Evaluation into the amounts of water injected to Unit 1 by fire engines

1. Introduction

Ultimately, Unit 1 to Unit 3 at the Fukushima Daiichi Nuclear Power Station lost all their water injection functions which had been expected to work in an accident, and fire engines were alternatively used for the emergency water injection. However, all of the amounts of water discharged from fire engines were not necessarily injected to the reactors, and part is considered to have flowed into other systems and equipment. This possibility comes from the confirmed facts that branch lines in the P&ID existed and some water was accumulated in the main condenser.

Attachment 1-4 reviewed, as a preparatory step for evaluating the actual amounts of water injected into the reactors, the fire engine operation records and possible bypass flow paths on the water injection line, through which water could have been lost.

This document reports the estimated result of the actual amounts of water injected into Unit 1 reactor, evaluating the amount of water lost through bypass flow paths identified in Attachment 1-4.

2. Alternative water injection to the reactor by fire engines and possible bypass flow paths

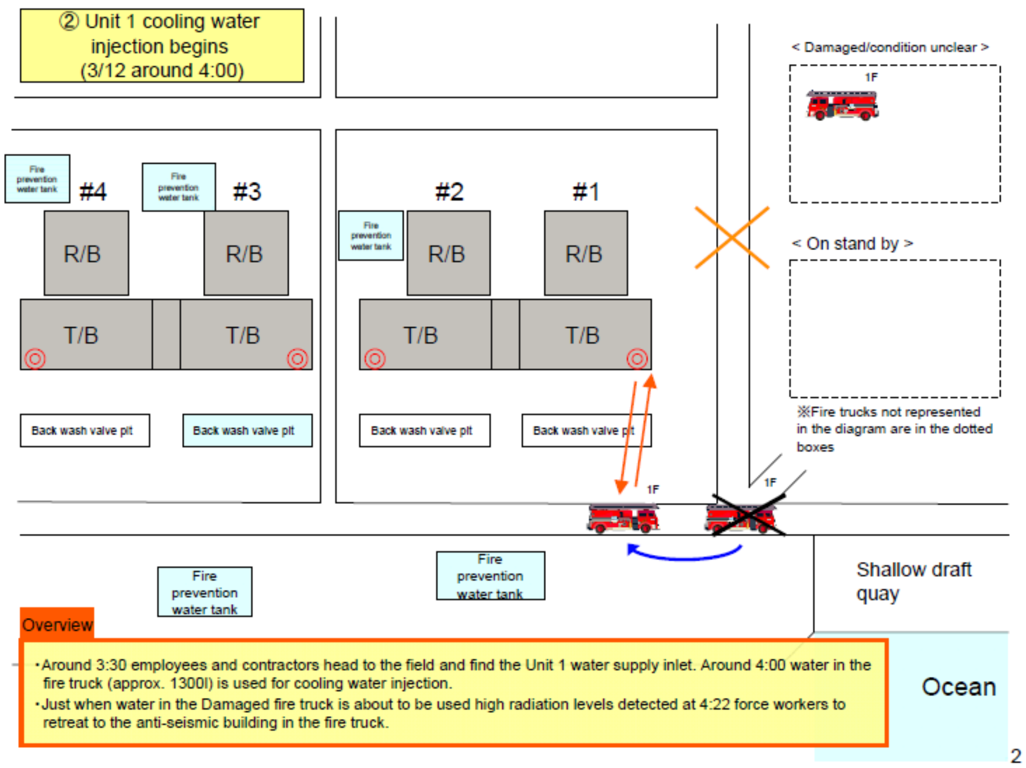
2.1. Alternative water injection to the reactor by fire engines

Table 1 shows the operational records of alternative water injection by fire engines. This should be the base for evaluating the amounts of water injected into the reactor. It integrates the chronological operation records (reviewed in the Fukushima Nuclear Accident Analysis Report by TEPCO, Table 1 in Attachment 1-4) and the chronological water injection records (Reference [1]). Concerning the configuration using fire engine hoses in each time period in Table 1, Figure 1 shows four different configurations (A to D) extracted from the schematics in the Fukushima Nuclear Accident Analysis Report by TEPCO (Reference [2]).

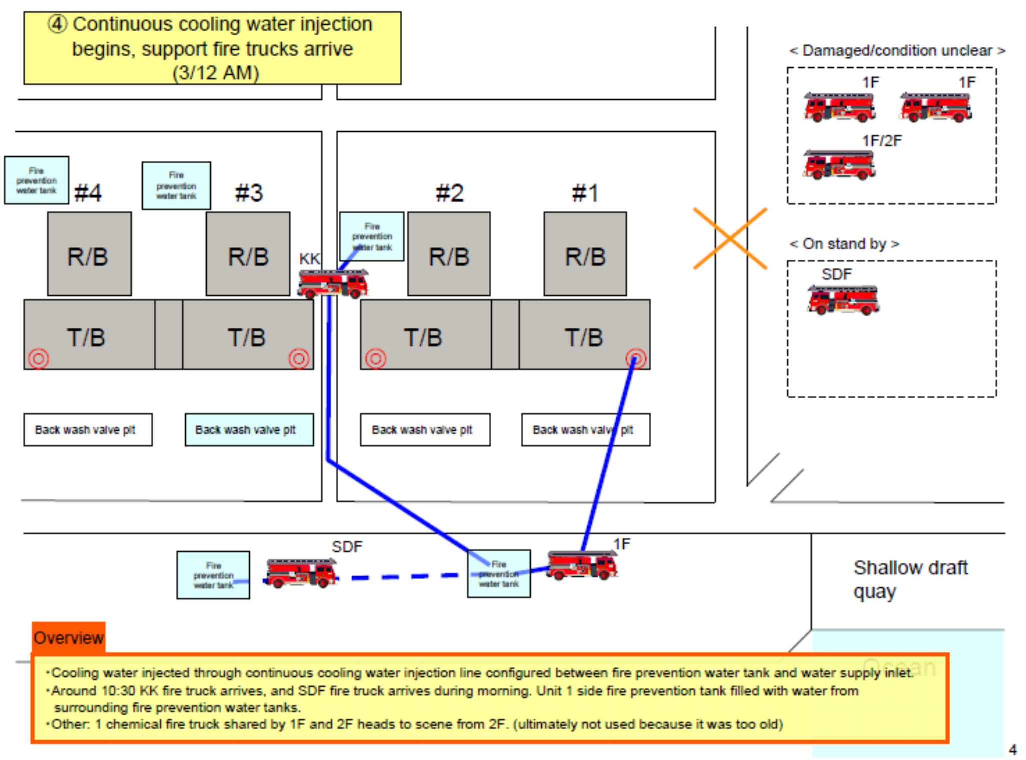
Table 1 Operational records of alternative water injection by fire engines

No.	Date, Time	Water injection	Remark	Water source	Configuration of fire hoses
Injection 1	3/12 ca. 04:00	Started		Freshwater	A
		Halted	1,300L injected		
Injection 2	05:46	Started		Freshwater	A→B
	05:52	Halted	1,000L injected		
	-	Started			
	06:30	Halted	1,000L injected		
	-	Started			
	07:55	Halted	1,000 injected		
	-	Started			
	08:15	Halted	1,000L injected		
	-	Started			
	08:30	Halted	1,000L injected		
	-	Started			
	09:15	Halted	1,000L injected		
	-	Started			
	09:40	Halted	15,000L injected		
	-	Started			
	14:53	Halted	80,000L (total) injected		
Injection 3	19:04	Started		Seawater	C
	21:45	Halted			
Injection 4	23:50	Started		Seawater	C
	3/14 01:10	Halted			
Injection 5	20:00	Started		Seawater	D
	3/19 00:00	(continued)			

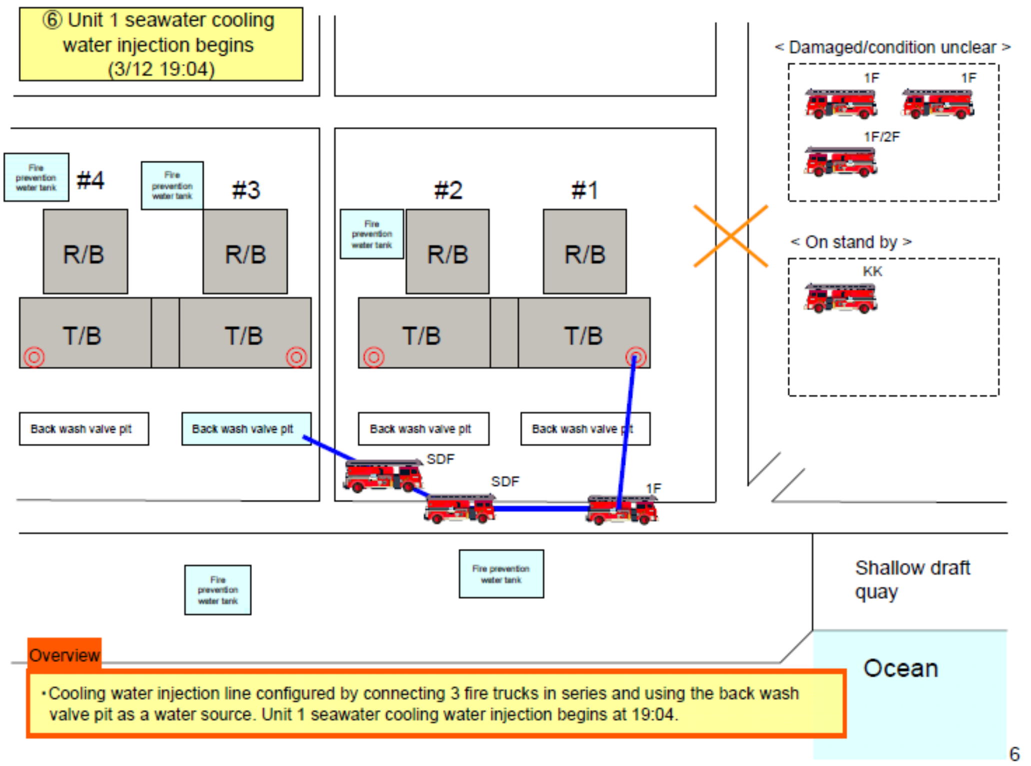
Note) Configuration of alternative water injection lines to the reactor was completed at 20:50 on March 11th, 2011, and water injection by a diesel-driven fire pump (DDFP) was put on stand-by status upon reactor depressurization. But, since the reactor was not depressurized by 01:48 on March 12th, when the DDFP pump tripped, no alternative water injection was assumed until about 04:00 on March 12th in the evaluation.



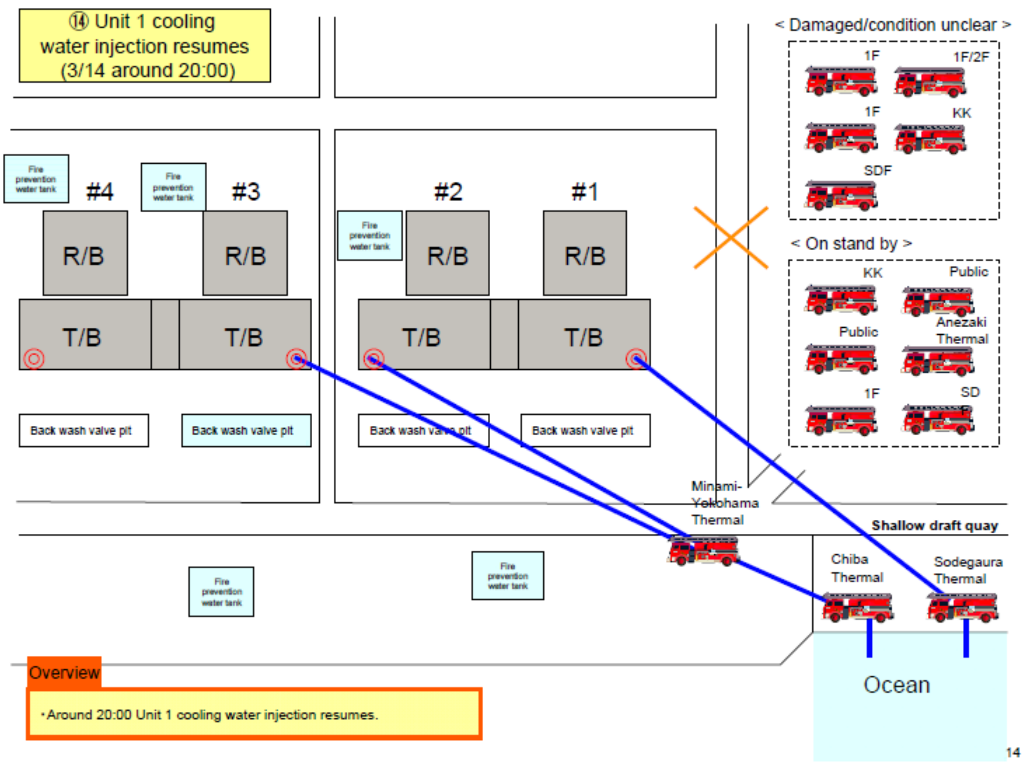
Configuration A (hose length: about 100m)



Configuration B (hose length: about 100m)



Configuration C (hose length: about 100m)



Configuration D (hose length: about 100m)

Figure 1　Schematics of water injection by fire engines showing their locations and hose configurations (excerpt) (Reference [2])

2.2. Possible bypass flow paths

At the beginning stage of alternative water injection by fire engines, the engines were connected to the water supply port attached to the outside of the turbine building for supplying fire extinguishing water, as shown in Figure 2 and they injected water to the reactor via the fire protection system (FP) and additionally the make-up water condensate system (MUWC).

The MUWC is a system to supply condensates, while the plant is in operation and also shut down, to various pieces of in-plant equipment for their cleaning and sealing. It also supplies water to tanks and equipment. This means that, if the MUWC was supplying condensates, as so designed, to some equipment just before the accident and if the line configurations were not changed thereafter, bypass flows could have flowed through these lines. To estimate the amount of water injected, flow rates to these possible bypass flow paths (Table 2 below) identified in Attachment 1-4 are assessed in this document.

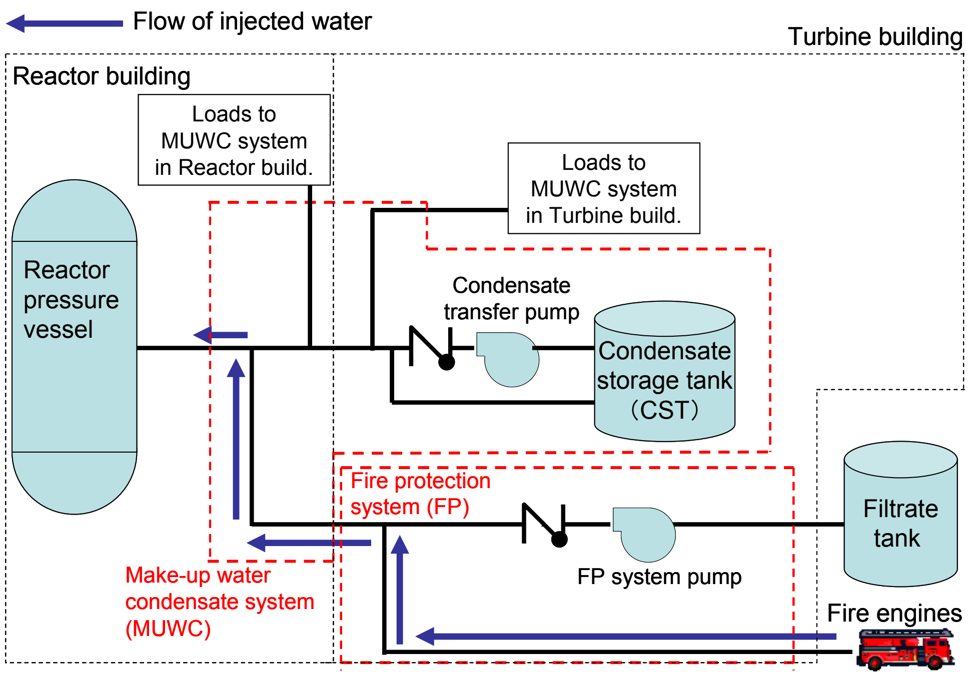


Figure 2 Line configuration for water injection by fire engines (Figure 1, Attachment 1-4)

Table 2 Possible bypass flow paths of Unit 1 (Separate Table 1-1, Attachment 1-4)

Path No.	Leak path	Pipe diameter	Remarks
1	Seal water line of condensate pump	3/4”	Flow to condenser
2	Minimum flow line of condensate transfer pump	4”	Flow to condensate storage tank
3	Evaporator make-up water line	2”	Flow to condenser
4	Seal water of valves	1/2”	Flow to system line
5	Seal water line of liquid waste neutralization pump	3/4”	Flow to system line
6	Seal water line of condenser vacuum breaker valve	3/4”	Flow to condenser
7	Mechanical seal water line of PLR pump	3/4”	Flow to equipment drain sump
8	Seal water line of feedwater pump	1”	Flow to condenser
9	Condensate demineralizer	8”	Flow to condensate demineralizer column
10	Seal water line of low- pressure heater drain pump	3/8”	Flow to equipment drain sump

3. Assumptions in evaluating the amounts of water lost

3.1. Assumptions concerning operational procedures of alternative water injection

The following assumptions were made in evaluating the amounts of water injected to the reactor and water lost to bypass paths, based on the operational information shown in Table 3.

<Assumptions in alternative water injection procedures>

- The discharge pressure of the fire engines was set uniformly at 1MPa, based on (i) the conversation record that the fire engines had been operated with the discharge pressure of about 1MPa; and (ii) the fire hoses used had been general use hoses of about 1MPa pressure-resistance for outdoor fire hydrants.
- The first injection period “Injection 1” was assumed to have started at 04:00 on March 12th.
- During the second injection period “Injection 2,” water was injected intermittently, and no clear time duration of water injection is available, since almost no records of the starting time of each injection exist. In the current evaluation under the condition of uniform pressure, water injection was assumed to have been done uniformly over the whole time duration, including the time period of no water injection. This is because the amount of water injected could be overestimated if the injection rate evaluated were applied to the whole time span.

Table 3 Operational history of alternative water injection by fire engines assumed in the current evaluation

Water injection			Discharge pressure of fire engines (analysis)	Discharge pressure of fire engines (recorded)	Configuration of fire hoses
Injection 1	Started	3/12 04:00	1MPa	Being operated with discharge pump pressure of about 1MPa.	A
	Halted	-			
Injection 2	Started	3/12 05:46	1MPa	〃	A→B
	Halted	3/12 14:53			
Injection 3	Started	3/12 19:04	1MPa	〃	C
	Halted	3/12 21:45			
Injection 4	Started	3/12 23:50	1MPa	0.46MPa at about 04:00 on March 13th. 0.65MPa at about 05:25 on March 13th.	C
	Halted	3/14 01:10			
Injection 5	Started	3/14 20:00	1MPa	3/15 23:00 1MPa 3/16 04:00 1MPa 3/16 08:00 0.7MPa 3/16 12:00 0.7MPa	D
	(End of analysis)	3/19 00:00	-	-	-

3.2 Definition of representative bypass flow paths

The alternative water injection line ① is configured as “fire engines – FP – MUWC,” as seen in Figure 3. Bypass flow paths are initially branched off the MUWC line in the water injection flow path to the reactor ②. The bypass flow paths are further branched off at their ends to 10 possible bypass flow paths in total, as is seen in Table 4. Among branches, no significant amounts of water flow into the small diameter piping due to the high pressure drop, and most water leaks into larger diameter piping. (For example, the representative bypass flow path ④ condenser line (Figure 3) is branched into four possible paths Nos. 3, 7, 8 and 9 (in Table 2). But path Nos. 3, 7 and 8 have larger pressure drops, letting no or very little water flow in them. Most of the water in the ④ condenser line flows into the largest diameter piping, path No. 9.) To sum up, three upstream bypass paths ③ CST minimum flow line, ④ condenser line, and ⑤ valve seal line dominate the evaluation of the net amount of water injected to the reactor. Among the ten possible bypass paths identified in Table 2, these three dominant paths can be defined as the representative bypass flow paths in Table 4.

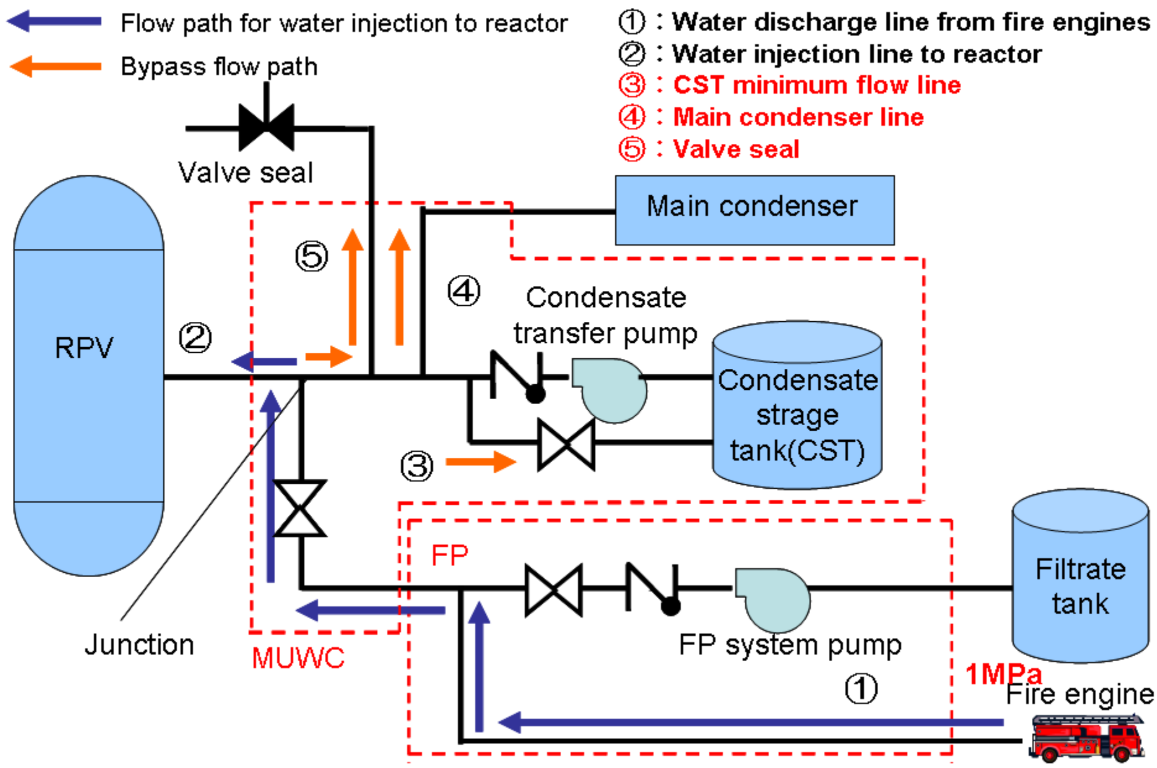


Figure 3 Representative bypass flow paths

Table 4 Grouping of possible bypass flow paths into the representative paths

Path No.	Location of leaks	Nominal diameter (in)	Representative bypass flow paths
1	Water seal lines of condensate pump	3/4	⑤: Valve seal line
2	Minimum flow line of condensate transfer pump	4	③: CST minimum flow line
3	Make-up water line of steam evaporator	2	④: Condenser line
4	Valve seal line	1/2	⑤: Valve seal line
5	Seal water line of liquid waste neutralization pumps	3/4	⑤: Valve seal line
6	Seal water line of condenser vacuum breaker valve	3/4	⑤: Valve seal line
7	Mechanical seal water line of PLR	3/4	④: Condenser line
8	Seal water line of feedwater pumps	1	④: Condenser line
9	Condensate demineralizer	8 inch	④: Condenser line
10	Seal water line of low-voltage heater drain pump	3/8 inch	⑤: Valve seal line

4. Methodology for evaluating the amounts of water injected to the reactor and lost to bypass flow paths

4.1. Methodology for evaluating the amounts of water injected to the reactor and lost to bypass flow paths

As discussed in Chapter 3.2, some of the alternative water discharged by fire engines was assumed to have been lost via the representative bypass flow paths, ③ CST minimum flow line, ④ condenser line and ⑤ valve seal line, and it must be evaluated to get the net amount injected to the reactor. The evaluation was carried out, in which cooling water (①) discharged from the fire engines ran through the FP piping to the MUWC piping, as is shown in the evaluation configuration of Figure 4, and branched off at one single junction to the line to the reactor (②) and the three bypass paths (③ to ⑤). The discharge pressure was assumed, as mentioned earlier in Chapter 3.1, to be constant throughout the time of the evaluation, based on the record that the fire engines had been operated with the discharge pressure of about 1MPa. (This assumption is not consistent with the discharged pressure measured and recorded partly, as shown in Table 3. This issue is discussed later in Chapter 6.2.)

By the law of energy conservation, when the respective pressure drop on the path is added to the pressure head of each bypass flow path (② to ⑤), the summed pressure head is equal to the pressure head at the junction point on the MUWC line as shown in Figure 4. The pressure head *P'* at the junction can be obtained by the following formula, using the fire engine discharge pressure P_1, pressure loss coefficient C_1, flow rate Q_1 and potential head $\triangle H_1$ coming from the difference in elevation:

$$P' = P_1 - C_1 \times Q_1^{\ 2} + \Delta H_1 \quad , \tag{1}$$

where the second term in the right side corresponds to the pressure loss.

Similar equations hold for each of the bypass paths, using pressure *P*, pressure loss coefficient *C*, and potential head difference $\triangle H$. Then respective flow rates can be expressed as in the following.

$$Q_2 = \sqrt{(P' - P_2 + \Delta H_2)/C_2} \tag{2}$$

$$Q_3 = \sqrt{(P' - P_3 + \Delta H_3)/C_3} \tag{3}$$

$$Q_4 = \sqrt{(P' - P_4 + \Delta H_4)/C_4} \tag{4}$$

$$Q_5 = \sqrt{(P' - P_5 + \Delta H_5)/C_5} = 0 \tag{5}$$

Since the sum of flow rates of all paths should balance the amount discharged from the fire engines, the following equation is obtained.

$$Q_1=Q_2+Q_3+Q_4+Q_5 \qquad (6)$$

In the current evaluation, P_1 was set at the fire engine discharge pressure 1MPa, P_2 was set at the reactor pressure, and P_3 to P_5 were set at the atmospheric pressure. The reactor pressure P_2, in the evaluation, was set as the D/W pressure, because it is inferred, in the previous MAAP analysis (Separate Volume 1), that the RPV had already been ruptured before water injection started. Thus, P_2 of 0.65MPa was used in “injections 1 and 2”, 0.5MPa in “injections 3 and 4” and 0.07MPa in “injection 5,” based on the measured D/W pressure in each respective period. The pressure loss coefficients were obtained from the specifications of the system/equipment and the hoses (100m length for hose configurations A to D), while the potential head $\triangle H$ is a known value determined by the elevation difference of piping layout. In consequence, when Equations (1) to (5) are used in the right side of Equation (6), the right side can be expressed only in terms of Q_1. The value Q_1 can be obtained by solving this equation.

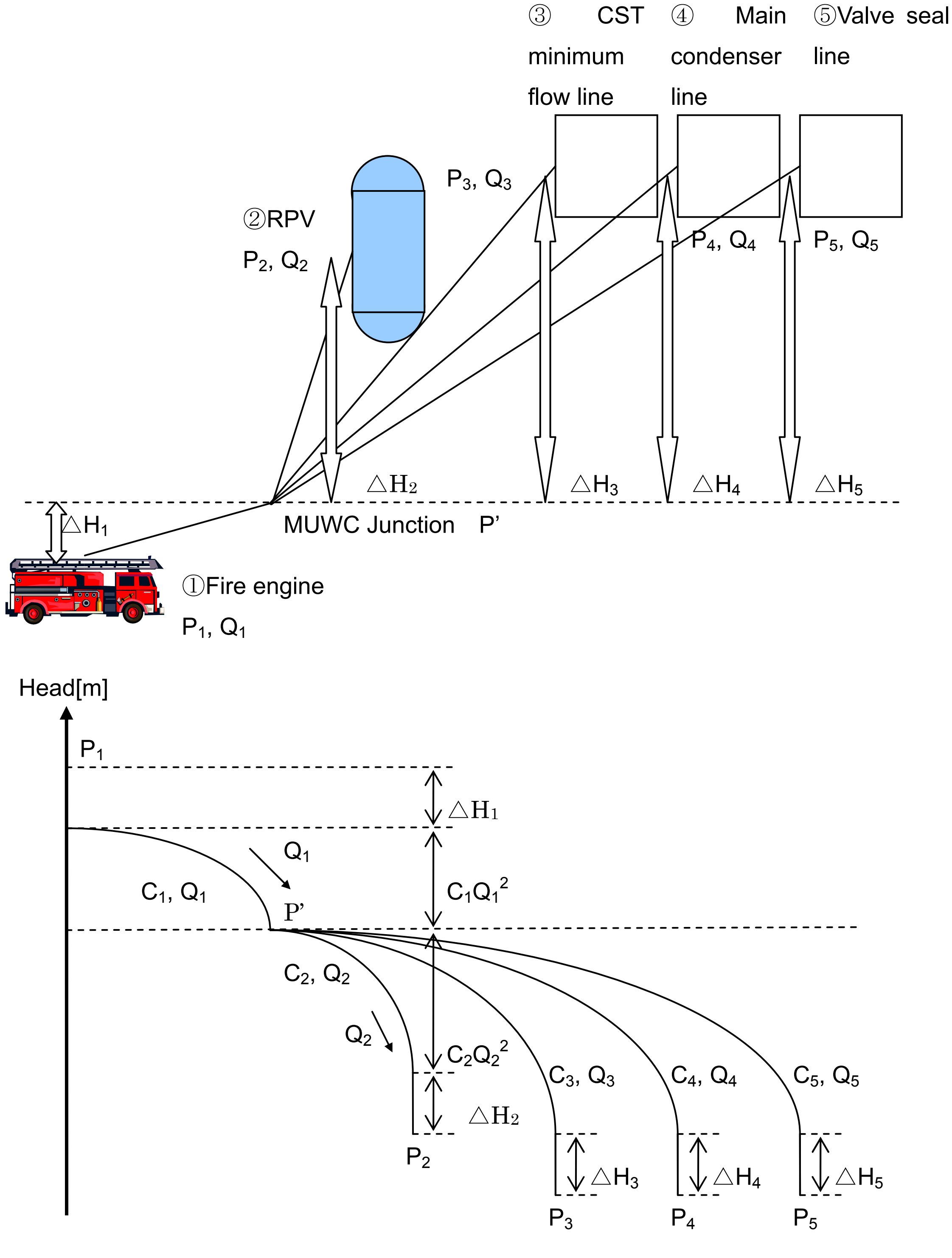


Figure 4 Evaluation configuration (above) and pressure heads in each path (below)

5. Evaluation results of the amounts of water injected to the reactor

5.1. Amounts of water injected to the reactor

Figure 5 and Table 5 summarize the amounts of water injected to the reactor obtained in the current evaluation. As discussed in Chapter 3.1, discharge pumps were operated intermittently during the time of “Injection 2” between 04:53 and 14:53 on March 12th, 2011. Therefore, the amount of injected water calculated under the constant discharge pressure of 1MPa was averaged over the subject time of “Injection 2”.

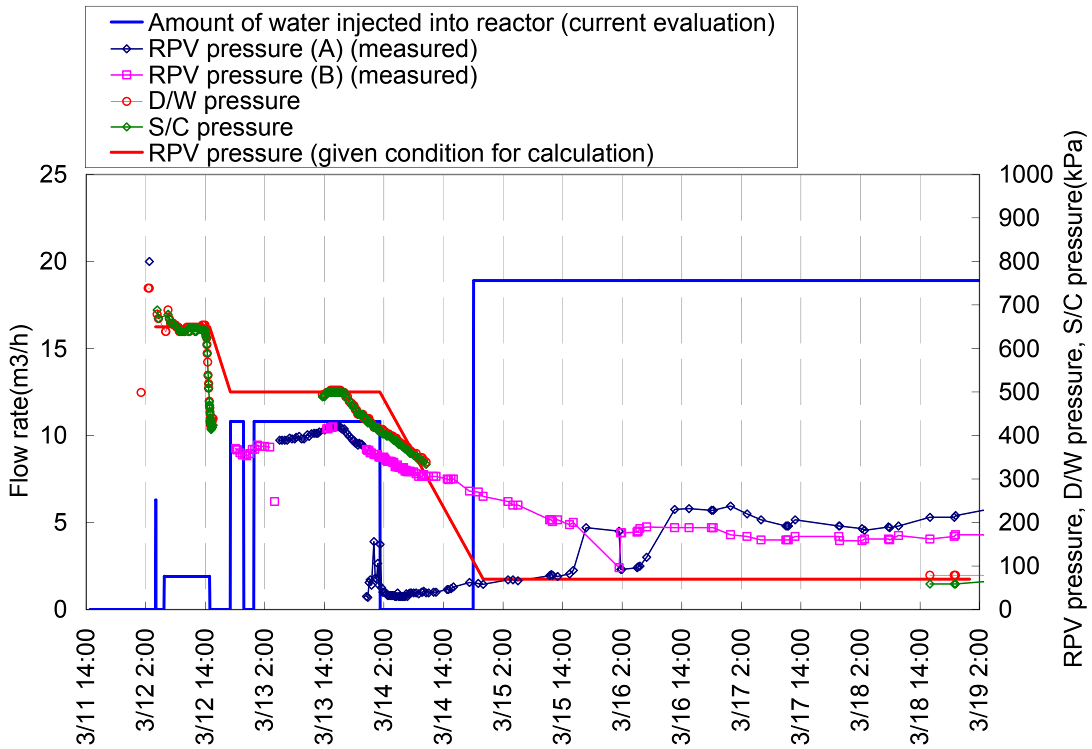


Figure 5 Water flow rate injected to the reactor and measured pressures

Table 5 Amounts of water injected to each path

Water injection (*1)			Amount of water injected (Input for MAAP analysis)	①Amount of water discharged by fire engines	②Amount of water injected into RPV	③Amount of water injected into CST	④Amount of water injected into condenser	Reactor pressure (condition for analysis)
			kg/s	m^3/h	m^3/h	m^3/h	m^3/h	MPa
Injection 1 (Freshwater)	Started	3/12 04:00	1.75	28.5	6.3	5.3	16.9	0.65
	Halted	3/12 04:02 (*2)						
Injection 2 (Freshwater)	Started	3/12 05:46	0.53	8.8(*3)	1.9(*3)	1.6(*3)	5.2(*3)	0.65
	Halted	3/12 14:53						
Injection 3 (Seawater)	Started	3/12 19:04	3.00	32.4	10.8	5.2	16.5	0.50
	Halted	3/12 21:45						
Injection 4 (Seawater)	Started	3/12 23:50	3.00	32.4	10.8	5.2	16.5	0.50
	Halted	3/14 01:10						
Injection 5 (Seawater)	Started	3/14 22:00	5.25	39.3	18.9	4.9	15.5	0.07
	(End of analysis)	3/19 00:00	-	-	-	-	-	-

(*1) Data in the red frame are the conditions used in the latest MAAP5 analysis (Attachment 3)

(*2) The time to halt water injection in "Injection 1" was regarded as the time when fire engines completed discharging water of 1,300L with the flow rate of 28.5m^3/h from 04:00 on March 12th.

(*3) The amount of water discharged by fire engines (recorded) during "Injection 2" is 26.8m^3/h, but the average value of the whole time was used instead including the period of halted discharge, because the discharge was intermittent.

5.2. Fraction of bypass flows in each path

Figure 6 shows the fractions of bypass flows in the respective paths. Since the pressure head required to inject water into the reactor increases with increasing reactor pressure, the fraction of water injection to the reactor was less, while the reactor pressure was high. In the current evaluation, in which the constant discharge pressure of 1MPa was assumed, water injection to the reactor was never completely zero within the reactor pressures measured, although part of the water had been lost to other bypass paths.

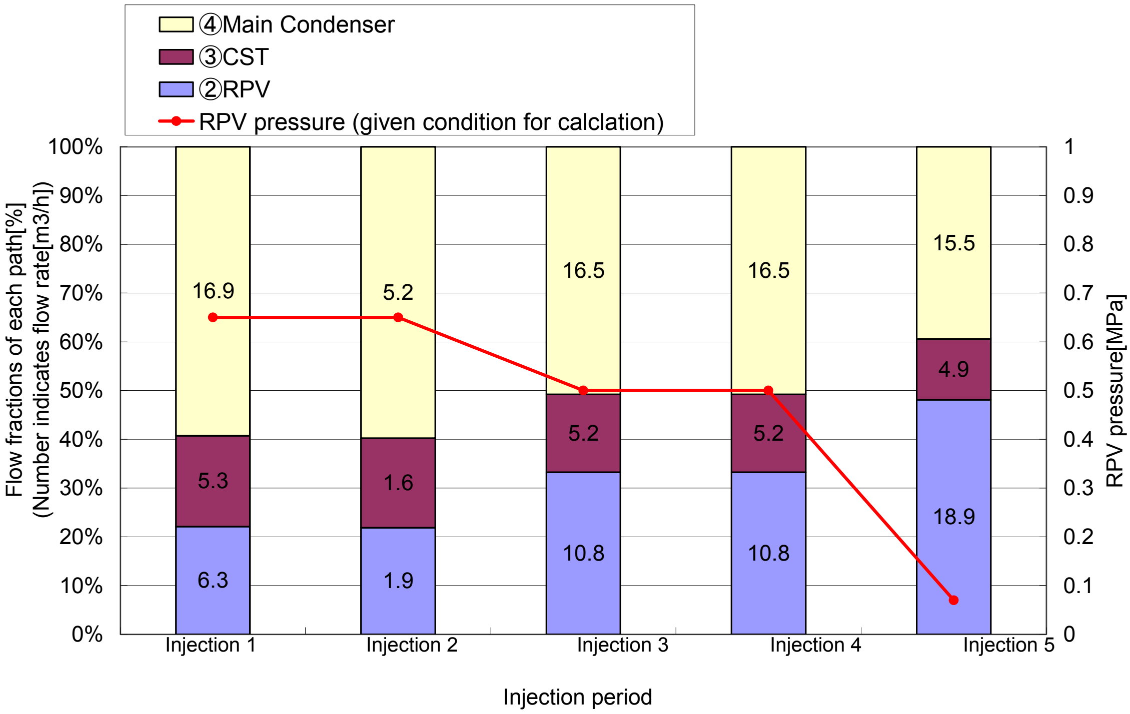


Figure 6 Reactor pressure and water fraction lost to bypass flow paths

5.3. Comparison of the amounts of water injected to the reactor obtained in the current evaluation and past evaluations

Figure 7 compares (a) the amount of water injected to the reactor obtained in the current evaluation, (b) the amount of water injected, as defined as input to the past MAAP analysis, and (c) the amount of water discharged by fire engines which was reported in Attachment 1-4. It can be confirmed that value (a) exceeded values (b) and (c) in almost all time periods (*Note). Meanwhile, during the time of “Injection 5” from 20:00 on March 14th, more than 1.5 times the value in Attachment 1-4 was evaluated to have been injected.

(*Note) During the time of “Injection 2” between 05:46 and 14:53 on March 12th, the value (a) was less than that of (c). The value (c) is obtained by dividing 80,000L, the total amount of water discharged as of 14:53 by fire engines during “Injection 2,” by the time duration of “Injection 2.” Therefore, it is straightforward that, when considering the leaks to the bypass paths, the value (a) is less than that of (c). In the previous MAAP analysis, too, the amount of injected water to the reactor was set at a smaller value than that of (c), since the total amounts of water discharged by fire engines were considered not to have reached the reactor. The value (a) in the current evaluation exceeded the value (b), which confirms that the previous MAAP analysis had been executed under more conservative conditions.

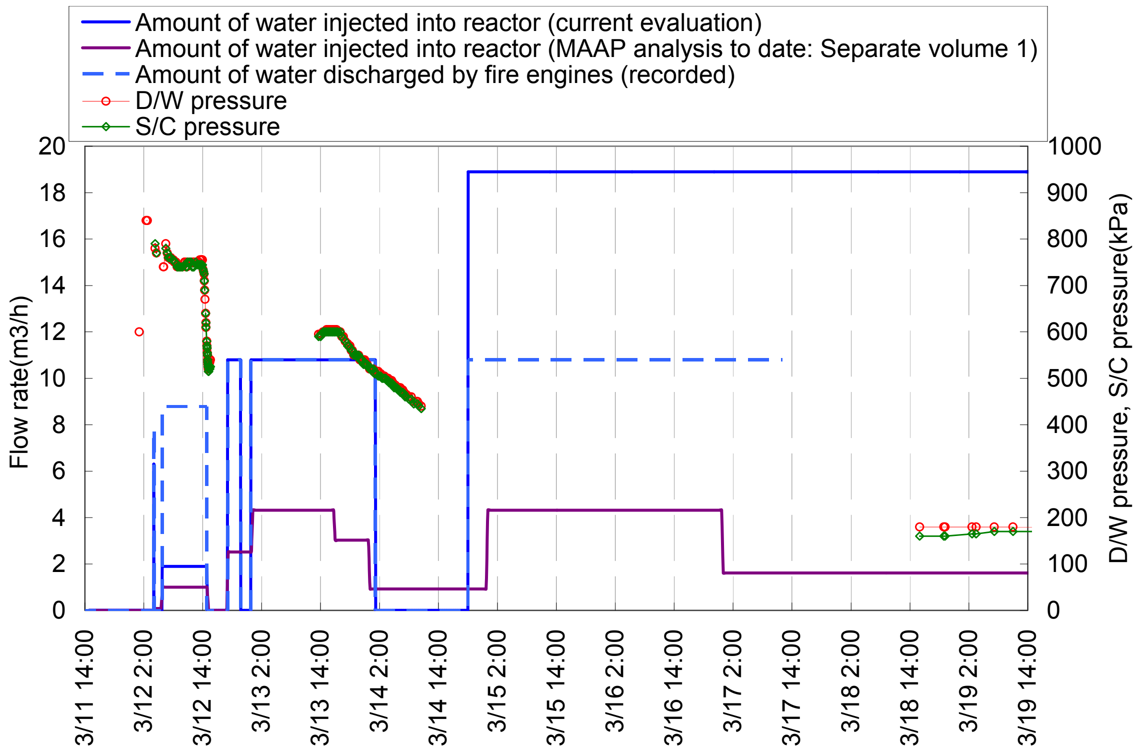


Figure 7 Comparison of the amounts of water injected to the reactor

6. Considerations

6.1. Consistency with the operational records of fire engines

Table 6 compares the discharge flow rates from fire engines calculated from the operational records during the time of “Injection 2” between 05:46 and 14:53 on March 12th. In this period, the fire engine went back and forth carrying about 1000L of water from the fire prevention water tank to the water supply inlet. The times when water injection was started and halted are recorded only during the time period [a] as shown in Reference [1], and the discharge flow rate during this period is calculated as $10m^3/h$. Since for times [b] to [h] no records were left on the time that water injection was started, the discharge flow rates cannot be calculated. The discharge flow rates were estimated, therefore, assuming the water injection started just after the immediate past water injection had been halted (i.e., the water injection had continued). This assumption corresponds to the maximum time duration of water injection. As a result, the discharge flow rates are considered to overestimate the actual discharge flow rates.

The measured D/W pressure did not change significantly from around 0.65MPa during “Injection 2”, as shown in Figures 6 and 7. Therefore, the discharge flow rates by fire engines will remain constant, as long as their operational conditions remain unchanged. Table 6 shows the discharge flow rates during periods [b] to [f] were less than that of [a], $10m^3/h$. This seems consistent if the actual duration of water discharged was considered to be shorter than the one assumed above. But the discharge flow rates of more than $36m^3/h$ of [g] and $11m^3/h$ of [h], exceeding $10m^3/h$ of [a], cannot be interpreted. This may indicate that there were variations in the time difference between the actual fire engine operations and the recorded acknowledgement in the seismic isolation building and that the discharge flow rates as calculated from the water injection records has some uncertainties. On the other hand, if water was discharged from fire engines with the rate of $28.5m^3/h$ obtained by analysis, the time of water discharge should have been about 2min during [a] and about 32min during [g]. Comparing this with the maximum discharge time in Table 6, the difference is at most several minutes. It is not extraordinary, under such emergency response situations (at that time venting operations were the most urgent operation and involving all personnel), even if such time difference existed in the communication between workers on-site and workers in the isolation building. In consequence, the discharge flow rates from fire engines are considered to have no significant contradiction to the start/halt times of water injection in the record.

Table 6 Amount of water discharge during “Injection 2” obtained from records and from the current evaluation

Incidents during “Injection 2”				Maximum duration of water injection	Total amount of water injected (recorded)	Minimum amount of water discharged by fire engines (calculated from total water injected)	Evaluated discharge flow rate by fire engines (calculated from 1MPa discharge pressure)
Time zone	Date, Time	Injection	Note	(min)	(L)	(m^3/h)	(m^3/h)
[a]	3/12 05:46	Started		6	1000	10	28.5 (during injection)
	05:52	Halted	1,000L injected				
[b]	05:52	Started		(38)	1000	>1.6	
	06:30	Halted	1,000L injected				
[c]	06:30	Started		(85)	1000	>0.7	
	07:55	Halted	1,000L injected				
[d]	07:55	Started		(20)	1000	>3	
	08:15	Halted	1,000L injected				
[e]	08:15	Started		(15)	1000	>4	
	08:30	Halted	1,000L injected				
[f]	08:30	Started		(45)	1000	>1.3	
	09:15	Halted	1,000L injected				
[g]	09:15	Started		(25)	15000	>36	
	09:40	Halted	15,000L injected				
[h]	09:40	Started		(313)	59000	>11	
	14:53	Halted	80,000L (total) injected				

(*1) Time points and durations in the parenthesis are the values calculated with the assumption that the discharge starting time was the same as the discharge halt time in the immediate previous discharge.

6.2. Discharge pressure of fire engines

As shown in Table 3, the discharge pressure of fire engines was assumed to be constant at 1MPa in the current evaluation, based on the record that fire engines had been operated at about 1MPa. It is reasonable to assume the pressure to be constant unless the pump rotation speed had been adjusted, because the discharge pressures of fire engines do not change generally regardless of its discharge flow rates as long as they are below about 30m^3/h.

However, lower discharge pressures below 1MPa were also recorded in Table 3, during the time of "Injection 4 (between 23:50 on March 12th and 01:10 on March 14th)" and "Injection 5 (between 22:00 on March 14th and 00:00 on March 19th)." In other words, it is not clear, either, when fire engines were actually run at about 1MPa of discharge pressure. It is quite possible that fire engines were run at the discharge pressure other than 1MPa.

In the current evaluation of the amounts of water injected the subject time periods were also evaluated, assuming 1MPa as the discharge pressure. Meanwhile, the current evaluation gave larger amounts of water injected than the amounts of water discharged from fire engines in Attachment 1-4. It is possible; therefore, that the current evaluation overestimated the amounts of water injected and water had been injected actually at lower flow rates.

6.3. Correlation with PCV pressure changes

Figure 8 shows the changes of amount of water injected and D/W pressure when fire engines halted their operation during "Injection 4 (between 23:50 on March 12th and 01:10 on March 14th)." The amount of water injected to the reactor drops immediately to 0m^3/h when fire engines halt operation, but the D/W pressure did not show rapid changes and decreased gradually over that time. This indicates that the conditions in the reactor do not substantially change even if fire engines halt operation, further indicating a possibility that the actual amount of water injected did not drop sharply as given in the current evaluation. As seen in Table 3, fire engine operation at lower discharge pressures than 1MPa assumed in the current evaluation is also recorded. If these discharge pressures are correct, the amount of water injected to the reactor should be less and it is possible that it had been already 0m^3/h before fire engines halted operation.

Furthermore, the amount of water injected to the reactor was obtained in the current evaluation by using one representative D/W pressure during each of five time periods of water injection, i.e., no consideration was given to the feedback effects from the developing conditions in the reactor. In reality, injected water may contribute to steam generation in the reactor, increase the D/W temperature and pressure, and eventually reduce the amount of water injection. On the other hand, it can be considered that, when the amount of water injection drops, the D/W will respond conversely and may increase the amount of water injection. This balance may decide the actual amount of water injection. Examination into this issue is yet to be done.

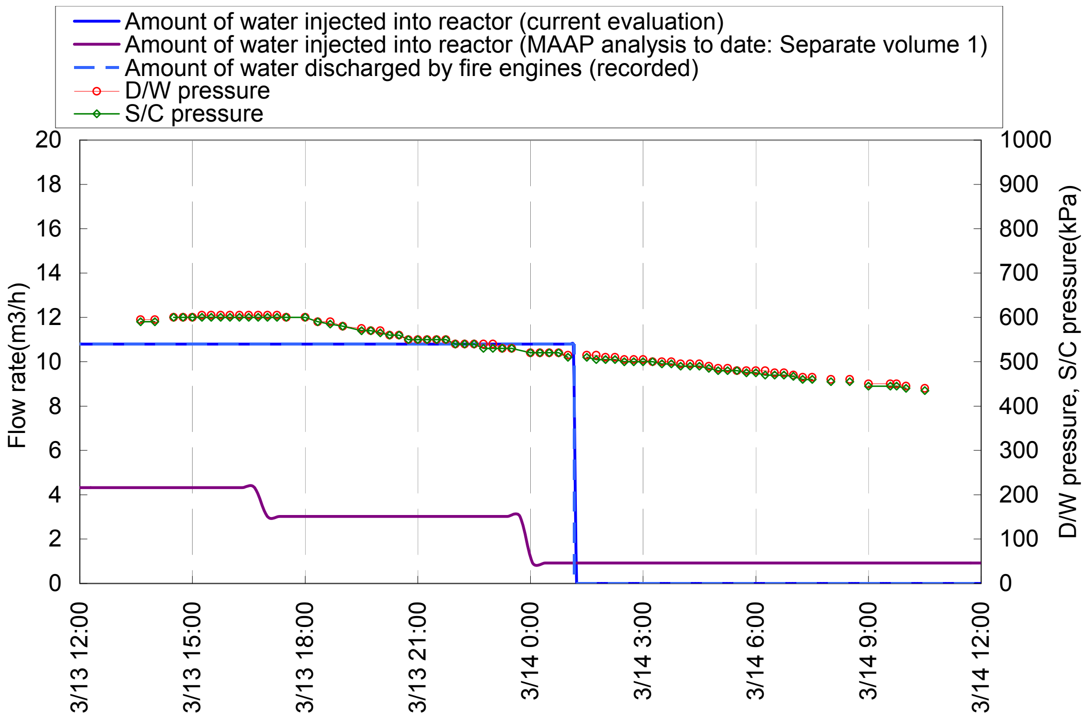


Figure 8 Changes of the amount of water injected and D/W pressure

7. Summary

The amounts of water injected into the Unit 1 reactor by fire engines have been evaluated with consideration of the flows lost to other bypass flow paths. In the current evaluation, the fire engine discharge pressure was assumed to be constant at 1MPa, based on the fire engine operational records, and ten possible bypass flow paths identified in Attachment 1-4 were grouped into three representative (and dominant) paths. The result showed that the amounts of water injected to the reactor obtained in the current evaluation were generally bigger than those given by MAAP analysis to date as described in Separate Volume 1 or the amount corresponding to the discharge flow rates by fire engines in Figure 5 in Attachment 1-4.

In the evaluation approach, however, the amounts of water injected to the reactor depend substantially on the fire engine discharge pressure assumed. In reality, discharge pressures less than 1MPa assumed in the current evaluation were recorded, which indicates a possibility that the actual amounts of water injected to the reactor were even less than the current amounts obtained. Furthermore, plant parameters such as the D/W pressure did not change significantly at around the time when fire engines stopped operation. When these findings are combined, it also seems possible that the amount of water injected to the reactor might have been less or even zero already before fire engines stopped their operation. Further examination is needed for these overestimated evaluation results and also for the amounts of water injection to the reactor in detail with consideration for the D/W pressure changes and their effect on the amounts of water injection.

Further examination is needed to understand the progression of incidents, based on the results obtained in the current evaluation, while referring to the core conditions analyzed by MAAP. Examination will also continue on Unit 2 and Unit 3, referring to the results in the current evaluation.

References

[1] Annex 2, Fukushima Nuclear Accident Analysis Report, TEPCO, June 20, 2012, pp.33-35. Refer also to Table 1 in [Attachment 1-4] Examination into water injection by fire engines, Results of the Investigation and Examination on the Unidentified and Unsolved Matters of the Fukushima Nuclear Accident, December 13, 2013.

[2] Attachment 10-4 (3), Fukushima Nuclear Accident Analysis Report, TEPCO, June 20, 2012