Analysis Method on Severe Accident Issues for SMART

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1. Introduction

The Korean integral reactor of SMART (System-integrated Modular Advanced ReacTor) has been developed, which contains core, reactor coolant pumps, steam generators and pressurizer within a single reactor pressure vessel. For the safety enhancement, SMART has the design characteristics of adopting the inherent and passive safety, simplified safety system, and advanced man-machine interface. For the economic enhancement, SMART has the design characteristics of applying the system simplification and the component modularization. For the operation enhancement, SMART design considers the simplified operation strategy and convenient maintenance. The nominal thermal power of SMART is 365 MW_{th}. The severe accident management technology development and severe accident analysis had been performed in SMART-PPE (Pre-Project Engineering) with K.A.CARE in Saudi Arabia from December 1, 2016 till November 30, 2018. This paper is focused on analysis method on severe accident issues in SMART-PPE.

2. Severe accident mitigation concept and systems

The concept of the basic design of SMART to terminate the progression of severe accidents is to prevent the reactor vessel rupture by cooling the external reactor vessel wall using the method to fill the reactor cavity with cooling water, which is the IVR-ERVC (In-Vessel corium Retention through External Reactor Vessel Cooling). If reactor vessel rupture is prevented, the integrity of the reactor containment area can be maintained by preventing the progression of the ex-vessel severe accident. The IVR-ERVC is used in the accident management of the existing LWR and for the severe accident mitigation design for the Advanced Light Water Reactor (ALWR). In addition, the SMART is designed to assure the safety sufficiently against ex-vessel severe accident phenomena in terms of the defense-in-depth. The severe accident mitigation design of SMART is focused on the following severe accident issues.

- Combustible Gas Combustion and Explosion
- Containment Over-temperature or Over-pressure
- Molten Core Concrete Interaction (MCCI)
- High Pressure Melt Ejection (HPME)
- Direct Containment Heating (DCH)
- Fuel Coolant Interaction (FCI)
- Containment Bypass by Steam Generator Tube Rupture (STGR) and so on
- In-Vessel corium Retention through External Reactor Vessel Cooling (IVR-ERVC)

The severe accident mitigation design of SMART is same as the severe accident mitigation design of existing next-generation LWR like APR1400. Therefore, there is no new severe accident phenomenon or issue with respect to SMART design. As it is possible to use the results of experimental and analytical studies to resolve the issues of severe accidents in the existing LWR and the concept of the designs for severe accidents in the existing LWR has sufficient reliability, it is possible to apply such results to SMART.
The severe accident mitigation system for the SMART is as follows:

- The system that cools down the outer wall of the reactor vessel is installed in order to cool the molten core material inside the reactor vessel using Cavity Flooding System (CFS) with In-Containment Refueling Water Storage Tank (IRWST) for the IVR-ERVC.
- The safety depressurization system of the Automatic Depressurization System (ADS) to prevent the Direct Containment Heating (DCH) by High Pressure Melt Ejection (HPME) is installed to make low pressure in the reactor vessel before the reactor vessel failure.
- Hydrogen mitigation system of the Passive Autocatalytic Recombiner (PAR) is installed to remove hazards from hydrogen combustion considering the amount of hydrogen to be generated by 100% fuel cladding oxidation.
- The SMART has the pathway to release the hydrogen in core to the Upper Containment Area (UCA) of the reactor containment area through ADS, Safety Injection Tank (SIT) room, associated piping, and the Radioactive material Removal Tank (RRT) for hydrogen control.
- The Ancillary Containment Spray System (ACSS) that provides to prevent a catastrophic failure of the UCA of the reactor containment area. The ACSS flow rate provides sufficient heat removal to prevent the upper containment pressure from exceeding the containment performance criteria, and function to remove the fission products in the UCA of the reactor containment area during a severe accident.

3. Analysis Method

SMART reactor building has very large volume and has open-type internal structure so that hydrogen is mixed well and hydrogen concentration is maintained uniformly at low level. Also, the reactor building is designed firmly enough to withstand hydrogen combustion. PARs are installed in order to control the quantity of hydrogen generated during a severe accident. In order to assess the position and performance of hydrogen mitigation feature, detailed analysis has been performed using CINEMA-SMART computer code.

CINEMA-SMART computer code has been developed for severe accident sequence Analysis for SMART, which is based on CINEMA-APR1400. This code is results of merging the COMPASS (In-Vessel Melt Progression), the SPACE (RCS Thermal Hydraulic Behavior), and the SACAP (Severe Accident in Containment).

A hydrogen combustion is physically impractical in LCA because of steam rich and oxygen starvation condition. But a hydrogen combustion is possible in UCA during a severe accident where only dry hydrogen is released through RRT vents. So, 3-dimensional detail analysis of hydrogen behavior in UCA was conducted. The pressure and the temperature of the reactor containment area are analyzed by CINEMA-SMART computer code for the representative severe accident scenarios. The transients of the pressure and the temperature during the representative severe accident scenarios are analyzed for the period of more than for 24 hours of accident condition. Most conservative condition for the pressurization point of view is defined and the behavior of the pressure and the temperature are analyzed for 72 hours of the accident condition.

The severe accident analysis should be based on realistic or best estimate assumptions, methods and analytical criteria and take into account, among other considerations, provision for mitigation of MCCI. In order to satisfy the requirements, it is necessary to understand and best implement the available analytical tools, taking into account the relative strengths of each tool and how these apply to the design features of SMART.

The severe accident progression for the representative accident sequences including SBO, SBLOCA and TLOFW is analyzed by using CINEMA-SMART computer code which consists of CSPACE code for the core and the reactor coolant system and SACAP code for the containment. The MCCI analysis module is embedded in SACAP code.

When the CFS is operated normally, the reactor vessel is sufficiently cooled by the ERVC and MCCI does not occur. However, it is assumed that the reactor vessel is failed even with the operation of the CFS with a conservative point of view for assessing the consequences from MCCI. To reflect this dedicated assumption, the CFS operation is made to start right after the corium release from the core in the code calculation.

The integrity of the reactor containment is of the key interest of the analysis. The result of the erosion depth along the concrete floor can tell whether BMT would occur or be prevented. The long-term behavior of MCCI is the ultimate result to see how its ending scenario is in terms of the BMT risk. Also the result of the pressure of the containment area can present the significance of the pressurization due to MCCI and it can be seen whether the pressurization is considerable or not. The generation rates of the steam and the non-condensable gases would be the most dominating factors for pressurization

It is known that DCH cannot be generated if safety depressurization system is operated in the high-pressure core damage accident sequence. It is shown using CINEMA-SMART computer code that the reactor coolant pressure at the time of reactor vessel rupture is lower than the pressure to cause HPME if safety depressurization system is operated. SMART design has CPRSS as a passive safety feature, which has the suppression function as a heat sink and the trapping effect of the released debris from the cavity to UCA (Upper Containment Area). Since the TCE/LHS method couldn't include the scrubbing effect between two cells of LCA (lower Containment Area) and UCA, it could give conservative results.

TEXAS-V is used to estimate the variations of pressure from the ex-vessel steam explosion. Uncertainty analysis is performed by best estimated evaluation methodology. The integrity of the structure of the reactor containment area is assessed. In order to assess the limit of the reactor cavity structure against the pressure pulse of ex-vessel steam explosion, the integrity of the structure of the reactor containment area is assessed by comparing with the design impact limit of the reactor cavity structure.

In IVR-ERVC analysis, the thermal load from the corium to the external reactor vessel wall when the molten core material is relocated in the lower hemisphere plenum of the reactor vessel during a severe accident is estimated using the CINEMA-SMART computer code. The natural circulation mass flow rate, which is formed in the annular gap between the external reactor vessel wall and insulator, is estimated using the SPACE computer code. CHF, which corresponds to the maximum heat removal from the external reactor vessel wall depending on the estimated natural circulation mass flow rate, is determined using SULTAN and KAIST experimental results. The success criteria of the IVR-ERVC to prevent reactor vessel failure during a severe accident is determined by comparing of the thermal load with the CHF. Finally, structure analysis on reactor vessel wall performs to evaluate the structure integrity of the reactor vessel wall in ERVC condition using ANSYS computer code.

Table I shows computer codes for severe accident issue analysis.

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Table I: Severe Accident Analysis Code for SMART.

Title	Computer Code	
	SMART330 SSAR	SMART-PPE
Severe Accident Sequence Analysis	MELCOR	CINEMA-SMART
External Reactor Vessel Cooling Analysis	ATOP(In-Vessel), ANSYS(Vessel), RELAP5(Ex-Vessel)	CINEMA-SMART, ANSYS, SPACE
Direct Containment Heating & Vessel Depressurization Analysis	TCE(DCH), MELCOR(RCS Dep.)	Modified TCE/LHS, CINEMA-SMART
Steam Explosion Analysis	TEXAS-V(SE), ABAQUS (Structure Integrity)	TEXAS-V, ANSYS
Molten Core Concrete Interaction & Debris Bed Coolability Analysis	MELCOR	CINEMA-SMART
Hydrogen Distribution & Burning Analysis in Containment	MELCOR	CINEMA-SMART, ContainmentFOAM