

Analysis of Core Degradation in Fukushima Unit 1 Accident with MELCOR

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1. Introduction

A severe accident of Fukushima Daiichi occurred in March, 2011, which originated from an earthquake and tsunami. There were six plants in the Fukushima Daiichi, and Units 1, 2 and 3 operating at that time. It was estimated that core degradation occurred in all plants and the vessel failure occurred in the case of Units 1 and 3. In order to understand the accident and conduct decontaminations and decommission, it is important to know the conditions of the degraded core and position of the molten core materials. In this study, an accident analysis of Fukushima Daiichi Unit 1 was performed using MELCOR 1.8.6. The behavior of the initial stage of the accident was focused during 30 hours after the reactor scram, because it was predicted that the vessel failure (severe accident) occurred before 20 hours. A hydrogen explosion also occurred at about 24 hours after the accident, and thus the phenomenon of core degradation before 30 hours was highlighted. Moreover, the effect of the amount of fresh water injection on the core degradation was performed by changing the amount of injection water. It was expected that a large portion of the injection water could not reach the core because of leakage. Thus, core damage was observed according to the amount of water that reached the core.

Several studies have been performed to understand the phenomenon of the accident of Unit 1 [1], and comparison analyses of the results were conducted.

The plant geometries and operating conditions were obtained from TEPCO (Tokyo Electric Power Company) through the OECD/NEA BSAF (Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Station) Project.

2. Simulation method

The analysis was conducted using MELCOR 1.8.6. The plant input data and information of the geometry were obtained from TEPCO. This calculation was conducted to deal with a core heat-up, core melt, core debris behavior and RPV failure during 30 hours after the accident. In-depth discussions about the MCCI and fission product will be handled in the future.

2.1 Nodalization

The reactor building for a BWR/4 reactor with a Mark 1 containment was employed. The primary containment vessel (PCV) was divided into two regions, a pedestal and the rest of the drywell. Vent leg and

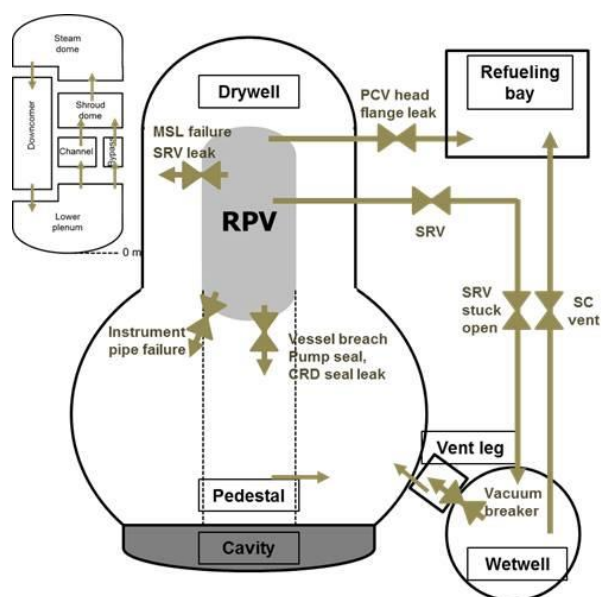
suppression chamber were also modeled. Reactor pressure vessel (RPV) consists of 6 regions, i.e., a downcomer, lower plenum, channel, bypass, upper shroud dome and steam dome. Each control volume was connected using a flow path. The core and lower plenum were divided into 4 rings and 16 axial nodes, which contain 10 axial levels for the active fuel region. There was also a 5th ring to model the lower plenum. All geometric input for the core, RPV, PCV, reactor building and flow paths were obtained from TEPCO through the BSAF project. A nodalization diagram is shown in Fig. 1.

2.2 Operating conditions

Boundary conditions were required to simulate the behavior of the plant after the reactor scram. The data were obtained from TEPCO data, and some conditions, which were not demonstrated specifically, were assumed.

Safety equipment such as an SRV, IC (Isolation condenser), and fresh water injection were considered. The failure of main steam line, SRV stuck open and instrument pipe leakage were also reflected. In addition, steam flow into the turbine and water flow from the turbine were modeled at the initial stage of the accident.

Fig. 1 Nodalization of RPV and PCV



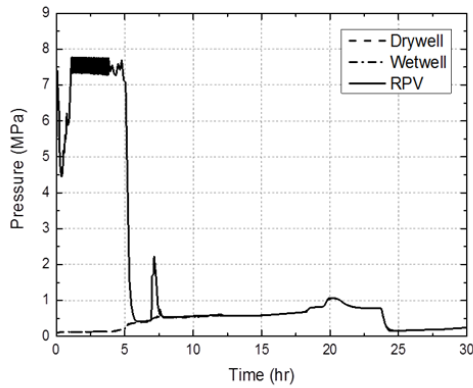


Fig. 2 Pressure of reactor vessel, drywell and wetwell

The SRV operation mode was changed from relief mode to safety mode at the point of the tsunami. Operating pressure data (opening/closing) of the SRV were described by BSAF data. Operation of the isolation condensers was considered. The full capacity of one isolation condenser is 42.2 MW. The timing of fresh water injection was also obtained from TEPCO data, and the amount of water was varied. Suppression chamber venting was also considered.

Some boundary conditions were not fixed, and thus assumptions were necessary to conduct a simulation. In the case of an instrument pipe leakage, the leakage area was fixed to 0.00014 m^2 by considering a TEPCO report [2]. It was assumed that a failure occurred when the temperature of instrument pipe was larger than 1000 K. In the case of main steam line failure, creep rupture model was used with Larson-Miller correlation, and the material was assumed to be carbon steel. The leakage gases were assumed to flow into the PCV. SRV gasket failure was also assumed if the gas temperature inside the valve is larger than 750 K and 3% of total flow steam is released into a drywell (0.0002262 m^2). It was assumed that the PCV head flange leakage occurred when the pressure inside PCV is higher than 0.75 MPa, and leakage area is enlarged as the pressure increased.

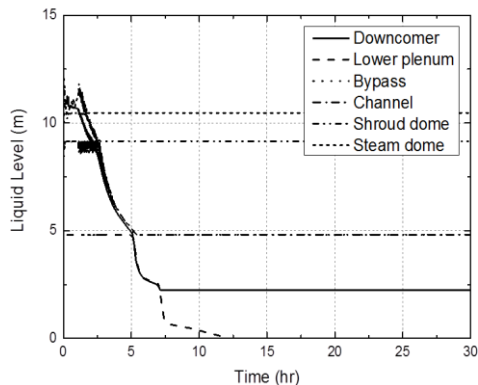


Fig. 3 Water level in reactor pressure vessel

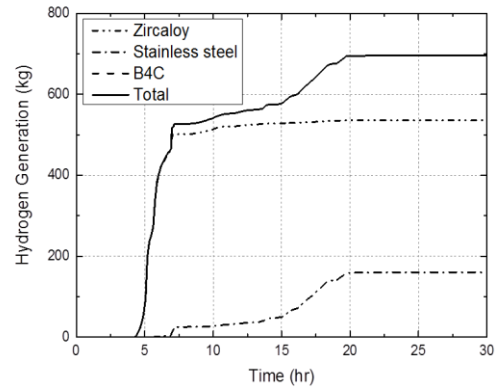


Fig. 4 Hydrogen generation from the oxidation reaction

The flow rate of steam into the turbine building and water into the downcomer were reflected, and the amount of steam and water were determined using the measuring data provided from TEPCO.

3. Results and Discussions

3.1 General plots

At the initial stage of the accident, RPV pressure decreased slightly and recovered immediately. This is because the high temperature steam was released into main steam line and low temperature water was injected into the downcomer for a moment before the arrival of tsunami. The pressure was recovered instantly due to the decay heat. The RPV pressure decreased sharply when the two isolation condensers were operated. However, isolation condenser was not conducted properly after the arrival of tsunami. Thus, the RPV pressure increased again, and remained at the operating pressure of SRV. The pressure behaviors of RPV, drywell and wetwell are indicated in Fig. 2.

As shown in Fig. 3, water level in the RPV decreased continuously after reactor scram. The RPV pressure was maintained at about 7.5 MPa owing to the operation of

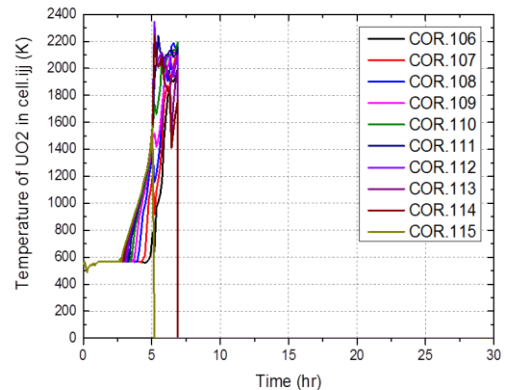


Fig. 5 Temperature of innermost UO_2

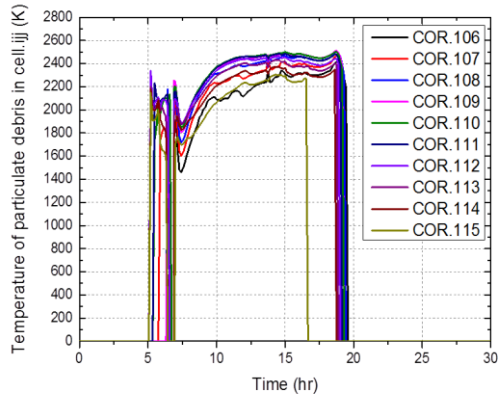


Fig. 6 Temperatures of innermost particulate debris

the SRV, but caused a decrease of the water level by a discharge of steam. Although the isolation condensers were operated at the initial stage of accident, it did not last for long. Owing to the continuous operation of SRV, all liquid water in the RPV was eliminated at 12.21 hours after reactor scram. A lower head failure occurs at 15.41 hours after reactor scram.

The temperature of core increased rapidly at 4.36 h owing to the oxidation of Zr. The Zr oxidation was an exothermic reaction, and a large amount of water was evaporated due to addition of the oxidation reaction heat. When the temperature of instrument pipe was larger than 1000 K, the instrument pipe leakage occurred and the time was at 5.33 h. At 5.16 h, the main steam line was failed because of the high temperature and pressure, and thus there was no pressure difference between the PCV and RPV.

The wetwell liquid water temperature increased because of the operation of SRV. The drywell temperature increased due to the leakage of instrument pipe and main steam line failure. At 18.33 h, the temperature of drywell increased sharply, because a high temperature corium was ejected into the cavity.

Hydrogen can be generated from a zircaloy water reaction and from a steel water reaction. The zircaloy oxidation reaction occurred at 4.36 h. The total hydrogen generation amount is 718 kg, among these, 533 kg of hydrogen generated from a zircaloy water reaction and 185 kg of hydrogen generated from stainless steel water reaction. The result is shown in Fig. 4.

3.2 Fuel plot

When the water inside RPV was dried up, the cooling efficiency of fuel rod decreased. Fuel temperatures started to increase exponentially at 3.1 h, and top of fuel rods were uncovered at that time. The temperatures of innermost UO_2 and particulate debris were indicated in Fig. 5 and Fig. 6, respectively. The decay heat was generated continuously and the water in the core was removed due to the operation of SRV. So, the

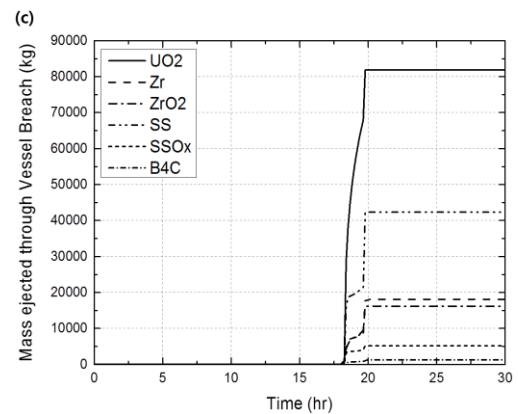
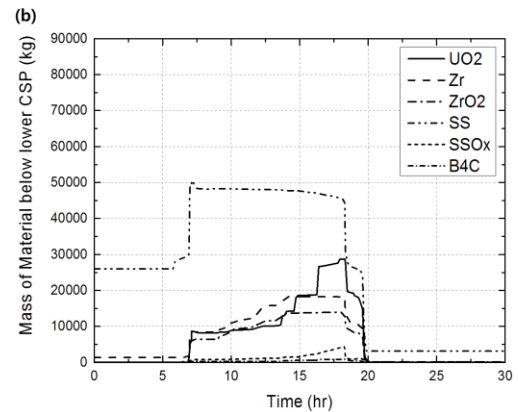
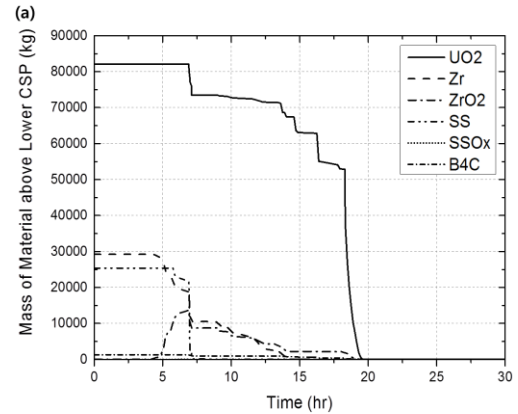


Fig. 7 Mass of core materials (a) above lower core support plate (b) below lower core support plate (c) ejected through vessel breach

temperature of fuel rod increased to the melting temperature of core materials.

The first fuel relocation occurred at 5.19 h, and most fuel rods were relocated to lower fuel support plate at 6.91 h. The eutectic reactions were not considered. The accumulated molten materials heated up the core lower support plate, and the molten materials were transferred to the lower plenum. Most of fuels were relocated to the lower plenum at 7.07 h. After 18.33 h, molten materials

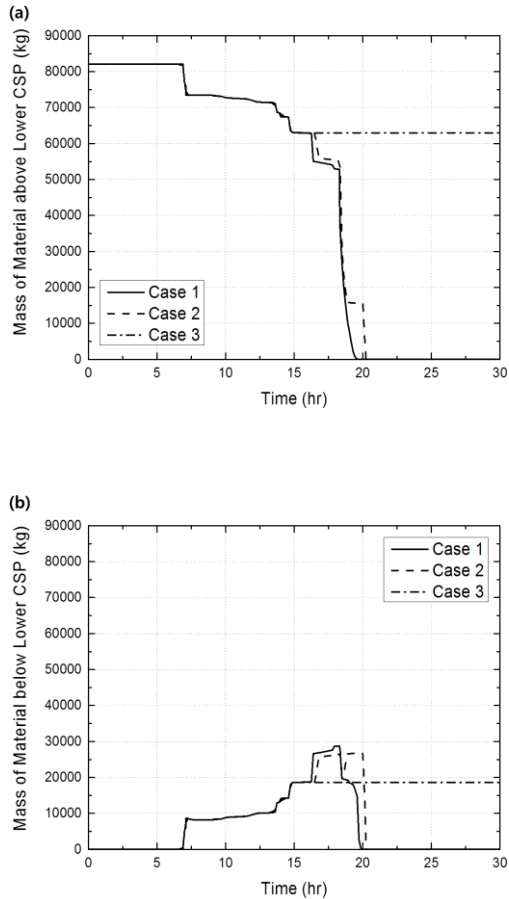


Fig. 8 Mass of core materials (a) above lower core support plate (b) below lower core support plate

were first ejected into the pedestal, and the overall materials were relocated on the cavity at 19.86 h.

3.3 Molten materials plot

There were some materials in the core, such as U, Zr, SS, B₄C. Initial core material masses were indicated as below. (UO₂ fuel: 82,101 kg, Zircaloy: 30,554 kg, Steel: 54,391 kg and Control rod poison: 1,227 kg) Total mass

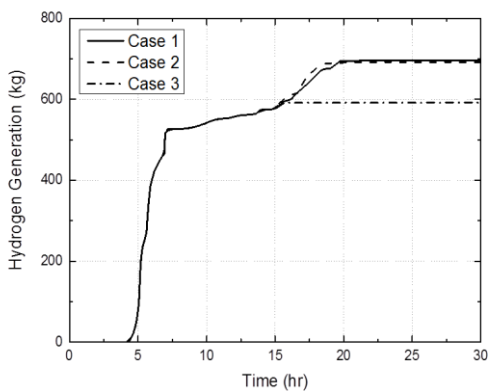


Fig. 9 Comparison of hydrogen generation from oxidation reaction in each case

Table I: Table of events in base case of Fukushima Daiichi Unit 1 accident

	Event	Time [hours]
1	Earthquake time	0
2	MSIV closure time	0
3	Activation of IC	0.096
4	Tsunami arrival time	0.667
5	First occurrence of water level at TAF	2.418
6	SRV gasket seals failure	4.246
7	Onset of hydrogen generation	4.362
8	Fuel clad failure time	4.441
9	First occurrence of water level at BAF	5.087
10	Main steam line leakage on	5.158
11	Core instrument pipe leakage on	5.211
12	Core support structure failure	6.910
13	Lower plenum dryout	11.618
14	Water injection time	15.000
15	Lower head penetration	15.501
16	Beginning of debris ejection to cavity	18.287
17	Drywell head flange seals failure	18.391

of materials according to the location are shown in Fig. 7(a), (b) and (c).

When the materials react with H₂O at high temperatures, oxide compounds are generated. The easily oxidizable materials were oxidized first, such as Zr and SS. ZrO₂ was produced at 4.36 h.

The total amounts of materials including the melted materials above the core support plate was reduced gradually as the materials were relocated to the lower core support plate. The total molten materials were transferred to the cavity in a pedestal at 18.33 h.

The masses of molten Zr and SS exiting RPV through the failed lower head at 19.78 hours were 18,102 kg and 42,333 kg, respectively. The masses of molten UO₂ exiting RPV through the failed lower head at 19.78 hours were 81,831 kg. The masses of molten ZrO₂ and SSO_x exiting RPV through the failed lower head at 19.78 hours were 16163.8 kg and 5173.1 kg, respectively. The masses of molten Zr and SS can be important, because it can make hydrogen by reacting with concrete in a cavity.

3.4 Variation of the amount of water injection

At about 15 hours, fresh water injection started. From the data of TEPCO, the flow rate of injection water was about 0.08 kg/s for 9 hours. However, the amount of water must not be large by considering the damages of core. There are a lot of reasons that hinder the injection, such as pipe leakage, internal pressure. The quantity of water was changed, and its effect on core was observed in this study. Three cases were specified according to the amount of injection water. Case 1 is the base case as indicated above. In cases 2 and 3, the amount of water was increased to 10 and 50 times, respectively.

As shown in Figs. 8(a) and (b), the core was cooled properly in case 3. Although the core support plate (CSP) was damaged, none of the materials above the CSP were relocated to the lower plenum. In addition, the reactor vessel did not fail in case 3. The degradation rate was delayed slightly in case 2, but noticeable changes were not observed. As the temperature of core was decreased, the oxidation reaction rate was also decreased. Thus, the amount of hydrogen in case 3 was smaller than the others, as indicated in Fig. 9.

4. Conclusions

An analysis of the Fukushima accident was also performed by Sandia National Laboratories [1], but several conditions were revised and added in this study. First, the flow rate of the steam into turbine and water into downcomer were considered at the initial stage of accident. The water level followed well the measured data by adding this mechanism. Second, SRV stuck open was included in this calculation. SRV stuck open can occur due to high temperature and frequent operation, and was modeled in calculation. The timing of SRV stuck open was closed to the timing of MSL failure, and thus the depressurization of RPV could have originated from both of MSL failure and SRV stuck open. The effect of injection water was observed, and it was found that the proper water injection can prevent a severe accident at the initial stage of the accident.

In conclusion, an analysis of the severe accident occurring in Fukushima Unit 1 was conducted by using MELCOR. The analysis results were consistent with the measured data provided by TEPCO. It is very important to know the degree of core damage and the location of

molten materials. This research not only provides useful information to handle the accident but can also contribute to make a better plant design in the case of a severe accident. An analysis of MCCI and the fission products will be scheduled soon.

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