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Severe Accident Analysis for Wolsung Nuclear Power Plants

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Abstract

Severe accident analysis has been performed for the Wolsung nuclear power plants in Korea to investigate severe accident phenomena of CANDU-600 reactors as a part of Level II PSA study. The accident sequence analyzed in this paper is loss of active heat sinks (LOAH) which is caused by loss of off-site power, diesel generators, and DC power. ISAAC (Integrated Severe Accident Analysis Code) computer code developed by KAERI (Korea Atomic Energy Research Institute) was used in this analysis. This paper describes the important thermal-hydraulics and source term behaviors in the primary system and inside containment, and the failure mechanisms of calandria vessel and containment. In addition, some insights for accident management program (AMP) are also given.

I. Introduction

CANDU reactors possess two inherent supplies of water surrounding the core, the moderator that surrounds the fuel channels and the shielding water that surrounds the calandria. Recent research activities revealed that these design features can function as the unique heat sinks to cool the fuel in the event of a total loss of coolant and emergency cooling water, and delay or retain the melt in the calandria vessel[1].

At present, three CANDU plants are under construction and KEPRI (Korea Electric Power Research Institute) is performing Level II PSA. Several accident sequences were analyzed to construct containment event trees (CETs) and determine success criteria during the PSA study. The selected accident sequences are loss of active heat sinks (LOAH), large and small break LOCA, steam generator tube rupture (SGTR), and in-core pressure tube rupture (PTR). The analysis was performed using ISAAC computer code developed by KAERI[2].

According to the analysis, the overall accident progression and phenomena show a similar trend for all accident sequences, and LOAH comprehensively describes the failure mechanism of calandria vessel and containment among all accident sequences. Thus, LOAH is regarded as the representative accident sequence in this paper.

This paper describes the important thermal-hydraulic variables for LOAH sequence, such as the primary system pressure and temperature, calandria vessel failure, and the fuel temperature in the primary loops. After a failure of the pressure tube, the amount of molten corium, which is relocated to the calandria, the calandria vault, and to the basement, is tracked. The distribution of CsI and noble gases inside containment are also provided. The major key events of LOAH sequence are summarized and compared with those of station blackout (SBO) sequence in PWR plants. SBO is the worst accident sequence in typical PWR plants, which is comparable to LOAH in CANDU plant. Finally, the technical insights obtained from the study and considerations for accident management program for CANDU plants will be suggested.

II. Analysis Procedure

To simulate the horizontal core, six representative fuel channels are defined in each loop:three channels at the broken and unbroken steam generator loops, respectively. Each representative fuel channel has the different power profile at the different elevations, and the user specifies the power distribution as an input. The containment is nodalized into twelve compartments including the dousing tank, calandria vault, and two end shields. Containment failure pressure of 432 kPa (63 Psia) is assumed.

To simulate LOAH sequence, a transient is assumed to occur by loss of off-site power (class IV Power) with subsequent loss of diesel generators and DC power. As a result, steam generator feed water, calandria moderator cooling, shield cooling for calandria vault and end shields, and other active safety features are not operable. The containment sprays are assumed to be inoperable too. Therefore, the heat sinks which could remove heat from the primary system are the initial water inventory in the steam generators, moderator in the calandria, and the water in the calandria vault.

The liquid relief valves (LRVs) are assumed to open at the start of event. Main steam isolation valves (MSIVs) which are located in the steam lines close at 0 second. However, main steam safety valves (MSSVs) open and close at the set point. The code running time for the analysis is 300,000 seconds (3.5 days).

III. Discussion of Analysis Results

The primary heat transport system pressure, as shown in Figure 1, decreases due to the reactor scram and the heat transfer to the steam generators. As the steam generator loses its inventory, the PHTS pressure increases and reaches the set point of the degasser condenser tank (DCT) relief valve (11.37 Mpa(a), 1650 psia) at 2.5 hours after the initiation of the accident. At about 6.5 hours, the pressure tubes fail due to high tube wall temperature, thus, the pressure drops down and balances with the calandria pressure. Even though loop 1 (unbroken) and loop 2 (broken) are modeled separately, they behave in the same manner due to their same conditions.

The system inventory in each loop is given in Figure 2. Initially, it is about 33 tons and increases to 43 tons due to the inflow from the pressurizer. After the primary system gets over-pressurized, the coolant is discharged through the DCT relief valves to the containment. The PHTS water inventory of 3.5 tons is left at 4 hours and then gets depleted following the failure of pressure tube.

The pressure in the unbroken and broken steam generator are shown in Figure 3. The heat transferred from the primary system increases the secondary side pressure to the set point of the MSSV (5.11 Mpa, 742 psia) until the pressure tubes fail at 6.5 hours. After that, the steam generator pressure decreases due to the reverse heat transfer to the primary side and then does not vary much after the completed loss of PHTS water inventory. Though the four steam generators in the plant are modeled separately in the code, they show the identical system behavior because the boundary conditions are the same. Once steam generator water inventory is depleted at 2.4 hours into the accident, the PHTS heats up and the pressure increases (refer to Figure 1).

Figure 4 shows the average and maximum core temperature in loop 1 and loop 2. Since the maximum temperature shows the hottest core temperature in the core at a certain time, the temperature distribution over 2000K between 8 and 16 hours and after 58 hours, indicates that the core experiences melting. Around 6.5 hours, the corium starts being relocated into the bottom of the calandria. As the molten material drops to the calandria moderator, the molten jet will break up into particulates resulting in quenching and zircaloy oxidation.

The hydrogen mass generated from the loop 1 is shown in Figure 5. Note that three quarters of hydrogen is generated before 20 hours. The in-core hydrogen mass includes hydrogen generated from the oxidation of fuel clad and pressure tube, while the total generation also includes hydrogen generated from the oxidation of calandria tubes. The total amount of hydrogen generated from the core is about 170 kg.

Figure 6 illustrates the moderator inventory in the calandria. Since the calandria cooling is not available, the moderator temperature and pressure increases due to the heat transferred from the primary heat transport system. When the calandria pressure exceeds the containment pressure by 140.5 kPa (20 Psid), the calandria rupture disc fails at 4 hours and the calandria loses its moderator. As the water inventory decrease, the fuel channels located at the upper part of calandria will be heated up and face melting (Figure 4). The initial inventory of 217 tons dries out at 15 hours into the accident. The sudden mass jump around 41 hours occurs following the failure of calandria bottom which is submerged in the calandria vault water. This water mass decreases, as the corium, relocated in the calandria vault floor, interacts with water outside the calandria.

The corium mass distribution along the accident progression is illustrated in Figure 7. After the failure of pressure tubes, about 126 tons of corium is transported into the calandria between 7 hours and 20 hours, and then into the calandria vault following the calandria vessel failure at 41 hours. This amount of corium ablates the concrete floor in the calandria vault from 54 hours. The ablated thickness of concrete indicates that calandria vault floor melts through in 75 hours (Figure 8).

Figure 9 shows the containment pressure. The initial pressurization until 14 hours is caused by both the steam inflow through the degasses condenser tank (DCT) relief valve and moderator evaporation after corium relocation into the calandria. After the depletion of calandria moderator around 14 hours, the containment pressure temporarily decreases for a short period until steaming is produced from the calandria vault. The containment fails at 26 hours after corium relocation into the calandria vault. The sharp peak around 42 hours is due to steam generation in the containment basement after calandria vault floor melts through.

The water level in the calandria vault is shown in Figure 10. The calandria vessel fails around 41 hours when the calandria becomes uncovered from outside after molten corium is relocated into the calandria.

Figure 11 shows the mass fraction of CsI in the calandria and containment. As CsI mass is released from the core channels, most of it is deposited on the PHTS heat sinks, containment walls, and in the water pools. Initially about 24% of CsI is deposited on the calandria vessel wall. However, as the calandria wall temperature increases above 1000K after the calandria is uncovered in the calandria vault, most of CsI which is deposited on the wall revaporized and subsequently is transported to the containment. Unlike CsI, most of noble gases is immediately transported to the containment.

Figure 12 shows the mass fraction of noble gases and CsI released to the environment. As shown, approximately 95 % of noble gases is released to the environment, while only about 2.8 % of CsI is released to the environment.

IV. Technical Insights and Considerations for AMP

As mentioned in the previous section, LOAH is the most severe accident sequence where no safety functions are operable, which is comparable to SBO sequence in PWR plants. In the event of an SBO accident in a typical PWR plant, the reactor vessel fails about 4 hours into the accident if any safety functions are not operable[3]. On the contrary, it takes about 26 hours until the containment fails, 41 hours until calandria fails, respectively, since moderator and calandria cooling water can function as inherent heat sinks to cool fuel and delay the calandria failure. These design features provide operators with enough time to cope with accident in comparison with PWR plants. Major key events for LOAH sequence are summarized and compared with those of SBO sequence for typical PWR plant (UCN 3&4) in Table 1.

The containment failure pressure is relatively low in comparison with that of PWR plant because design pressure and free volume of CANDU plant is one-third (124kPa(g)) and 60% of PWR, respectively. Thus, the containment failure occurs earlier in CANDU than in PWR. For this reason, it is expected that containment over-pressurization is more critical and more serious than that in PWR. Therefore, the containment heat removal system such as dousing spray (short-term heat sinks) and local air coolers (long-term heat sinks) will be a more important factor than in PWR to reduce the containment failure probability for the steady pressurization sequence. Therefore, particular attention is required for these systems to maintain operability.

Another interesting point is the mass of Zircaloy in the core. Since most of the incore structure in CANDU is made of Zircaloy except the fuel itself, the mass of Zircaloy is about 1.8 times longer than that of PWR. Therefore, the hydrogen concentration in containment is about 3 times higher than that in typical PWR considering the containment free volume ratio, if all of the Zircaloy reacts and generates hydrogen. However, it is not expected to challenge the containment integrity by hydrogen explosion because 44 hydrogen ignitors are installed to reduce hydrogen concentration by burning it as soon as the concentration reaches the flammable limit.

V. Conclusion

Severe accident analysis was performed for Wolsung plants, CANDU-600, which are under construction in Korea. Through the analysis of several selected accident sequences, the safety of the Wolsung plants to severe accidents has been evaluated, and the safety level has been identified as acceptable. The results of this analysis were also used to construct containment event trees (CETs) and determine success criteria in performing full scope Level II PSA. The results of PSA study indicate that Wolsung plant provides considerable response to any challenge from the selected severe accident sequences. In addition, technical insights to comprehend the overall severe accident phenomena have been derived and considerations for establishing accident management program (AMP) of CANDU plants are provided.

References

1. Severe Accident Phenomena and Research for CANDU Reactors, L.A. Simpson, P.M. Mathew, A.P. Muzumdar and D.B. Sanderson, AECL, Canada.
2. Development of Computer Code for Level 2 PSA of CANDU Plant, KAERI/RR-1573/95, KAERI, 1995.
3. A Study on Effectiveness of Inherent Heat Sinks and Their Cooling System During Loss of Feed Water Sequence at Wolsung Plants, PSA 96, Dong Ha Kim, KAERI.
4. Final Safety Analysis Report for Wolsung NPP 2/3/4, KEPCO, 1995.
5. Level 2 PSA for PHWR (Interim Report), KEPCO, 1996.

Table 1. Summary of Key Events

CANDU (Wolsung 2/3/4)		PWR (UCN 3/4)	
Events	Time (hr)	Events	Time (hr)
Fuel channel uncovery	2.92	Core uncovers	0.82
Fuel channel dryout	4.0		
Fuel bundle failure	6.57	Fuel melts	1.6
calandria dryout	14.3		
Calandria failure	41.4	Reactor faisl	3.6

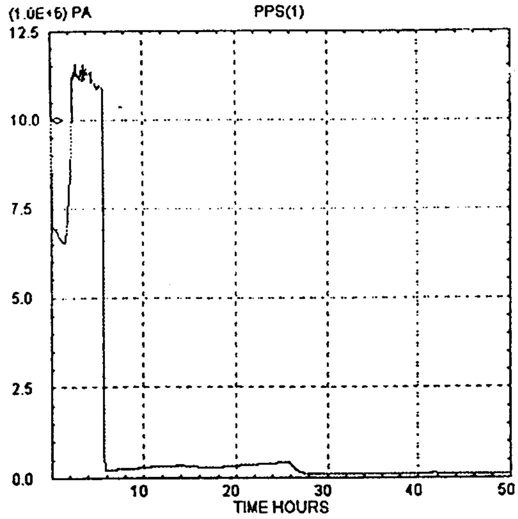

FIGURE 1. PHTS PRESSURE

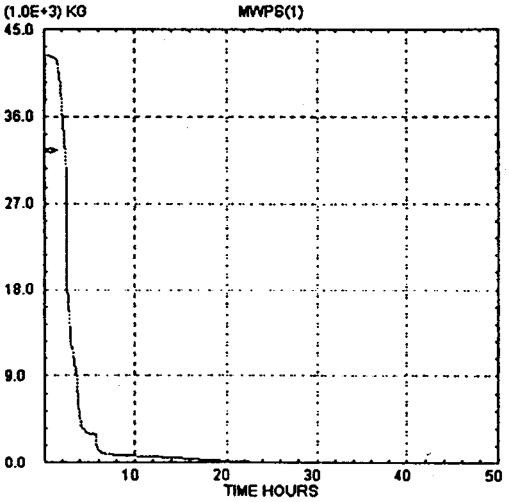

FIGURE 2. PHTS WATER INVENTORY

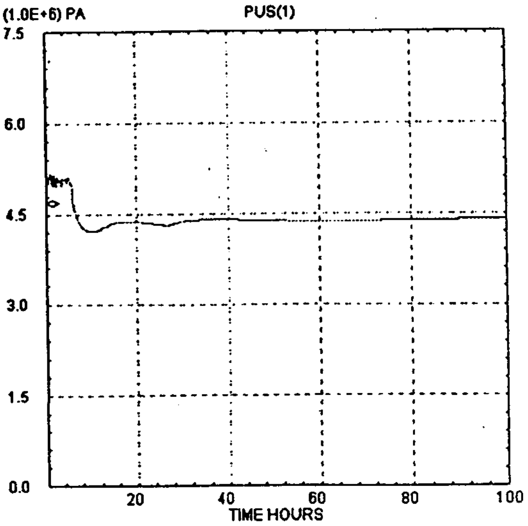

FIGURE 3. STEAM GENERATOR PRESSURE

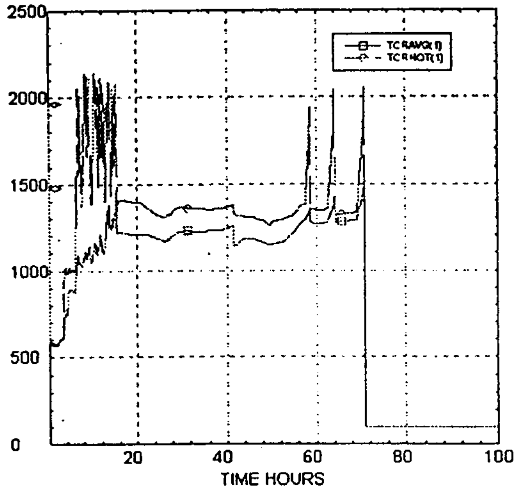

FIGURE 4. CORE INVENTORY

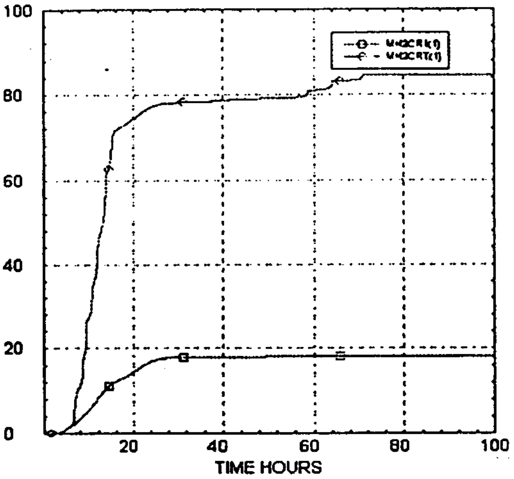

FIGURE 5. HYDROGEN MASS

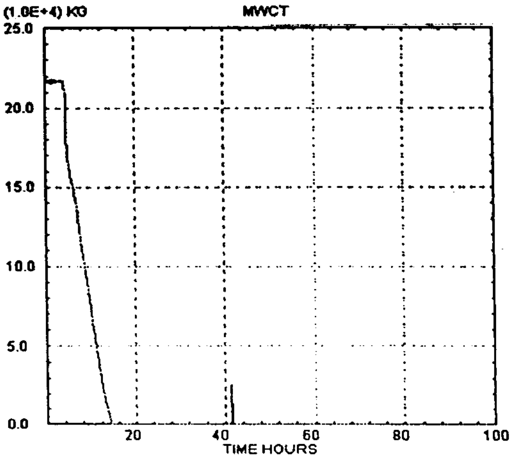

FIGURE 6. WATER MASS IN THE CALANDRIA

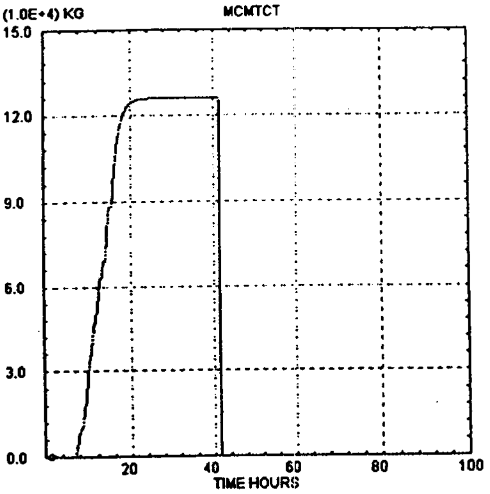

FIGURE 7. CORIUM MASS IN THE CALANDRIA

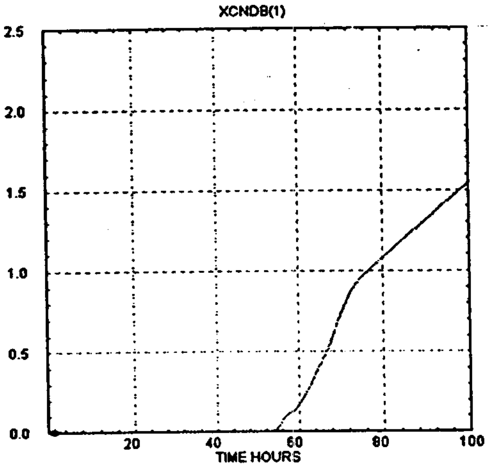

FIGURE 8. CONCRETE ABLATION THICKNESS ON THE CALANDRIA VAULT FLOOR

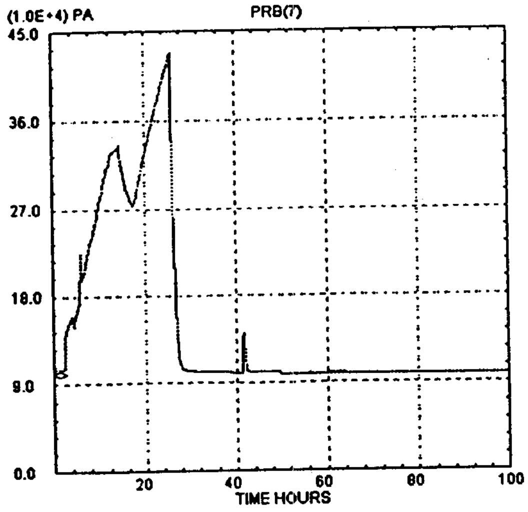

FIGURE 9. CONTAINMENT PRESSURE

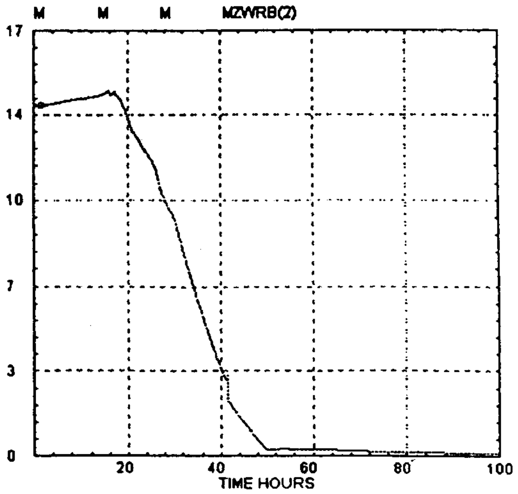

FIGURE 10. WATER MASS IN THE CALANDRIA VAULT

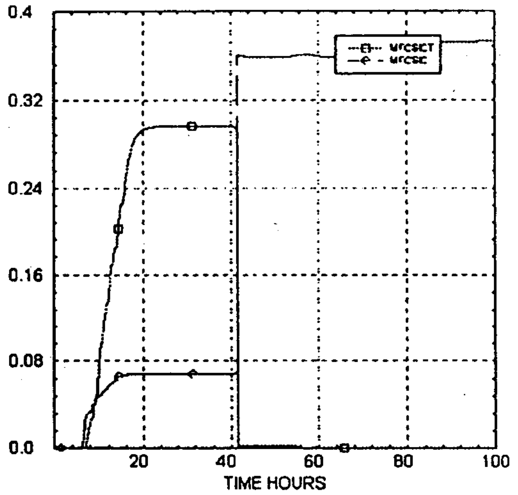

FIGURE 11. MASS FRACTION OF CsI IN THE CALANDRIA AND CONTAINMENT

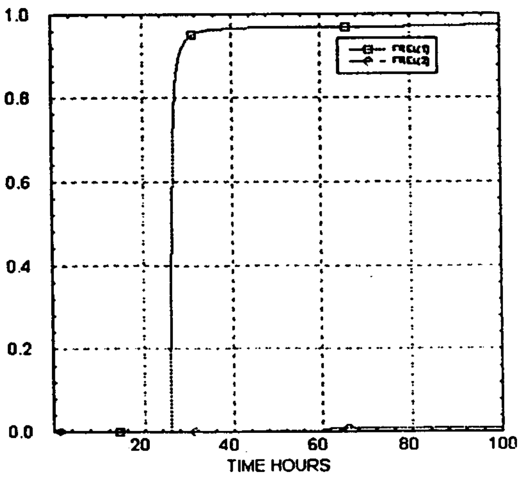

FIGURE 12. MASS FRACTION OF NOBLE GASES AND CsI RELEASED TO THE ENVIRONMENT