Reactor pressure changes from about 02:00 to about 12:00 on March 13th

1. Overview of subjects for examination

At Unit-3 of the Fukushima Daiichi Nuclear Power Station, the reactor pressure started to increase when the high pressure coolant injection (HPCI) system was manually shut down at 02:42 on March 13th, 2011. The pressure was maintained at about 7MPa for about five hours, but it dropped sharply at about 09:00 on March 13th and was below 1MPa. This sequence of pressure changes (Figures 1 and 2) is reviewed below, in which the rapid depressurization of the reactor at about 09:00 is assumed to have been done by the automatic depressurization system (ADS) (not by a break of the reactor boundary).

It should be noted that the time recorded on the chart of Figure 2 is not consistent with the real time. This is because the recorder was switched off in order to extend the DC power life, since the reactor pressure was outside the range of the narrow range pressure indicator when the reactor pressure decreased below 1MPa during the HPCI operation. When the pressure increased after the HPCI was shut down, the power supply of the recorder was switched on.

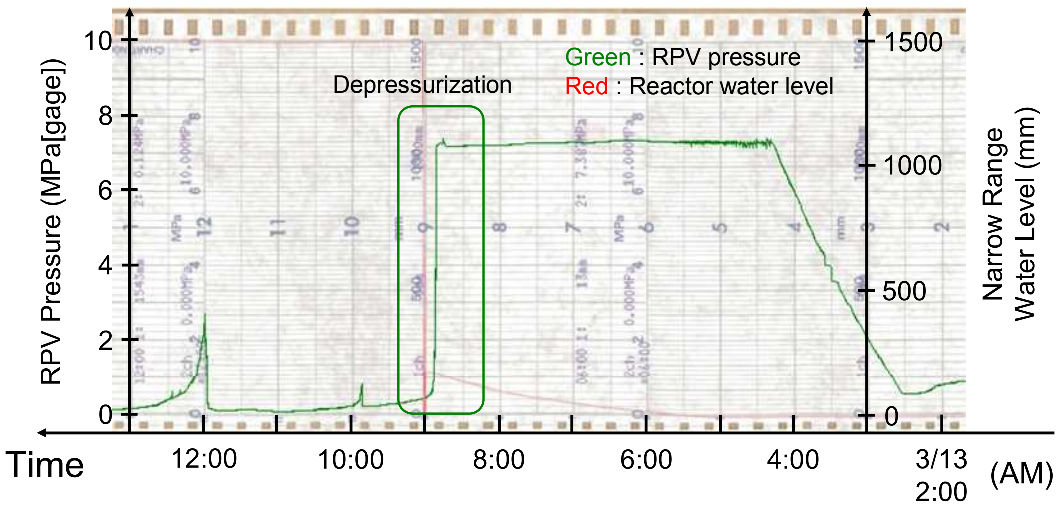

Figure 1 Reactor pressure time chart (wide range).

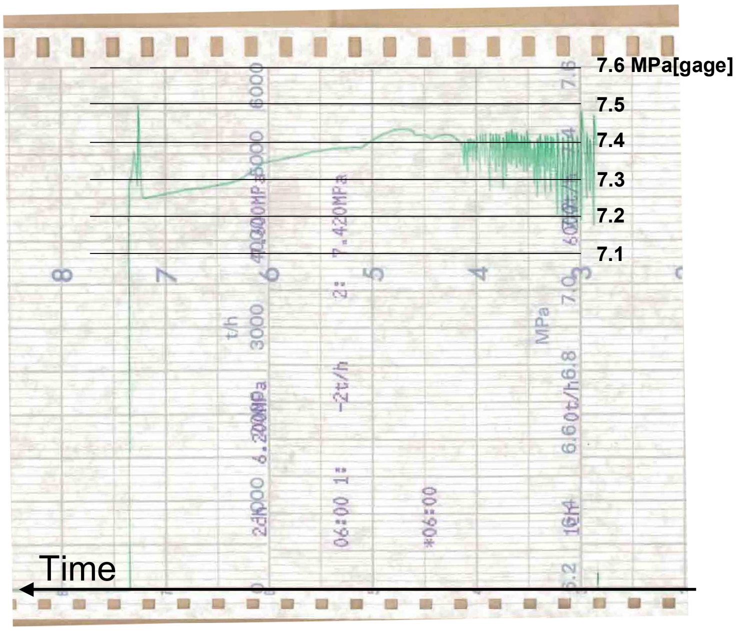

Figure 2 Reactor pressure time chart (narrow range).

2. HPCI shutdown to reactor pressure increase

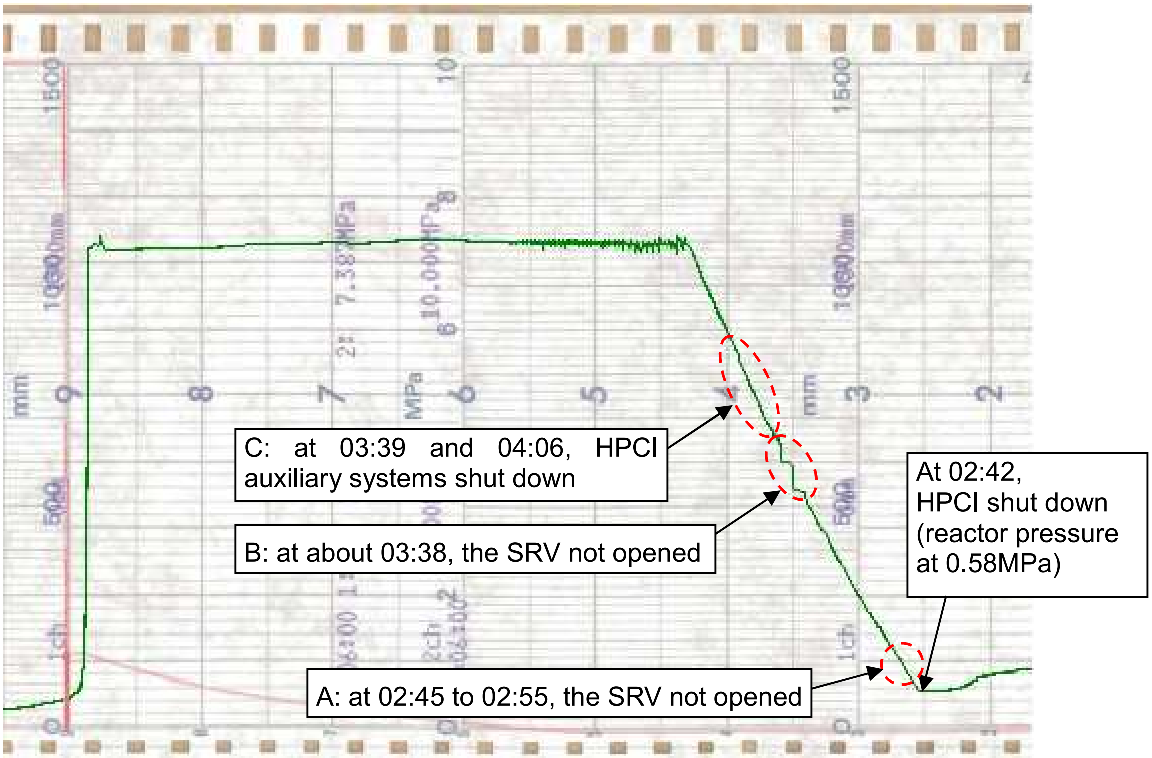

Figure 3 Reactor pressure time chart (wide range).

The operational maneuvering actions taken during this time period are listed below.

- At 02:42 on March 13th, the HPCI was manually shut down
- At 02:45 on March 13th, immediately after the HPCI was shut down, opening operation of the main steam safety relief valve (SRV) (A), by turning on the switches of pressure relief mode or ADS mode, was tried but failed. The SRV was judged not to have opened

because the pressure did not decrease (same hereinafter).

- Thereafter, opening operations of all SRVs (by turning on the switches of pressure relief mode or ADS mode) were tried but failed.
- At 03:38 on March 13th, the opening operations of all SRVs (by turning on the switches of pressure relief mode or ADS mode) were retried, but failed again.
- At 03:39 on March 13th, the HPCI auxiliary oil pump (AOP) was manually shut down.
- At 04:06 on March 13th, the HPCI condensate pump was manually shut down.

In Figure 3, no pressure changing trend due to SRV maneuvering is visible in time periods A and B. The causes could be related to the PCV pressures (back pressures), the nitrogen gas pressure necessary for opening the SRVs, power supplies to solenoid valves, etc.

To begin with dynamic relationships (the nitrogen gas supply pressures to the SRVs, reactor pressures and PCV pressures) were examined (Figure 4), which had been required to open the SRVs.

Details of the examination methods are given as Item 5.5 in Attachment 2-12. The following assumptions were made in the examination.

(i) SRV aperture: fully opened

(ii) D/W temperatures: constant at 120 deg C over the whole period of interest

(iii) N_2 gas supply pressure from accumulators: maximum value of the design

(iv) Leaks from the N_2 gas supply line to SRVs: none

(v) D/W pressure: constant at 0.36MPa[abs], the value at 04:45 on March 13th, over the time span of 02:00 to 04:40 on March 13th when no measured data had been recorded

Assumption (ii) was based on the results of MAAP analysis over the period shown in the graph (from 02:00 to 06:00 on March 13th, Figure 3) (See Attachment 3 for the MAAP analysis). Assumption (v) chose the higher value 0.36MPa[abs] that was measured at 04:45 on March 13th, making it harder for the SRVs to open, since no measured data had been recorded from 22:00 on March 12th at 0.27MPa[abs] to 04:45 on March 13th at 0.36MPa[abs].

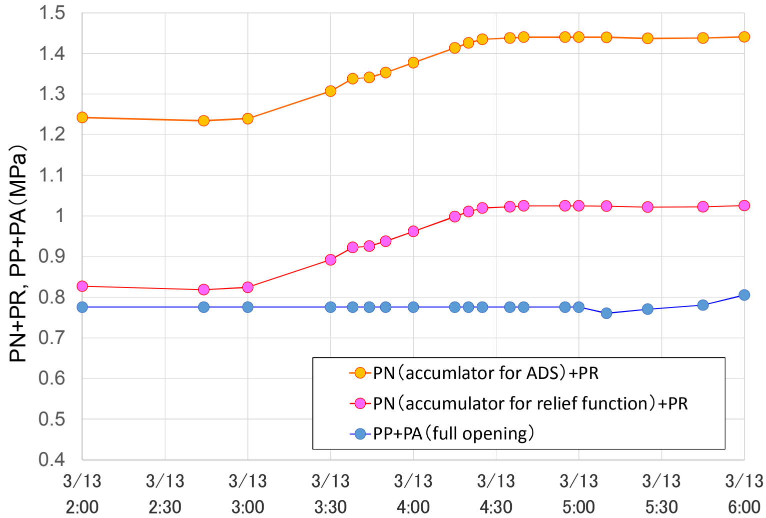

Figure 4 Dynamic relations between nitrogen gas supply pressures to SRVs, D/W pressures and reactor pressures

Figure 4 compares the force to open the SRVs, PN+PR (forces from the N_2 gas supply pressure and reactor pressure) and the force to close the SRVs, PP + PA (forces from the drywell pressure and spring/valve elements). When PN+PR＞PP+PA, the SRVs can be opened as in the design. It is seen that both ADS functions and relief functions could have worked as in the design.

At Unit-3, the ADS functions were not activated before (times A and B) and the reactor pressure decrease was observed at about 09:00 on March 13th probably due to the activated ADS functions. Therefore, the nitrogen gas pressures required to open the SRVs are considered to have been secured at the time points (A and B) in the ADS accumulators. It is highly likely that the ADS functions could have been activated (see Attachment 3-3 for reactor depressurization behavior at around 09:00 on March 13th).

Next, power supplies to solenoid valves were examined. At time C the auxiliary equipment of the HPCI (an auxiliary oil pump and a condenser pump) operated by the DC power sources were shut down. The reactor depressurization at about 09:00 on March 13th is considered to be due to the ADS functions being activated. In other words, the voltage required to activate the ADS was secured at time point (C) by shutting down the HPCI auxiliary equipment, but before then it could have been insufficient at time points A and B when the SRVs had been maneuvered.

Consequently, the cause of the failure to activate relief functions and ADS functions of all SRVs at time points A and B could have been due to insufficient voltage because of battery depletion.

Additionally, at time point B (reactor pressure of about 4MPa) the reactor pressure was being held constant for a while and followed twice by a sharp increase. If the SRVs opened a little, the reactor pressure might have been held constant, but the sharp increases immediately after cannot be explained. The recorder pen might have been unable to work normally because of a depleted DC power source. The cause of the pressure change at time point B cannot be identified at this time.

3. SRV actions prior to the rapid depressurization

The reactor pressure decreased and increased repeatedly over the time period D, as can be seen in Figure 5, after it had reached once to just above 7MPa. These oscillations indicate that the SRVs worked. The reactor pressure started to decrease when it exceeded about 7.4MPa. When referring to the design pressures in Table 1, it can be seen that SRV (C) might have worked (this is discussed in more detail in Chapter 5); this would be because some of the DC power source had been reserved by shutting down the HPCI auxiliary systems twice at 03:39 and 04:06.

Thereafter, after about 05:50, the reactor pressure oscillations apparently due to the SRVs working disappeared and started to decrease gradually. The reasons can be any of the following.

- The nitrogen gas in the SRV accumulators had been completely depleted when activating SRVs during time period D.
- The power source had been depleted (another report may be relevant, which said that the stop valve (DC125V) of the reactor core isolation cooling (RCIC) system could not be operated at 05:08).
- The steam production greatly decreased due to the decreased reactor water level.
- The rapid change of reactor pressure vessel could have become unmeasurable for unknown reasons.

The first reason, the possibility that the nitrogen gas was likely to have been depleted, can be considered reasonable because the amplitude of the oscillations was gradually reduced. But the actual reason for the gradual decrease of reactor pressure seems more likely to be that some gaps had been created by roughened contact surfaces between the SRV elements and seats due to repeated SRV activations, and that was combined with the third reason, the decreased steam production due to decreased reactor water level.

In time period E, there is a time point F, when the reactor pressure decrease became faster for a while. Figure 6 shows the reactor water levels around this time in detail. The fuel range reactor water level indicator showed that, from slightly before 07:40 on March 13th, the reactor water level decrease stopped at the top of active fuel (TAF) -3,000mm (the lower limit of the measurement range of water level indicator was TAF-3,700mm). When corrected[*1)], this water level (plotted in grey in Figure 6) corresponds to about BAF+1m. But there is no reason for the water level to stop decreasing, when the reactor pressure was gradually decreasing while no water was being injected. This suggests a high possibility that the water level indicator showed higher values than reality due to partial evaporation of water in the reference level column and that the actual water level had decreased to below the bottom of active fuel (BAF), which was the lower limit of the measurement range of the water level indicator; that is, the actual reactor water level can be considered to have decreased to around BAF (or even below). Therefore, it may be possible that the reactor water was not directly heated, the steam production decreased, thus accelerating the reactor pressure decrease. Under such circumstances, the fuel could have been overheated and part of it might have melted.

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*1) The water level was corrected by using the MAAP (Modular Accident Analysis Program) results of the containment vessel temperatures, which had no measured values. It has been noted that MAAP results underestimated the water level decrease, thus delaying the accident development. The actual containment vessel temperatures might have been higher, thus the water level had a possibility of overestimation by such correction.

Concerning the time period E, the Government Investigation Committee on the Accident pointed out in its report that there was a high possibility for losing the reactor pressure through an unknown path other than the SRVs (break of the reactor vessel boundary). The possibility of the break of reactor vessel boundary by the damage of in-core instrumentation tubes, for instance, cannot be excluded, when a possibility of fuel melting is considered as discussed above.

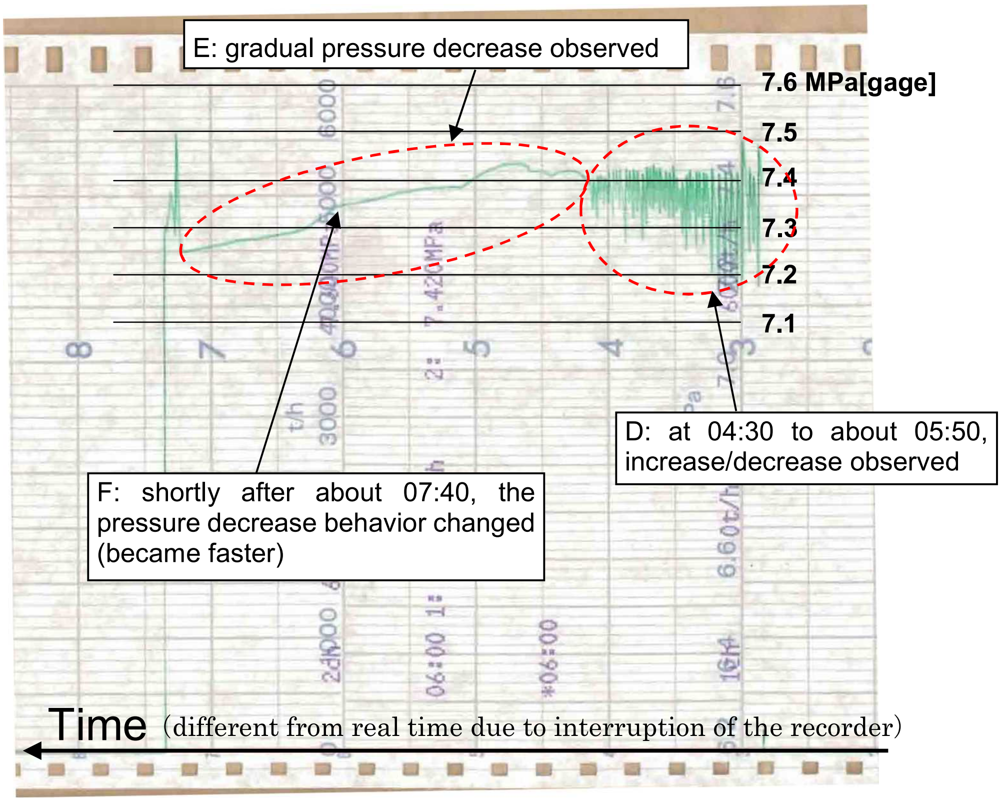


Figure 5 Reactor pressure time chart (narrow range).

Table 1 Working pressures of SRV relief function and safety function: MPa[gage]

	A	B	C	D	E	F	G	H
Relief function	7.51	7.58	7.44	7.58	7.51	7.58	7.51	7.58
Safety function	7.71	7.78	7.64	7.71	7.64	7.78	7.71	7.78
ADS available?	Yes	Yes	Yes	—	Yes	—	Yes	Yes

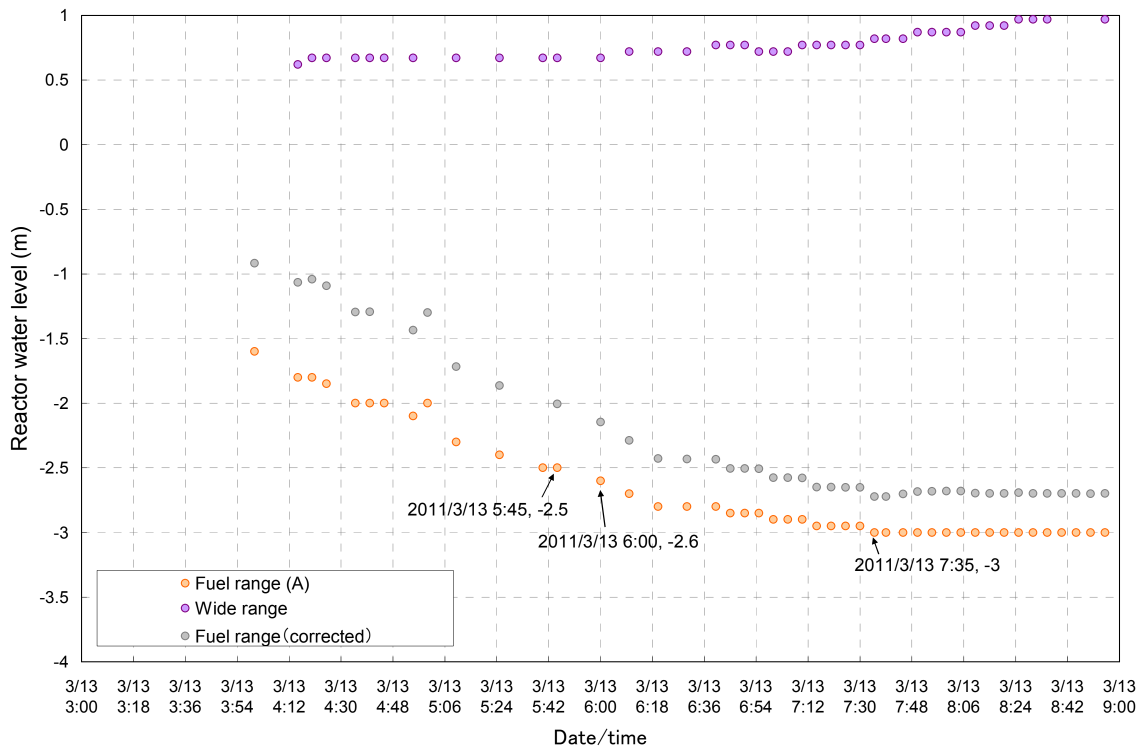


Figure 6 Reactor water level time chart.

4. Pressure behavior at depressurization

The pressure behavior at depressurization is given in Figure 7 (time period G). The gradually decreasing reactor pressure suddenly jumped to about 7.5MPa[gage]. It decreased once, and thereafter, it increased sharply again (up to about 7.38MPa[gage] this time) and while it was again gradually decreasing, it suddenly decreased sharply.

The first peak could be due to steam production when part of the melted fuel was transferred to the bottom of the reactor vessel, which increased the pressure, because some time had passed since the water injection had been halted and because the reactor water level was likely to have been below BAF around this time, as seen in Figure 6. From the SRV working pressures shown in Table 1, one or more of SRVs (A), (E) and (G), which had the design working pressure of 7.51MPa[gage], might have worked at this time. Actually, there is a report, saying the display lamps of SRVs (A) and (G) were switched on upon this rapid depressurization.

It is possible that the ADS function worked, causing the rapid pressure decrease thereafter. The ADS can be considered to have worked upon pressure increase of the suppression chamber (S/C) (the pressure indicator at the RHR pump discharge had detected the S/C pressure increase): i.e., [the reactor pressure increased to 7.51MPa[gage]] → [some steam moved to the S/C upon SRV working] → [S/C pressure increased] → [ADS worked]. (Deliberation on this depressurization behavior is being examined in a separate report.)

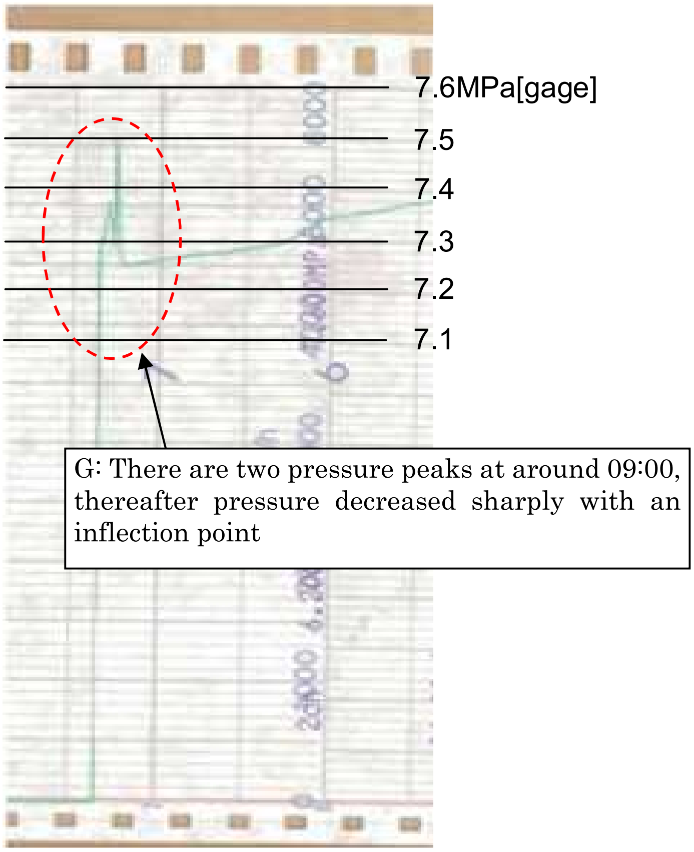


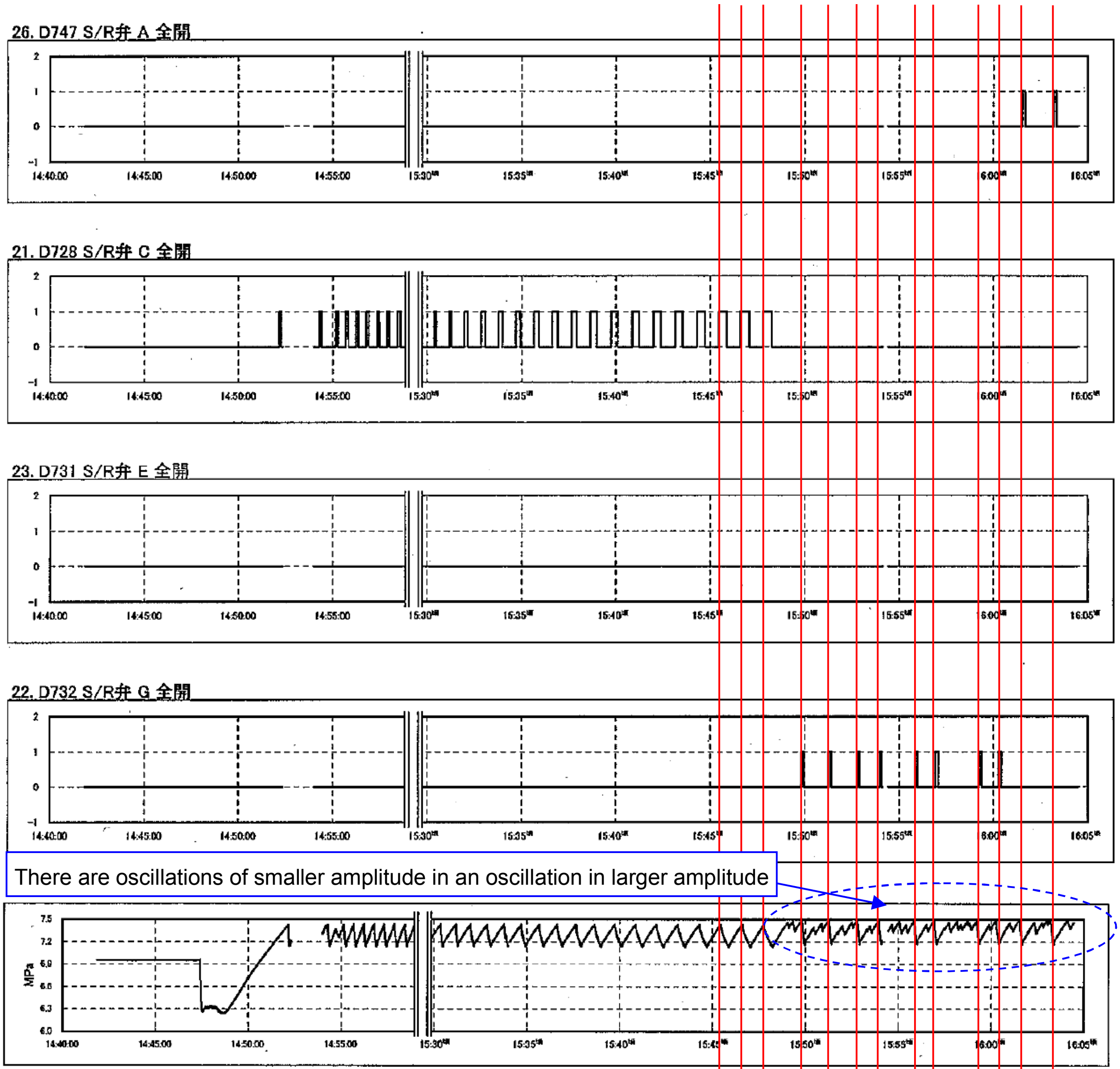
Figure 7 Reactor pressure time chart (narrow range)

5. Pressure oscillations during the time period D in Figure 5

During this time period, some frequent pressure oscillations were seen, probably due to SRV actions, but they are not necessarily consistent with the SRV designed working pressures (start / stop of blow-out).

Figure 8 shows the data recorded on the transient recorder (the data immediately after the earthquake are included therein). The first four graphs show the timings of SRV actions, while the last graph shows the reactor pressure changes (narrow range reactor pressure indicator). As shown by the red lines added for explanatory purposes, basically the reactor pressure decreased when the SRVs were opened. While SRV (C) was working, the reactor pressure seems to have changed between the design values for working. Thereafter, when SRVs (G) and (A) worked, the reactor pressure changed with an amplitude less than the designed pressures of start / stop of blow-out, when the SRVs were not in the open state. It can be presumed that SRV (C) with the lowest design working pressure received the signal to work, but it remained half-open because of insufficient nitrogen gas (depleted supply in the accumulators).

During the time period D in Figure 5, too, it is possible that the insufficient nitrogen gas was sent to the SRV, thus causing oscillatory pressure changes of small amplitude in the reactor pressure.



(The bottom graph shows the recorded reactor pressure data)

Figure 8 Records of the transient recorder.

6. Pressure behavior from about 09:00 to about 12:00 on March 13th

Figure 9 shows the pressure changes from just after 09:00 to about 12:00 on March 13th. The information on operating maneuvers during this time period is given below.

- After depressurization at 09:00 on March 13th, ten batteries were connected in series to the SRV control panel.
- At about 09:50 on March 13th, SRV (A) was operated on the control panel to open (the operation to activate the ADS functions).

At around 12:00 on March 13th, a reactor pressure increase was confirmed. But on the control panel, the indicator lamp was found to be unlit. Battery wires were found disconnected. After restoring the battery wires, the SRV was operated to open.

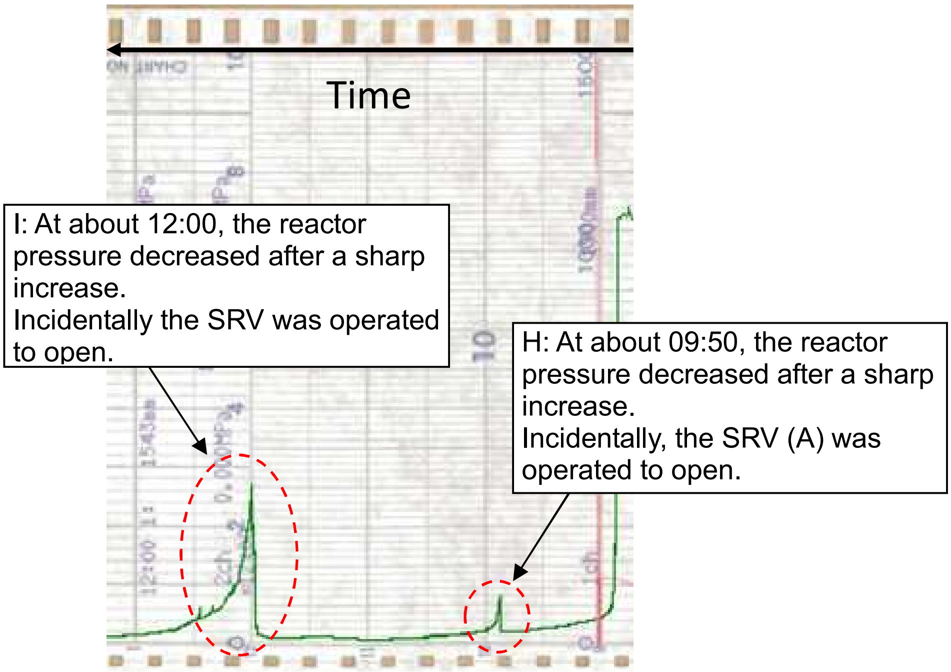


Figure 9 Reactor pressure time chart (wide range)

As Figure 10 shows, the fuel range water level indicator readings were less than the TAF level (the wide range water level indicator readings were increasing despite no water injection and very likely overestimating the water level because of the water in the water level indicator piping being evaporated). After 09:00, the fuel range water level indicator readings increased far more sharply than before. From 09:25, water injection to the reactor by fire engines started. Water might have been injected into the reactor to a certain degree, as the reactor pressure decreased to below 1MPa. But, after 13:00 on March 13th the water level indicator readings stayed constant. The readings might have been affected by water evaporation in the water level indicator piping. Therefore, the actual reactor water level was unlikely to be as indicated by the indicator readings.

If the SRVs had closed when the reactor water inventory was not sufficient, the reactor pressure increase would not have been as sharp as seen in Figure 9. At time points H and I in Figure 10, violent generation of steam and hydrogen would have occurred in the reactor vessel by relocation of part of the molten fuel to the lower plenum. If the pressure increase was simply caused by the SRV closure, the pressure increase rate would have been similar to that after the HPCI stopped operation as seen in Figure 3.

Regarding the reactor pressure decrease at about 09:00 on March 13th, the depressurization rate indicates that six SRVs opened (the ADS functions were activated), but the depressurization rate at time point I was more gradual than that at around 09:00. Therefore, even if six SRVs were opened at about 09:00 to activate the ADS functions, all six SRVs might not have been able to be kept open by this time point I. As discussed above, the reactor water level was likely to have decreased and the reactor temperatures were likely to have been high by this time I. Consequently, gaseous leaks might have occurred from the reactor vessel to the D/W, although the timings of leaks are unknown. The gradual decrease of reactor pressure at time point I might have been caused by the successful openings of SRVs or gradual leaks of gases in the reactor vessel to the D/W after the gas generation in the reactor vessel had ceased.

The reactor depressurization rate at time H is about the same rate as that at about 09:00 on March 13th and it is possible that the SRVs could have been kept open until about this timing after having activated the ADS functions.

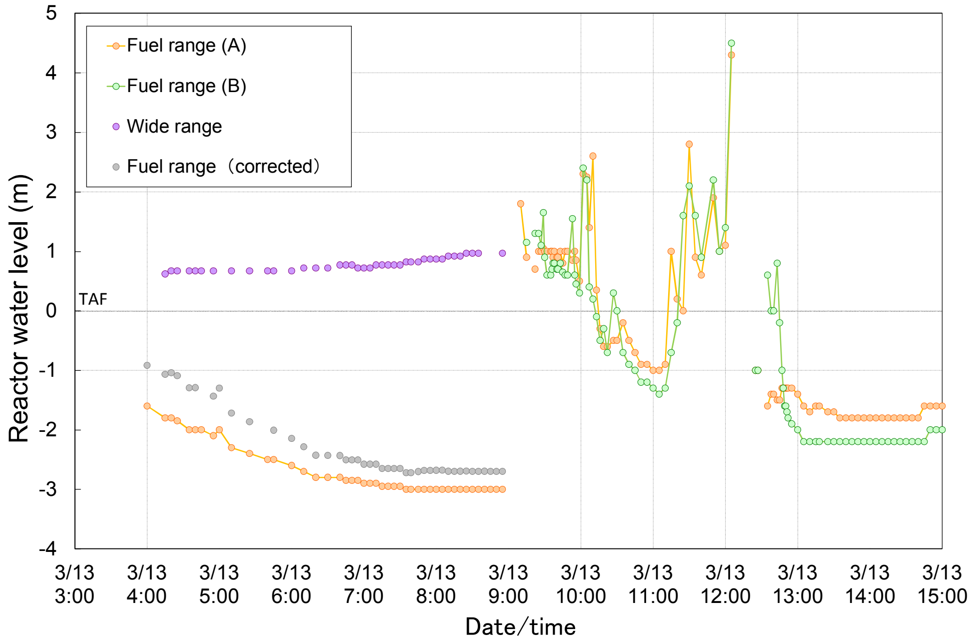


Figure 10 Reactor water level changes (03:00 to 15:00 on March 13th)

7. Summary

The reactor pressure changes before and after the rapid reactor depressurization have been examined. Unclear matters still remaining are summarized below.

- It was attempted to open the SRVs both in time period A and in time period B, but the reactor pressure changed in a different manner.
- The reactor pressure increased rapidly in time period B, and after the increase slowed down for a short while.
- No explanation is possible on the second pressure peak behavior in time period G.

These issues will continue to be examined.