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Station Blackout Initiated Event Chronology in LWR/HWR NPP

Soo Yong Park*, Kwang Il Ahn
Korea Atomic Energy Research Institute, 989-111 Daedeokdaero, Yusong, Daejeon, 305-353
** Corresponding Author: sypark@kaeri.re.kr*

1. Introduction and Methodology

Since the crisis at Fukushima nuclear power plants, a severe accident progression has been recognized as a very important area for an accident management and emergency planning. The purpose of this study is to investigate the comparative characteristics of a severe accident progression among the typical pressurized water reactor (PWR), boiling water reactor (BWR) and pressurized heavy water reactor (PHWR). The OPR 1000-like (ABB-CE type PWR), Peach Bottom-like (BWR/4 RCS with a MARK I Containment), and Wolsong1-like (CANDU6 type) plants are selected as reference plants of typical 1000 MWe PWR, 1140MWe BWR, and 600 MWe PHWR, respectively.

The design parameters of these plants are quite different. Some of the major different design features of CANDU6 plant from other light water reactors, in terms of a severe accident, are that the plant adopts a duel primary heat transport system and has an additional amount of cooling water in the calandria vessel (calandria tank, CT) and calandria vault (CV). Another feature is that the CT is always submerged in water because the CV is flooded during normal operation. The containment (reactor building, R/B) failure pressure of the CANDU6 plant is considerably lower than that of the typical PWR or BWR4/MARK-I. The containment vessel free volume of MARK-I is much smaller than that of the PWR or CANDU6 plant. Since there is no steam generator (SG) or passive cooling system, the amount of cooling water inventory in BWR4 is relatively less than other plants. Meanwhile the minimum available time of battery power against station blackout (SBO) accident is different among plant types: six hours for BWR4 and four hours for 1000MWe PWR. Therefore, plant responses against the severe core damage scenarios like Fukushima accident are expected to be much different. By identifying plant response signatures, the appropriate correction actions can be developed as part of severe accident management.

A SBO scenario, where all off-site power is lost and the diesel generators (DGs) fail, is simulated as an initiating event of severe accident sequence. The scenario has been taken as a very low frequency, but high-risk accident event. All current generation reactors are designed to cope with SBO only partially. For the simulation of SBO, all the emergency core cooling (ECC) systems, auxiliary feedwater (AFW) system except for turbine driven pump (TDP), and the containment spray are assumed to be inoperable for 1000MW PWR. All the ECC systems, moderator cooling system, end-shield cooling system (ESC), and local air coolers (LACs) are assumed to be inoperable to simulate the severe core damage case for CANDU6 plant. All the ECC systems except for high pressure cooing injection (HPCI) and reactor core isolation cooling (RCIC), reactor water cleanup, standby liquid control, low pressure cooling injection (LPCI), and core spray are assumed to be not working for BWR4/MARK1 plant.

The thermal hydraulic and severe accident phenomenological analyses for the evaluation have been performed using the PWR and BWR versions of MAAP (Modular Accident Analysis Program) 4.06[1] for the PWR and BWR4/MARK1 plants, respectively. On the other hand, ISSAC (Integrated Severe Accident Analysis Code for the CANDU Plants) 4.02[2] has been used for the CANDU6 plant. The ISAAC program has been developed based on MAAP4. Therefore, most basic thermal hydraulic or radiological models of those two computer codes are similar. Only the plant specific system models are different from each other.

2. Results and Conclusions

Following the SBO accident, the core is uncovered after SGs have dried out. Since there is no recovery action after accident initiation, the fuel channel rupture (4.1 hours), corium relocation (6.4 hours), water dryout in the calandria (12.8 hours), containment (R/B) failure (28.2 hours), and CT failure (47.0 hours) are occur sequentially in CANDU6 plant. In the likely manner, the core melt start (10.2 hours), corium relocation (11.7 hours), reactor vessel failure (12.0 hours), and containment failure (113.1 hours) also occur in 1000MW PWR. Meanwhile, the core melt start (8.9 hours), corium relocation (11.8 hours), reactor vessel failure (12.3 hours), and containment failure (17.9 hours) occur consecutively in BWR4/MARK1. The summary of event occurrence times from the MAAP PWR/BWR and ISAAC simulation for the SBO scenario is represented in Table 1.

Based on the ISAAC and MAAP calculations, the results show that the accident progression of CANDU6 type reactor until corium relocation is considerably earlier than those for PWR or BWR4. These result from the design differences among the three plants. As stated above, the 1000MW PWR is equipped with turbine driven AFW systems and MSSVs which can provide a secondary feed and bleed function for the SBO scenario using battery power. In the meantime, BWR4/MARK1 plant has mitigation systems of HPCI and RCIC against the SBO accident. The systems are operable with no electric power other than battery power. They are designed to inject substantial quantities of water into the reactor while it is at high pressure by TDP.

On the other hand, the failure time of CT in CANDU6 is greatly delayed compared to the others. There is an assumption that the relocated molten corium on the calandria bottom would be coolable in the CANDU6 plant because the in-vessel corium retention, so-called, by an external vessel cooling might be very feasible [3]. The delay is due to the additional cooling water in the CT and CV, and the lower volumetric decay heat power of the molten corium on the CT bottom. Moreover it has a very large heat transfer area to the outside water of the CV through the vessel wall. Another advantage, in terms of calandria integrity for CANDU6 plant, is that the system always maintains a low pressure at the time of a CT failure since the rupture disks are opened during the moderator evaporation. These increase the feasibility of the in-vessel corium retention through an external vessel cooling. In contrast with CT integrity, the calculation results show that the containment failure of CANDU6 plant occurs considerably earlier than that of PWR due to the lower failure pressure of the containment (R/B). The most vulnerable design in terms of containment integrity is a MARK-I type plant, the failure occur very earlier due to very small containment volume. Based on these calculations, CANDU6 has an advantage in maintaining its calandria integrity, and 1000MW PWR has an advantage in its containment integrity during the SBO accident.

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REFERENCES

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[3] S.Y. Park et al, “An Investigation of an In-vessel Corium Retention Strategy for the Wolsong Pressurized Heavy water Reactor,” Nuclear Technology, 158, 109 (2007).

Table 1. Comparison of the Accident Progression of the 1000MW PWR, CANDU6, and BWR4/MARK1 for a Station Blackout Accident (unit: hours)

Event	1000MW PWR	CANDU6	BWR4/MARK1
Battery power depleted	4.0	N/A	6.0
PSV (or LRV) open	7.3	2.6	< 0.1
SG dryout	7.5	2.5	N/A
Core uncovery start	8.5	3.7	7.7
Core melt start(PWR, BWR4) or fuel channel rupture (CANDU6)	10.2	4.1	8.9
Corium relocation start	11.7	6.4	11.8
RV (or Calandria vessel) dryout	11.9	12.8	12.0
RV (or Calandria vessel) failure	12.0	47.0	12.3
Containment (or R/B) failure	113.1	28.2	17.9