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Development of Phenomena Identification and Ranking Table (PIRT) of Thermal-Hydraulic Phenomena for SMART100-DECs to Implement T-H Model and Validation Items in SPACE

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1. Introduction

The Phenomena Identification and Ranking Table (PIRT) of Thermal –Hydraulic (T-H) phenomena is used to identify the key phenomena associated with the intended application, then rank the relative importance and current state of knowledge for each identified phenomenon by the experts in the related field. This ranking provides the guidance of code development and improvement for the specific simulation of the plant behaviors.

The Safety and Performance Analysis CodE for nuclear power plants (SPACE) has been developed for the safety analysis of operating PWRs and the design of advanced water reactors. The SPACE adopts advanced physical modeling of two-phase flows, mainly two-fluid three-field models that consists of gas, continuous liquid, and droplet fields. Based on that the Nuclear Safety and Security Commission (NSSC) approved the use of the SPACE for licensing applications of Korean PWRs in 2017. In addition, the SPACE has been improved continuously to extend its application for the Design Extension Conditions (DECs).

SMART100 is System Integrated Modular Advanced Reactor with 100 MWe and fully Passive Safety Systems (PSSs). The design of SMART100 was upgraded from the standard design of SMART and developed by Korean Atomic Energy Institute (KAERI). Unlike loop-type commercial reactors, the SMART100 plan adopts a helically coiled steam generator, and internal pressurizer inside the Reactor Pressure Vessel (RPV). The main objectives of this paper are to develop and generate PIRT of important T-H phenomena for expected DECs of SMART100, and to implement T-H models and validation items in SPACE for the reference reactor and scenarios.

2. Methodology

The experts who have extensive experience and knowledge in the design and safety analysis of nuclear power reactors and in thermal-hydraulics develop the SMART100-DEC PIRT. There are seven steps that have been taken in consideration for this development due to PIRT report for multiple failure accidents, Korean Next Generation Reactor (KNGR) and SMART-P: 1) Review, verify, and identify the plant design data and characteristics. 2) Define important high-level systems and components. 3) Derive key accident and scenarios. 4) Define the primary evaluation criteria. 5) Partition scenario into convenient time phases. 6) Identify plausible phenomena/processes by phase and component, and 7) Rank importance and knowledge levels. [1] [2]

Step 1 (Review, Verify, and Identify the Plant Design Data and Characteristics)

The basic design of SMART100 is to provide core-cooling capability during all Design-Basis-Accidents (DBAs) without additional operational actions for at least 72 hours. It has new-featured components and systems such as four mechanically independent trains for the Passive Safety Injection System (PSIS), and Passive Residual Heat Removal System (PRHRS), and two independent trains for Automatic Depressurization System (ADS), The PSIS provides heat removal from the core without AC power or operator action and supplies borated water into the RCS by gravity to prevent core uncover. The PRHRS connected to the secondary system and removes the RCS heat by natural circulation. The ADS is connected to the upper part of the reactor closure head and rapidly depressurizes the RCS to activate SIT earlier for the LOCA. In addition, it can be manually operated for a total loss of secondary heat removal (TLOSHR) accident for feed and bleed function with PSIS. [3]

Step 2 (Define Important High-Level Systems and Components)

It is useful to partition SMART100 into high-level systems, subsystems, and components to identify the influence on the main phenomena/processes. Table I summarizes the high-level systems, subsystems, and components that used in the PIRT development of SMART100-DECs.

Table I: High-Level Systems, Subsystems, and Components of SMART100.

System	Subsystem	Component
Fuel	Fuel assembly	Pellet
		Gap
		Clad
RCS	RPV	Upper plenum (UP)
		Flow mixing header assembly (FMHA)
		Lower plenum (LP)
		Break
	Loop	(UP,FMHA,LP,SG_Primary)
	Core	Core
	RCP	RCP
	PZR	Vessel
		Surge space
		Heater
		PZR safety valve (PSV)
	SG	Primary (shell) side
		Secondary (tube) side
		Break
	Main steam line	Break
PRHRS	Heat changer	Steam line
		Tube
		Feed line
	ECT	Emergency core tank (ECT)
	Makeup Tank	Makeup Tank
	Loop	(Steam line-tube-feed line-pipe)
PSIS	CMT	Core makeup tank (CMT)
	SIT	Safety injection tank (SIT)
	PBL	Pressure balance line (PBL)
	SIL	Safety injection line (SIL)
	IRWST	In-vessel water storage tank
	Loop	(PBL-Tank-SIL)
ADS	ADS	Depressurization valve
		Orifice
		Pipe
CVCS	CVCS	Chemical & volume control system
CCWS	CCWS	Component cooling water system
Containment	LCA	Lower containment area (LCA)

Step 3 (Derive Key Accident and Scenarios)

This step is required to identify the DEC scenarios for SMART100. In consistence with the DEC scenarios proposed by IAEA, WENRA, EUR and Korea regulatory body in the conventional PWRs, thirteen DECs scenarios are initially considered. The major cause of each DEC scenario is identified in a loop-type PWR with their corresponding safety requirements. After that the compatibility of each accident of SMART100-DECs was evaluated and each proposed scenarios for SMART100-DECs was discussed by expert panel. Finally, the most appropriate five scenarios for SMART100-DECs were selected for PIRT development. [4]

1. Anticipated Transient Without Reactor Scram.
2. Multiple Steam Generator Tube Rupture.
3. Total Loss of Feed Water.
4. Loss of Safety Injection or Recirculation Concurrent with a Small-break Loss of Coolant.
5. Main Steam Line Break Concurrent with Steam Generator Tube Ruptures.

Step 4 (Define the Primary Evaluation Criteria)

To judge the relative importance of phenomena/process in key accident scenarios for SMART100-DECs, Figure of Merits (FoMs) as primary evaluation criteria will be used based on regulatory safety requirements such as Peak Clad Temperature (PCT), RCS pressure, core mixture level, restriction in radioactive discharge and etc. Table II shows the FoMs for each key accident of SMART100-DECs, which are determined by expert panel after reviewing the regulatory requirements and all selected scenarios based on the main phenomena/process.

Table II: FoMs for Selected Scenarios of SMART100-DECs.

No.	Accident	FoMs
1	ATWS	RCS pressure
2	MSGTR	Radioactive discharge
3	TLOFW	Core mixture level
4	Loss of safety injection/recirculation concurrent with SBLOCA	Core mixture level, PCT
5	MSLB+SGTR	Radioactive discharge

Step 5 (Partition Scenario into Convenient Time Phases)

After reviewing the five key scenarios of SMART100-DECs by expert panel, the scenarios have been divided into time phases according to the dominant T-H phenomena/process. This is because the relative importance of T-H phenomena is time dependent as the accident progresses. The partitioned phases of each accident scenarios are summarized in Table III.

Table III: Convenient Time Phases for Selected Scenarios of SMART100-DECs.

No.	Phase	Phase Description
1	I	RCS pressurization due to energy imbalance (initiated by loss of normal feedwater)
	II	RCS depressurization after opening of PSV
2	I	RCS depressurization by MSGTR
	II	Affected SG isolation and RCS pressurization
	III	PRHRS heat removal
3	I	RCS heat up & pressurization due to loss of heat sink
	II	Bleed and feed (ADS manual open)
4	I	Blowdown (2 in break)
	II	Natural circulation (Actuation of PRHRS)
	III	RCS depressurization & boil-off (ADS manual open)
	IV	Core makeup and recovery (SIT injection)
5	I	Steam line break dominant (before closure of MSIVs)
	II	Steam generator tube rupture dominant (after closure of MSIVs)

Step 6 (Identify Plausible Phenomena/Processes by Phase and Component)

In step 6, the SMART100-DEC key accidents were divided into phases according to important phenomena/processes. Experts who have extensive experience and knowledge in the design and safety analysis of nuclear power reactors and in thermal-hydraulics already discussed all the anticipated phenomena and processes for each scenario. These phenomena/processes will be listed in Table VI at the appendix part of this paper.

Step 7 (Rank importance and Knowledge Levels)

Last step is to rank the importance level and knowledge level of each phenomenon/process in the key accidents for SMART100-DECs. The ranking of a phenomenon/process regarding the relative importance to the FoMs is to use a scale of low, medium or high as shown in Table IV. In addition, Table V lists the scales used for the ranking for the knowledge level in this PIRT development.

Table IV: Ranking Scale of Relative Importance of PIRT

Rank	Description
High	Phenomenon has dominant impact on the FoMs
	Phenomenon should be explicitly and accurately modeled
	Uncertainty should be individually determined and then combined statistically with other uncertainty sources
Middle	Phenomenon has moderate influence on the FoMs.
	Phenomenon should be well modeled; accuracy maybe somewhat compromised
Low	Phenomenon has small effect on the FoMs.
	Phenomena should be represented in the code, but almost any model will be sufficient.
	Combined uncertainty of phenomena may be determined in a bounding fashion or maybe eliminated when justified.

Table V: Ranking Scale of Knowledge Level

Rank	Description
High	Fully known with small uncertainty
Middle	Partially known with high uncertainty
Low	Very limited knowledge with very high uncertainty

3. Results and Discussion

3.1 T-H Model and Validation Items in SPACE

This PIRT was developed through the discussions of the expert panels participated in the PIRT meeting to reach the common understanding and conclusion for SMART100-DECs. Based on these results, we can derive and summarize the improvement items for T-H model and validation items of the SPACE for reference reactor and accidents scenarios as shown below:

1. Improvement in PSIS tanks components models:

Water inventory of primary side is maintained by CMT or SIT injection flow. The injection flow of CMT or SIT is determined by hydraulic condition in the tank. Thus, the estimation of thermal-hydraulic condition on the CMT or SIT is important. Therefore, the validation of component model for the CMT/SIT of SMART100 is required. Existing PIPE component can be used to model SIT and CMT using multiple volumes. A new single volume tank model with special treatment of interaction between steam and subcooled water may improve numerical stability and reduce flow and pressure oscillation.

2. Validation of boron transport model:

Boron reactivity is important in long term shutdown reactivity. The boron from CMT and SIT reaches the core by boron transport. The SPACE code has models to calculate boron transport and was review in terms of governing equation and discretization scheme. Further review of boron transport using code to code comparison with RELAP5 may be carried out.

3. Component model for helically coiled tubes and break of the SG:

SMART100 adopts helically coiled tubes inside of SG built in the reactor vessel. In the scenario of the MSGTR accident, residual and decay heat from the core are mainly removed through the SGs by heat transfer or break flow. Since the estimation of heat transfer at intact tubes and break flow at ruptured tubes has significant impact in this analysis, the proper component model for helically coiled tubes which has more complex geometry than the SG tubes of conventional PWR is needed.

4. Validation of the component model for the PRHRS:

Residual and decay heat transferred by helically coiled tubes of SG are finally removed by PRHRS. PRHRS consists of heat exchanger for heat transfer between secondary side and ECT, and ECT as a heat sink. Since ECT water level has an effects on the heat transfer capability of PRHRS, estimation of ECT water level is important. Thus, the validation of component model for the PRHRS of SMART100 is required.

5. Addition to Decay Heat Model:

SPACE code supports the four decay heat standards such as ANS-5.1-1973, 1979, 1994, and 2005 at present. Decay heat standard was revised in 2014 and this is not included in the decay heat models of SPACE. Decay heat model based on ANS-5.1-2014 is expected to be added to SPACE to calculate the decay power more precisely.

3.2 PIRT of importance T-H phenomena for expected DECs of SMART100

The results of PIRT development of importance ranking for the selected key accidents were summarized in Table VI at the appendix part of this paper. In addition, this PIRT can be used to improve and evaluate the capability of the SPACE for the SMART100-DECs.

4. Conclusion

Firstly, The PIRT for SMART100-DECs was developed and generated to identify the T-H phenomena expected during the transients and accident conditions of key scenarios. Secondly, T-H models and validation items for reference reactor and accidents scenarios have been derived to be implemented in SPACE. Finally, this work have been done by experts from seven different entities (K.A.CARE, KAERI, FNC, KEPCO NF, KEPCO ENC, PNU and KHNP) who have extensive experience and knowledge in the design and safety analysis of nuclear power reactors and in Thermal-hydraulics.

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REFERENCES

[1] Gary E. Wilson and Brent E. Boyack, 1998, The role of the PIRT process in experiments, code development and code applications associated with reactor safety analysis, Nuclear Engineering and Design 186 pp.23-27.

[2] KHNP et al., 2016, PIRT report for multiple failure accident, 2016-50003339-전-0817TM.

[3] KHNP et al., 2019, SMART100 Standard Safety Analysis Report.

[4] KAERI et al., 2020, Selection of SMART-DEC accidents for evaluating the capability of the SPACE, JRDC-TR-SP-20-09.

APPENDIX

Table VI: The Results of PIRT Development of Importance Ranking for SMART-DECs

System	Process/Phenomena	SMART100 DECs and Phases												
		ATWS		MSGTR			TLOWF		SBLOCA + Loss of SI				MSLB + SGTR	
		I	II	I	II	III	I	II	I	II	III	IV	I	II
Fuel	Fission power	H	H	H	L	L	H		L	L	L	L		
	Decay power	L	L	L	H	H	H	H	M	H	H	M	M	H
	Reactivity feedback (MTC)	H	H	M	L	L	L		L	L	L	L	H	M
	Reactivity feedback (FTC)	M	L	M	L	L			L	L	L	L	M	L
	Reactivity feedback (Boron)	L	H										M	M
	Shutdown worth								L	L	L	L	H	H
	Local power peaking								L	H	L	L		
	Gap conductance								L	M	L	L		
	Cladding deformation								L	M	L	L		
RCS	Discharge (Critical) flow (break at RPV)								H	H	H	H		
	Natural circulation	L	L				L	L	L	L	M	L		
	Boron transport	L	H											
	Wall heat transfer (covered)	L	L	H	L	L	L	L	L	L	L	L	H	L
	Wall heat transfer (Uncovered core)	L	L				L	H	L	H	M	L		
	Asymmetric power distribution								L	L	L	L	M	L
	Asymmetric flow distribution								L	M	M	L	L	L
	Interfacial friction		L				L	M						
	flow resistance			L	L	M			L	L	L	L		
	Pump performance (single/two-phase)	L	L	M	M	L	L	L	M	L	L	L	M	L
	Coast down of RCP					L	L	L	M	L	L	L		L
	Flashing			M	L	L			L	L	L	L		
	Level swelling	H	H				H	M	L	L	L	L	M	L
	CCFL (surge space)							M	L	L	L	L		
	Discharge (Critical) flow (at PSV)		H				H		L	L	L	L		
	Heat transfer to secondary side at SG	L	L	H	H	H	L	L	L	M	M	L		
	Direct condensation at SG primary side						L	M	L	L	L	L		
	Water mixture level change at SG	L	L	L	L	L	L	M	L	L	L	L		
	Flow resistance at SG (primary side)			L	L	M			L	L	L	L		
	Wall heat transfer at SG (secondary side)	L	L	H	H	H	L	L	L	M	M	L	H	L
	Flashing at SG (secondary side)								L	L	L	L	M	L
	Discharge (Critical) flow at SG break			H	H	L							H	L
	Discharge (Critical) flow at MSL break												H	
PRHRS	Hx steam line flow resistance				M	M			L	L	L	L		
	Hx tube wall heat transfer (condensation)	M	H						L	M	M	L	H	M
	Hx tube flow resistance				M	M			L	L	L	L		
	Hx feed line flow resistance				M	M								
	ECT pool circulation (3D effect)								L	M	M	M		
	ECT heat transfer (convective/ boiling)	L	M		L	L			L	M	L/M	L/M	L	L
	Loop natural circulation	M	H						L	M	M	L	H	M
PSIS	CMT Injection flow (mixture level change)	L	L				H	H	L	L	L	L	L	M
	CMT Boron injection	L	H						L	L	L	L	M	M
	CMT Direct condensation						L	M	L	L	L	L		
	CMT Wall heat transfer (condensation)						L	M	L	L	L	L		
	CMT Thermal stratification						L	M	L	L	L	L		
	SIT Injection flow (mixture level change)		L			M		M			H	H		
	SIT Boron injection		L								L	L		L
	SIT Direct condensation w/air		L			L		L			M	L		
	SIT Wall heat transfer		L			L		L			M	M		
	SIT Thermal stratification		L			L		L			M	L		
	PBL Wall heat transfer (condensation)						L	M			M	L	M	M
	SIL Direct condensation							L			L	L	L	M
	Loop Recirculation flow						M	L	L	M	M	L		
ADS	Discharge (Critical) flow							H		H	M	L		L
CVCS	Charging / letdown flow			L										
Containment	Back pressure								L	L	L	L		