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Long-term Containment Cooling in Fukushima Unit 1: Insights into Consequences from Sensitivity Studies

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ABSTRACT

The Fukushima accidents have already provided, and will continue providing, relevant insights into different aspects of major management actions conducted at the time. Based on the analyses carried out within the OECD/BSAF2 project with MELCOR 2.2 on Unit 1, this study explores what the alternative water injection, after roughly 10 days after the accident onset, would have meant in case it had occurred earlier or later in the sequence, or it had been stronger or weaker than it supposedly was. Containment pressure and fission product release to the environment are the main figures of merit in this study.

1 INTRODUCTION

On 11 March 2011 an earthquake hit Japan shore at 14:46 (local time). Units 1 through 3 of Fukushima Daiichi Nuclear Power Plant (NPP) were shut down, and all electrical lines feeding the plant were off. Almost one hour later the ensuing tsunami flooded turbine buildings and the backup diesel generators became inoperative. This lack of offsite and onsite power made the situations evolve into the severe accident domain and became a worldwide concern. Since then, all stakeholders (regulators, vendors and researchers among others) launched many activities for understanding, mitigating and preventing this type of accidents. Many NPPs have been required to implement technical upgrades that should enhance safety even further.

In November 2012 the OECD-NEA launched the international BSAF project (Benchmark Study of the Accident at the Fukushima Daiichi NPP). The objectives were the analysis of the accident progression providing the status of the Fukushima Units 1, 2 and 3 to get the best understanding of the sequences developed; to improve models of Severe Accident (SA) codes; and to provide useful information to support safe and timely decommissioning activities. This first phase of the project was followed up by a second one, the major insights gained on the accident from both phases may be found in [1], [2].

This study investigates the Alternative Water Injection (AWI) conducted in Unit 1 of Fukushima Daiichi NPP (hereafter referred as 1F1) after more than 10 days since the accident onset (long-term cooling) [3].

Based on the analyses carried out within the OECD/BSAF2 project with MELCOR 2.2, the main aim of the study is to assess the sensitivity of accident unfolding to AWI in case it had occurred differently than postulated. The consequences of the scenarios set in the study are followed in terms of containment thermal-hydraulics and Source Term to the environment.

The AWI strategy deduced from the outcomes of the CIEMAT's participation on the BSAF project [3], [4], the AWI registered in the operator's log [5], and a non-AWI case are confronted to the available measurements to select the reference case. Then, from such reference case, changes in AWI magnitude and timing are postulated and containment pressure response and Fission Product (FP) leaking to Reactor Building (RB) are investigated.

In section 2, the Evaluation Model (EM) used in this analysis is depicted. Section 3 focuses on obtaining the reference case of this study. In section 4, a discussion is carried out related to the sensitivity on the AWI strategy and its consequences. Finally, in section 5, some conclusions and remarks are highlighted.

2 MELCOR & THE 1F1 EVALUATION MODEL

MELCOR is a fully integrated, engineering-level computer code that models the progression of severe accidents in light water reactors [6]. 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 heat-up, degradation, and relocation; core-concrete attack; hydrogen production, transport and combustion; fission product release, transport and behaviour.

The 1F1 EM has been built, following the SOARCA project recommendations [7], with a total of 84 Control Volumes (CV): 38 CVs to describe the Reactor Pressure Vessel (RPV), 27 CVs for the Pressure Containment Vessel (PCV) and 19 CVs for the Reactor Building (RB). Additionally, the environment has been split in 3 CVs.

The RPV (Figure 1) has been discretized into the steam-dome, dryers, separators, shroud dome, annulus, lower plenum and 32 CVs for the core active region. In order to track fuel degradation a specific nodalization of the core (COR package) is set in 4 radial- and 8 axial nodes, with 4 more additional axial nodes for the core plate and the lower plenum.

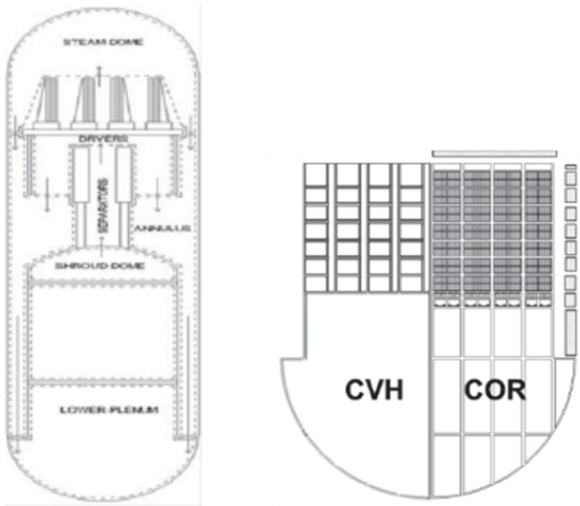

Figure 1 - RPV nodalization

The PCV nodes (Figure 2) have been distributed as follows: 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.

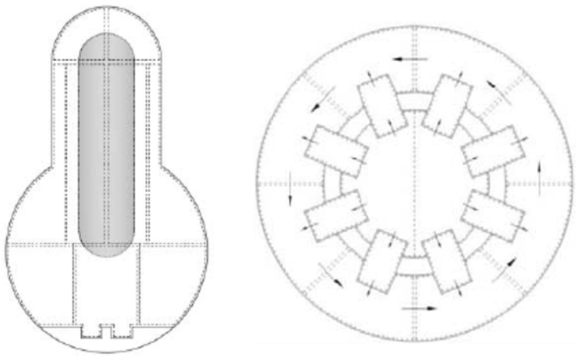

Figure 2 - PCV nodalization

In case of RPV failure Molten Corium Concrete Interaction (MCCI) has been modeled as two interconnected cavities defined ad-hoc, one of which is the pedestal region and the other the DW floor outside the pedestal (Figure 3).

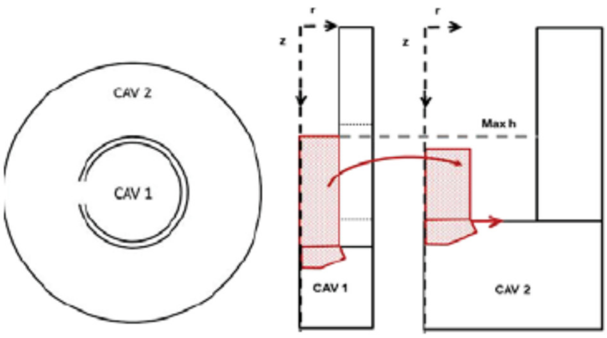

Figure 3 - Cavity nodalization

The systems modeled were the isolation condenser, whose operation was limited to the beginning of the transient and the AWI system, composed by the fire brigades motor-pumps, which where modeled by means of control functions and a pressure dependent table for the injection rate. Also worth mentioning the SRVs performance has been modeled through the inclusion of the corresponding tabular functions.

3 REFERENCE CASE

In order to select the reference case, three different AWI scenarios have been compared to measurements, specifically to the DW pressure evolution (Figure 4). The case A corresponds to the AWI reported in the operator's log, the case B to a non-AWI operation and case C to the CIEMAT's estimation for the AWI operation to fit the measurements (Figure 5). Note that other than AWI operation, all the cases are exactly the same. Since the aim of the study is the long term cooling operation, the results shown in the figures correspond to the time interval between 200 and 400 hours after the 1F1 scram.

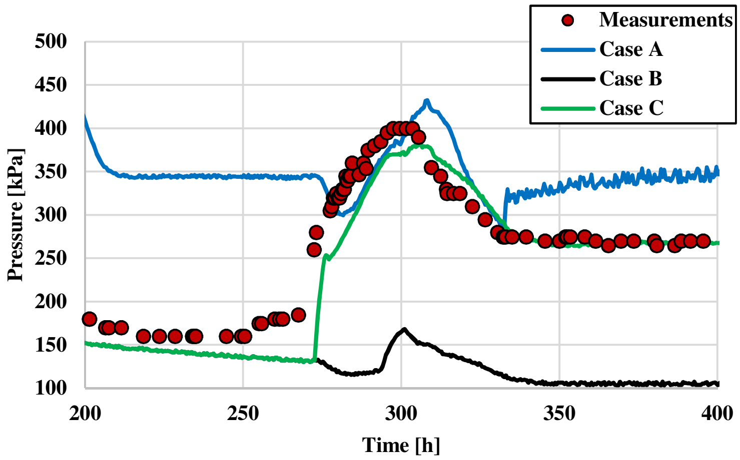

Figure 4 - Dry well pressure

Clearly, the case A pressure evolution differs from the measured one (Figure 4). According to [1], the AWI described in the operator's log was intended, but it seems that the water did not reach the RPV. This might be due to the high pressure within the PCV and the pipe branching between the injection point and PCV outlet, which might have found other flow paths with lower resistance to the water flow. The case B (no AWI) also shows major deviations with respect to the measurements. Then, it was inferred that the unexpected sharp increase of PCV pressure in Unit 1 after more than 270 h since the onset of the accident, had to do with the successful AWI. This is consistent with the fact that at this time such external injection was moved to a different entry point. Then, by setting the beginning of the AWI operation at around 273 hours, case C supplies an AWI curve in accordance with the thermal-hydraulics measured during the 1F1 accident. As shown in Figure 5, a good fit to PCV pressure footprint required water mass flow rates peaking around 2 kg/s right at the moment of injection. As for the remaining flow rates from 325 h on, it is still a matter of discussion.

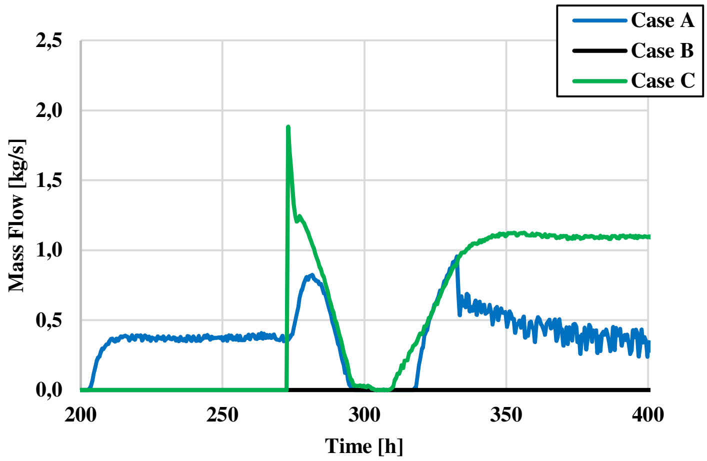

Figure 5 - Alternative Water Injection rate reaching the RPV

4 AWI SENSITIVITY ANALYSIS

In order to explore the potential effects of long term cooling based on the Fukushima scenario picked in section 3, two sensitivity cases are conducted. The first one is focused on cooling magnitude (i.e., mass flow rates); the second one addresses the AWI timing (i.e., shifting AWI to earlier and later times from the postulated 273 h). The figures of merit for both analyses have been DW pressure and the FP mass leaked to the environment (in terms of relative contribution to what already leaked at the time of AWI); in particular, the Cs_2MO_4 mass leaked has been tracked down, as Cs is mostly transported in the form of molybdates. A time window of 200 h has been set to show results (from 200 h to 400 h), so that the effects of the actions are clearly displayed.

The “magnitude study” consisted of two additional cases to the reference one: a reduced (case C1) and an increased (case C2) water injection by an order of magnitude in both cases. Figure 6 displays the cumulative AWI.

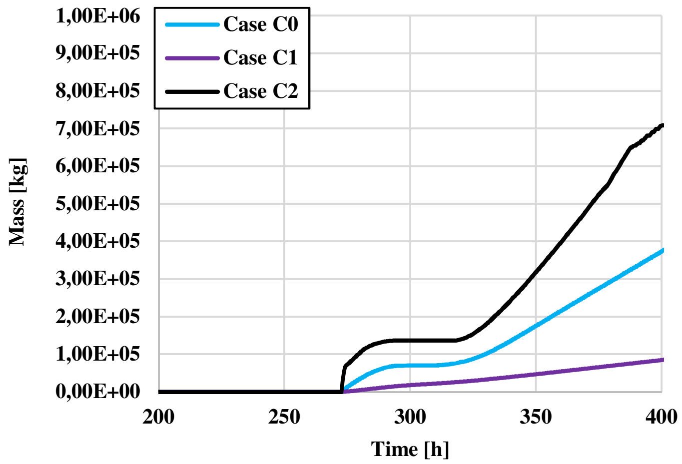

Figure 6 - Cumulative AWI

As shown in Figure 7, qualitatively the 3 cases unfold similarly: a DW pressure peak is shown at around 305 h and then pressure reaches a sort of plateau until roughly 400 h. Nonetheless, there are some quantitative differences worth discussing. As for the pressure peak, it should be noted that despite C1 and C2 are “symmetrical” with respect to the mass flow rate, the pressure change is not: C1 means a 1 bar reduction while C2 does a 0.5 bar increase, approximately. In addition, the plateau pressure depends on injected flow rate: the higher the water mass flow rate, the higher the pressure. This is consistent with the steaming caused by water contact with the molten materials spread onto DW floor and the consequent containment pressurization.

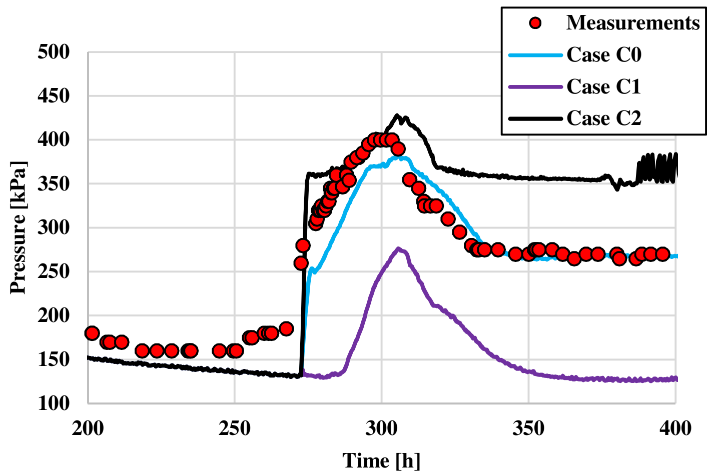

Figure 7 - Dry well pressure

Figure 8 displays the Cs_2MO_4 mass leaked to the RB. It should be noted that in-RB source term is dominated by a leak path to model PCV leak in the torus room, so that presumably, just a fraction will make it to the environment. As observed, only in case of high flowrate, AWI means a minor addition to the already leaked mass to the environment. The relative increase in the case of low flow rates is about a factor of 8 at 400 h and clearly shows a growing trend (whereas the other two cases are already in steady state). Anyway, the amount released was predicted in all the cases to be less than 5.5% of the initial inventory of this Cs species.

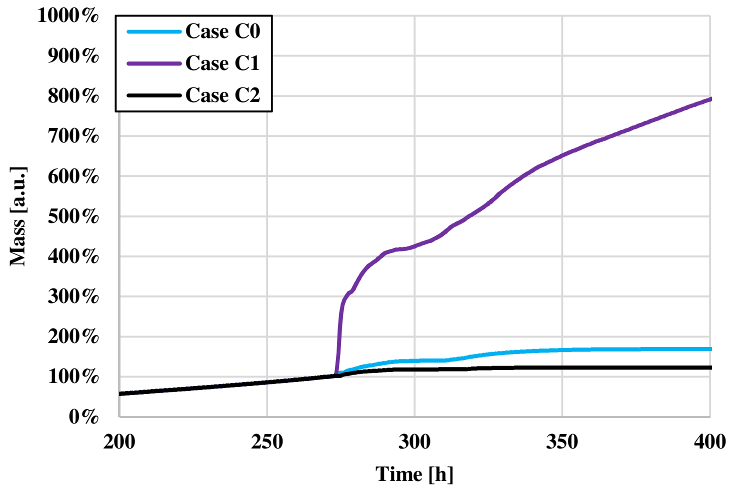

Figure 8 - Cs2MO4 cumulative leaked to the RB

The reason for this continuous FP leaking at a reduced AWI is the concentration rise occurring in DW atmosphere (Figure 9) at the time and the presence of such species for quite long time in the DW, which is not the case for the other cases where AWI is substantially higher.

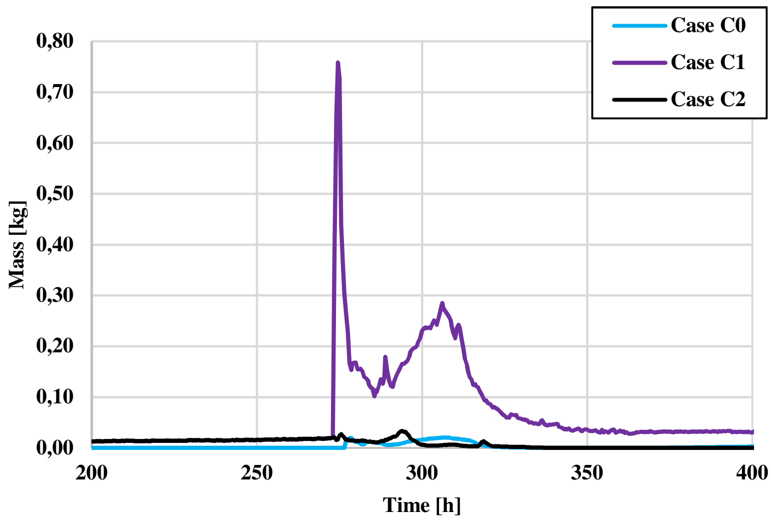

Figure 9 - Cs2MO4 airborne mass in DW

The source of that mass in the DW atmosphere is the hot deposits on the RPV surfaces, which from the onset of AWI undergo substantial revaporization unlike the other cases in which this phenomenon is hardly noticeable (Figure 10). The low AWI in C1 causes a prompt increase of temperature of the heat structure where Cs_2MO_4 got deposited earlier in the accident due to additional oxidation of metals in the core and in the pedestal. This does not happen in C0 and C2 because the amount of water injected is enough to cause quenching of the hot metal in the RPV.

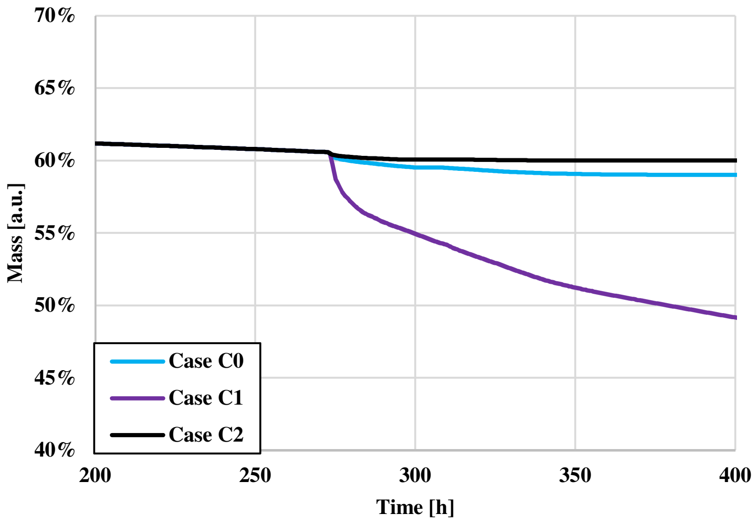

Figure 10 - Cs2MO4 mass ratio to total released in RPV

The second sensitivity study targets the effect of different AWI timing while keeping the system injection capability.

Figure 11 shows the DW pressure for the reference case (C0) and two other cases assuming a 70 h earlier AWI (C3) and a 70 h later AWI (C4). Each case illustrates the effect of water vaporization on DW pressure, as expected. Figure 12 displays the cumulative AWI in these three cases.

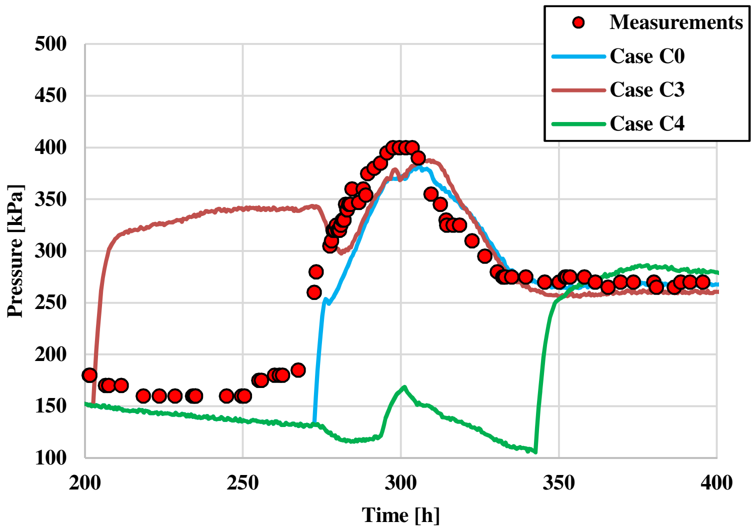

Figure 11 - Dry well pressure

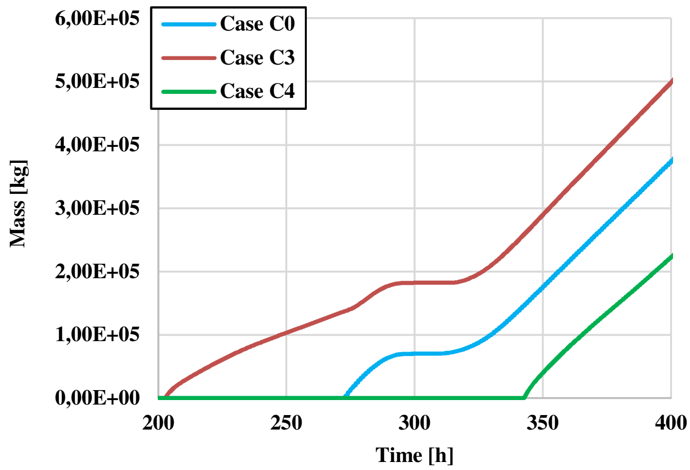

Figure 12 - Cumulative AWI

FP mass released (Cs_2MoO_4)to the RB is different for the 3 cases (Figure 13). However, differences in the relative increase of the leaked mass are just a few percent points. This contrasts with the huge noted increase when discussing the AWI magnitude impact. Anyway, the main difference with respect to the previous sensitivity case is that while the AWI timing might not notably affect the relative leaking rate, the reduced AWI in the previous injection meant an enormous change in the same variable.

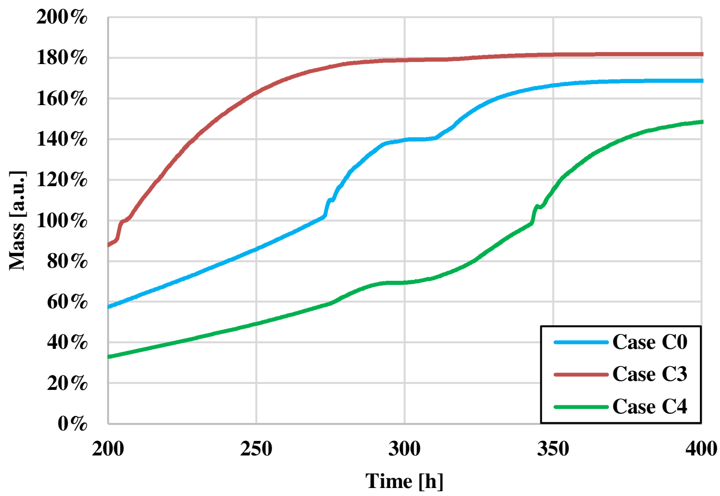

Figure 13 - Cs2MO4 cumulative leaked to the RB

5 FINAL REMARKS

Based on the CIEMAT's scenario postulated in the frame of the OECD/BSAF projects, the previous sections have explored the potential impacts of alternative water injection conditions (magnitude and timing) on accident unfolding in terms of containment pressure and leaked mass into the reactor building. The simulations conducted with MELCOR 2.2 have shed some insights into accident management, in particular:

- A reduced water injection might cause undesirable mobilization of deposits and increase of the relative release of fission products to the environment, regardless pressure level in containment (permanent failure path to reactor building set before the alternative water injection operation).

- Unlike the alternative water injection magnitude, timing seems not to have a major effect on Source Term.

Despite the interest of the above major observations, one should note that they are strongly scenario-dependent and, for instance, the lack of effect of containment pressure is due to permanent leaking paths prior to the alternative water injection; otherwise some containment pressure effect should be presumed.

Thus, in an attempt to make more generic observations from this study, it might be concluded that once containment tightness is lost and permanent flow paths have been set, effects of a later water injection would not be heavily dependent on timing, but the amount and rate of water injection might substantially affect the radioactive load on the environment.

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