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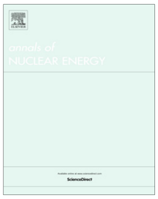

Analysis of the accident in the Fukushima Daiichi nuclear power station Unit 3 with MELCOR_2.1

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ABSTRACT

During the major accident occurred at the Fukushima Daiichi nuclear power station in March 2011, three units of the nuclear power plants suffered extensive damage to the reactors and buildings. It is widely believed that all three reactor cores experienced some melting.

In the present paper, the Fukushima Unit 3 accident has been studied by using Melcor_2.1. An initial calculation was performed by using design conditions or operators reported actions. Several series of sensitivity cases have been performed in order to reproduce the main accident measurements (e.g. pressure histories of the reactor pressure vessel, dry-well and wet-well; downcomer water levels and the observed hydrogen explosion time). The sensitivity studies consisted in variations of Reactor Core Isolation Cooling and High Pressure Coolant Injection operation, Alternative Water Injection, venting, leaking to the dry-well and failure parameters of the lower head. The outcomes of the sensitivity calculations have pointed out the likely-state of the U3 core after 6 days of the accident start.

1. Introduction

During the accident occurred at the Fukushima Daiichi nuclear power station in March 2011, three units of the nuclear power plants suffered extensive damage to the reactors and buildings. It is widely believed that all three reactor cores experienced some melting. Several analyses of the accident sequence have been performed in the years following the accident by using different computers codes. Despite the efforts to understand the sequence, there are still unresolved issues. Uncertainties concerning the boundary conditions are still not completely resolved and make it very difficult to correctly capture the accident evolution. In particular, Unit 3 has been studied by Gauntt et al. (2012) with MELCOR and MAAP, EPRI (2013) with MAAP, Robb et al. (2014) with MELCOR, TEPCO (2014a) with MAAP, Pellegrini et al. (2014) with SAMPSON and Bonneville and Luciani (2014) with ASTEC. The mentioned studies were not able to reproduce the observed pressure in the dry-well/wet-well (DW/WW) after ca. 45:00–68:00 h after SCRAM, nor have they been able to predict the H_2 explosion conditions at the top of the reactor building at the observed time in U3. Sevón (2015) was able to calculate with MELCOR flammable hydrogen concentration at the top of the building at 68:15 h; however, the pressure trend in the DW/WW was not completely captured after ca. 45:00 h. Finally, Cardoni et al. (2014) were able to calculate with MELCOR plausible sequences (varying from in-vessel to ex-vessel scenarios) leading to the hydrogen explosion at ca. 68:00 h and to roughly predict the pressure trends in the DW/WW. Additionally, the OECD/NEA/CSNI (2014) Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Station (BSAF) project is ongoing.

The present study adopted a step-by-step approach to define the boundary conditions for the various phases of the accident sequence in such a way as to calculate the sequence as well as possible up to 6 days after the SCRAM, while remaining consistent with available records from the plant operation. The period of 6 days corresponds roughly to the unavailability of AC power. The main goal of the study is to reconstruct the sequence as closely

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Abbreviations: AWI, Alternative Water Injection; BAF, Bottom of Active Fuel; BSAF, Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power Station; CAV, cavity in MELCOR; CST, condensate storage tank; COR, core package in MELCOR; CV, control volume (i.e. used for hydrodynamic nodalisation in MELCOR); DW, dry-well; DC, direct current; FP, fission product; HPCI, High Pressure Coolant Injection; LV, large venting valve; MCCI, Molten Core Concrete Interaction; MELCOR, Methods for Estimation of Leakages and Consequences of Releases; MO, motor operated venting valve; PCV, Primary Containment Vessel; RCIC, Reactor Core Isolation Cooling; RPV, reactor pressure vessel; SPR, containment sprays package in MELCOR; SRV, safety relief valves; SV, small valve in the venting line; TAF, Top of Active Fuel; U3, Unit 3; WW, wet-well.

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as possible bearing in mind gaps and uncertainties in the measurements, and limitations in the physical modelling of MELCOR and in the achievable spatial resolution. Understanding of the degradation processes and optimising their modelling, though desirable, are not the main aims of the current investigation.

The investigation concentrates on the core uncovery, degradation and relocation, including possibly ejection into the cavity. Fission product (FP) release from the fuel is included in the core degradation, but transport through the containment and leakage to the reactor building and environment are not addressed in the present study. A credible account of the core degradation and its impact on system integrity are necessary prerequisites to evaluation of the FP release.

The simulation task is difficult because so many of the components including measurement devices were not functioning normally. Furthermore, the operators may have been impaired to take measurements or perform accident management actions at certain times, as a consequence of the devastation caused by the tsunami and/or the events that happened to the different units in the plant (e.g. hydrogen explosion, evacuation due to high level of radiation, etc.), so that much of the plant data are incomplete or uncertain. Nevertheless, the most reliable or/and complete data for Unit 3 have been identified after an extensive review of the available technical data, namely plant design, boundary conditions, accident data and uncertainties.

The main data that have been used for the present analysis are available in the information portal for the Fukushima Daiichi Accident Analysis and Decommissioning Activities (TEPCO, 2014b). The most reliable data used for the analysis are:

- The times at which the hydrogen explosions took place in each unit.
- The pressure history in the reactor pressure vessel (RPV) and in the containment DW/WW have been identified as fairly complete and reliable data, which is fortunate because this serves as a trail of footprints that point to what was happening.
- The times and rates of fresh or sea water injection (by means of fire engine pumps) into the reactor system, though unfortunately the rate of delivery to the RPV itself is uncertain.
- The time when the operators vented the containment to control the pressure, though unfortunately it is uncertain if all the venting operations were successful or had taken place at the reported time and the percentage of the valve opening is unknown.
- The water level measurement is available but it is subject to gaps and uncertainties.

The analysis was performed using a generic MELCOR 2.1 input model based on Peach Bottom power plant (SNL, 2012; Carbajo, 1994). The input was adjusted to the specifics of Fukushima. The description of the main features employed by MELCOR 2.1 as well as the chosen nodalisation and main models for the analysis is presented in Section 2. An initial calculation was performed and several sensitivity studies were performed, where the times and the magnitude of boundary conditions, such as water injection reaching the RPV, steam extracted from RPV, venting, RPV and Primary Containment Vessel (PCV) failures, were evaluated. Additional sensitivity cases were performed in order to evaluate the conditions at which fuel rods were collapsed into debris. The chosen values are described in Section 2.3, they gave the best agreement with the measured pressures and better representation of the H_2 high concentration in the reactor building during the period leading up to the explosion. In view of the scale of the study and length of the paper, most of the sensitivity studies were omitted and only a selection which represents the analysis the best was included in the present paper. The detailed description of the chosen sensitivity cases was included in Section 3, where uncertainties and open issues derived from the study were identified. The case which described the best the sequence was selected from the sensitivity cases, therefore a plausible accident degradation sequence of Fukushima U3 was included in Section 4, followed by the overall conclusion of the paper in Section 5.

2. Description of the employed severe accident code (MELCOR)

2.1. General description

MELCOR (Methods for Estimation of Leakages and Consequences of Releases) is a system-level code for whole plant analysis of reactor accidents, developed at Sandia National Labs since 1982 on behalf of the USNRC. It was first released in the USA in 1986 and internationally in 1989. The latest version, designated 2.1 is being used for the present simulations. The general models used by MELCOR are described in the manual (SNL, 2008), only the specifics models used in the present analysis will be described in Sections 2.2 and 2.3.

2.2. Nodalisation and main models employed for the analysis

The input model encompasses the reactor vessel together with the associated coolant circuits, the containment dry-well (DW) and wet-well (WW) and the reactor building. A fairly detailed hydraulic noding is used for the active core region, which is divided into 5 fuel channels each subdivided into 5 axial nodes (CV1mn; m = 1, . . ., 5, n = 1, . . ., 5) and 5 bypass channels with a single axial node (CV5m1; m = 1, . . ., 5) to resolve the effect of core radial and axial profiles on the fluid conditions. A total of 30 hydraulic cells are therefore used for the core. The core channels are separate from each other and from the bypass along the active length, but the bypass regions are connected by crossflow paths. The simulation includes opening of connecting paths between the core and bypass following breach of the respective channel boxes. The remainder of the RPV, that is the feedwater line, downcomer (CV310), jet pumps (CV300), lower plenum (CV320), upper plenum (CV345), separator (CV350), drier (CV355) and steam dome (CV360) is represented more coarsely with just 7 cells. The vessel noding is shown in Fig. 1. The feed and circulation lines are also represented with single cells for each of the main segments from-to the RPV.

As is customary in MELCOR modelling, the noding of the core (COR) components is more detailed than the hydraulic noding. The radial COR noding is the same as the hydraulic noding but the fuel assemblies, comprising the fuel rods, spacer grids and channel boxes, are divided into 10 axial cells (numbered 7–16) so that each axial hydraulic cell contains two axial COR cells. The fuel channels are inside the channel boxes and the bypass volumes that contain the control blades are outside. The upper support structure occupies node 17. The vessel lower head, the lower support and other structures extend to the bottom of the vessel and span nodes 1–6 which are associated with the single hydraulic node CV320. Penetrations in the RPV lower head structure for the control assembly drive housing and guide tubes are included in each radial node.

The noding of the containment and reactor building is shown in Fig. 2. The 4 parallel steam lines to the turbine are modelled individually. The WW is divided into a lower (CV220, normally liquid) and an upper (CV221, normally steam and nitrogen) volumes. Four cells are used to model the DW (CV 200, CV201, CV202 and CV 205). The containment is inerted with nitrogen. Included in the ensemble of steam system and containment nodes are the safety relief valves (SRV) and connections to the WW, the turbine-driven RCIC and HPCI and connections back to the vessel, as well as the