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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Abstract – The paper presents the development of a Phenomena Identification and Ranking Table (PIRT) for Thermal-Hydraulic (T-H) phenomena in the context of the SMART100 nuclear power plant design. The SMART100 is a System Integrated Modular Advanced Reactor with 100 MWe and fully Passive Safety Systems (PSSs). The objective of the study is to identify and rank the key T-H phenomena associated with Design Extension Conditions (DECs) for SMART100 and implement them in the Safety and Performance Analysis CodE (SPACE), a code used for safety analysis and design of nuclear power plants.

The PIRT development involves seven steps: reviewing and identifying plant design data, defining important systems and components, deriving key accident scenarios, defining primary evaluation criteria, partitioning scenarios into time phases, identifying plausible phenomena/processes by phase and component, and ranking their importance and knowledge levels. The SMART100-DECs PIRT is developed by experts with extensive experience in nuclear power reactor design and thermal-hydraulics.

The paper provides detailed descriptions of each step, including the SMART100 design features, high-level systems and components, key accident scenarios, evaluation criteria, time phases, and the identified phenomena/processes. The importance and knowledge levels of each phenomenon/process are ranked using defined scales.

The results of the PIRT development are discussed, focusing on the improvement of T-H models and validation items in SPACE. Several areas for improvement are identified, such as the models for PSIS tanks components, boron transport, helically coiled tubes, PRHRS, and decay heat. The PIRT serves as a valuable tool for enhancing the capability of SPACE in analyzing SMART100-DECs. The study was conducted by experts from various entities with support from the King Abdullah City for Atomic and Renewable Energy (K.A.CARE) and the Korean Atomic Energy Institute (KAERI).

Overall, the developed SMART100-DEC PIRT and the identified improvement areas contribute to advancing the understanding and simulation of T-H phenomena for the SMART100 nuclear power plant design

**Keywords:** PIRT, SPACE, SMART100, DECs, T-H

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.

1. **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-PPE: 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 SBLOCA.
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 |

1. **Results and Discussion**
   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. 1. Improvement in PSIS tanks components models:
2. 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.

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

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.

1. Validation PRHRS component model:

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.

1. 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 model based on ANS-5.1-2014 is expected to be added.

1. ***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.

1. **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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**APPENDIX**

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

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | | SMART100 DECs and Phases | | | | | | | | | | | | |
| System | Process/Phenomena | 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 |  |  |