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MELCOR modeling and sensitivity analysis of Fukushima Daiichi unit 2 accident considering the latest TEPCO investigations

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A B S T R A C T

Fukushima Daiichi accident occurred on 11 March 2011 due to the Great East Japan Earthquake and the following tsunami. Recently, Tokyo Electric Power Company (TEPCO) published investigation reports pertaining to the status of unit 2 and other issues that were confirmed. The present study modeled unit 2 accident with MELCOR 2.1 code and performed sensitivity analysis, in order to provide information towards understanding severe accident. The two-phase flow rate and its void fraction in the steam line connecting to the turbine of reactor core isolation cooling (RCIC) system were calculated using the developed RCIC operation model, and the pump injection rate was obtained as well. The suppression chamber (S/C) was divided into three layers with flow path connection to model thermal stratification and the mixing flow at SRV discharge, thereby enabling to capture the measured dry well (D/W) pressure. Through sensitivity analysis of seawater injection, it indicates that the likely seawater injection rate was about 1–2% of the total flow rate through fire engines, and the corresponding reactor pressure vessel (RPV) lower head failure time was located in 92.84 h– 96.17 h. As a result, about 74% of total fuel debris discharged into the reactor pedestal, and the release fractions of noble gas, iodine and cesium to the environment were about 0.741, 0.0167 and 0.00331, respectively. Even though the plausible accident progression was tentatively given, there are still many uncertainties concerning models, boundary conditions and the accident progression.

1. Introduction

Fukushima Daiichi accident occurred on 11 March 2011 due to the Great East Japan Earthquake and the following tsunami. Reactor scram initiated at the occurrence of earthquake, and AC and some DC electrical power supplies lost following the arrival of tsunami. It is widely acknowledged that the reactor cores of units 1–3 have experienced some degradation. Tokyo Electric Power Company (TEPCO) and international research institutes have made great efforts to investigate accident progression and to decommission nuclear power plant. From the preceding investigations, it seems that the core damage of unit 2 is less serious than units 1 and 3 (Kim et al., 2016). Despite many efforts to understand accident progressions, the investigation results still have many uncertainties due to complicated site environment and lack of monitored data.

A retrospection of unit 2 accident progression is presented in Fig. 1. The RCIC system started operation following the occurrence of earthquake, but it automatically tripped several times due to high reactor water level. The water source of RCIC was switched from condensate storage tank (CST) to suppression chamber (S/C) at about 5:00 on 12nd March due to water consumption. The RCIC was confirmed stopping operation until RPV water level was found trending downward at 13:18 on 14th March, but the reason was not clear. As the loss of reactor cooling and the consequent water boiling in RPV, the SRV started to operate at about 70 h. In order to enable water being injected into RPV, the RPV was depressurized at approximate 75 h through manually opening SRV. Seawater injection though fire engine initiated following RPV depressurization, but unfortunately one hour later the workers discovered that an engine had run out of fuel and no seawater was being injected into the reactor. With the operators' onsite treatment, the second water injection commenced at 19:54 on 14th March, and another fire engine was put into operation as well. The operators have attempted many times to vent the containment including W/W and D/W to reduce pressure but all attempts were unsuccessful. Later, however, the containment pressure decreased from 0.73 MPa at 7:20 on 15th March to 0.155 MPa at 11:25 without specific indication. The detailed information and event timeline could be found in Refs. (Institute of Nuclear Power Operations, 2011;

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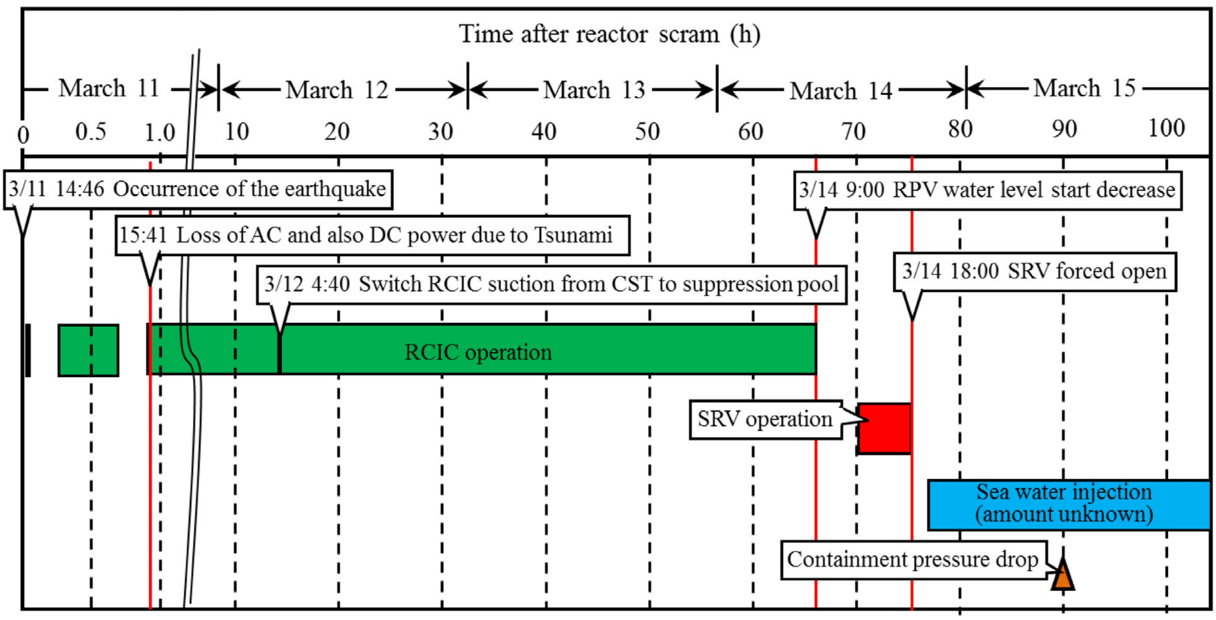

Fig. 1. Event progress of unit 2 accident (Li, 2014).

Examination Committee on Accident at Fukushima Daiichi Nuclear Power Station, 2011).

The unit 2 accident has been studied by TEPCO (Tokyo Electric Power Company, 2015a) with MAAP, Gauntt et al. with MELCOR (Phillips et al., 2012), Sevon with MELCOR (Sevón et al., 2013), Kim et al. with MELCOR (Kim et al., 2016) and Bonneville et al. with ASTEC (Bonneville and Lucian, 2014). The researchers developed models for analyzing unit 2 accident with the integral codes, and gave their understandings on the accident progression. However, these studies are not able to well reproduce the measured pressure in RPV and D/W, especially the RPV pressure in period of 78–83 h after reactor scram and D/W pressure at SRV forced open. The operation performances of turbine and pump in RCIC system were neglected in modeling, by assuming a constant injection rate or a function related to void fraction in steam line. The MELCOR modeling by Kim et al. considered the impact of turbine efficiency, but the pump operation which correlates injection rate to turbine output work was not taken into account. S/C thermal stratification as well as mixing flow at SRV discharge which probably happened in accident has significant influence on D/W pressure. In the preceding research, only Sevon's modeling attempted to divide the S/C into two layers to produce thermal stratification, but the mixing flow at SRV discharge was difficult to be modeled using MELCOR code. Thus, the pressure decreasing trend at SRV operation and sustaining stable at SRV forced was not predicted. The seawater injection though fire engines is another big uncertainty affecting RPV pressure, D/W pressure and core degradation. The injection rate to reactor is not only determined by pump pressure head, RPV pressure, gravitational head, but also affected by neighboring reactor because the fire engine was injecting water to units 2 and 3 simultaneously. Some of water seemed to flow to the outside parts of reactor, such as CST and main condenser, due to complex pipe connections. Sensitivity study on the exact seawater injection amount into the reactor has not been performed.

The researchers have performed many analyses with the integral severe accident codes and provided valuable information towards understanding severe accident, but there are still some uncertainties and unclear matters that need to be confirmed, e.g. the operation performance of RCIC, thermal stratification in S/C and seawater injection amount through fire engines. Moreover, TEPCO has published its new investigation results on unit 2 PCV condition, which points out that some parts of pedestal structures were destroyed and some molten materials were found in the pedestal (Tokyo Electric Power Company Holdings, 2017). Even though the specific causes have not been clarified, the possibility of RPV failure such as penetration tube failure or localized break cannot be ruled out. Some issues were confirmed as well in TEPCO 4th progress report (Tokyo Electric Power Company, 2015b), such as SRV operations after reactor core damage and S/C thermal stratification. Therefore, it is necessary to model accident in detail considering TEPCO's investigations, and perform sensitivity analysis on uncertainties.

The purpose of the present study is to model Fukushima Daiichi unit 2 accident and do sensitivity analysis by considering the RCIC operation condition, S/C thermal stratification and mixing flow, and the seawater injection through fire engines. These models were developed on the basis of Sevon's modeling for unit 2 accident (Sevón et al., 2013). The seawater flow rate that was injected into the reactor through fire engines was determined, and the plausible accident progression was proposed. The RPV lower head failure time, debris discharge amount and components and fission products (FPs) release were evaluated.

2. MELCOR 2.1 modeling of unit 2

2.1. Plant system

Nodalization scheme of plant system is presented in Fig. 2. The reactor building was divided into volumes of floors 1–4, floor 5, shield volume and torus room. Within containment the volumes of pedestal, drywell, sump, venting line and wetwell (W/W) were included. The volumes of control volumes are listed in Table 1. Flow paths were set between volumes allowing fluid circulation according to the plant actual configuration. Furthermore, considering the specific accident progression of unit 2, some flow paths were modeled as well, such as the SRV flange gasket leakage path, PCV leakage path and torus room flooding (seawater inundating torus room) path. The RCIC system, driven by a steam turbine and pumping water for RPV injection, was modeled as well. The exhaust of RCIC turbine was discharged to S/C. The suction side