Challenges and Sensitivities in the Modelling of Fukushima Unit 1 Unfolding with MELCOR 2.2

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Abstract

The Fukushima accident occurred in Japan on 11 March 2011 has revived the interest for the analysis of severe accidents. The scarce and sometimes unreliable data concerning boundary conditions, effectiveness of accident management measures and equipment performance, pose a tough challenge in modelling the Fukushima accident scenarios.

Throughout an analysis of the challenges posed by the Fukushima Unit 1 data recorded, this paper describes the major postulates proposed by CIEMAT concerning the equipment and component responses, the effectiveness of accident management actions and the MELCOR model applied. Among most influencing assumptions are those related to the reactor pressure vessel (RPV) leaking pathways and failure mode, the water flow rate entering the reactor, the potential leaking pathways and failure mode and location from the primary containment vessel (PCV) to the reactor building, the corium relocation from RPV to the cavity and its distribution in the PCV, the potential stratification of the suppression pool and the hypotheses made a priori concerning fission product release and transport. Based on the postulated scenario and model, a remarkable agreement of the thermal footprints in terms of RPV and PCV pressures during 500 h has been achieved, in which the RPV and PCV leaks/failures as well as venting played a determining role in the short run of the accident and water injection heavily conditioned the long one. As for the scarce data related to fission products (FP), a consistent agreement is found in the suppression chamber, but estimates in the Dry-Well are about an order of magnitude below measurements despite showing the observed trend. A number of factors might affect FP comparisons to data, from the approximate method to derive dose rates (measurements) from FP masses (MELCOR results) to the RPV and PCV postulated failures. Anyway, based on the data available the set of hypotheses and approximations made seem to make up a defensible scenario for Fukushima-I Unit 1.

The studies and results presented in this paper have been achieved under the frame of the OECD/BSAF projects through the CSN-CIEMAT collaboration agreement on severe accidents research.

Keywords: Fukushima Unit 1; MELCOR analysis;

1. Introduction

Building up an entire scenario from sparse and often questionable pieces of information, like scarce data recorded during the event and/or few footprints left, is always a challenge. This forensic work turns out to be tough when the event is a so complex system as a nuclear reactor severe accident. Since 2011, an international project framed under the auspices of the OECD/NEA and participated by a reduced number of partners, adopted this forensic approach to find out defensible scenarios that could explain the evolution of the accidents at the units 1 through 3 of the Fukushima Daiichi Nuclear Power Plant. The project is known as BSAF (Benchmark Study of the Accident at the Fukushima Daiichi Nuclear Power) and its second phase has just finished. Spain has taken part in both project phases through CSN and CIEMAT; an illustration of the first phase results have been reported elsewhere (Herranz et al., 2015a-b; Pellegrini et al., 2016).

The Fukushima accident, occurred in Japan on 11 March 2011, has revived the interest for the analysis of severe accidents. Despite the low probability of this type of events, Fukushima has brought forward two irrefutable facts: those highly unlikely accidents may, though, happen; and, once happened, their consequences might be of sizeable dimensions and long lasting. As a consequence, there has been an enormous interest worldwide to thoroughly understand the accident unfolding as a way to gain insights for prevention of these accidents and, as highly stressed since then, mitigation of their consequences.

This paper is a radiography of the interpretation challenges posed by the Fukushima Unit 1 data recorded and a synthesis of CIEMAT’s response in terms of major postulates concerning the equipment and component performance, the effectiveness of accident management actions and the MELCOR 2.2 model applied. Among most influencing assumptions are those related to the reactor pressure vessel (RPV) leaks and failure, the water...
flow rate entering the reactor, the potential leaks and failure from the primary containment vessel (PCV) to the reactor building, the corium relocation from RPV to the cavity and its distribution in the PCV, the potential stratification of the suppression pool and the hypotheses made a priori concerning fission product release and transport.

This work has been supported by CSN through the CIEMAT-CSN collaboration agreement on Severe Accidents (ACAS).

2. Forensic challenges

Pressure histories in the Reactor Pressure Vessel (RPV) and the Primary Containment Vessel (PCV) were monitored in 1F1 along the accident (TEPCO, 2011). However, as noted in Fig. 1, very few data points were recorded during the first 12 h. In particular, P_{RPV} recording halted right after the tsunami and there is only one point at around 5 h and the next one at roughly 12 h. Similarly, containment pressure signals were missing until 10 h, then another point was recorded at 12 h and from then on a good recording took place until wetwell venting took place (around 1 day after the accident), after which signal was lost again.

![Fig. 1. Pressure data recorded during the first 30 h (TEPCO, 2011)](image)

Scarcity of data along this early phase is crucial because it is in this period (0 - 12 h) when core degradation leading to RPV and PCV failure occurred. The information available is far from being enough to know the mechanism responsible for RPV failure (i.e., main steam-line break; safety relief valve gasket failure; incore instrumentation tube failure; …) that should have determined to a good extent the in-containment pressure load. The only facts to support any hypothetical scenario is that in between 5 and 12 h RPV got depressurized and that PCV pressure reached 6 bar at around 10 h and then it experienced a spike peaking at 8.5 bar at about 12 h. Then P_{PCV} history describes a nearly steady state for almost 9 h until containment venting. Any postulated scenario should support this observed profile of pressured at both locations consistently.

Beyond containment venting, interpretation of P_{PCV} data recording is still a challenge (Fig. 2). As noted, a pressure increase occurred right after venting and, although a peak is shown at around 50 h, data are missing in between 75 h and 175 h, approximately. In addition, in the long run of the accident something should have happened that made pressure raise again about 2 bars in roughly 25 h (275 h – 300 h); given the accident progression up to that time, it is hard to imagine a natural phenomenon being responsible for it at such long run, so that as it will be discussed below, such an increase seems likely to be associated to accident management.
Fig. 2. Recorded data along the accident (TEPCO, 2011)

Scarcity of data allows figuring out a number of scenarios responding partially to the above signals. Nonetheless, as more data are being collected, such a number is being squeezed.

Despite all the challenges described above, different forensic analyses performed under the frame of the OECD/BSAF project agreed on relevant aspects of the accident (Pellegrini et al., 2016): the massive degradation of reactor core, the failure of RPV, the nearly complete fall of corium into the pedestal, the PCV failure and the unsuccessful water injection until very late in the accident (around 275 h).

In addition to thermalhydraulic data, the Containment Atmosphere Monitoring System (CAMS) provided dose rate measurements in the drywell and in the suppression chamber from 50 h on (the signals between 50 and 100 h seem not to be reliable, though). No direct clues concerning the accident progression can be easily derived from these measurements, but at least they give qualitative insights, such as the decreasing trend with time or the initially recorded level (around 102 Sv/h at 50 h; a bit lower at the suppression chamber).

3. MELCOR modelling

The sequence has been simulated with the MELCOR 2.2 code (Humphries et al., 2015). MELCOR is a fully integrated, engineering-level computer code that models the progression of severe accidents in light water reactors. It includes a broad spectrum of phenomena, from core degradation to source term to the environment; just to mention a few: thermal-hydraulic response in the reactor coolant system, reactor cavity, containment, and confinement buildings; core heatup, degradation, and relocation; core-concrete attack; hydrogen production, transport and combustion; fission product release, transport and behavior. Worth to note, that default options have been systematically taken in most of the MELCOR active models.

3.1. MELCOR plant description

Most geometrical and material information concerning 1F1 were provided by the NPP owner (TEPCO) and are considered confidential; the user, though, may play a role in the plant description through the nodalisation. Fig. 3 shows the main features of the nodalization set in the MELCOR input deck (Herranz et al., 2015).

A total of 65 compartments have been used to describe RPVs (38 volumes) and PCVs (27 volumes). The RPV has been split in steam-dome, dryers, separators, shroud dome, annulus, lower plenum and 32 volumes for the core active region. In order to track fuel degradation a specific nodalisation of the core is set in 4 radial nodes and 8 axial nodes (an additional one for the core plate and 3 more nodes describing the lower plenum of the RPV). The PCV nodes have been distributed as follows (Fig. 3): 9 nodes for the Dry Well (DW), 8 circumferential nodes for the Wet Well (WW) and 8 more nodes for the vents in between DW and WW. In case of RPV failure Molten Corium Concrete Interaction (MCCI) has been modeled as 2 interconnected cavities defined ad-hoc, one of which is the pedestal region and the other the DW floor outside the pedestal. Finally, the reactor building has been modeled with a total of 19 control volumes, 25 flow paths and 57 heat structures (Fig. 2 c).
As for safety systems, some explanations might be worth. The 2 Isolation Condensers (IC) in Unit 1 have been modeled as a single energy sink based on an enthalpy withdrawal from the vessel (i.e., latent heat at the dome conditions is removed from the RPV according to the IC efficiency). The IC efficiency imposed has been set in such a way that the first 50 min RPV pressure oscillations are captured. The 4 SRVs have been modeled as valve controlled flow paths between the RPV and the S/C, each one discharging steam and non-condensable in a different azimuthal location of the suppression pool (with ~2.0 m submergence). The set-points have been defined as specified in the OECD/BSAF benchmark. The PCV venting at 14:30 h on March 12th has been modeled as time valve controlled flow path from the Wet-Well (WW). The cross section area set corresponds to the one of the small WW venting valve of Unit 1.

3.2. Phenomena modelling

Even though the MELCOR user faces with a number of options throughout the input deck construction, here only those really relevant in the scenario are discussed and the reason why is given.

As for radionuclides, the way they are defined in classes has an influence in the fuel release kinetics. Thirteen classes have been considered, which are represented by the following elements: Xe, Cs, Ba, I2, Te, Ru, Mo, Ce, La, Cd, Ag, CsI and CsM. Cesium inventory is split into three classes which account for different chemical compounds: Cs, for CsOH; CsI, for CsI; and CsM, for Cs2MoO4. Nonetheless, more than 90% of Cs is associated to class CsM. The I2 class accounts for the gas molecular iodine.

Suppression pool is possibly the most outstanding feature of Mark-I containments due to its double effect as a steam sink and a fission product filter. Thus, its thermal status (i.e., subcooling vs. saturation) is key in the accident evolution. As described above, CIEMAT has set a circumferential nodalization to account for the effect that just one SRV operated during the accident, but consideration has also been given to the fact that a vertical
stratification could also build in the injection node. Steam coming from RPV is at high temperature and will transfer its sensible and latent heat to water around injection point, so that such water will decrease its density and buoyancy forces will make it rise to pool surface. Based on this conceptual picture, CIEMAT has assumed a “perfect axial stratification”: the water layer below the injection spot is ignored so that the thermal inertia of the suppression pool, particularly of the injection node, is reduced.

The long-run of the accident when RPV fails is highly dependent on the interactions between the hot material falling from the RPV and materials it finds on its way in the PCV. Long term pressurization due to gases emitted during MCCI, potential hydrogen and carbon monoxide combustion, liner melt-through and basemat penetration are four containment threats directly associated to it. This makes cavity modelling extremely important. CIEMAT has proposed a two-region cavity: the pedestal region (CAV1), which receives the molten material after the vessel rupture; and the out-pedestal region (CAV 2), which receives a fraction of the corium in the pedestal whenever material piles up 0.1 m over the material level in DW floor and, of course, is over the solidus temperature. The fraction transferred is dependent on the material temperature (it is 1.0 at T>Tliquidus). The other important aspect is the spreading rate of material in CAV2 whenever temperature is higher than 1350 K (Tsolidus). CIEMAT has set a maximum velocity of 2.2·10^{-3} m/s, based on the analyses made in the SOARCA study (USNRC, 2012).

3.3. MELCOR results

A good number of hypotheses and approximations to build up the postulated scenario were necessary to be made, as it will be presented in next section. Such assumptions led to the results shown in Figs. 4 to 7. The analysis domain extends over 3 weeks (500 h) from the initial time (reactor scrams).

As for, Fig. 4, the PRPV data are apparently captured in a broad sense, but there might be a number of scenarios other than a sharp RPV depressurization at about 11.5 h that would be equally plausible, as no data are available between 5 and 12 h. Data on water level in RPV might have been of a great help for scenario interpretation in this period, but unfortunately their recording was limited to the first two hours of the accident. In case that the accident progressed according to the scenario proposed, it would mean that during the in-vessel phase nearly half of the zirconium inside the RPV would have oxidized resulting about 570 kg of H2 (plus almost 100 kg from stainless steel oxidation).

As in the case of RPV, containment pressure (Fig. 5) is well captured according to the data available. Pressure levels at 10 and 12 h are reached, the 9 h pseudo-equilibrium steady state is attained and the rest of data are well matched with the data in the mid- and long-run. In other words, the postulated scenario looks to satisfactorily capture the containment evolution through the hypotheses and assumptions made. This evolution depends to a good extent on the 129.0 tons of corium falling in the pedestal once RPS fails, of which around 25% is still in metallic form. As a result of the molten corium-concrete interaction (MCCI), a substantial amount of combustible gases (more than 16 tons) would have been generated ex-vessel (Fig. 6), most of them from the pedestal (75% approx.) but a non-negligible fraction (25% roughly) from the molten material spread on the drywell floor. In addition, the corium was responsible for an axial ablation of pedestal deeper than 3 m and a “liner melt-through” melt-through that resulted in a sand-cushion leak at 50.9 h.
Finally, concerning fission products, Fig. 7a shows that noble gases and cesium have been estimated to entirely released from the fuel, while iodine and tellurium were massively released (more than 90% of their mass initial inventory) but not so much; it is worth noting that a non-negligible fraction of molybdenum (around 28%) was also released during the in-vessel phase in form of molybdate. Once the transport of all these materials throughout the plant has been calculated and masses translated in dose rates (an approximate method agreed under the OECD/BSAF project applied), the consistency with data recorded is considered reasonable given the outstanding uncertainties affecting the MELCOR estimates shown in Fig. 7b. In short, consistency con data trends and order of magnitude seems also to support the postulated scenario.

![Containment pressure evolution](image1)

**Fig. 5.** Containment pressure evolution

![Ex-vessel gas generation from MCCI](image2)

**Fig. 6.** Ex-vessel gas generation from MCCI.

![Key variables describing fission products](image3)

**Fig. 7.** Key variables describing fission products.

- **a.** Fission products release from fuel (initial inventory)
- **b.** PCV dose rate
4. Postulated scenario

The main features of the scenario have been briefly described in section 2, so that this section focuses on the postulated scenario that CIEMAT proposes by summarizing the main hypotheses and approximations made. Initial analysis conditions, like the decay heat power and radionuclide inventory were adopted from the TEPCO description (TEPCO, 2012).

4.1. Leaks and failures

In addition to the Main Steam Line (MSL) failure, there would be three transfer paths of mass from RPV to PCV: SRV gasket, core instrumentation breaks and instrumentation sealing. All of them were initially considered in the modelling and the results were reported elsewhere (Herranz et al., 2015b). Finally, it was considered that a plausible scenario could be a gasket leak when the SRV location reaches 723 K (the size involving a height of around 1 mm) and an approximate 2 mm leak from the lower plenum (compatible with the instrumentation seal failure).

As for PCV leaks, three potential locations have been assumed: PCV flange, high containment pressure and a temperature higher than 755 K at the location (USNRC, 2012); DW sand cushion leak whenever liner melt-through conditions attained (corium hotter than 1200 K reaches the liner); WW bellows leak (inspired in observations of a leak in that location and local dose rates measured). They all have been simulated as valve controlled flow-paths. Note that DW flange leak allows pressure to get a kind of steady state during periods of gas production within the DW (i.e., during the ex-vessel phase due to MCCI). The sand-cushion failure criterion has been imposed so that PCV pressure estimates experienced a decrease in the mid-term of the accident (50.9 h). The WW bellows leak might well be a combination of such a leak and a WW vent leak, since consequence would be similar.

Finally, two nominal leakages have been set in the RB. They are placed in the first and second floors and they both open at the explosion time (24.83 h). In addition, the roof and wall panels removal at the time of explosion has been also simulated.

4.2. Mitigation action: external water injection

External water injections have been modeled as mass and energy sources into the RPV. The water injection described in the input deck has been associated to high uncertainty (NEA, 2014) and it was largely discussed within the OECD/BSAF project. CIEMAT assumed that water injection was unsuccessful until 273 h, when the injection point was moved from core sprays to the feed water line. The reason for it might be not enough pumping pressure and/or water diversion once within the Unit 1 loops.

5. Concluding remarks

This paper synthesizes the forensic work done by CIEMAT under the frame of the OECD/NEA BSAF projects in the understanding of the accident unfolding of Unit 1 of Fukushima Daiichi. By analyzing all data recorded available as a whole a scenario compatible with the known accident footprints to date has been proposed. Its main characteristics are:

- RPV leaks to DW, other than the RPV bottom failure, through the SRV gaskets (steam and hydrogen) and through RPV bottom (water).
- PCV failure at DW upper head flange, which explains the pseudo steady-state of PCV pressure (local high temperature), at the sand-cushion, which would support the PCV pressure decrease right after about two days of the accident (liner melt-through) and at the region of WW-DW bellows, which is consistent with dose rates and temperatures measured in the nearby.
- RB major failure, as observed, right after the venting.
- Unsuccessful water injection until well advanced the accident (273 h), which flowrate governs the late evolution of the accident together with the progression of MCCI.

In addition to these features concerning scenario boundary conditions, the CIEMAT’s model includes other major signatures concerning plant and phenomena modeling that might affect the results substantially. Among them SC nodalization and cavity modeling should be highlighted. Needless to say that aspects like nodalization might also have an effect; nonetheless, CIEMAT’s model evolution has involved several nodalization schemes and they never led to drastic changes in results.
In order to keep on progressing in the thorough understanding to the accident unfolding, particularly on all those aspects concerning FP behavior and corium spreading, which analysis should be still considered preliminary, a follow-on project of OECD/BSAF under the OECD/NEA auspices has been launched in 2019: Analysis of Information from Reactor Buildings and Containment Vessels of Fukushima Daiichi Nuclear Power Station (ARC-F).

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References


