Effect of External Water Injection on Core Degradation and Fission Product Release in Fukushima Unit 1 Accident

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ABSTRACT

The severe accident of Fukushima Daiichi occurred on March 11, 2011, which originated from an earthquake and tsunami. There were six units in the Fukushima Daiichi nuclear power station. Units 1, 2 and 3 were operating and Units 4, 5 and 6 were shutdown at that time. It was estimated that partial or full core degradation occurred in all three operating units, according to the results of Phase I of OECD/NEA BSAF Project. Furthermore, it was estimated that a RPV lower head penetration failure might occur in the case of Units 1 and 3. Understanding the situation of the accident and tracking of the current molten corium locations are essential to conduct decontaminations and to control the site situations hereafter. Cooling of the reactor vessel and corium debris is one of the most important works to prevent or mitigate a severe accident. In the case of Units 1 and 2, it was well known that external water injection started after about 15 hours and 80 hours from the reactor scram, respectively. The amount of water reaching the reactor pressure vessel and the start time of the external water injection are crucial factors to remove the decay heat in the vessel and are directly related with the degree of core degradation. In this research, some relationships were observed between the core damage progression and the injection mass flow rate of water or the timing of the injection. Moreover, the actual injection water flow rate and the extent of fission products release were estimated by comparing the measured data (for instance, pressures of reactor vessel and drywell). MELCOR 2.1 was used in this study.

KEYWORDS
Severe Accident, Fukushima, Alternative water injection, Fission products

1. INTRODUCTION

Analysis results of the severe accident of Fukushima Daiichi Unit 1 are described in this paper. The analysis was conducted by using MELCOR 2.1-6342. 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 this calculation, the boundary conditions which are provided for a common case calculation were modified to minimize the difference between calculated value and measured value (RPV, PCV pressure and water level in pressure vessel). Finally best estimate case calculation results were obtained, and the boundary conditions of the best estimate case are indicated in Table 1. Four groups of boundary conditions were provided for a common case analysis. For the best estimate calculation, some of the boundary conditions are slightly modified as shown in Table 1.[1] In the conditions of group 2, such as the timing and flow rate of alternative water injection were shown. However, the exact condition about the flow rate were remains unknown, because of leakages in the flow pipe. In this study, it is focused on the core degradation with changing the amount of water reached to the

Table I. Summary of boundary conditions for the best estimated case for Fukushima unit 1

Unit 1	Contents
Group 1	- SRV operation: One SRV operation Safety mode (7.75, 7.36 MPa/opening, closing pressure) - Isolation condenser: Two subsystems are considered (remove steam in steam dome, supply water in downcomer) Operation time (followed given data)
Group 2	- Alternative water injection: Injection time is given. - Suppression chamber vent: Venting time is the same with common case, that is, 23.76 hr to 24.73 hr Venting area is 0.010363 m^2
Group 3	- Instrument pipe leakage: Leakage time (temperature is larger than 1000 K) Leak area (assumption: 0.00014 m^2) - Main steam line failure: Larson-Miller creep rupture model (carbon steel) - SRV gasket leakage: Leakage time (temperature is larger than 750 K) Leak area (assumption: 3% of total flow area) From steam dome to drywell - PCV head flange leakage: basically the leakage area 0.012 m^2 is activated when the pressure is over than 0.75 MPa Leakage area is enlarged due to degradation

RPV during performing alternative water injection. Not only core degradations but the behavior of fission product release was considered.

2. Methods

2.1. Nodalization

A schematic diagram of the RPV and PCV are shown in Fig. 1. The RPV consists of downcomer, lower plenum, core (channel + bypass), shroud dome and steam dome. The core parts of each unit were modeled as a single volume, and thus the effect of temperature distribution according to the location in core part was ignored. The lower plenum consists of 4 axial levels, and the fourth level represents the lower core support plate. The core part consists of 4 rings and 12 axial levels, as shown in Fig. 2. Levels 6 to 15 only contain fuel. Steel consists of supporting structure and non-supporting structure, and the non-supporting structure does not have the ability to support other core components. The area ratio of rings 1, 2, 3 and 4 is 0.19, 0.24, 0.28 and 0.29, respectively. The primary containment vessel was divided into two regions,

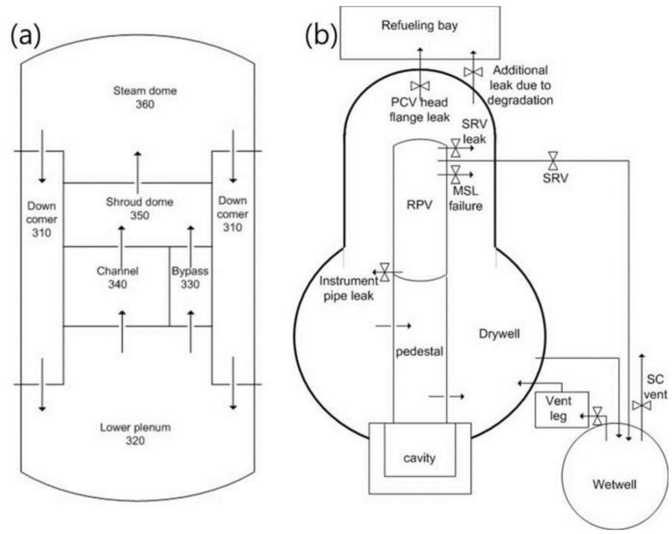

Figure 1. Nodalization. (a) RPV (b) PCV

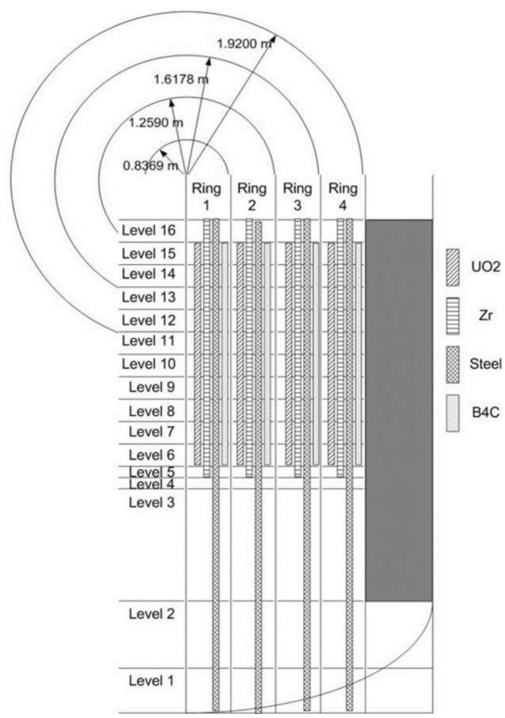

Figure 2. Core part nodalization.

one part is pedestal region and the other is residual drywell part. Modeling of cavity was conducted to simulate an MCCI reaction. The geometry of the cavity is shown in Fig. 3. When RPV failure occurred, the molten materials in the vessel were ejected into the cavity from the reactor vessel.[2]

2.2. Best estimate boundary conditions

The boundary conditions of best estimate case are shown in Table 1. The boundary conditions of group 1 include operation conditions of SRV (Safety Relief Valve) and IC (Isolation Condenser). In order to simulate the IC, given flow rate of steam were removed from steam dome and the same flow rate of water, which has temperature of 558.15 K were supplied to downcomer. In boundary conditions of group

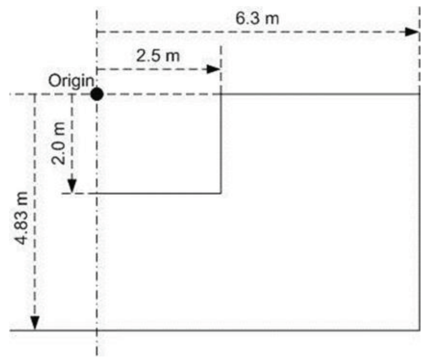

Figure 3. Geometry of cavity

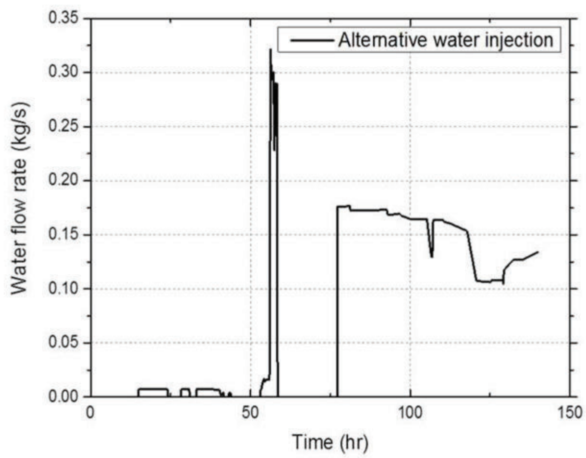

Figure 4. Alternative water flow rate in base case.

2, although the alternative water injection time followed the given date from TEPCO, the amount of injected water was decreased to 10 percent. The graph of water flow rate is indicated in Fig. 4. Compared with the measured data of RPV pressure, pressure peak was observed due to the generation of steam. Thus some leakages from PCV to reactor building were inserted in this calculation to match calculation result with the measured data. Suppression chamber venting was conducted properly under the conditions indicated in Table 1. In boundary conditions of group 3, a number of leakages were considered, such as SRV seal leakage, instrument pipe leakage, main steam line failure and PCV head flange leakage. In the case of head flange leakage, it was assumed that the leak area was enlarged due to degradation of seal over a period of time. In general, the calculation results followed the measured data (RPV and PCV pressure) well, but there are some unmatched points. It should be noted that there are uncertainties in the operating conditions during the accident, such as the quantities of external water injection and leakage from the PCV.
Total initial masses of fuel, zircaloy, stainless steel and control poison were 80229.0, 33156.0, 33710.0 and 1277.0 kg, respectively. Initial water mass in RPV was 137862.0 kg.

2.3. Alternative water injection

It was estimated that the real amount of water reaching the RPV through a fire truck was smaller than the injection water, as shown in Fig. 4. This is because that the pipe was damaged by earthquake. Although the time of water injection could be accurate, the water flow rate remains unknown. However, the amount

Table II. Fukushima unit 1 analysis timelines

Event	Time [hr]
Earthquake	0.0
Activation of isolation condenser	0.1
TAF uncover	2.8
Gap release	4.7
SRV gasket leakage	5.2
BAF uncover	5.2
Instrument pipe leakage	5.3
Lower head penetration fail	9.6
Debris ejection to cavity	10.0

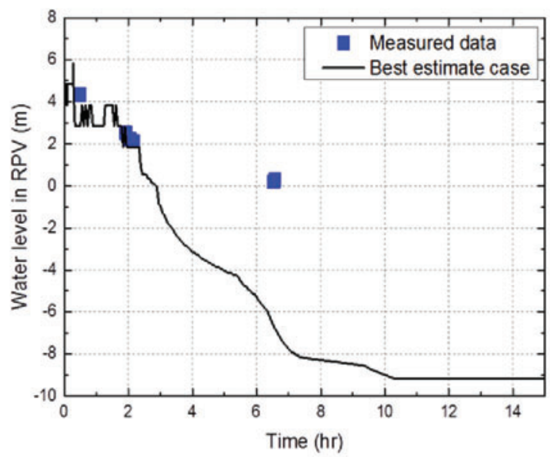

Figure 5. Water level in pressure vessel.

of injected water is one of the major factors affecting the accident process, because it can remove the decay heat in the RPV. Therefore, not only the amount of molten corium but also the amount of released fission products could have been affected by the amount of water reaching the RPV. From the calculation results, it was shown that the first water injection time (14.7 hr) was later than vessel failure time (10.0 hr), and thus the water injection could not prevent the vessel failure. However, the continuous water injection after the vessel failure may have affected the MCCI reaction and fission product release. Therefore, not only the molten corium behavior but also the fission product release was examined by increasing the amount of injected water 100 times in this study.

3. Results and Discussion

3.1. General description

Analysis results of the Fukushima unit 1 accident are summarized in Table 2. Water level and pressure in RPV at the initial stage of accident are shown in Figs. 5 and 6, respectively. The water level decreased continuously right after the stopping of isolation condenser. The decay heat made liquid coolant to steam, and the steam exited from the vessel through the SRV. The pressure decreased sharply during operating of isolation condenser, but increased again right after stopping of isolation condenser. The pressure remained below high limit of SRV for operating of SRV. At 5 hr, the pressure decreased slightly because some portion of gas was released to drywell through the SRV gasket leakage and instrument pipe

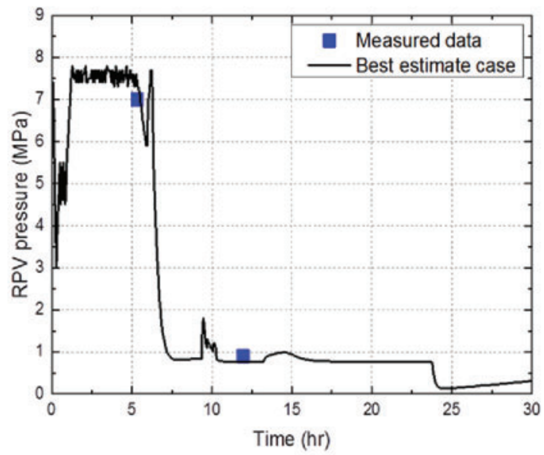

Figure 6. RPV pressure at initial stage of accident.

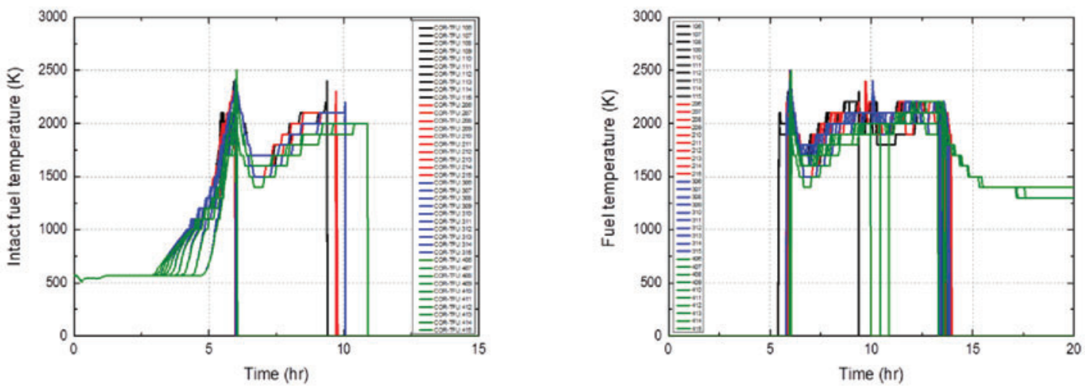

Figure 7. Fuel temperatures. (a) intact (b) particulate debris

leakage. At about 7 hr, flow path was connected between RPV and drywell because of main steam line failure. As the temperature of fuel rods were increased (Fig. 7), the relocation of molten fuel to lower plenum occurred. In Fig. 7, black, red, blue and green line represents the temperature of rings 1, 2, 3 and 4. The molten corium in the vessel was transferred to cavity when the lower head penetration failure occurred at 10.0 hr. Almost all molten core materials were transferred at this time because of large break area in lower head, and the drywell pressure increased sharply due to the gas generation in the cavity with MCCI reaction. The core material masses which ejected to cavity are shown in Fig. 8. The RPV pressure was the same as the drywell pressure since main steam line has failed, and the drywell pressure is shown in Fig. 9. Suppression chamber venting occurred from 23.89 hr to 24.73 hr, and the pressure decreased drastically. After closing the suppression chamber venting valve, the pressure increased again. It was found that the drywell pressure was maintained below about 0.5 MPa from the measurement data while large amounts of gases were generated from MCCI reaction. This means that leakage paths could have existed between drywell and reactor building. Therefore, some leakage paths were assumed at 38, 51 and 77 hr. In addition, the flow rate of water injection was reduced to 10 percent of given data. This is because a sudden pressure peak was observed when water was added into the core. By reducing the injection water flow rate, the trend of RPV pressure followed the measured value generally and no peak was observed.

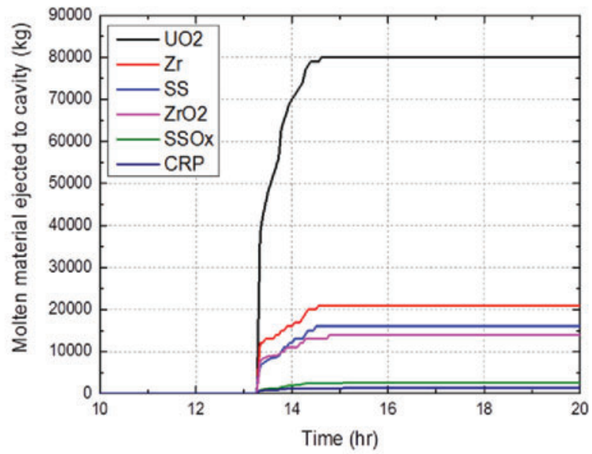

Figure 8. Material mass ejected to cavity

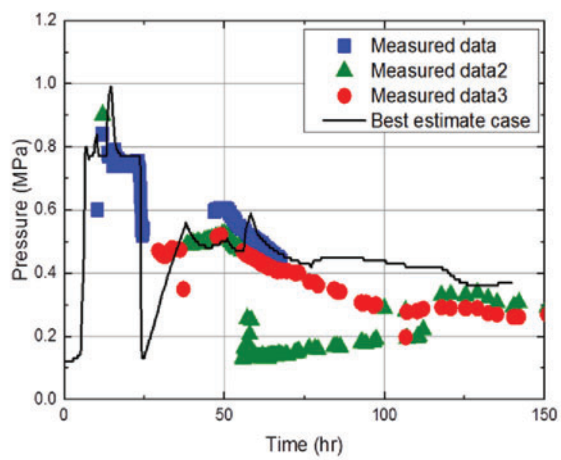

Figure 9. Drywell pressure with measurement data.

3.2. Aerosol in atmosphere

In this section, it is mainly focused on the aerosol mass in atmosphere. Fission products were released from fuel as a vapor, and aerosol could be formed according to the temperature and pressure conditions of control volume. When a fission product vapor pressure exceeded the saturation vapor pressure, aerosol was formed in an excess amount. Aerosol and vapor mass of Cs in atmosphere and aerosol mass of Cs in pool were indicated in Figs. 10 at RPV, PCV and wetwell. Concentration of Cs increased highly after fuel gap released. At 5 hr, Cs released from fuel rods were transferred to PCV due to the main steam line rupture.[3] When the steam in RPV was transferred to wetwell through SRV, the concentration of fission product in wetwell increased. The results of fission product behavior in best estimate case before conducting alternative water are the same with the results in given data. However, the total amount of released fission products can be varied according to the amount of water reached to downcomer during performing alternative water injection. In Figs. 11, it is indicated that the total radioactive Cs masses in

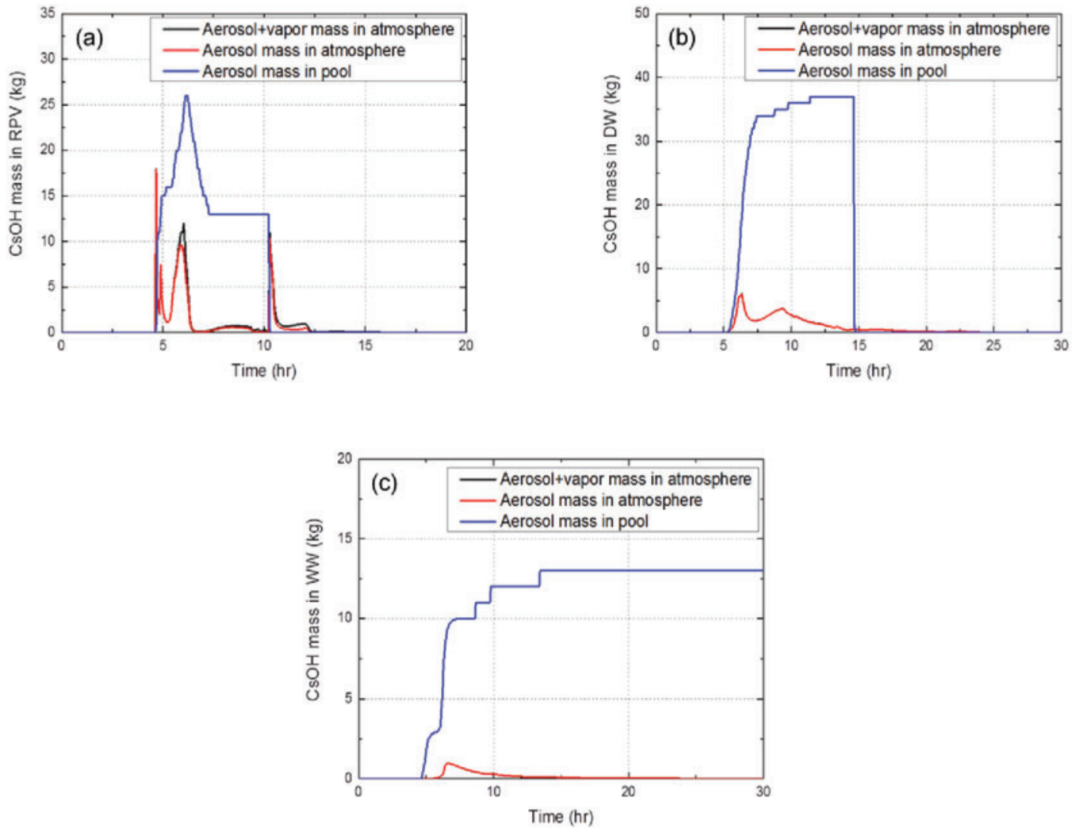

Figure 10. CsOH mass in atmosphere and pool (a) RPV (b) PCV (c) Wetwell.

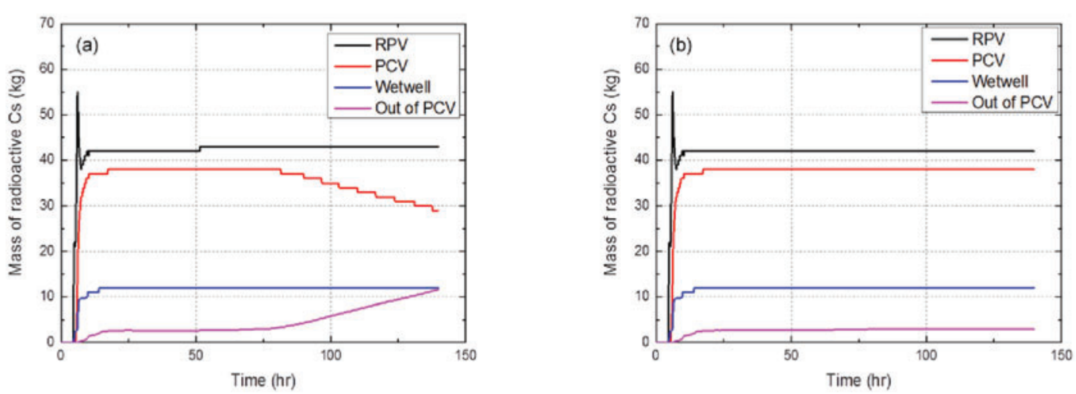

Figure 11. Radioactive Cs mass (a) in best estimate case (b) in given data case.

best estimated case and given data case. The total mass includes deposition mass, mass in atmosphere and pool. As shown in Fig. 11, in the case of smaller water injection, more Cs was released to out of PCV. The difference was originated from the deposition mass in cavity as shown in Fig. 12. The heat structures used in the calculation was indicated in legend and total deposition mass of Cs was compared. In the best estimate case, the deposition mass in the floor of pedestal region decreased at 75 hr. Although some portion of the removed masses was transferred to the floor of drywell region, most of the masses were released outside the PCV. The reason was originated from the temperature of the floor of pedestal. The

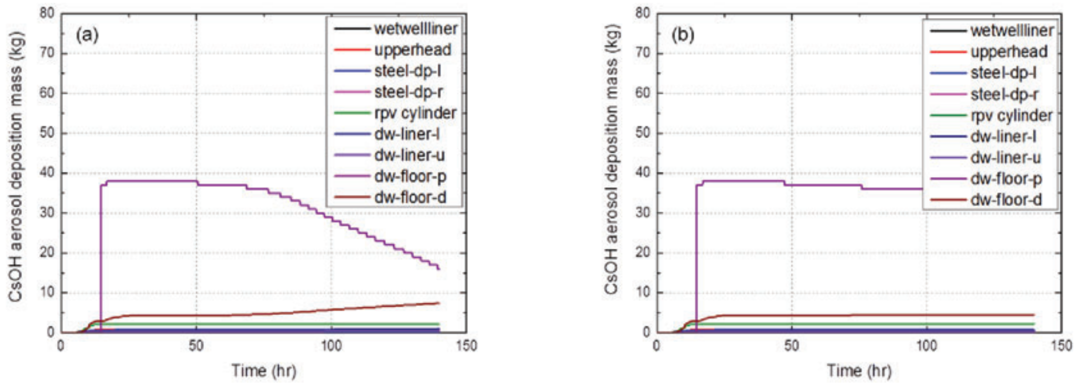

Figure 12. Deposition mass of Cs (a) best estimate case (b) original water injection case.

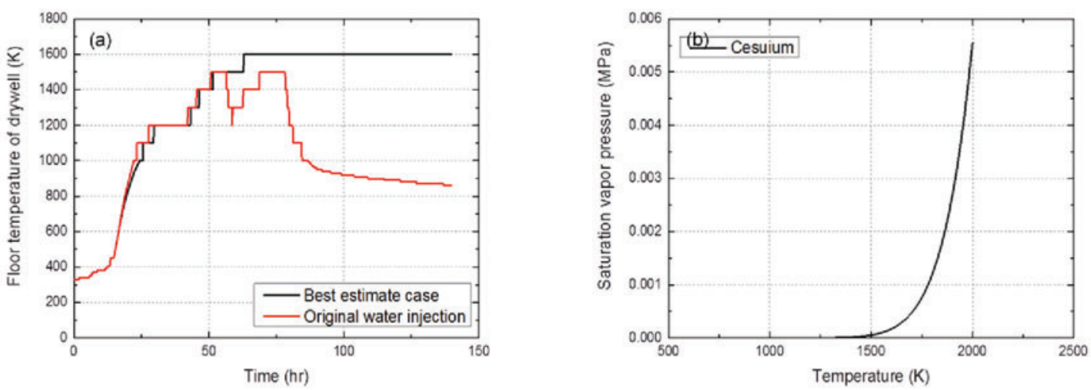

Figure 13. Floor temperatures and Saturation vapor pressure (a) comparison of floor temperature (b) saturation vapor pressure of Cesium

comparison result of floor temperature is shown in Fig. 13(a) and the saturation vapor pressure of Cesium is shown in Fig. 13(b). The floor temperature increased gradually when the molten core material ejected into the cavity. Although alternative water injection was conducted, the amount of water was too small to cool down the temperature of the pedestal floor in best estimate case. In the case of original water injection which using given data, the temperature was decreased slightly after about 50 hr. When stable sea water supply was performed at about 75 hr, the floor temperature had dropped below 1000^{o}C. The graph of Cesium saturation vapor pressure was made by using MELCOR Reference Manual.[4] As shown in Fig. 13(b), the saturation vapor pressure is increased exponentially above 1500^{o}C. In MELCOR fission product vapor evaporation model, the Cesium concentration difference between atmosphere and saturation concentration corresponding to the temperature of the surface is important to determine the evaporation rate. Therefore, the alternative water injection flow rate affects the temperature of floor or molten corium in cavity, and the temperature difference can affect the amount of released fission products.[5]

4. Conclusions

Analysis of severe accident in Fukushima unit 1 was conducted by using MELCOR 2.1. First of all, the calculation results were compared to the measured data, and best estimate model was established by considering boundary conditions, such as main steam line pipe failure, suppression chamber venting and so on. Alternative water injection is one of the most important conditions to affect core degradation. However, the timing of water injection was later than lower head vessel failure in this scenario. Second, the effect of the injected water into the vessel according to flow rate was found in view of releasing of fission product aerosol. Although the vessel failure was not affected by alternative water injection, large amount of water can reduce the amount of released fission product aerosol. Only Cesium was considered in this study, and it is necessary to consider the geometry of reactor building in order to predict the amount of released fission products accurately.

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