Water Injection Influence for Accident Progression in Fukushima Dai-ichi Unit 1

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On the 11th of March 2011, the Great East Japan Earthquake and the ensuing tsunami hit the Fukushima Dai-ichi nuclear power station. Fukushima Dai-ichi Units 1 to 3 lost all DC and AC power; as a result, there was no water injection to Unit 1 during the early phase of the accident. The operator tried to use a fire engine to provide cooling after the earthquake, but the effective water flow rate to the RPV is still unknown. The effective water flow rate is very important for investigating the accident progression as well planning the decommissioning activities. Therefore, the effective water flow rate is investigated in this paper.

MAAP5 code is used to survey the influence of post-accident operational activities, particularly with regard to the water injection. Sensitivity analyses were performed in order to determine the possible conditions which correlate with the measured data from Fukushima Daiichi Unit 1 and investigate the internal condition of the Primary Containment Vessel (PCV) after the accident.

The result of this study shows that the effective water injection to the RPV that was required for mitigating the accident progression was probably not achieved until the 23rd of March 2011. As a result, the concrete erosion depth becomes severe due to Molten Core Concrete Interactions (MCCI). However, this severe result does not necessarily correlate with the current PCV internal condition.

The water injection rate to the RPV had a large impact for the accident progression in Fukushima Dai-ichi Unit 1. However, using the results of the analysis from Unit 1, it is difficult to explain the current plant condition, when the water flow rate to the RPV is reasonable. Therefore, this paper includes possible assumptions to explain the difference between the analysis result and the real plant condition.

I. Introduction

As a result of the Great East Japan Earthquake, with the epicenter being off the coast of Sanriku and the tsnumai that occurred subsequently on the 11th of March 2011, Units 1, 2 and 3 of the Fukushima Dai-ichi Nuclear Power Station fell into serious condition that far exceeded a design basis event. This eventually resulted in a severe accident where all of their respective emergency core cooling systems did not work or ceased to work, and all AC power and the ultimate heat sinks were not recovered. Unit 1 in particular was not able to conduct water injection for mitigating the event during the early accident phase. Therefore, it is thought that the majority of the fuel in the Reactor Pressure Vessel (RPV) melted and then fell onto the pedestal floor.

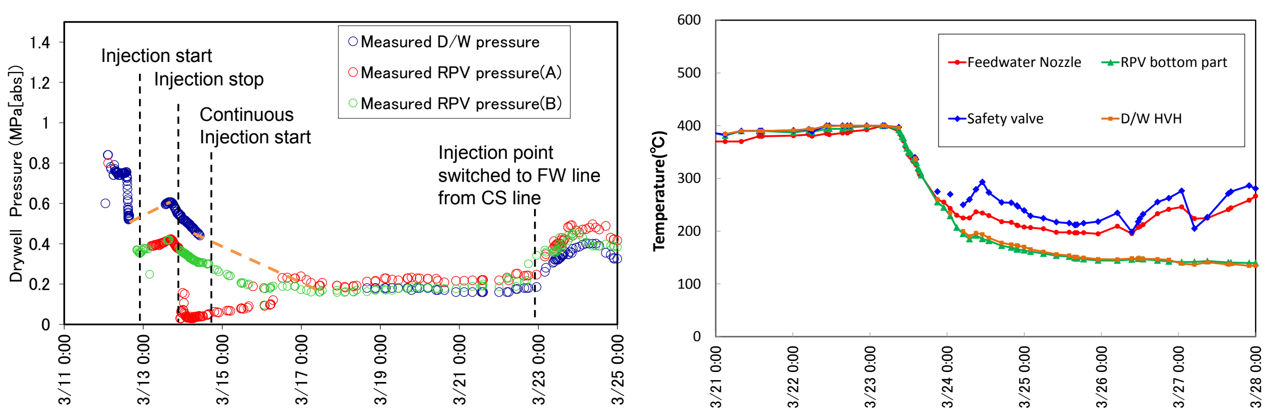
Investigations of the Fukushima Dai-ichi accident for decommissioning activities and debris retrieval are continuously carried out by TEPCO [1] and the International Research Institute for Nuclear Decommissioning (IRID). Evaluations and analysis that reflect the results of the data analysis and any new findings that are obtained are conducted. However, the type of events which occurred in the internal structures of the PCV are still not understood. Accident progression analysis was carried out using MAAP4 code [2] and MAAP5 code [3], however as some inputs include information that has a low reliability, the results obtained do not necessarily provide accurate predictions. For example, the water injection rate from the fire engine to the RPV would largely affect the current debris condition. The water injection rate in Unit 1 that is estimated from using measured data is shown in this report. Any differences between the calculated results from the MAAP5 code [4] using this water injection rate and the current known state of the PCV internal structures are described.

II. Estimation of reached water to RPV

Table I shows the operation history of fire engines that is summarized in TEPCO's reports [5] [6]. Water injection from the fire engines was carried out intermittently to provide a water supply to the core spray line until the 14th of March, and then was continuously injected from 20:00 onwards on the same day. On the 23rd of March, the injection point from the fire engines was switched from the core spray line to feed water line. Figure 1 shows the measured data of the pressure and temperature in Unit 1. Though the measured data of the pressure inside the drywell (D/W) was recorded intermittently, the estimation on how the data has changed can be done by combining the dots in a line. If water had been injected, the pressure in the containment vessel would have varied as a result of the steam generation rate being altered as a result of molten debris cooling. However, the pressure inside the D/W changed linearly. Therefore, by looking at the date when significant steam generation is observed due to the cooling of the molted debris, it can be deduced water injection would have occurred sometime after the 23rd of March. The temperature in the containment vessel, as shown in Fig.1.(b) also decreases after the 23rd of March. Hence, it is assumed that the water injection into the reactor that was conducted before the 23rd of March was effectively none or very small as a result of no pressure change being observed in the containment vessel.

TABLE I. Operation history of fire-engine

No	Date	Time	Injection	Source	Remarks
1	March 12	Around 4:00	Start	Fresh Water	1300 L injected
			Stop		
2		5:46	Start		1000 L injected
		5:52	Stop		
		-	Start		1000 L injected
		6:30	Stop		
		-	Start		1000 L injected
		7:55	Stop		
		-	Start		1000 L injected
		8:15	Stop		
		-	Start		1000 L injected
		8:30	Stop		
		-	Start		1000 L injected
		9:15	Stop		
		-	Start		15,000 L injected
		9:40	Stop		
		-	Start		Total of 80,000 L (Fresh water) injected
		14:53	Stop		
3		19:04	Start	Sea Water	
		21:45	Stop		
4		23:50	Start		Continue to March 14 1:10
	March 14	1:10	Stop		
5		20:00	Start		Continue to March 23
6	March 23	-	-	Sea Water	Injection point was switched from CS line to FW line



(a) (b)

Fig. 1. Measured internal PCV pressure and temperature in Fukushima Dai-ichi Unit 1

III. Analysis result used the estimated water injection rate
III.A. Analysis Condition

The timing of the events in this analysis was set up based on a report issued by TEPCO on the 20th of June 2012[5]. Table II shows the main analysis conditions. In this evaluation, two scenarios for the water injection rate were used; one is set as zero which is estimated from the measured pressure and temperature data and the other scenario is the evaluated result by taking into account of leakage into other lines [7]. Figure 2 shows the water injection rate from the fire engine in the water injected case. In the leakage from the primary containment vessel (PCV) scenario, the gases leak from the D/W after closing the suppression chamber (S/C) venting valve was assumed (leakage area: 1.2e-4m^2) and at 18:00 on the 13th of March the expansion of leakage area was also assumed (leakage area: 2.5e-4 m^2). These leakage areas are assumed so as to much the measured PCV pressure and the MAAP calculation in the no injected case. The leakage from the PCV top head is set after the pressure reaches approximately 0.74 MPa (abs) by lifting PCV head up due to the increasing internal pressure [7].

TABLE II. Major Analytical Conditions for Unit 1

Items	Conditions
Initial reactor output	1380 MWt
Initial reactor pressure	6.92 MPa (abs) (Measured value)
Initial reactor water level	4376 mm from TAF level (Measured value)
Number of active core node partition	Radial direction: 6 nodes Axial direction: 29 nodes
Burst temperature of cladding tube	727 °C (1,000 K)
Spatial capacity of reactor containment vessel	D/W space: 3,410 m^3 S/C space: 2,620 m^3
Water volume in suppression pool	1,750 m^3
Decay heat	ANSI/ANS5.1-1979 model (Parameters are adjusted to obtain decay heat to the results of decay heat evaluation through ORIGEN2.)

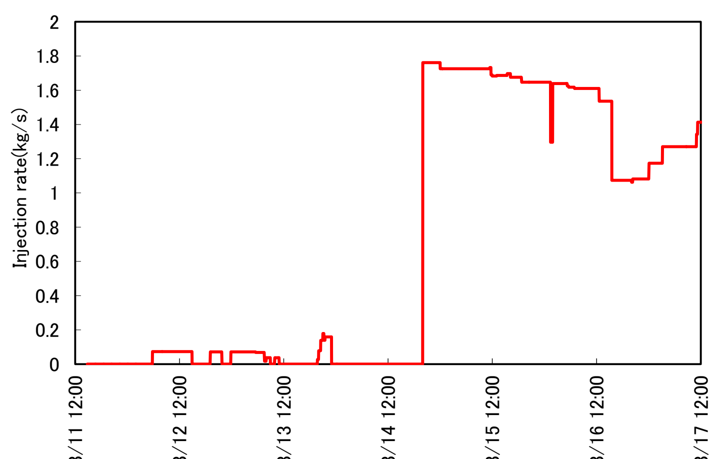


Fig. 2. Water injection rate from fire engine in water injected case

III.B. PCV pressure

Figure 3 shows the calculated PCV pressure. In the scenario where there is no water injection, the D/W pressure varied linearly similar to the measured data. While in the scenario where there was water injection, the PCV pressure increased at the point where water was injected continuously from the 14th of March onwards since steam was generated by cooling of the molten debris. However, the pressure in the PCV significantly increased on the 23rd of March after switching the injection point. Thus, in the scenario where there is water injection, it is not consistent with the measured data. In order for the measured PCV pressure and the calculated result with water injection to the RPV to match, the leakage area should change conveniently at the point where water injection is conducted. However, this assumption is unrealistic. Using the output of MAAP, it is thought by looking at when a pressure transient in the PCV occurred, the assumption that very little water reached the RPV before switching from the core spray line to the feedwater line on the 23rd of March is the most likely and persuasive scenario.

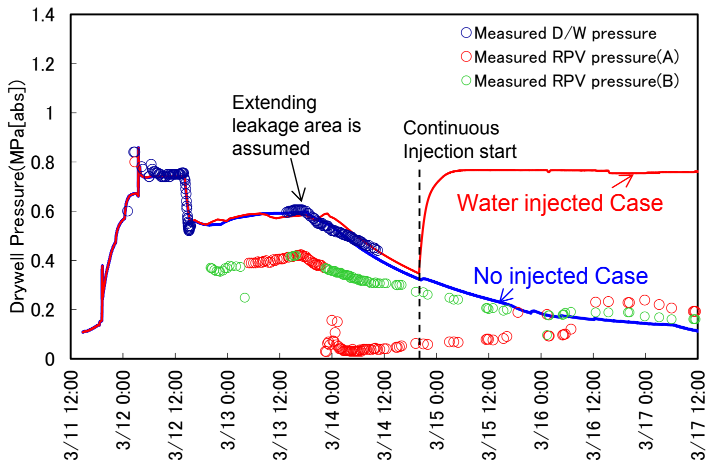


Fig. 3. Calculated PCV pressure

IV. Injection rate sensitive analysis

IV.A. Water injecting condition

Figure 4 shows the water injection rate for the sensitivity analysis. As shown in Fig. 3, the water injection conducted before the 14th of March has little influence on the result. Thus, the water injection rate before the 14th of March was set to zero and a continuous water injection rate was set as a parameter. The sensitivity analysis was performed in the range of 0.01 to 1 kg/s.

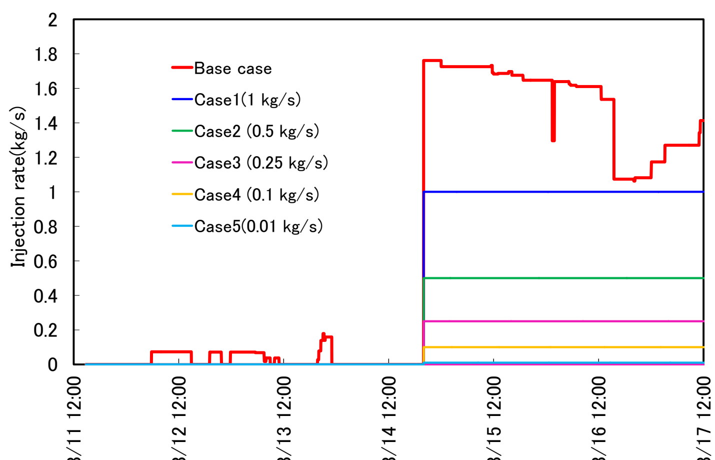


Fig. 4. Water injection rate for sensitive analysis

IV.B. Pressure in the containment vessel

Figure 5 shows the pressure of D/W at each water injection rate. If the water injection rate is varied from 1 kg/s (Case1) to 0.1 kg/s (Case4), the pressure was increased just at the point where water injection was conducted since a large amount of steam was generated in comparison with the water leakage rate from the containment vessel. Only in Case 5 which is less than 1% of the water injection rate of the base case did the pressure vary linearly, which is similar to the measured data. It is considered that if water did reach the RPV and it was injected onto the molten debris, the water which reached the RPV was only a small fraction of the initial amount.

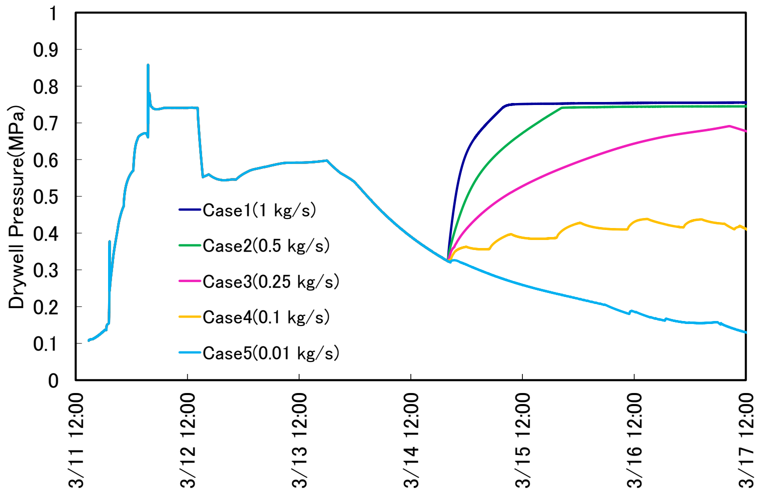


Fig. 5 Drywell pressure in sensitive analysis

V. Concreate ablation

Significant concrete ablation occurred for all the scenarios. Therefore, even if continuous water injection rate started from the 14th of March and it reached the RPV, pedestal concrete would still be significantly damaged in the MAAP5 calculation. However, from an investigation of the PCV internal structures which was conducted by a robot on the 15th -16th of April 2015, the pedestal was still standing and significantly large damage was not observed in the observed region. Therefore, we need to clarify the reason why the pedestal was still standing, in spite of the small amount of water injected into the RPV. The possible reasons that could be used to explain this presently are shown below.

・Generated heat or corium mass on the PCV floor may have been be smaller than expected
- ✓ More volatile fission product might have been released from the corium
- ✓ More corium might have remained in the RPV and stuck on the CRD housing
- ✓ The heat produced from the chemical reaction during the MCCI event may have been much smaller than expected

(e.g. Generated steam from concrete might bypass the corium and be released directly to the PCV atmosphere.)

・Sideward concrete ablation might be much smaller, and downward concrete ablation might be much larger.
- ✓ In CCI test [9], sideward concrete selectively ablated in the case where siliceous concrete was used. However, opposite phenomena might have occurred in Unit 1.

・Aeolotropic concrete ablation might be happened
- ✓ Pedestal concrete might be partially ablated and penetrated by MCCI; however significant concrete ablation in the pedestal might not happen in most of the region.

・Other unknown phenomena that are difficult to observe in laboratory scale MCCI experiments might have occurred.

VI. SUMMARY AND CONCLUSION

As a result of analyzing the behavior of the measured pressure and temperature of the Fukushima Dai-ichi Unit 1 power plant, the possibility that very little water injection reached the RPV is suggested. When an attempt was made to correlate the calculated pressure with the measured data in the water injected scenario, the water leakage area must correspond with the water injection rate at the time. This will need to happen from the moment water injection is initiated. However, such a change in the leakage area is too convenient and unrealistic. Hence, injection rate before the 23rd of March was probably very small and PCV pressure did not increase as a result of water injection being conducted. In the sensitivity analysis of the water injection rate, the injection rate that can reproduce the measured pressure data is one hundredth of the water injection capacity from the fire engine.

If a small amount of water is assumed to be injected as shown above, the result of predicted concrete ablation length is over the pedestal thickness in the MAAP5 calculation. However, when the PCV internal structure was investigated in Unit 1 on April 15-16 2015, pedestal was still standing and no great damage was observed in the region. This result, therefore, does not correspond with the result of the MAAP5 calculation. Hence, a phenomenon that has not ever been assumed to occur in an MCCI event might have occurred in Unit 1. We need to clarify how concrete ablation progressed in Unit 1 in order to predict the current debris condition for the decommissioning activities and debris retrieval.

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