COMPARATIVE STUDY OF FILTERED CONTAINMENT VENT SYSTEM APPLICATION ON PLWR AND PHWR

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The comparative fission product behaviors of a severe accident sequence were analyzed for a typical PLWR and PHWR. The OPR-1000 and CANDU6 were selected as reference plants. A station blackout scenario, where all off-site power is lost and the diesel generators fail, was simulated as an initiating event of the severe accident sequence. The analysis is focused on the fission product release from the core, the fission product distribution inside the containment, and the fission product release into the environment. Furthermore, the analysis is performed depending on the assumed operation condition of FCVS. The opening/closing pressure of the FCVS and the operation set-point of the dousing spray system are the major parameters of a containment (or reactor building for CANDU6) pressure response and fission product release characteristics.

I. INTRODUCTION

Since the accident at the Fukushima Dai-ichi nuclear facility, the venting of the containment has become an essential accident management measure for the preservation of its structural integrity during a severe core damage accident in a nuclear power plant (NPP). The basic premise of the containment venting system is that a catastrophic failure of the containment structure can be avoided by discharging steam, air, and incondensable gases like hydrogen into the atmosphere. However, unfiltered containment venting can result in significant radioactive releases into the environment, and these releases may be largely reduced by implementation of filtering systems on the venting lines that have already been integrated in some existing venting systems. Complementary safety evaluations performed after the Fukushima accident have led many countries to consider the implementation of a filtered containment vent system (FCVS) for NPPs in which these are not currently applied as enhancements of the response capability to severe accident situations. In addition, such evaluations have led some countries to consider improvements of existing venting systems and their operating procedures (Ref. 1).

In Korea, for example, the Fukushima accidents triggered a discussion on the need to protect against containment failure by over pressurization, and how to mitigate the uncontrolled release of radioactivity into the environment. Through this process, the requirements will be proposed soon, along with general technical specifications, which are expected to include various aspects of the filtering efficiency such as the decontamination factors, operating periods including the autonomous operation time, passive characteristics, equipment, and system design/performance requirements. No special requirements are expected yet but prevention of aerosol re-suspension and iodine-species revolatilization may be required because these phenomena in FCVS can be long-term main suppliers of radioactive release. Currently, operators at the Wolsong-1 unit CANDU6-type pressurized heavy water reactor (PHWR) finished installing the FCVS at the end of 2012 as a starter during preparation to obtain approval for continued operation after 30 years of operation. The remaining NPP units in Korea are in the process of considering the installation of the FCVS (Ref. 1).

This paper is intended to be an investigation of the comparative characteristics of a fission product source term release or distribution during a severe accident among the typical 1000 MW(electric) PLWR and CANDU6 plants.

II. ANALYSIS METHODOLOGY

The OPR-1000 and CANDU6 plants were selected as typical PLWR and PHWR reference plants, respectively. Some of the major design features of the CANDU6 plants that differ from those of other light water reactors are that the plants adopt a dual primary heat transport system and have an additional amount of cooling water in the calandria vessel and calandria vault. Another feature is that the calandria vessel is always submerged in water because the calandria vault is flooded during normal operation. The reactor building failure pressure of the CANDU6 plant is 0.427 MPa(a) (Ref. 2), which is considerably lower than that of the OPR-1000 (0.963 MPa(a)) (Ref. 3). The reactor building free volume of the CANDU6 (48,000 m^3) is much smaller than that of the OPR-1000 (77,220 m^3). Meanwhile, the minimum available time of battery power against a station blackout accident is about 4 hours for the OPR-1000; CANDU6 has no battery power.

A station blackout scenario (SBO), in which all off-site power is lost and the diesel generators fail, is simulated as an initiating event of a severe accident sequence. All emergency core cooling (ECC) systems, the auxiliary feedwater system except for the turbine driven pump, and the containment spray are assumed to be inoperable for the OPR-1000. To simulate a severe core damage case for the CANDU6 plant, all emergency core cooling systems, the moderator cooling system, end-shield cooling system, and local air coolers are assumed to be inoperable. The SBO scenario is expected to provide the most challenging conditions in terms of in-containment thermal-hydraulic and suspended radioactive species concentration conditions.

For the evaluation, thermal hydraulic, severe accident phenomenological, or radiological analyses have been conducted using the PWR version of MAAP (Modular Accident Analysis Program) 5 (Ref. 4) for the OPR-1000. On the other hand, ISAAC (Integrated Severe Accident Analysis Code for the CANDU Plants) (Ref. 5) has been used for the CANDU6 plant. The ISAAC program was developed based on the MAAP program. Therefore, the most basic thermal hydraulic or radiological models of these two computer codes are similar. Only the plant specific system models are different.

The MAAP and ISAAC codes have features to generically model an FCVS. The FCVS model has the basic functionality required to allow users to model typical filtered containment vent system designs. Fission product filters can be modeled in each containment junction, and the aerosol decontamination factor can be input either as a constant or as a function of the particle size. The FCVS installed at the CANDU6 plant in Korea is an AREVA system (Ref. 6) with a combined venturi scrubber unit, which comprises a high-speed venturi section and a metal fiber filter section. For the analysis of the effectiveness of the FCVS, some assumptions were made for both the OPR-1000 and CANDU6 plants. One of the assumptions was that the FCVS consists of a filter housing, which includes a water pool, two distributed heat sinks to represent the bottom/wall of the water pool, and a lumped (equipment) heat sink to represent the dry filter structural material. The assumed values used for the FCVS geometry and decontamination factors (DF) are shown in Table I.

TABLE I. Assumed FCVS Geometry and Decontamination Factors

Parameters	Values
Total free volume of FCVS	66 m^3
Initial water mass in filter housing	20,000 kg
Volumetric flow rate of FCVS	9.0 m^3/sec at 300 kPa(a)
DF of water pool with venturi scrubber unit	DF=1,000 for particle size > 1.5 μm DF=100 for particle size > 1.0 μm DF=30 for particle size > 0.5 μm DF=10 for particle size > 0.1 μm
DF of metal fiber filter section.	DF=10 for particle size > 0.1 μm
Opening / closing pressure of FCVS	Depending on the assumptions of the sensitivity cases

III. ANALYSIS RESULTS

III.A. Analysis of CANDU6

Table II shows analysis cases for the CANDU6 depending on the assumed operation condition of the FCVS. The opening/closing pressure of the FCVS and the operation set-point of the dousing spray system are the major parameters of the reactor building pressure response and the fission product release characteristics of the CANDU6. No-CFVS is a base scenario case without FCVS operation. The opening/closing pressure of the FCVS-P1 case is the value taken from the severe accident management guidance of the reference plant (Ref. 7), and the opening pressure of FCVS-P2 case is an arbitrarily increased value obtained by doubling the open/close pressure difference of the FCVS-P1 case. In order to minimize the release of fission products generated during the core damage process, the opening time of the FCVS-C3, FCVS-C4 and FCVS-C4a cases are delayed after the cooling water of the calandria vault reaches saturation temperature. Meanwhile, in order to maximize the effectiveness of the spray system, in the FCVS-C4 and FCVS-C4a cases, the dousing spray system starts only after the reactor building pressure has increased sufficiently to reach 0.299 MPa (a). For the FCVS-C4a case, the FCVS is not closed once the vent system is open, which minimizes the peak pressure generated by the molten corium-water interaction in the calandria vault when the calandria vessel fails.

TABLE II. Analysis cases of CANDU6 with the assumed operation conditions of FCVS and Dousing spray system

<table>
<tr><th>Analysis Case</th><th>FCVS Opening Pressure</th><th>FCVS Closing Pressure</th><th>Dousing Spray Operation Set-point</th></tr>
<tr><td>No- FCVS</td><td>N/A</td><td>N/A</td><td rowspan="4">0.115 MPa(a) (16.7 psia)</td></tr>
<tr><td>FCVS-P1</td><td>0.225 MPa(a) (32.6 psia)</td><td rowspan="4">0.151 MPa(a) (21.9 psia)</td></tr>
<tr><td>FCVS-P2</td><td>0.299 MPa(a) (43.4 psia)</td></tr>
<tr><td>FCVS-C3</td><td rowspan="3">0.299 MPa(a)(43.4 psia) after calandria vault water is saturated</td></tr>
<tr><td>FCVS-C4</td><td rowspan="2">0.299 MPa(a) (43.4 psia)</td></tr>
<tr><td>FCVS-C4a</td><td>No Closing</td></tr>
</table>

The plant responses for an SBO accident in the CANDU6 for the analysis cases of FCVS-P1, FCVS-P2, and FCVS-C3 are shown in Figures 1 through 5. Figure 1 illustrates the aerosol mass behavior of CsI in the reactor building. As shown in the figure, the aerosol quantity reaches peak values at approximately 9 hours and 51 hours after accident initiation; the timings of these correspond to the occurrence of the in-core fuel rod damage and the molten corium-concrete interaction phenomena in the calandria vault (Figures 2 and 3). That is, a large amount of fission products are introduced into the reactor building due to fuel rod damage in the reactor core, or due to MCCI in the calandria vault; these fission products are removed by a deposition mechanism, such as gravity settling, or diffusion over time.

Figure 4 illustrates the reactor building pressure behaviors of the analysis cases for the CANDU6. Up to the point at which the FCVS opening set point is reached, the pressure responses are identical. Once the FCVS opening set point is reached, the pressure decreases for the FCVS case, whereas, for the base case, the pressure continues to rise until the reactor building fails at approximately 19.8 hours leading to depressurization. The results of the sequences with the FCVS are as follows.

III.A.1. FCVS-P1 case

This case has the lowest operating pressure; the FCVS opens three times during a period of three days. A significant amount of CsI is released into the environment during the first of the FCVS openings at 6.7 hours (Figure 5), because the core damage is actively in progress (Figure 2), and therefore a large amount of radioactive material is present in the reactor building during this time period. Meanwhile, the second and third openings occur at about 19.8 hours and 42.4 hours, at these times the majority of the fission products of the core damage are deposited, and external release rate owing to MCCI is negligible because MCCI has not yet occurred (Figure 3). At up to 72 hours, the total release fraction of the CsI group is about 1.71E-5.

III.A.2. FCVS-P2 case

The opening/closing pressures are 0.299 MPa(a)/0.151 MPa(a), which double the opening/closing pressure differences compared with the case of FCVS-P1; FCVS opened three times during a period of three days. A significant amount of CsI is released into the environment during the first of the FCVS openings at 9.2 hours (Figure 5) because the core damage is still actively in progress (Figure 2). Meanwhile, the second and third openings occur at about 22.7 hours and 42.2 hours; the external release rate is negligible because most of the CsI aerosol introduced due to core damage is deposited and the MCCI has not yet initiated. The total CsI release fraction reaches about 1.01E-5 at 72 hours.

III.A.3. FCVS-C3 case

The opening/closing pressure are the same as in the case of the FCVS-P2, on condition that, in order to minimize the external release of the fission products generated during the core damage process, the FCVS does not open until the cooling water in the calandria vault reaches saturation temperature. The calculation results show that the calandria vault water reaches saturation temperature at 16.2 hours. Therefore, the vent system is first opened at 16.2 hours and is then closed at 35.0 hours (Figure 4). In this time period, some of the CsI group fission products, which are released from the damaged fuel rods, are released into the environment from 16.2 hours even-though Figure 5 shows the value higher than the release rate of 10^{-7} (Figures 1, 2 and 5). Meanwhile, the second opening occurs at about 41.2 hours, when the calandria vessel fails; however, external release rate is negligible because most of the CsI aerosol introduced due to core damage has been deposited and the MCCI has not yet initiated. The total CsI release fraction reaches about 2.80E-7 at 72 hours.

The CsI release fraction of the FCVS-C3 is reduced by a factor of 36 compared with that of the FCVS-P2 case because there is little external release of the fission products that are generated during the initial core damage. In contrast, the reactor building pressure increases up to about 397 kPa(a) at 12 hours at which the moderator within the calandria vessel is depleted (Figure 4). It can be seen that this peak pressure is close to the reactor building failure pressure of 427 kPa (a) (50 % confidence level, median value). That is, if the reactor building withstands the peak pressure generated at the moderator depletion point, which is a characteristics of the CANDU6 type nuclear power plants, the CsI release fraction is significantly reduced, however, the greater risk lies in the maintenance of the reactor building integrity.

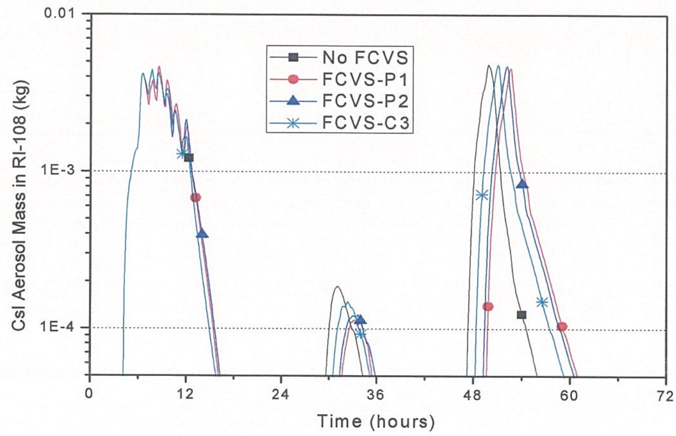

Fig. 1. CsI Aerosol Mass Behavior in Reactor Building for CANDU6 SBO Accident

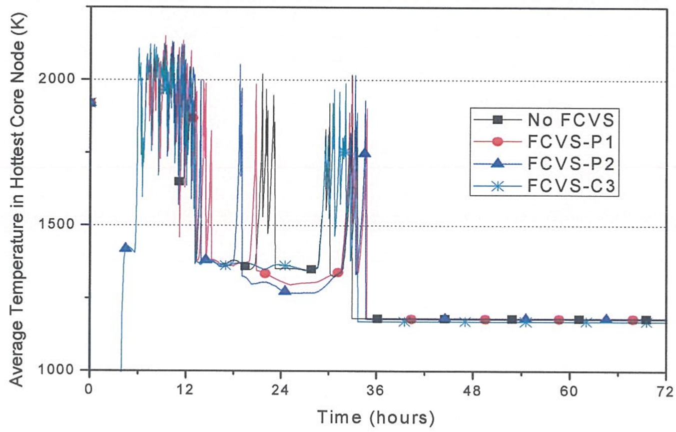

Fig. 2. Hottest Core Node Average Temperature for CANDU6 SBO Accident.

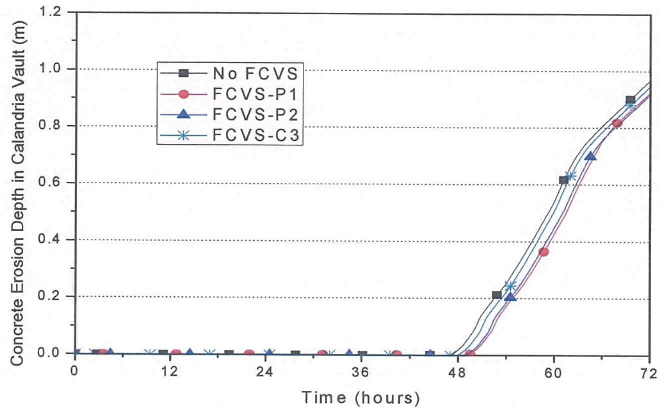

Fig. 3. Concrete Erosion Depth in Calandria Vault for CANDU6 SBO Accident

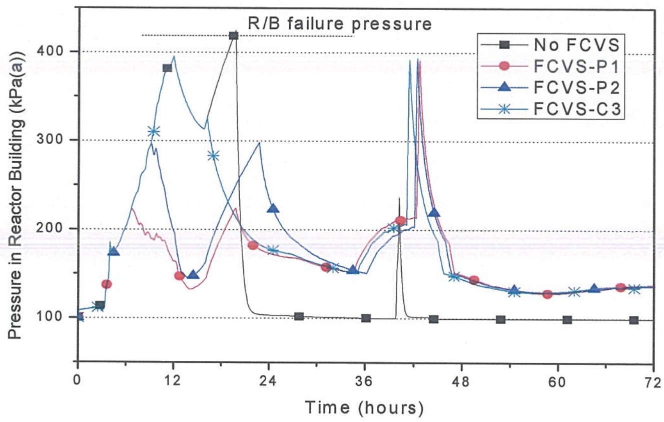

Fig. 4. Pressure Behavior in Reactor Building for CANDU6 SBO Accident

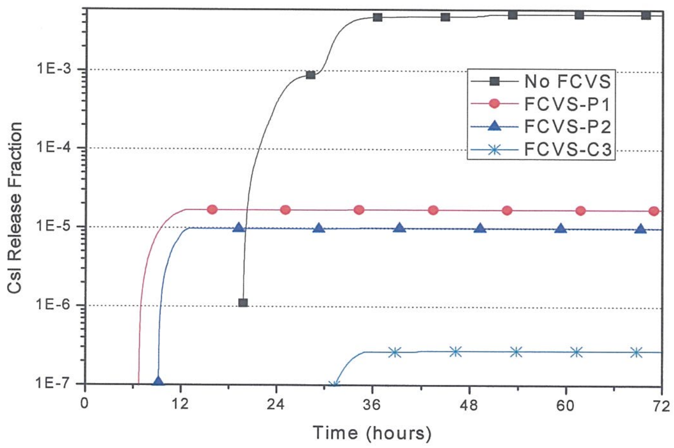

Fig. 5. Fraction of CsI Release into Environment for CANDU6 SBO Accident

Figure 6 shows the reactor building pressure behavior for the cases of FCVS-C3, FCVS-C4, and FCVS-C4a. The vent opening time, the reactor building peak pressure, and the CsI release fraction vary depending on the operating conditions of the dousing spray system, as shown in Table II. The analysis results for the FCVS-C3 are described in the preceding paragraph; the FCVS C4 and FCVS-C4a cases are as follows.

III.A.4. FCVS-C4 case

The opening/closing pressures are the same as those in the FCVS-P3 case, with the condition that the FCVS is opened only after the calandria vault water reaches saturation temperature. Though the dousing spray system is currently designed to operate automatically at the reactor building pressure of 0.115 MPa(a), in order to maximize the effectiveness of the spray system it is assumed that this system will operate at 0.299 MPa(a) in the FCVS-C4 case. The reactor building pressure increases to about 397 kPa(a) at 12 hours for the FCVS-C3 case, but the peak pressure drops to 0.328 MPa(a) for the FVCS-C4 case owing to the efficient operation of the dousing spray system at about 8.6 hours (Figure 6). However, the peak pressure at about 42 hours, generated at the time of calandria vessel breach by corium-water reaction in the calandria vault still reaches 0.402 MPa(a), which can threatens the reactor building integrity. The total release fraction of the CsI groups at up to 72 hours is about 2.90E-7, similar to that of the FCVS-C3 case (2.80E-7).

III.A.5. FCVS-C4a case

The opening of the CFVS and the operation of the dousing spray system are the same as in the FCVS-C4 case; however, for the FVCS-C4a case, the vent system does not close once it has open. As a result, the vent system is opened at 17.3 and 40.9 hours and is closed at 34.3 and 45.2 hours for the FCVS-C4 case, but the system is open at 17.3 hours and remains open. The calculation results show that the peak pressure of the calandria vessel breach time at about 42 hours reaches 0.402 MPa(a) for the FCVS-C4 case; however, this value drops to 0.301 MPa(a) for the FCVS-C4a case because the vent system stay open (Figure 6). The total release fraction of the CsI groups up to 72 hours slightly increases to 4.46E-7 compared to the FCVS-C4 case (2.90E-7); this is beneficial in terms of maintaining the reactor building integrity.

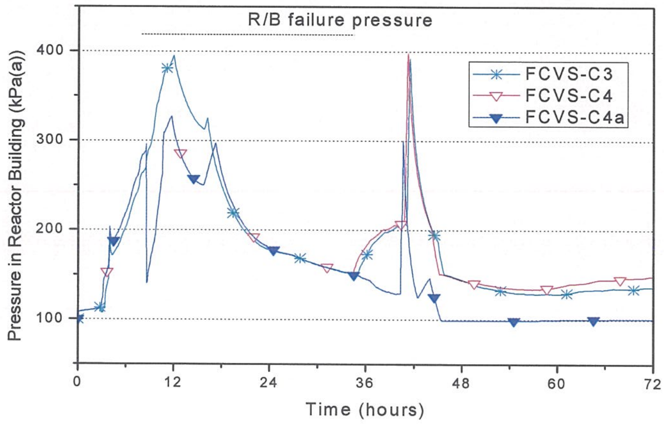

Fig. 6. Pressure Behavior in Reactor Building for CANDU6 SBO Accident

III.B. Analysis of OPR-1000

Table III shows the analysis cases of the OPR-1000 depending on the assumed opening and closing set points of the FCVS. The opening and closing pressures of the FCVS are the major parameters of the containment pressure response and fission product release characteristics. The No-CFVS is a base scenario case without FCVS operation. The opening pressure of 0.4944 MPa(a) (0.3930 MPa(g)) in the FCVS-100 case is the containment design pressure of the reference plant; the closing pressure is 0.3765 MPa(a) (0.2751 MPa(g)) in the FCVS-100 case represent a 30% decreased value compared to the opening pressure, based on the gauge pressure. The opening pressure of 0.6123 MPa(a) (0.5109 MPa(g)) in the FCVS-130 case and 0.6909 MPa(a) (0.5895 MPa(g)) in the FCVS-150 case represent increase of 30% and 50%, respectively, from the containment design pressure.

TABLE III. Analysis cases of OPR-1000 with assumed operation conditions of FCVS

Analysis Case	FCVS Opening Pressure	FCVS Closing Pressure
No- FCVS	N/A	N/A
FCVS-100	0.4944 MPa(a) (71.7 psia)	0.3765 MPa(a) (54.6 psia)
FCVS-130	0.6123 MPa(a) (88.8 psia)	0.4944 MPa(a) (71.7 psia)
FCVS-150	0.6909 MPa(a) (100.2 psia)	0.4944 MPa(a) (71.7 psia)

The plant responses to the SBO accident in the OPR-1000 for the analysis cases are shown in Figures 7 through 11. Figure 7 illustrates the aerosol mass behavior of CsI in the containment annular compartment. As can be seen in the figure, the aerosol quantity has peak values at about 12 hours and 36 hours from accident initiation, the timing of which correspond to the occurrence of the in-core fuel rod damage and the molten corium-concrete interaction phenomena, respectively, in the reactor cavity (Figures 8 and 9). That is, a large amount of fission products are introduced into the containment due to the fuel rod damage in the reactor core, or by the MCCI in the reactor cavity; these fission products are removed over time by deposition mechanisms, such as gravity settling or diffusion.

Figure 10 illustrates the containment pressure response of the analysis cases for the OPR-1000. Up to the point at which the FCVS opening set point is reached, the containment pressure responses are identical. Once the FCVS opening set point is reached, the containment pressure decreases for the FCVS case, whereas, for the base case, the pressure continues to rise until the containment fails at approximately 60.0 hours, leading to depressurization. For the sequences with the FCVS, the results are as follows.

III.B.1. FCVS-100 case

This case has the lowest operating pressure, and the FCVS opened five times in three days. Fraction of CsI release into the environment is approximately the 3.92E-6 of the level of the initial core inventory during the first (22.6 hours) and second openings (33.7 hours) of the FCVS (Figure 11), because most of the fission products introduced by the core damage have been deposited and the MCCI has not yet initiated during this time period. In addition, the total fraction of CsI released reaches a level of approximately 1.49E-5 after the next three openings (45.9, 54.0, and 62.8 hours), because a significant amount of CsI aerosol, caused by the MCCI, remains in the containment atmosphere.

III.B.2. FCVS-130 case

Even at the intermediate operating pressure, the FCVS opened five times in three days. fraction of CsI released into the environment is approximately 9.73E-7 during the first opening (26.1 hours) (Figure 11). The CsI aerosol introduced by the core damage is deposited and the MCCI does not initiate until the first opening. The total CsI release fraction reaches a level of about 1.72E-5 after the next four openings (42.9, 51.4, 59.3 and 68.0 hours), because a significant amount of CsI aerosol caused by the MCCI remains in the containment atmosphere.

III.B.3. FCVS-150 case

This case has the highest operating pressure; the FCVS opened three times in three days. The CsI release fraction into the environment is as low as 8.22E-7 during the first opening (35.3 hours) (Figure 11), because most of the CsI aerosol that resulted from the core damage has been deposited and the MCCI does not initiate. The CsI release fraction is about 1.08E-5 after the next two openings (53.1 and 67.1 hours), because of the aerosol caused by the MCCI.

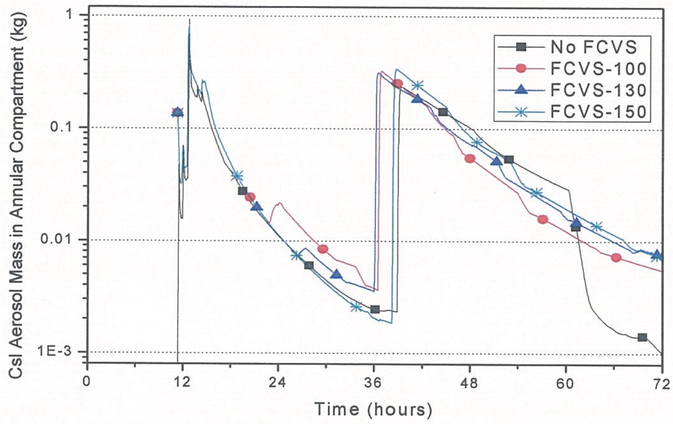

Fig. 7. CsI Aerosol Mass Behavior in Containment for OPR-1000 SBO Accident

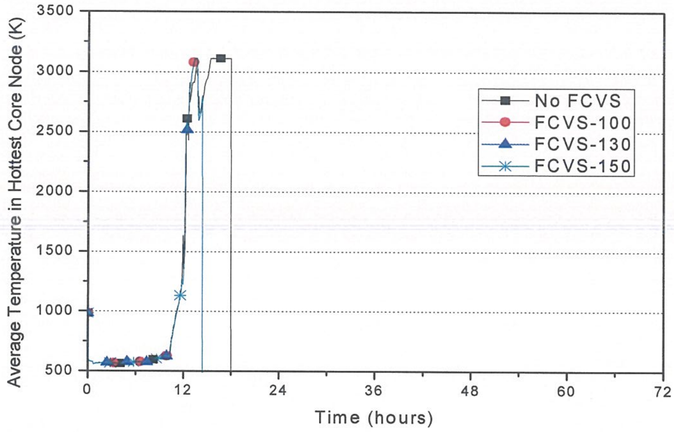

Fig. 8. Hottest Core Node Average Temperature for OPR-1000 SBO Accident

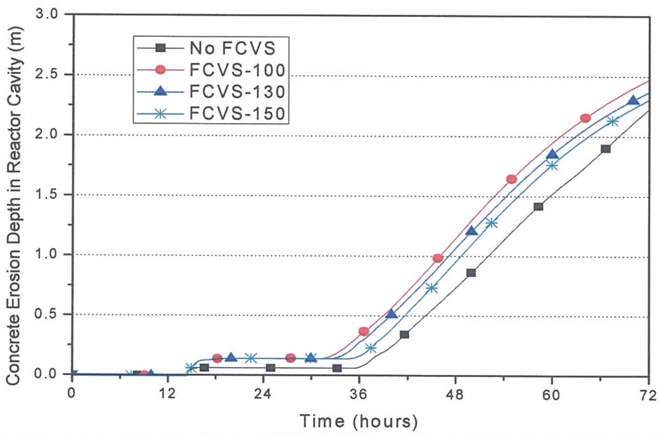

Fig. 9. Concrete Erosion Depth in Reactor Cavity for OPR-1000 SBO Accident

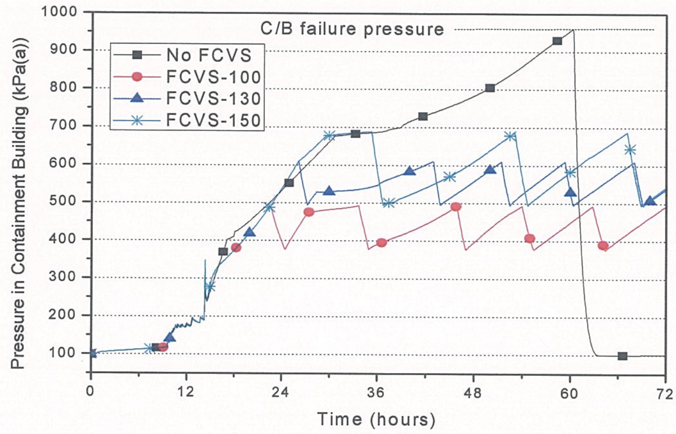

Fig. 10. Pressure Behavior in Containment for OPR-1000 SBO Accident

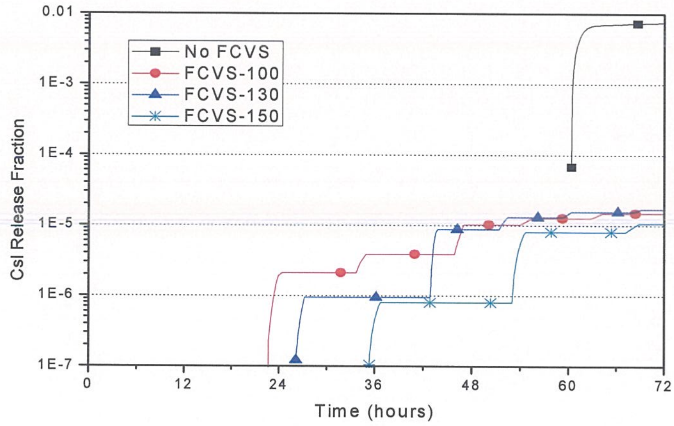

Fig. 11. Fraction of CsI Release into Environment for OPR-1000 SBO Accident

IV. SUMMARY AND CONCLUSION

Based on MAAP and ISAAC calculations, the results show that the calandria vessel failure time of the CANDU6 (39.8 hours) is greatly delayed compared to that of the OPR-1000 (14.3 hours). Without deliberate venting, fission product release into the environment occurs very early for the CANDU6 plant owing to the low reactor building failure pressure; meanwhile, the OPR-1000 has a robust design against a station blackout accident in terms of the fission product release.

The operation of a filtered venting system can have the desired effects only if it is operated as intended. Therefore, the timing of and criteria for a vent opening are important with regard to the potential and mode of the containment failure. Delayed venting at high pressure may increase the likelihood of penetration failure or of catastrophic containment failure. Early venting at a low containment pressure, on the other hand, may lead to unintended early release of the radioactivity prior to the implementing of adequate protection measures for the population. For the radiological consequences to remain acceptable, the venting strategy should be considered only when the radioactivity levels in the containment are sufficiently low. For example, the venting should be carried out to avoid the time period of significant core degradation or MCCI, if possible. The fission product release into environment is sensitive to the MCCI rather than the core degradation for OPR-1000; in contrast, it is sensitive to the core degradation than the MCCI for CANDU6.

A proper mitigating operation using the filtered venting systems for OPR-1000 and CANDU6 has the potential to prevent a containment failure or to minimize accident consequences. One challenge in implementing a venting strategy is to assess the actual pressure margin to containment failure. The OPR-1000 has a sufficient margin to the ultimate containment failure pressure so as to delay the venting operation, but CANDU6 does not. Radioactivity can be significantly reduced depending on the venting strategy and the effective dousing spray operation for CANDU6; however, this strategy should also take into account the reactor building integrity.

The limitations of this analysis result from uncertainty regarding severe accident phenomena, including fission product release and transport, molten core concrete interaction, or aerosol modeling. The uncertainties are inherently very large for an analysis of the fission product behavior during a severe accident. Moreover, no detailed plant specific data on the decontamination factors were available, and thus four levels of decontamination factors were assumed depending on the particle sizes, as shown in Table I. Therefore, the obtained numerical value of the fission product release rate is not necessarily reliable in an absolute manner, though a relative parametric comparison on a similar basis would be very useful.

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