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Severe Accident Mitigation Technology 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 to improve the SMART safety include 1) vessel depressurization using ADS (Automatic Depressurization System) to prevent DCH(Direct Containment Heating) in case of a reactor vessel failure 2) reactor cavity flooding using the cavity flooding system with the IRWST (In-containment Refueling Water Storage Tank) for IVR-ERVC (In-Vessel corium Retention through External Reactor Vessel Cooling) to prevent the reactor vessel failure 3) hydrogen control system to remove hazards from hydrogen combustion considering the amount of hydrogen to be generated by 100% fuel cladding oxidation.

2. Severe accident mitigation design

The equipment to mitigate the effect of severe accident in SMART is installed, which can satisfy the containment performance criteria and the safety goals. Severe accident mitigation systems are normally functioned in the severe accident environment, which is not necessary for the safety class. The equipment that cools down the outer wall of the reactor vessel be installed in order to cool the melted core material inside the reactor vessel. The equipment to prevent the hydrogen explosion and the direct containment heating phenomenon which can cause the early failure of the containment is installed, which is PARs (Passive Autocatalytic Recombiners) to remain the total hydrogen concentration below 10%, including hydrogen generated from the 100% cladding oxidation reaction.

Under the IVR-ERVC condition, the water from the IRWST is flooded into the reactor cavity passively by gravity. A reactor vessel insulation used to reduce the heat loss during normal operation is installed between the outer reactor vessel and the reactor cavity wall. The water inlet, steam outlet, and water circulation outlet are installed in the reactor vessel insulation for the IVR-ERVC of the SMART. The required systems for an IVR-ERVC are the safety depressurization using the ADS, the CFS (Cavity Flooding System) with the IRWST, and the reactor vessel insulation design for water contact to the outer reactor vessel wall and with the generated steam venting.

3. IVR-ERVC

An integral reactor of a SMART has a big reactor vessel size in comparison with other reactors, because the main components of the steam generators, pressurizer, and reactor coolant pumps are located inside the reactor vessel. Thus, a lower plenum is large with a comparison of the thermal power. The total mass of the core materials of the SMART is smaller than that of the OPR1000 and APR1400, because the thermal power is small. However, the reactor vessel size and thickness of the SMART are bigger than those of the OPR1000 and APR1400, because the main components are located inside the reactor vessel. The ICI (In-Core Instrumentation) nozzles are not located in the lower hemispherical reactor vessel of the integral reactor. In general, if these nozzles are located in the lower plenum of the reactor vessel, they affect the evaluation of the IVR-ERVC. Fig. 1 shows a schematic diagram of the IVR-ERVC concept for the SMART.

An IVR-ERVC analysis for the SMART, the thermal load analysis for the corium to the reactor vessel wall was performed using a simple model. A two-layer formation of the upper metallic and lower oxidic layers was considered in the lower plenum of the reactor vessel. The thermal load analysis is concentrated on the heat flux distribution in consideration of a focusing effect in a thin metallic layer. This effect of the metallic layer is mainly determined by the molten pool configuration in the lower plenum of the reactor vessel. The melt pool configurations inside the lower plenum affect the initial thermal load to the outer reactor vessel and play a key role in determining the integrity of the reactor vessel. A numerical model had been developed for a thermal load response to the outer RPV during a severe accident. The model was based on a simple mechanistic model using an energy balance equation. The governing equations were solved using a non-linear Newton-Raphson method. From the thermal load analysis in the lower plenum of the reactor vessel, the maximum heat flux from the corium pool to the outer reactor vessel is approximately

0.5 MW/m^2 in the metallic layer, owing to the focusing effect.

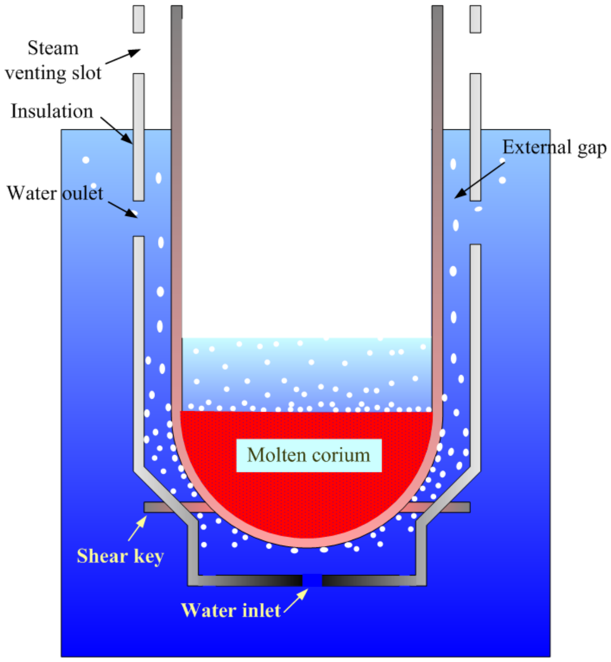

Fig.1 IVER-ERVC concept for SMART

An analysis of a two-phase natural circulation flow in the annular gap between the outer reactor vessel and the insulation was performed to determine the coolant circulation mass flow rate using the heat flux boundary condition of the thermal load from the corium pool to the outer reactor vessel using the SPACE computer code. An increase in the heat flux to the reactor vessel leads to an increase in water circulation mass flow rate in the case with a water outlet hole. However, an increase in the heat flux does not lead to an increase in the water circulation mass flow rate in the case without a water outlet hole, because this is a pool boiling condition. An increase in the coolant circulation mass flow rate leads to an increase in the CHF on the outer reactor vessel. The CHF with the water outlet hole is bigger than that without the water outlet hole. Thus, it is necessary to install the water outlet hole at the reactor vessel insulation to increase the heat removal rate on the outer reactor vessel under the IVR-ERVC condition of the SMART.

The average natural circulation mass flow rate at the water inlet was approximately approximately 60 kg/m^2.s. From KAIST's experimental results on the CHF as a function of coolant circulation mass flux, when the coolant circulation reaches 60 kg/m^2.s, the CHF value is approximately 1.11 MW/m^2. From the thermal load analysis from the corium pool to the outer reactor vessel wall, the maximum heat flux is approximately 0.5 MW/m^2 in the metallic layer, owing to the focusing effect. The maximum heat removal on the outer reactor vessel is approximately 1.11 MW/m^2. For this reason, the thermal margin for success of the IVR-ERVC during a severe accident is sufficient in the SMART. A more detailed analysis on the thermal load is necessary because of uncertainties, such as a three-layer formation by layer inversion. A verification experiment on the natural coolant circulation and the CHF as a function of angle is necessary.

4. Hydrogen Control in Containment

The hydrogen mitigation system controls hydrogen, which is generated at higher rate during a severe accident compared with the DBA (Design Basis Accident). The hydrogen mitigation system consists of PAR in order to treat effectively the hydrogen release that shows diverse generation characteristics during a severe accident. For the hydrogen generation during a severe accident, 199.8 kg of hydrogen is considered by the reaction between 100% of fuel cladding metal and water in accordance with LWR (Light Water Reactor) safety review guideline. The hydrogen mitigation feature is installed so that hydrogen concentration does not exceed 10% assuming uniform distribution in the reactor containment building and the combustible gas concentration in each cell of the reactor containment building is sufficiently low as widespread flame acceleration or deflagration-to-detonation transition is not generated in order to avoid the reactor building damage caused by the combustion of combustible gases in the reactor building.

SMART reactor containment building has very large volume so that hydrogen is mixed well and hydrogen concentration is maintained uniformly at low level. Also, the reactor containment 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.

5. Summary

The severe accident management technology for SMART is a reactor vessel depressurization using the ADS, the reactor cavity flooding using the cavity flooding system with the IRWST for the IVR-ERVC, and hydrogen control system to remove hazards from hydrogen combustion considering the amount of hydrogen to be generated by 100% fuel cladding oxidation.

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