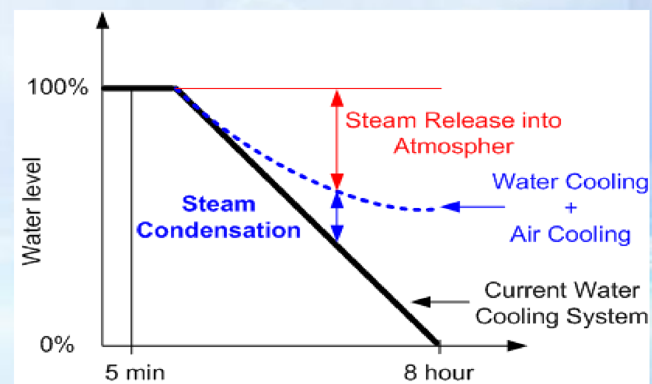
- HEMS/PECCS (Passive Safety Injection System)



- Air-Water Combined Cooler (for SBO)



(a) Air-Water Combined Cooler

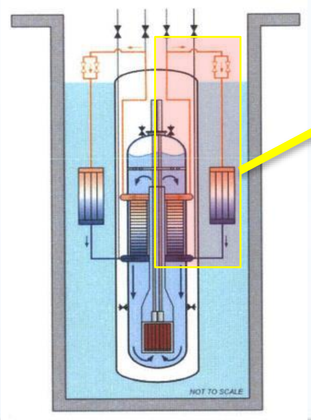


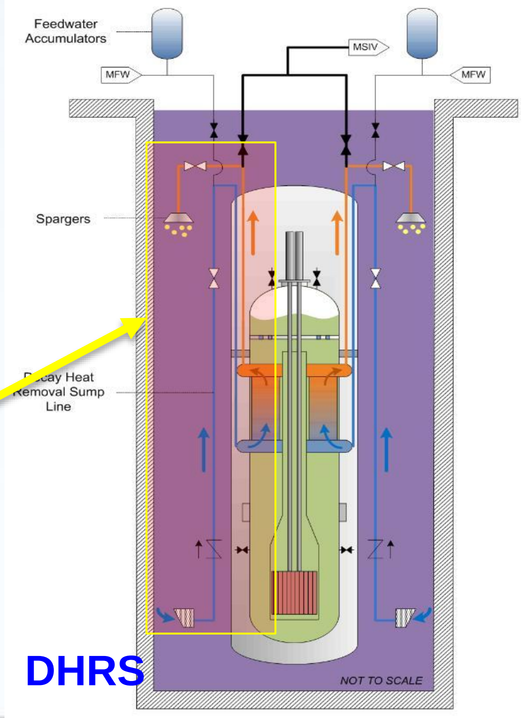
(b) Extension of Cooling Time

Passive Safety Systems: NuScale

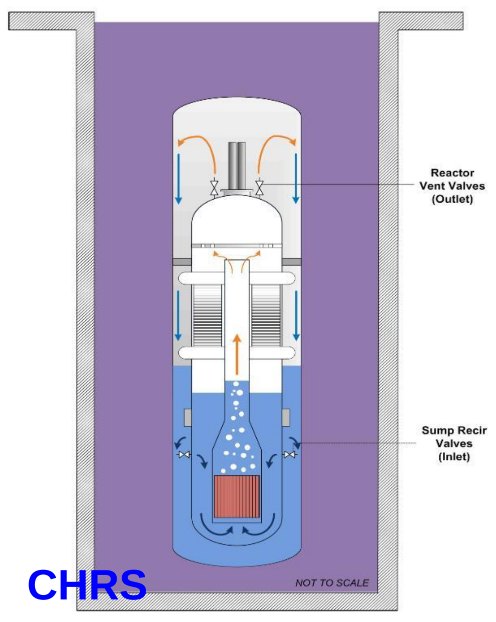
- DHRS (Decay Heat Removal Using Steam Generators), CHRS (Decay Heat Removal Using Containment), inherent PSIS & PCCS (no dedicated system)
  - High-pressure containment vessel (CNV) is in vacuum state and submerged in a reactor pool.
  - Decay heat is removed to the pool by decay heat removal through SG (DHRHX → NC & Sparger) or condensation on the inside wall of the containment.

DHRS
(2014 ver.)





DHRS



CHRS