IMPORTTANT FEATURES AND THEIR RESISTANCE TO THE SEVERE ACCIDENT IN ADVANCED INTEGRAL WATER REACTOR SMART

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ABSTRACT

SMART with a thermal power capacity of 330 MWth, is under development at the Korea Atomic Energy Research Institute. SMART is an integral type pressurized water reactor that contains a pressurizer, reactor coolant pumps, and steam generator cassettes in a single reactor vessel. SMART adopted an in-vessel retention by an external reactor vessel cooling strategy to terminate a severe accident progression. The capability of the external cooling strategy was evaluated and it was concluded that the external vessel cooling is achieved when the cavity flooding system works successfully. The load from a direct containment heating was evaluated with the assumption of reactor vessel failure even though the external vessel cooling strategy was adopted. The load from hydrogen burn was also evaluated. Based the results of these evaluations, we concluded that the reactor containment building of SMART performs its function and maintains its integrity during a severe accident progression.

INTRODUCTION

SMART (**S**ystem integrated **M**odular **A**dvanced **R**eac**T**or) is an integrated pressurized light water reactor developed by Korea Atomic Energy Research Institute (KAERI), whose standard design is under regulatory review in Korea. A pressurizer, reactor coolant pumps (RCPs), and steam generator cassettes (S/Gs) are within in a single reactor vessel as shown Fig. 1. There are no pipings that connect the reactor vessel, steam generators, and reactor coolant pumps. The possibility of large break loss of coolant accident is eliminated inherently. In addition, intrinsic safety of the SMART is achieved by the large coolant inventory, the low power density, passive residual heat emoval, high secondary design pressure and large containment, etc. Unlike Fukushima Mark-I design, SMART passive safety is insured by four-train passive residual heat removal system (PRHRS) that provides natural circulation cooling in the secondary sides of steam generators. In addition, two emergency diesel generators (DG) and an alternative diesel generator insure the AC power supply to active engineered safety features.

Severe accident was considered in the design stage. The important features of SMART for severe accident is described the following section. The capability of an external reactor vessel cooling strategy, the resistance to the direct containment heating and hydrogen burn were also evaluated and summarized.

IMPORTANT FEATURES FOR SEVERE ACCIDENT

SMART has the following features to prevent or mitigate a severe accident.

- Very large containment free volume

The containment type of SMART is a large dry containment. SMART has a very large containment free volume. The free volume of SMART is 43,891 m^3, which corresponds to 133 m^3/MWth. The containment free volume of OPR 1000, which is a typical Korean PWR and has 2815 MW of thermal power, is 77,220 m^3, for which the free volume per unit power is 27.4 m^3/MWth. The free volume ratio to thermal power of SMART is almost 5 times larger than that for typical Korean PWRs.

- Cavity flooding system

SMART has a cavity flooding system which consists of 2 trains. This system supplies water to the reactor cavity during severe accident progression. Water in the in-containment refueling water storage (IRWST) flows to the cavity by gravity when an operator opens the block valves which are closed normally.

- Passive autocatalytic recombiner (PAR)

SMART installed 4 PARs to control hydrogen generated during a design basis accident. Additional 8 PARs are installed to control the hydrogen concentration during a severe accident progression. PAR starts to work from 2.0 % hydrogen concentration and stops when the hydrogen concentration decreases below 0.5 %.

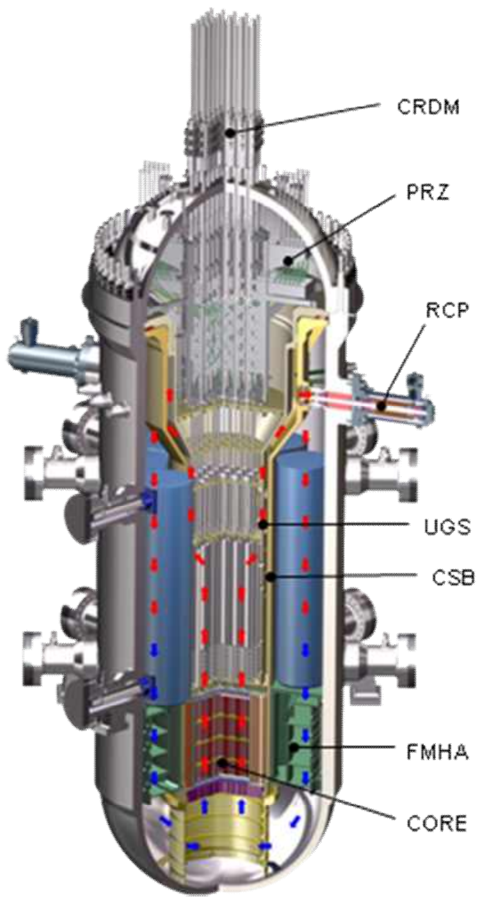

Fig. 1 The layout of integral reactor vessel of SMART

- Safety depressurization valves

Two trains of safety depressurization valves (SDVs) are installed on the top of the pressurizer. These valves are normally locked closed to prevent inadvertent opening because the inadvertent opening of SDVs induces a loss of coolant accident (LOCA). The capacity of SDV is sufficient to reduce RCS pressure below the threshold pressure for high pressure melt ejection. The discharge location of SDV is the reactor drain tank instead of IRWST to prevent the accumulation of hydrogen within the IRWST.

- Large cavity floor area

The cavity area of SMART is 64 m^2. This corresponds to 0.194 m^2/MWth, which is larger than the NRC requirement for corium coolability in the reactor cavity, which is 0.025 m^2/MWth. The large cavity area makes the corium coolable when water exists in the cavity.

EXTERNAL REACTOR VESSEL COOLING

There are three requirements for external reactor vessel cooling. First, there should exist a water pathway through which water can flow to the reactor cavity and submerge the reactor vessel at all times during a severe accident progression. Second, the critical heat flux at the reactor outer surface should be higher than the heat removal capability of the outer surface of the reactor vessel. Third, the reactor vessel should maintain its integrity during the external vessel cooling process.

There are two water pathways from IRWST to the reactor cavity, as described in the above section. When the operator opens the block valves on the cavity flooding system, then the water in the IRWST flows to the reactor cavity by gravity. The water level reaches the feedwater piping and the lower head of reactor vessel submerges in the water. It takes about 30 minutes for the reactor lower head to be submerged in the water when 1 train of the cavity flooding system operates. As the water vaporizes in the reactor cavity, the water in the IRWST flows to the reactor cavity and maintains the water level equal to the level in the reactor cavity. Fig. 2 shows the schematic of the external reactor vessel cooling.

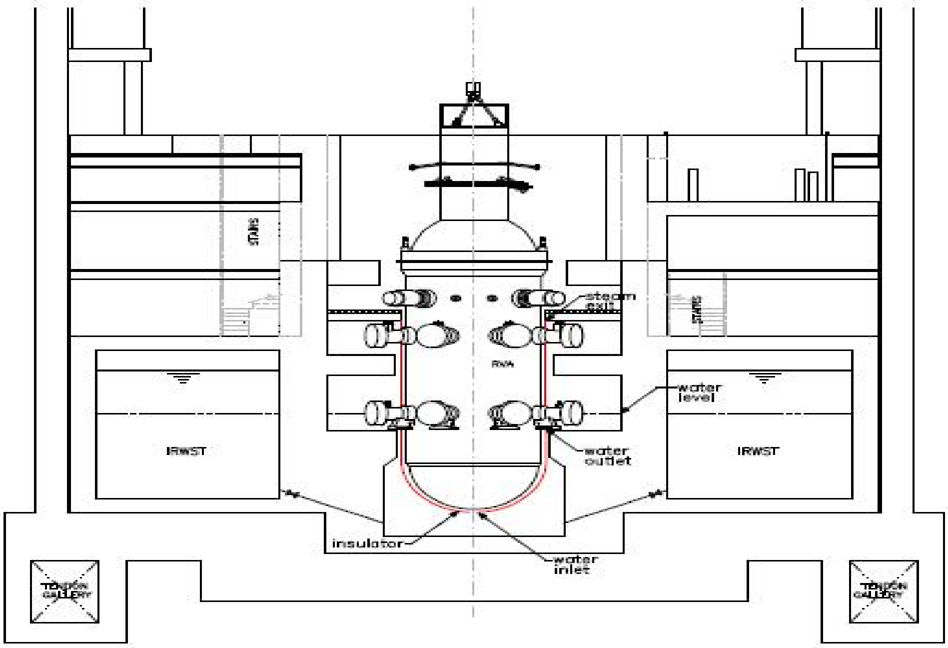

Fig. 2 Schematic of the external reactor vessel cooling

When all core material melts and relocates to the lower head, the volume of corium becomes 4.7 m^3 which is 11.8% of lower head volume (39.9 m^3) and the height of the corium from the bottom of the reactor lower head becomes 0.79 m. This corresponds to 45^o from the center of the reactor lower head. The heat capacity of the corium in the reactor lower head is 1.86 MW from MELCOR calculation, which is 0.56% of the full power of 330 MW. The heat flux to the inner surface of the vessel becomes 0.14 MW/ m^2 if it is assumed to be uniform. The two phase flow rate within the annulus between the reactor vessel and the thermal insulator is calculated for this heat flux using a RELAP5 code. It is determined to be 68.8 kg/sec. The critical heat flux at the outer surface of the reactor vessel is determined for this flow rate using a SULTAN experiment [1] and KAIST experiment [2]. The critical heat flux was 1.0 ~ 1.1 MW/m^2 approximately which is much greater than the internal heat load of 0.14 MW/m^2.

There are uncertainties for the internal heat load because the behavior of the corium in the lower head is still unknown exactly. One uncertainty is how many layers are formed in the corium pool. Some insist there are two layers, while others insist three layers. The heat flux at the hottest point depends on the number of layers formed. Thus we did a sensitivity study for the increased internal heat load. Two loads, 0.25 MW/m^2 and 0.5 MW/m^2, were studied. Two phase flow rate was calculated for each heat flux. The flow rate increased as the inner surface heat flux increased and critical heat flux wss slightly increased. The critical heat flux was approximately 1.2 MW/m^2 for 0.25 MW/m^2 and 1.3 MW/m^2 for 0.5 MW/m^2.

During the external reactor vessel cooling process, the plastic strain of the reactor vessel wall was calculated using a MIDAS/SMR code [3]. The maximum plastic strain was 2.4 x 10^{-11} for high pressure sequences and 2.9 x 10^{-7} for low pressure sequences. These values are far below the Larson-Miller criteria for the creep rupture of a reactor vessel, which is 0.18.

DIRECT CONTAINMENT HEATING

The direct containment heating (DCH) has been considered as an important early containment failure mechanism since the Zion PSA study. It is known that if the RCS pressure at the time of a reactor vessel failure is below 1.72 MPa, then a DCH cannot occur. Thus approaches are taken in the SMART analysis for DCH. One approach is to show the capability of SMART to reduce its RCS pressure below 1.72 MPa before the reactor vessel breach. The other approach is that the integrity of the containment is maintained even though the DCH occurs.

SMART is equipped with the safety depressurization valves (SDVs). The MISAD/SMR code is used to calculate the RCS pressure if the operator opens the SDVs. Even if a SDV is opened 2hours after the SAMG entry condition is reached, the RCS pressure decreases below 1 MPa a long time before the creep rupture of the reactor vessel. A core exit temperature of 650 ^{o}C is used as a transition signal from EOP to SAMG. Usually, an RCS pressure of 1.72 MPa is used as a cutoff value of high pressure melt ejection. Therefore, direct containment heating will be eliminated in SMART if the operator opens SDVs according to SAMG.

USNRC established the methodology to evaluate the potential of DCH through NUREG/CR-6075[4]. We evaluated the potential for a containment challenge due to the DCH for SMART using the methodology described in NUREG/CR-6075. The initial conditions for the DCH analysis are given in Table 1.

Table 1 Important variables for the initial conditions in DCH analysis

	Variables	**Scenario Va**	**Scenario VIa**
1	Volume of RPV lower plenum	39.002 m^3	39.002 m^3
2	Initial diameter of lower head failure	0.59 m	0.59 m
3	Mass of control rod material in the melt	0. kg	3,000. kg
4	Mass of UO_2 (prior to core damage)	16,280. kg	16,280. kg
5	Mass of Zr (prior to core damage)	4,396 kg	4,396 kg
6	Mass of steel in lower plenum	7,599 kg	7,599 kg
7	Coherence ratio multiplier	1.72	1.72
8	Pressure of RCS at vessel breach	17.0 MPa	9.0 MPa
9	Volume of RCS	281.276 m^3	281.276 m^3
10	Temperature of RCS gas at vessel breach	700 K	1000 K
11	Pressure of containment at vessel breach	0.25 MPa	0.25 MPa
12	Temperature of containment at vessel breach	400 K	400 K
13	Volume of containment	44,521.39 m^3	44,521.39 m^3
14	Volume of reactor cavity	244.0 m^3	244.0 m^3
15	Fraction of debris going to sub-compartments	0.175	0.175
16	Volume fraction of sub-compartment	0.01	0.01

Scenarios Va and VIa are determined as important accident sequences for the DCH. Scenario Va is a SBLOCA-like wet core, where a crucible is formed with massive relocation. RCS is repressurized by an operator and steam is saturated. Scenario VIa is the same as scenario Va except for partial repressurization by the operator and superheated steam. The containment load is calculated using the TCE (Two-Cell Equilibrium) model described in NUREG/CR-6075. The following variables are determined to be important to the load of DCH: molten UO2 mass at a vessel breach, fraction of oxidized Zr, melt-to-steam coherence ration, and hole size at a vessel breach. To get the distribution of the containment pressure load, Latin Hypercube Sampling technique is used to provide input sets for important uncertain variables in the TCE model. The peak pressure for the scenarios Va and VIa are illustrated in Fig. 3 and 4, respectively. The maximum pressure did not exceed 291 kPa and 318 kPa respectively. These pressures are lower than the design pressure of the SMART containment, which is 342.7 kPa. This means that the SMART containment maintains its integrity when DCH occurs.

Table 2 Important uncertain variables in DCH analysis

	Variables	Scenario Va	Scenario VIa
1	Distribution for molten UO_2 at vessel breach	Best 0.1 mt Max. 3.7 mt	Best 1.5 mt Max. 6.0 mt
2	Distribution for fraction of oxidized Zr	Best 40 % Max. 60 %	Best 40 % Max. 60 %
3	Distribution for coherence ratio	Standard deviation 0.3	Standard deviation 0.3
4	Distribution for containment failure pressure	Fragility curve of the reactor containment	Fragility curve of the reactor containment

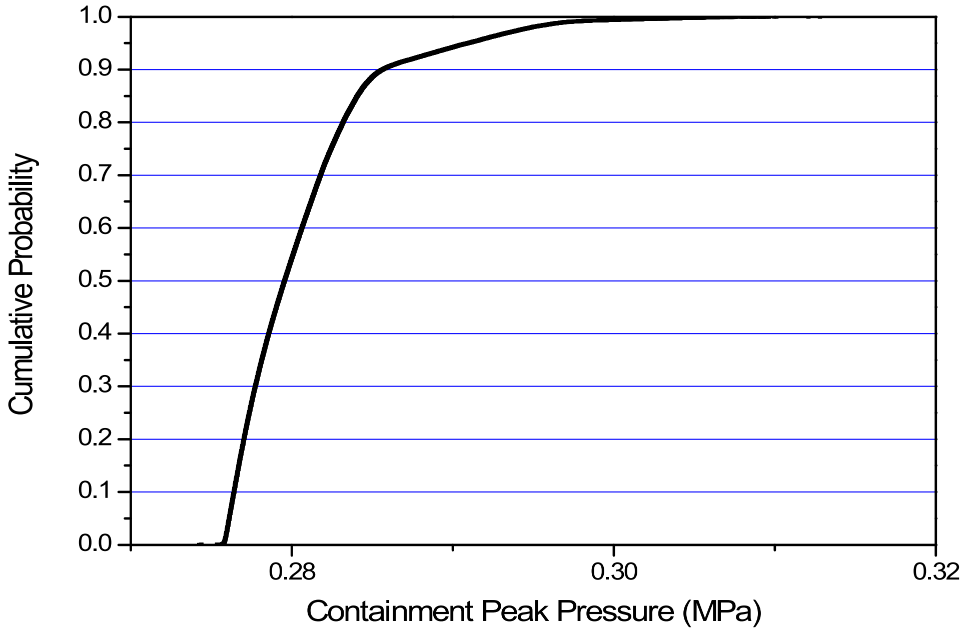

Fig. 3 Containment Peak Pressure (Scenario VIa)

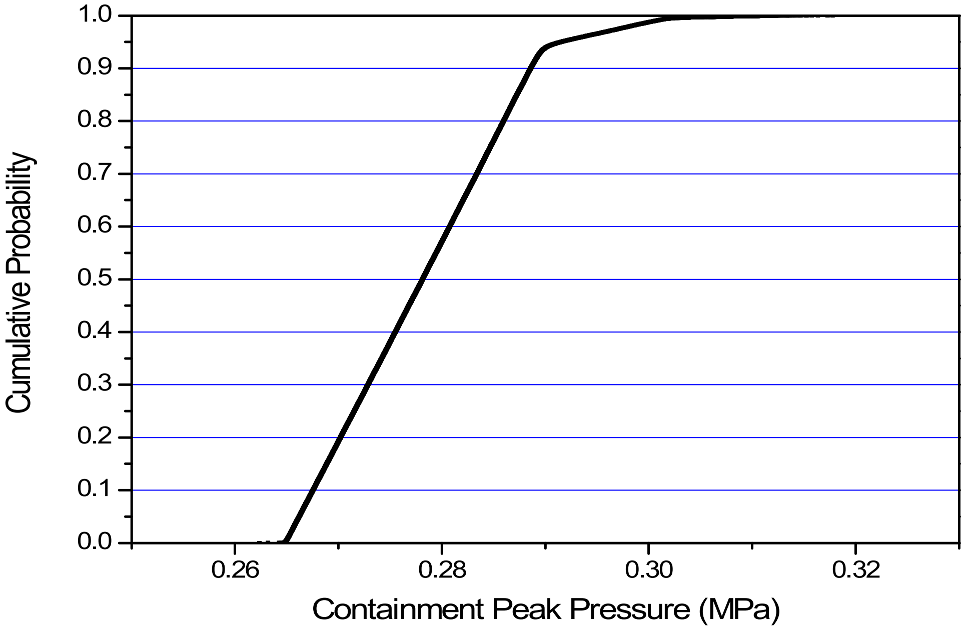

Fig. 4 Containment Peak Pressure (Scenario VIa)

HYDROGEN DISTRIBUTION AND COMBUSTION

Hydrogen burn, especially hydrogen detonation, is an important concern during severe accident progression. When 100% fuel cladding metal-water reaction occurs in SMART, 190.9 kg of H_2 is generated. If H_2 is released into the containment atmosphere and distributed uniformly, the average hydrogen concentration becomes 5.5 %. The inner structure of SMART containment is relatively simple, and it is believed to be easily well mixed uniformly. However, the hydrogen behavior within the containment was evaluated using the MELCOR code[5]. Containment was divided into 26 compartments in the MELCOR model. The hydrogen releases into the annular compartment (CV860) for LOCA, and the reactor draining tank compartment (CV840) for the general transient. Calculations showed that hydrogen concentration did not exceed 10% temporarily for the small LOCA and general transient as shown in Fig. 5 and 6. Even though the local hydrogen concentrations did not exceed 10% by volume, 4 small PARs are considered to install in upper reactor annular compartment (CV814) and 4 small PARs are also considered to install in the upper containment compartments (CV884 and CV889).

The maximum pressure load from hydrogen burn is calculated with the assumption of a 100% metal-water reaction and adiabatic isothermal complete burn. Fig. 7 shows the AICC pressure for SMART. The maximum pressure due to the hydrogen burn is determined as 231.4 kPa which is much below the design pressure of the SMART containment, which is 342.7 kPa.

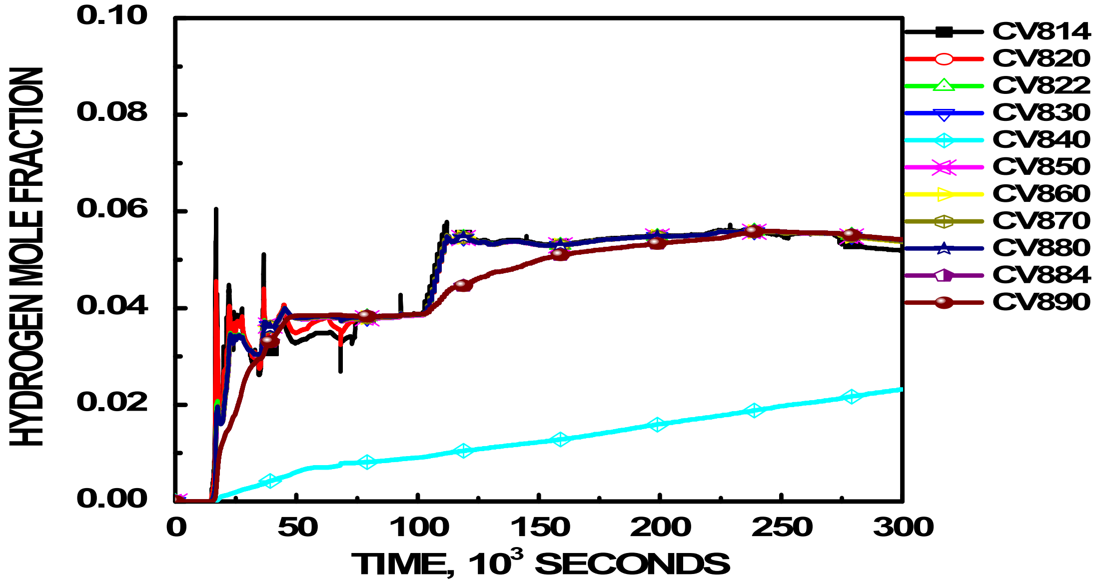

Fig. 5 The hydrogen concentrations at the various compartments for small LOCA before PAR installation.

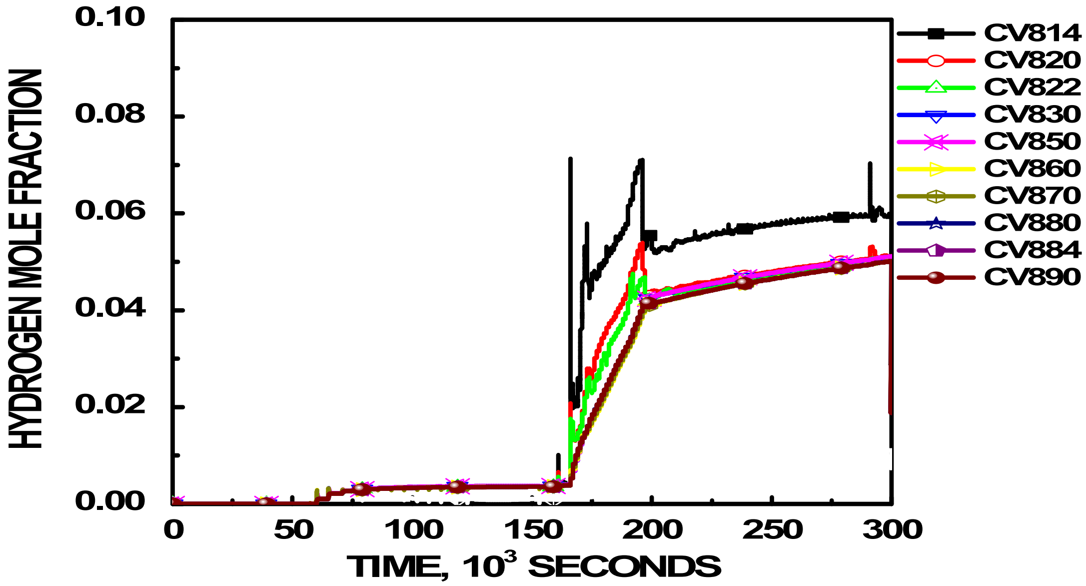

Fig. 6 The hydrogen concentrations at the various compartments for general transient before PAR installation

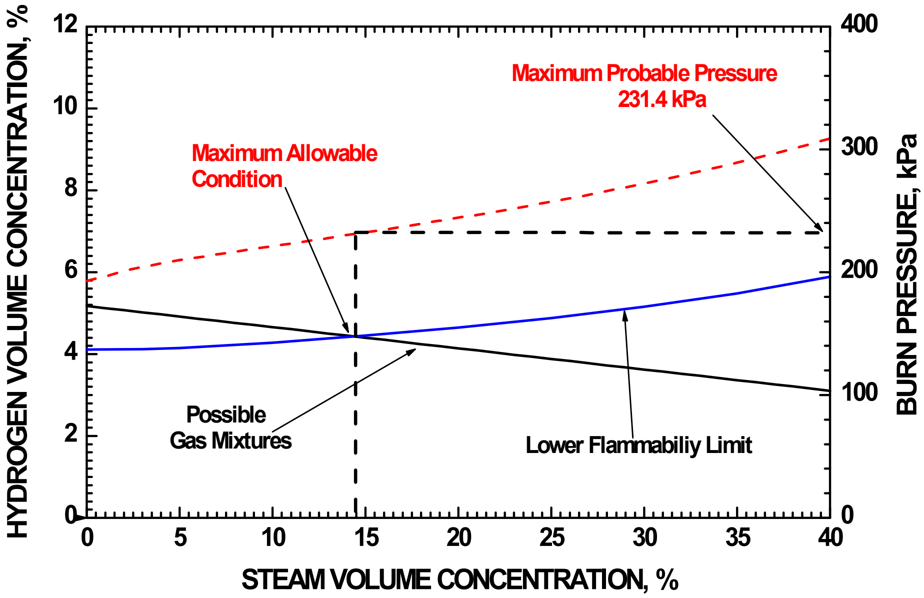

Fig. 7 The flammability limit of hydrogen and AICC pressure

CONCLUSION

An integral pressurized light water reactor, SMART developed by KAERI, is under regulatory review for the standard design. SMART has various features for severe accident mitigation. These features are cavity flooding system, safety depressurization system, and hydrogen control system. The potential of external reactor vessel cooling was evaluated and it is concluded that the integrity of the reactor vessel was maintained by the external reactor vessel cooling when the cavity flooding system worked successfully. The load from direct containment heating was evaluated using a two-cell equilibrium model. The pressure due to DCH was always below the containment design pressure. Hydrogen concentrations were calculated at various locations in the containment. The hydrogen concentration is maintained below 10% at most locations. At some places the concentration exceeded 10% temporarily but the flammable condition was not achieved for that period. The AICC load from all hydrogen burn at once was also evaluated, and it was below the containment design pressure. Based on the results of these evaluations, we concluded that the reactor containment building of SMART performs its function and maintains its integrity during severe accident progression.

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