Passive Containment Pressure and Radioactivity Suppression System

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I. INTRODUCTION

SMART is an integral reactor in which the main components (steam generators, pressurizer, and reactor coolant pumps) are directly mounted onto the reactor vessel or integrated into the vessel without the use of large coolant pipes. It has the rated thermal power of 365 MW. SMART was developed to enhance safety and improve the economics in Pre-Project Engineering (PPE) for First-of-a-Kind (FOAK) plant construction in the Kingdom of Saudi Arabia. The CPRSS (Containment Pressure and Radioactivity Suppression System) was first suggested in PPE to replace the Containment Spray System (Kang, 2015), which is an active system that uses pumps and can be replaced with a passive system in the CPRSS. The CPRSS utilizes the existing In-containment Refueling Water Storage Tank and the Emergency Cooling Tank coolant, the heat sink of the Passive Residual Heat Removal System, as the ultimate heat sink for long-term cooling and for significant removal of radioactive material. In this study, the CPRSS performance (i.e., heat sink capacity and pressure behavior) in the containment was evaluated using MARS, a systematic analysis code. As a result, the design pressure of the containment could be reduced by lowering the containment pressure effectively by removal of residual heat during a loss of coolant accident.

II. SYSTEM DESCRIPTION

The containment pressure and radiation suppression system (CPRSS) is an ESF (Engineering Safety Feature) system as shown in Figure 1, the functions of which are to suppress the increase of pressure and temperature (P/T) in the containment following accidents such as a LOCA and to remove the radioactive fission products from the containment atmosphere. The cooling strategy of the SMART during a LOCA is to cool the containment building within 72 hours by means of heat transfer by the sensible heat of water inside the IRWST and by natural circulation using the heat exchanger in the ECT. After 72 hours, the pressure of the containment is continuously reduced using the natural circulation provided by the heat exchanger inside the ECT. The system keeps the RCA P/T from exceeding the design P/T with sufficient margin during 72 hours without AC power sources or operator actions. After 72 hours, the CPRSS decreases the LCA P/T with the support of the non-safety system and maintains the LCA P/T with an increased design margin. Figure 2 shows the conceptual design for the CPRSS introduced in the PPE. The safety functions of the CPRSS are: to reduce containment pressure and temperature during a Loss of Coolant Accident (LOCA) and to suppress the spread of fission products from the containment atmosphere following the accident. The structure and operation principle of the CPRSS is given below. The CPRSS comprises a CPRSS lid, pressure relief lines (PRLs) and PRL-spargers, an IRWST, radioactive material transport lines (RTLs) and RTL-spargers, two radioactive material removal tanks (RRT), and CHRS as a subsystem of the CPRSS. The CHRS consists of four mechanically independent trains. Each train of the CHRS includes one CPRSS heat exchanger (CHX), a CPRSS steam line (CSL), two CSL isolation valves, a CPRSS discharge line (CDL) and CDL-spargers, two CDL isolation valves, a CPRSS return line (CRL), one CRL isolation valve, and one ECT. Here, the ECT is shared with the Passive Residual Heat Removal System (PRHRS) as shown in Figure 1. The system details are as follows. The CPRSS lid is installed on the floor of the fueling pool by stud bolting of a flange to a forged ring-plate. The LCA is leak-tight against steam and fission products. During an accident, the steam and the fission products are most likely to gather in the LCA first, to be released to the IRWST.

Figure 1. Schematic of SMART systems
The PRL is designed to connect the gas area in the LCA to the water area in the IRWST. The PRL serves to guide the mixture of steam and non-condensable gas, along with the fission products in the LCA, to the IRWST through the PRL-spargers during the accident. A PRL-sparger is installed at the end of a PRL. The steam and fission products passing the PRL are discharged into the IRWST through the PRL-sparger. The shape, size, and the number of holes in a PRL-sparger are designed to take into account the thermal-hydraulic loads (e.g., chugging) (Hujala, 2018). The PRL-spargers are placed in the IRWST as deeply, widely, and uniformly as possible. The arrangement of PRL-spargers was determined to take into account the thermal mixing in the IRWST. The CPRSS utilizes the IRWST as a heat sink, which acts as a temporary repository for a part of the accident energy released during the first 72 hours in the reactor containment area. The IRWST stores most of the mass-energy incoming from the LCA in the water pool through steam condensation, except for the removal of heat through the CHX. The capacity of the IRWST was determined to be sufficient to prevent the water temperature in the IRWST from reaching its saturation temperature, with sufficient margin for 72 hours following the LOCA. The RTL is designed to connect the gas area in the IRWST to the water area in the RRT. During the accident, the RTL serves to transport the steam-non-condensable gas mixture and fission products in the IRWST gas area to the RRT through the RTL-sparger. The size and the number of pipes were designed by taking into account the piping integrity (i.e., the IRWST and RRT penetrations). An RTL-sparger is installed at the end of each RTL. The steam-non-condensable gas mixture and fission products in the IRWST gas area following the accident, pass by the RTL and finally are discharged to the RRT through the RTL-sparger. The shape, size, and number of holes in an RTL-sparger are designed to take into account the thermal-hydraulic loads (e.g., chugging) (Hujala, 2018) and the fission product removal (e.g., iodine pool scrubbing). The RTL-spargers are placed in the RRT as deeply, widely, and uniformly as possible. The arrangement of the RTL-spargers was determined to take into account the thermal mixing in the RRT. The RRT is a containment internal structure located at the top of the IRWST. It is connected to the UCA via the RRT vent located at the top of the RRT. The RRT removes the fission products released from the LCA by dissolving the radioactive fission products (Beghi, 2018). During normal operation, the RRT is filled with water of pH 7.0–9.5. (Jung, S. H., 2015) The CHR is a subsystem of the CPRSS, which provides the function of removal of containment heat from the LCA. The CHR consists of four mechanically independent trains. Each train of CHR comprises one CHX, a CSL, two CSL isolation valves, a CDL and CDL-sparger, two CDL isolation valves, a CRL, one CRL isolation valves, one ECT, and instruments. CSL, CDL and CRL isolation valves are normal closed. The CHX is a heat exchange tube bundle located inside the ECT, and it consists of an inlet header, a vertical straight heat-transfer tube-bundle, and an outlet header. The CHX provides the function of removing the core decay heat and the reactor coolant sensible heat by condensing the steam released from the LCA through the heat exchange with the cooling water in the ECT. The heat removal capacity of the CHX was determined to be able to decrease the LCA P/τ within 72 hours following the LOCA using three (of four) CHR trains in consideration of the influence of non-condensable gases on heat transfer. The CSL is designed to connect the SIT compartment in the LCA with the CHX. The CDL is designed to connect the CHX with the water area in the IRWST, and the CRL is designed to connect the CHX with the gas area in the RVA compartment in the LCA. In the CPRSS, there are two flow paths for cooling when LOCA occurs. One is LCA-to-UCA path and the other is LCA-to-CA path. LCA-to-UCA path is separated by two flow paths. In one path (LCA-to-UCA), the vapor mixture in the LCA is released to IRWST through PRL by pressure difference between LCA and PRL exit, some vapor and air are transported to RRT through RTL after most vapor is directly condensed in IRWST water and then the remaining small amounts of vapor and air are finally discharged to UCA. In the other path of LCA-to-UCA, the safety injection tank (SIT) compartment in the LCA is connected to the IRWST via the CSL, CHX, and the CDL. The CDL outlet is on the IRWST and is eventually connected to UCA. In the event of LOCA, the CSL and CDL isolation valves are automatically opened by the battery after receiving the valve actuation signal from the pressure set (0.45 normalized by LCA design pressure) inside the LCA. In LCA-to-LCA flow path, the top of SIT compartment in the LCA is connected to the LCA via the CSL, CHX, and CRL. The exit of CRL is connected to the LCA through the CMT compartment. The LCA-to-UCA path forms during the first 72 hours following the accident. The LCA-to-LCA path is formed by manually open of CRL isolation valves after 72 hours. After 72 hours, condensation occurs in CHX due to opening of CRL and continuous steam mixture is inhaled into CSL due to pressure reduction inside CHX. In addition, condensate flow out to IRWST through the RTL by gravity.
III. THERMAL-HYDRAULIC ANALYSIS AND RESULTS

The possibility of large-break loss-of-coolant accidents (LBOCA) is inherently impossible due to the absence of large pipes in the SMART design (Kim et al., 2014). Therefore, a small-break LOCA (SBOCA) involving a double-ended guillotine break (connected to the RCS loop) is considered. The mass and energy releases following an accident like a SMLOCA, which provide the primary impact on the containment peak pressure and temperature, are provided as the flow boundary conditions for the LCA. The MARS (Multi-dimensional Analysis of Reactor Safety) code used for this analysis was developed to provide realistic multi-dimensional thermal-hydraulic system analysis of light-water-reactor transients (Chun, 2014). Figure 3 shows the MARS nodalization scheme for the T/H performance analysis of the SMART-CPRSS. The time-dependent volumes, TDV-100 and TDV-102, and the time-dependent junctions, TDJ-101 and TDJ-103, were used to provide the inlet boundary conditions for the M/E, which represents the high pressure steam-water (two-phase) flow released from the reactor vessel following a LOCA. In this analysis, the product of the M/E multiplied by 1.1–1.3 was applied to the input model to consider the uncertainty. To analyze the CPRSS T/H performance during the 10 days following a LOCA, the nodalization scheme in Figure 3 was used. In this analysis, the product of the LOCA M/E multiplied by 1.1 and 1.3 was applied to the input model to consider the uncertainty of 10% and 30%. In this analysis, the isolation valves in the CHRS train #4 were not opened, in order to consider a single failure, conservatively. The CPRSS performance evaluation time of 10 days was determined by considering the time required for external actions, including three days by only the passive method, due to the plant design method for dealing with a LOCA. When a LOCA occurs, a high-pressure two-phase flow of steam and water is released to the LCA from the reactor vessel. As the steam-water mixture is released from the M/E boundary, the LCA pressure increases and the CPRSS automatically operates due to the pressure difference between the LCA and IRWST. In the initial phase of the accident, the mixture of steam and non-condensable (NC) gas is released through the PRL and the CDL. The LCA-to-IRWST path via the CDL is opened by opening of the CSL and CDL isolation valves by a high-pressure LCA signal. In this phase, the LCA pressure increases sharply and reaches a maximum normalized pressure of 0.77 in the initial phase of the accident (see Figure 4). After tens of minutes, the gas mixture is released predominantly through the CDL. When the CPRSS discharges steam through the CDL, the CHX transfers the heat from the LCA to the outside environment. As the LOCA proceeds, the LCA and UCA pressure increase consistently for 72 hours and reach a normalized pressure of 0.74 and 0.41, respectively. The pressure difference between the LCA and UCA differs by the pressure head between the IRWST and RRT. Figure 5 shows the amount of energy removed from the CHXs in the three trains of the CHRS. These CHXs continuously remove more than 1 MW of heat while preventing pressure build-up in the LCA.
IV. CONCLUSION

The SMART CPRSS was developed to suppress the spread of radioactive material and rise in pressure in the containment using the IRWST and dedicated ECT (Emergency Cooling Tank) of the PRHRS (Passive Residual Heat Removal System) when a LOCA occurs. The preliminary thermal hydraulic evaluation of the CPRSS was performed using the MARS system code. In the LOCA, which maximizes UCA pressure, the design pressure of the SMART containment building by introduction of the CPRSS can be 60% and 40% lower than in the containment of the APR 1400 and the Standard Design Approval version of SMART, respectively. This is achieved by sparging the LCA steam directly into the water of the IRWST and RRT through an LCA-to-IRWST path via the CDL and then to a natural circulation loop through the LCA-to-LCA path via a CHX located outside the containment.

REFERENCES