Analysis of Fukushima Unit 2 Accident by Considering the Operating Condition of RCIC System and Torus Room Flooding

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ABSTRACT

The severe accident of Fukushima Daiichi occurred on March 11, 2011, which originated from an earthquake and tsunami. Core degradations were expected in Units 1, 2 and 3 from the results of Phase I of the OECD/NEA BSAF Project. Among the three plants, it was estimated that the core degradation of unit 2 is less serious. The operation of the reactor core isolation cooling (RCIC) system in unit 2 during the initial stage of the accident was expected to reduce the core damage because it removes the decay heat in the reactor pressure vessel. During normal operation, the steam from the main steam line drives the RCIC turbine and the mixture of steam and liquid water flow into the wetwell. The liquid water in the wetwell or condensate storage tank was supplied to the downcomer by using the energy from RCIC turbine. However, the efficiency of the RCIC pump was not clear when a mixture of steam and liquid water was supplied into the RCIC inlet. The enthalpy of the outlet of the RCIC pump can also be varied according to the efficiency of the RCIC pump. The energy in the outlet flow after passing the RCIC turbine can affect the pressure of the wetwell and drywell, and thus it can be important to analyze the accident. Furthermore, it was expected that torus room flooding occurred in the case of unit 2. The energy in the wetwell water can also be transferred to the water in the torus room through conduction. In this research, the accident analysis of Fukushima Unit 2 was conducted by considering the RCIC turbine efficiency and degree of torus room flooding.

KEYWORDS
Fukushima unit 2, Reactor core isolation cooling system, Torus room flooding, Heat transfer

1. INTRODUCTION

The analysis results of the severe accident of Fukushima Daiichi Unit 2 are described in this paper. The analysis was conducted using MELCOR 1.8.6. Plant input data and information of the geometry were obtained from TEPCO through OECD/NEA BSAF (Benchmark Study of the Accident at the Fukushima Daiichi) project. In the case of unit 2, it was generally known that the damage of the plant was less severe than in the other plants. It has been speculated that the decay heat was removed properly by operation of the RCIC turbine. However, there was no information regarding the RCIC turbine efficiency, or the flow rate of steam and water from the steam dome to the RCIC turbine. In addition, the water condition in the torus was affected by sea water flooding. Thus, the best estimate scenario of the Fukushima unit 2 accident is presented in this study and the effects of RCIC operation condition and torus room flooding was analyzed. Furthermore, it was found that some portions of the core material were damaged after stopping of the RCIC turbine before starting of the sea water injection. Depressurization of the pressure vessel was performed to inject water into the RPV. At that time, the drywell pressure increased in a short time and it might cause the release of fission products out of PCV. Although the amounts of fission

Table I. Summary of boundary conditions for best estimate scenario

Unit 2	Contents
Group 1	- SRV operation: Safety mode (7.87, 7.32 MPa/opening, closing pressure) - Water flow rate to RPV during RCIC operation:
Group 2	- Alternative water injection - RCIC operation condition
Group 3	- SRV gasket leakage: If temperature is larger than 1000 K Leak area (30% of total flow area) Flow path (from steam dome to PCV) - PCV head flange leakage: If PCV pressure is larger than 0.735 MPa
Group 4	- Torus room flooding

products were not large, some fission products would be released into the environment. Therefore, the effect of operating conditions of RCIC system and torus room flooding on the amounts of released fission products in the best estimate scenario were explained in this study.

2. Methods

2.1. Nodalization

The nodalizations of the reactor pressure vessel (RPV) and primary containment vessel (PCV) are indicated in Figs. 1. As shown in Fig. 1(a), the RPV consists of downcomer, lower plenum, core, bypass, shroud dome, steam dome and recirculation loop and so on. The steam dome was divided into three parts, a separator, dryer and residual steam dome. In particular, the flow path, which can collect the condensed water in the separator, dryer and steam dome, was simulated. Core and lower plenum model were shown in Fig. 2. The lower plenum consists of 6 axial levels and 6 rings. The core part consists of 16 axial levels and 5 rings. The UO_2 fuel were located in ten axial levels from level 10 to level 19. Flow paths between control volumes were indicated in Fig. 1(a). The volume of the primary containment vessel was divided into four regions. The lower part of the RPV was set to the pedestal and the residual drywell part was classified into three regions, lower, middle, and upper parts. A two-cavity model was employed to simulate the MCCI reaction, however, a lower head vessel failure does not occurred in this calculation. Suppression chamber and torus room were also modeled to simulate the torus room flooding. The suppression chamber was considered in a single volume. Heat transfer between water in wetwell and torus room was modeled by using heat structures. Vent leg was located between wetwell and PCV. It was also modeled that the operation of RCIC system and torus room flooding.

2.2. Best estimate boundary conditions

Through the BSAF project, four groups of boundary conditions were defined. The boundary conditions were revised to match the measured data and make best scenario of accident, and Table 1 provides a summary of boundary conditions for the best estimate scenario of the Unit 2 analysis. Group 1 boundary conditions include the SRV operation conditions and water injection flow rate to the RPV during the operation of RCIC. The SRV opening and closing pressure was 7.87 MPa and 7.32 MPa, respectively.

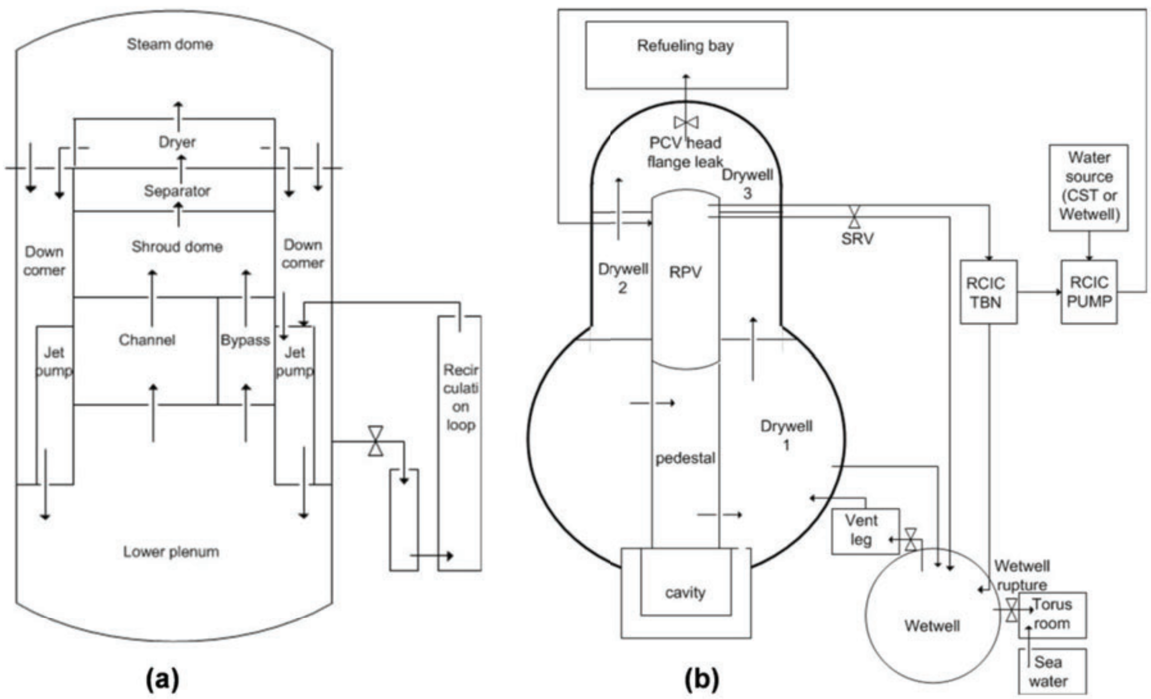

Figure 1. Nodalization. (a) RPV (b) PCV

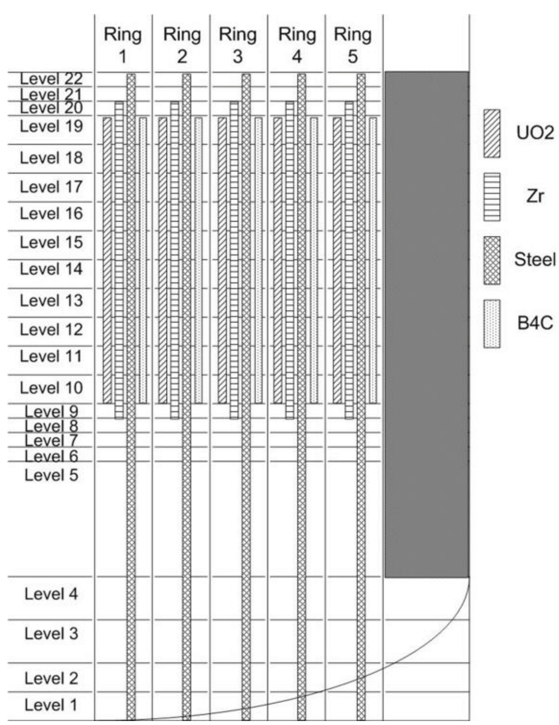

Figure 2. Nodalization of core and lower plenum.

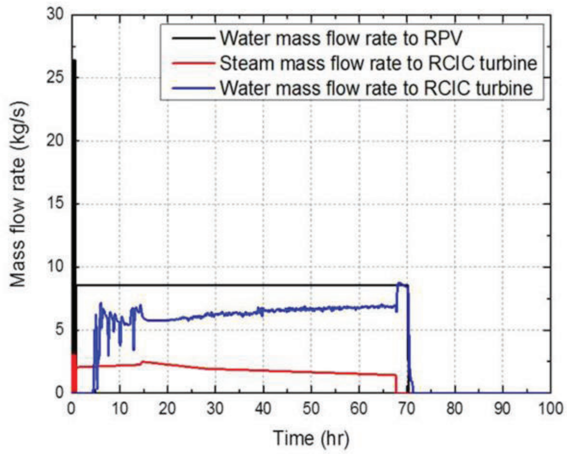

Figure 3. Mass flow rate of water and steam during operation of RCIC system.

During the operation of the RCIC system, water in CST or wetwell was transferred into the downcomer, and the flow rate of the water was set to the summation of the water and steam flow rate which was extracted from the steam dome to the RCIC turbine. The temperatures of each water source were obtained from the temperature of water in CST and wetwell. Alternative water injection conditions after depressurizing of the reactor pressure vessel and RCIC operation model are included in group 2. The flow rate of the alternative water was decided using the given data. The operation conditions of the RCIC system was indicated in section 2.3 specifically. Leakages, such as SRV gasket leakage and PCV head flange leakage, were considered in group 3. The leakage area of gasket was set to 30% of total flow area of SRV flow path. Flow path from PCV to refueling bay was made, in order to model PCV head flange leakage. The flow path is going to open when the pressure of the PCV is larger than 7.35 MPa. If the pressure of the PCV becomes larger than 7.35 MPa, it was modeled that as the pressure increased, the leakage area also enlarged. In group 4, the torus room flooding was modeled. It is generally acknowledged that torus room flooding occurred in unit 2, however it is not known that how many portion of wetwell was flooded. The flooded area is important to understand the accident because the water temperature can be affected by the heat transfer between water in wetwell and torus room. The water temperature in wetwell also can affect the pressure of drywell, and the drywell pressure is directly related to the amount of released fission products in the case of PCV head flange leak.

2.3. RCIC model

The operation of the RCIC system was one of the important factors to reduce the damage of the core in unit 2. Although the exact composition of water and steam in the inlet of the RCIC system was not known, the core in reactor vessel was cooled down properly by supplying low temperature water from CST or wetwell into the RPV. The RCIC systems were stopped at 70 hr and the removal of decay heat in RPV was not performed. After that, this analysis was indicated that some portion of core material were molten before injecting sea water into RPV. Thus it was found that the model of RCIC system does not affect the core degradations. However, the RCIC model can be important in view of fission products release. Outlet water passing the RCIC system went to the wetwell and increased the temperature of wetwell. The high water temperature in wetwell makes the drywell pressure high. As mentioned above, the PCV head flange leakage model in this analysis is directly related with the PCV pressure.

The mass flow rates of liquid water and steam are indicated in Fig. 3. The total water flow rate that was go into the RPV during the operation of RCIC system is also shown in Fig. 3, and the data which is black line, was given data in group 1 of boundary condition. In order to determine the liquid water flow rate,

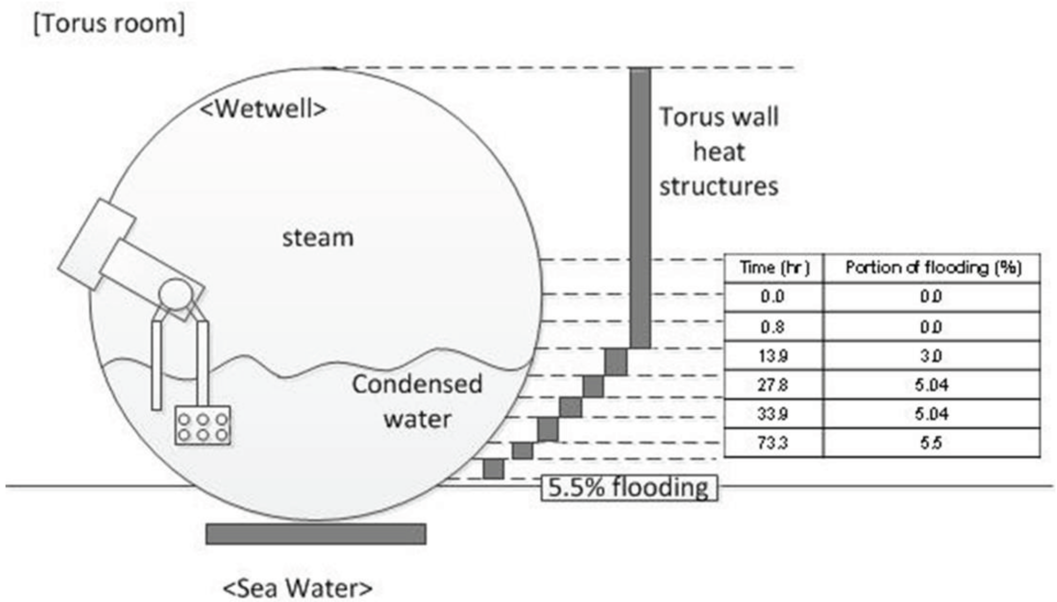

Figure 4. Schematics of wetwell wall to simulate flooding by tsunami.

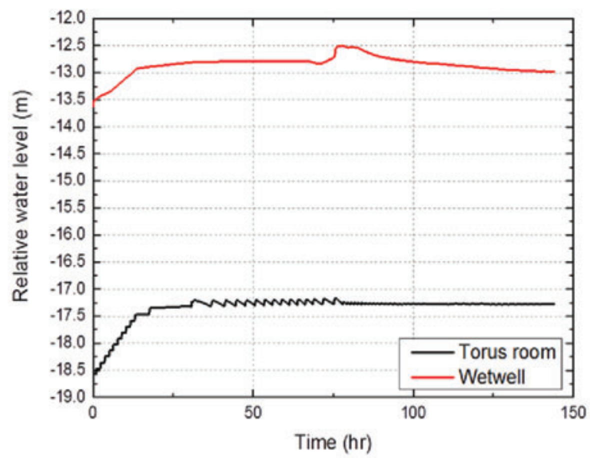

Figure 5. Water level of wetwell and torus room.

liquid water carry-over model was employed. It was assumed that all water above the height of main steam line in the RPV should be transferred to the RCIC turbine. During the operation of RCIC system, the water level in RPV can varied according to the inlet, outlet flow rate of RPV and temperature of water in RPV. Under the circumstance, it is reasonable that liquid water above the pipe were transferred to the inlet of RCIC turbine. The steam extraction rate from steam dome was determined by using given data and carry-over water flow rate.

Thermodynamic properties of the inlet water and steam in RCIC system was determined by considering the conditions of RPV. The liquid and steam temperature in steam dome was used. The supply water temperature into RPV was set to CST water temperature (15^{o}C) or wetwell temperature. It is difficult to define the state of steam and water mixture after passing the RCIC turbine. Thus it was assumed that the mixture consists of steam of 30% and liquid water of 70%. In addition, the saturation enthalpy of the mixtures at the wetwell pressure were employed. The enthalpy difference between inlet and outlet of the

Table II. Fukushima unit 2 analysis timelines

Event	Time [hr]
Earthquake	0.0
Activation of RCIC	0.07
Tsunami arrival	0.8
RCIC stop	70.3
Drywell depressurization (start/stop)	75.8 / 77.7
TAF uncover	76.4
Sea water injection	77.1
Gap release	77.9
UO2 relocation to lower head	83.06

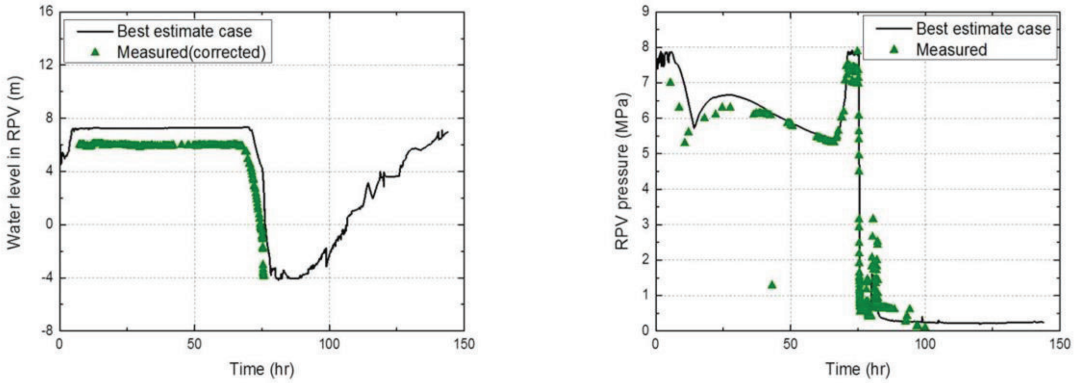

Figure 6. Water level and pressure in RPV with measured data. (a) water level (b) pressure.

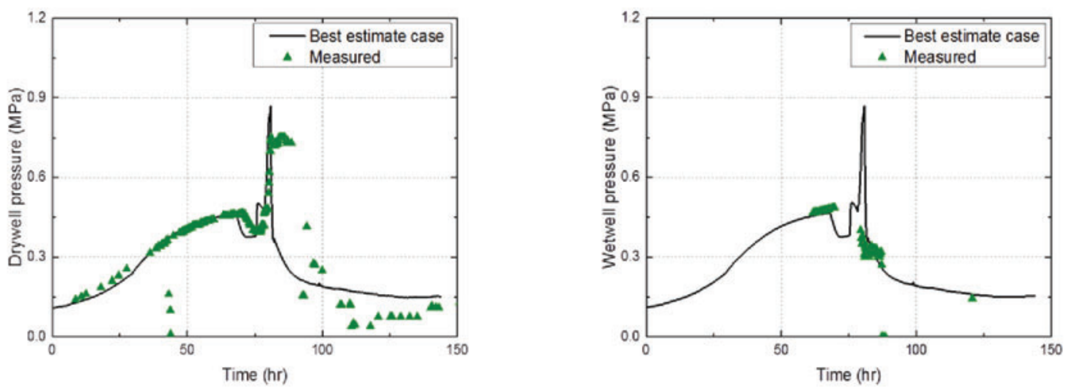

Figure 7. PCV pressure with measured data. (a) drywell pressure (b) wetwell pressure

RCIC system was enough to provide water into the RPV. The measured pressures of drywell and wetwell were well followed by using these model.

2.4. Torus room flooding model

In order to simulate the flooding of torus room, the wall of wetwell was divided into several heat structures, as shown in Fig. 4. Total area of the heat structure walls is set to the area of wetwell wall. It was assumed that the torus room flooding occurred at 0.8 hr which is the arriving time of the tsunami.

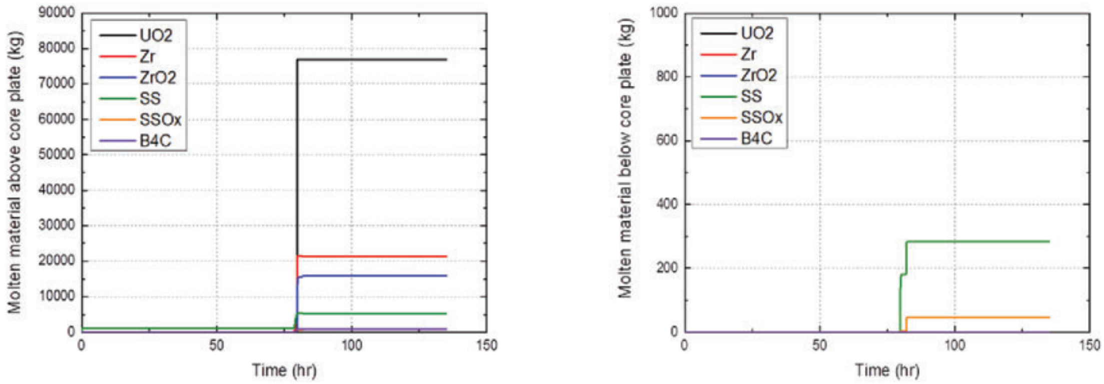

Figure 8. Masses of non-intact core materials. (a) above core support plate (b) below core support plate

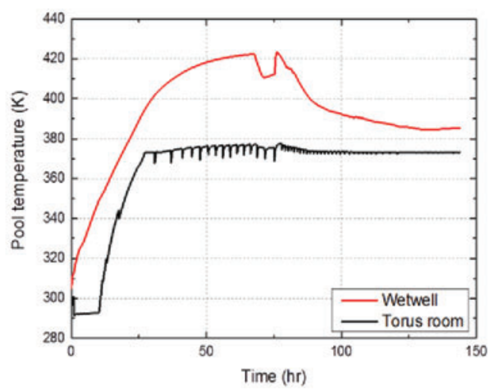

Figure 9. Pool temperatures of wetwell and torus room.

After that the flooding area of wetwell structure increased gradually, it was supposed that 5.5% of total wetwell structure area was flooded by the sea water. The heat structures consists of 1 horizontal wall at bottom and 10 vertical walls and the height of the vertical wall determined by considering the flooding area. The portion of flooding area with time is indicated in Fig. 4 and the relative water level of wetwell and torus room is shown in Fig. 5.

The flooding portion of wetwell is directly related to the temperature and pressure variation of the wetwell. The degree of flooding could be important to understand the accident because the PCV head flange leakage was generated by the pressure of wetwell and drywell.

3. Results and Discussion

3.1. General description

Analysis results of the Fukushima unit 2 accident are summarized in Table 2. At the initial stage of the accident, the RPV pressure remained at the SRV operating pressure, and water level in RPV was maintained because of the operation of RCIC system. The high temperature steam was ejected into the wetwell through the SRV. As shown in Figs. 6, decay heat generated in RPV was removed properly with the operation of SRV and RCIC system. The water temperature in wetwell was increased with the operation of SRV, and the pressures of wetwell and drywell were also increased, as indicated in Figs. 7.

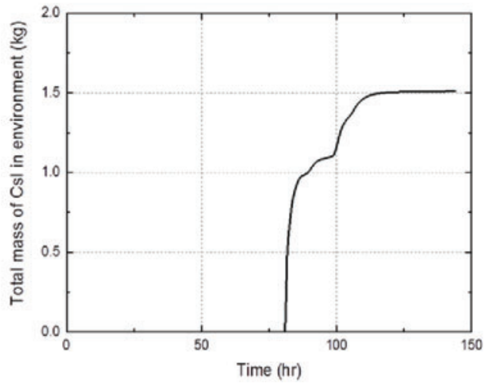

Figure 10. Total mass of released CsI to environment.

The RPV pressure increased at 14 hr, and the increment was expected to have originated from the change of water source from the CST to the wetwell water because the wetwell water temperature was higher than the water in the CST.

Due to the proper operation of the SRV and RCIC system, the RPV pressure and water level were stable during 70 hr. After the stopping of the RCIC system, the decay heat could not be removed continuously. The total amount of water inside the RPV was decreased, and it caused the degradation of the fuel rods, as shown in Fig. 8. To inject sea water into the RPV, the depressurization of the RPV was necessary. Thus, the depressurization of the RPV was achieved by opening the SRV manually at 76 hr.

After the stopping of the RCIC, the temperature of the fuel rods was increased rapidly. The fission products in fuel gap and fuel rods were released into the RPV. The released fission products were also transferred to the PCV due to the SRV gasket leakage.

After depressurization of the reactor vessel, the PCV pressure increased to about 1.0 MPa. To reduce the RPV pressure, the SRV operation, opening and closing, was conducted manually. After that, the RPV was filled with water and cooling of the reactor vessel was conducted properly. When the drywell pressure is larger than 0.75 MPa, a flow path was connected between PCV and refueling bay. As the PCV pressure is higher before depressurizing of the RPV, opening time of the flow path is longer and it means that more fission products would be released into the environment.

The drywell pressure increased gradually during the operation of the RCIC. This is because that the steam and water mixtures which contain high enthalpy were provided to wetwell. Therefore, the total amount of released fission products outside PCV could be different according to the RCIC model.

3.2. RCIC model and torus room flooding

As shown in Figs. 6, the water level was maintained to cover the top of fuel and the proper pressure was maintained during operation of RCIC system. On the other hand, the drywell and wetwell pressure was increased because of the temperature increment of wetwell pool. Another factor to affect the temperature of wetwell pool was the degree of torus room flooding. It was assumed that 5.5% of wetwell wall was flooded with sea water in torus room. Through the flooded area, heat transfer occurred from water in wetwell to water in torus room. The pool temperature in wetwell with considering the effects of RCIC system and torus room flooding is indicated in Fig. 9. After the operation of RCIC system, the wetwell temperature increased, and the water temperature in torus room was also increased with heat transfer from wetwell.

As shown in Fig. 7, the pressure peak at 75 hr was originated from the depressurization of RPV and water injection to the RPV. When the pressure in the drywell was higher than 0.735 MPa, a PCV head flange leak occurred, and thus the fission products in the PCV could be transferred to the reactor building and environment. Total mass of released CsI is shown in Fig. 10. In order to indicate the aerosol behavior of the other fission product, the released mass of cesium iodine is shown. The release of fission product was originated from the drywell pressure increment, and the RCIC model, depressurization of RPV and water injections contribute to the increase of drywell pressure.

4. Conclusions

In this study, an analysis of a severe accident in Fukushima unit 2 was conducted using MELCOR 1.8.6. First, the calculation results were compared with the measured data, and the best estimate model was established by considering the boundary conditions, such as the operation condition of the RCIC system and the torus room flooding. RCIC model and torus room flooding model was presented. From the analysis results, it was found that a vessel failure did not happen in unit 2. However, a noticeable point is that some portions of the fission products were released into the environment when the RCIC system was stopped. RCIC system contributes to the increment of drywell pressure, and it could be possible to affect the amount of released fission products to environment. Torus room flooding also would affect the pressure of drywell by removing the heat from the pool in wetwell.

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