Reactor pressure changes from about 02:00 to about 09:00 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.

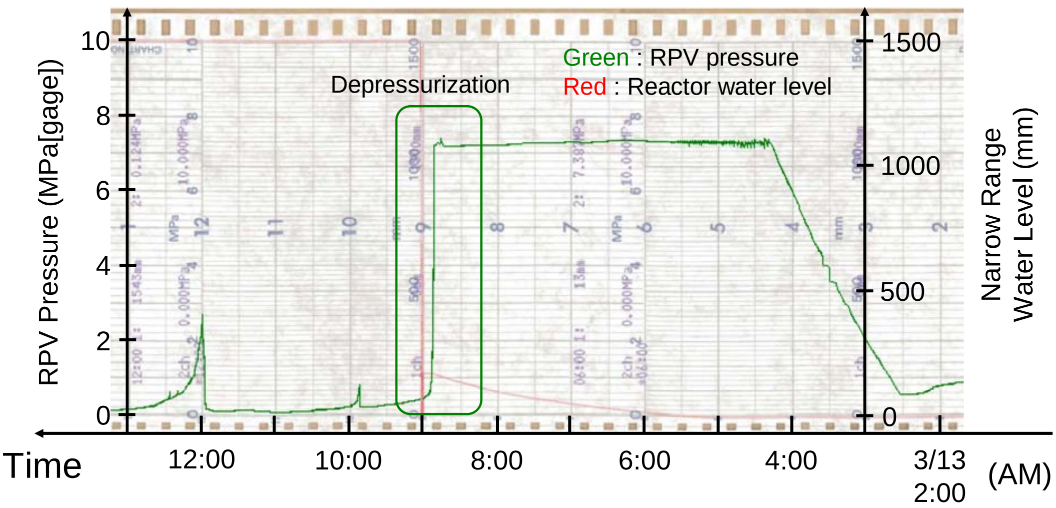

Figure 1 Reactor pressure time chart (wide range).

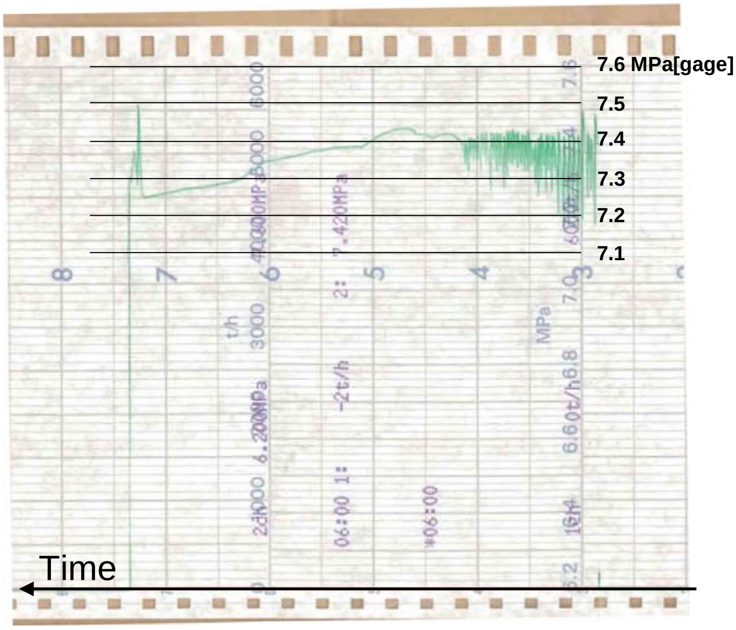

Figure 2 Reactor pressure time chart (narrow range).

2. HPCI shutdown to reactor pressure increase

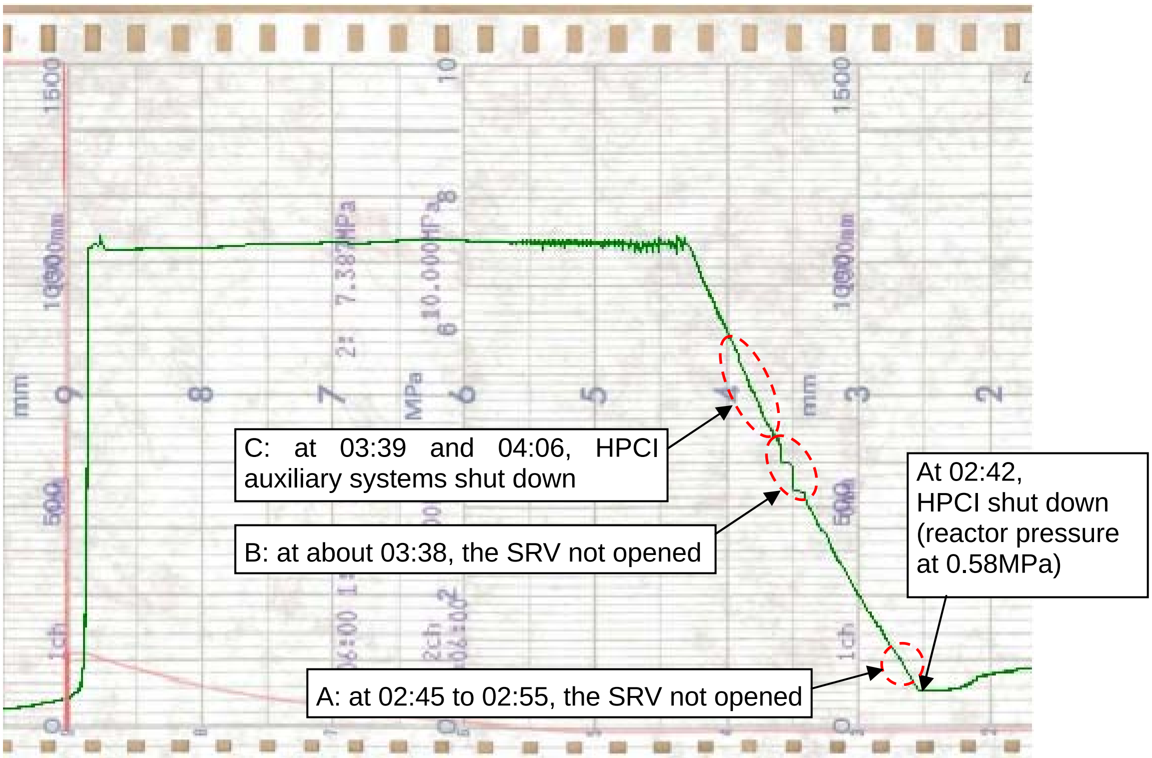

Figure 3 Reactor pressure time chart (wide range).

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 period A, but some changes are seen in time period B. It may be possible that the reactor pressure*1) for period A was insufficient according to the design pressure to open the SRV, but sufficient for period B.

The power supply might have been insufficient at time periods A and B, because it was at time period C when the HPCI auxiliary systems were shut down.

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*1) The valve element and valve rod of the SRVs are not fixed in the axial direction in order to avoid too much eccentric load to the valve element. If an SRV is operated to open it in the state of reactor cold shutdown (no load), the valve element remains on the valve seat without being raised. The design pressure difference between the front and back of the valve element to fully open the SRV remaining on the seat is 3.5kg/cm^2 (=343kPa), according to the SRV design specifications. The containment vessel pressure was not measured at around 03:00 on March 13th, but it can be estimated to have been about 200kPa[gage] based on the measured values at prior and later time points. This indicates the reactor pressure needed to be about 543kPa[gage] for SRV opening.

However, there are several unclear matters that are hard to explain, too. For example, the reactor pressure increased to about 1MPa by the end of time period A and the pressure difference required for opening SRVs might have been achieved; or at time period B (the reactor pressure was at about 4MPa), even if the pressure stopped increasing for a short while by having slightly opened the SRV, the pressure continued to increase suddenly right after. The scenario mentioned above is only one possibility. Furthermore, it is unlikely that all SRVs acted in the same manner, because, when activating the SRV relief function, the responses might depend on the SRV working pressures, especially for the SRVs with lower working pressures which had already operated many times, and the amount of driving nitrogen gas was likely to have been insufficient due to depletion.

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 4, 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 5 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*[2)], this water level (plotted in grey in Figure 5) 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.

*2) 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.

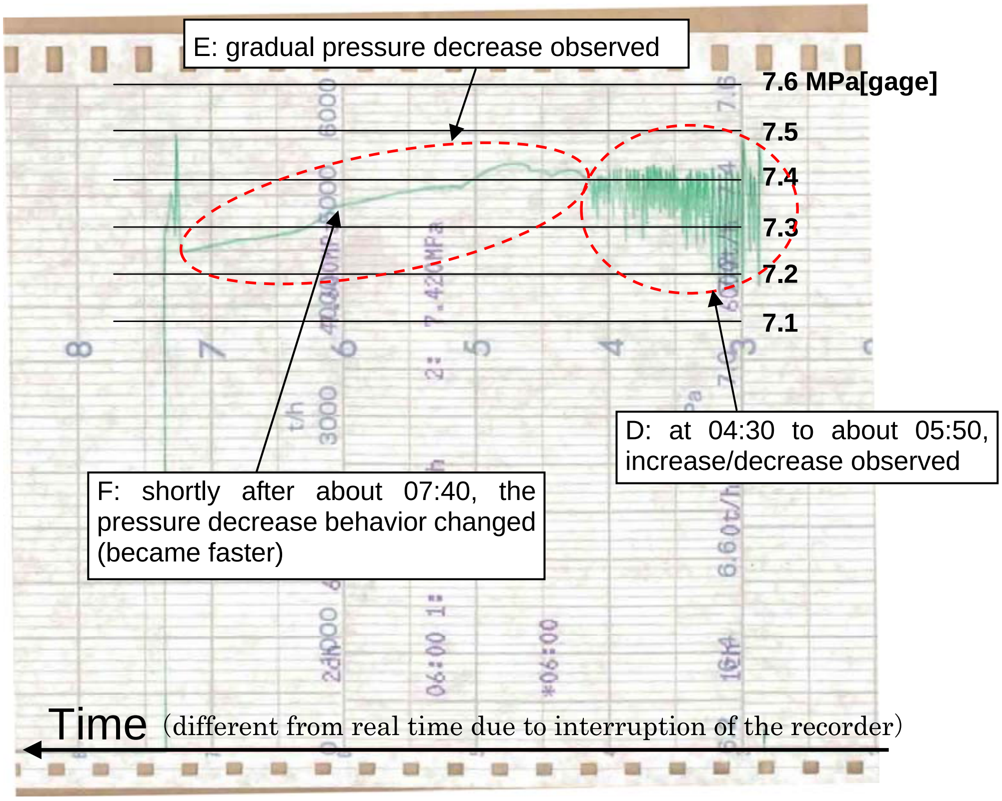


Figure 4 Reactor pressure time chart (narrow range).

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

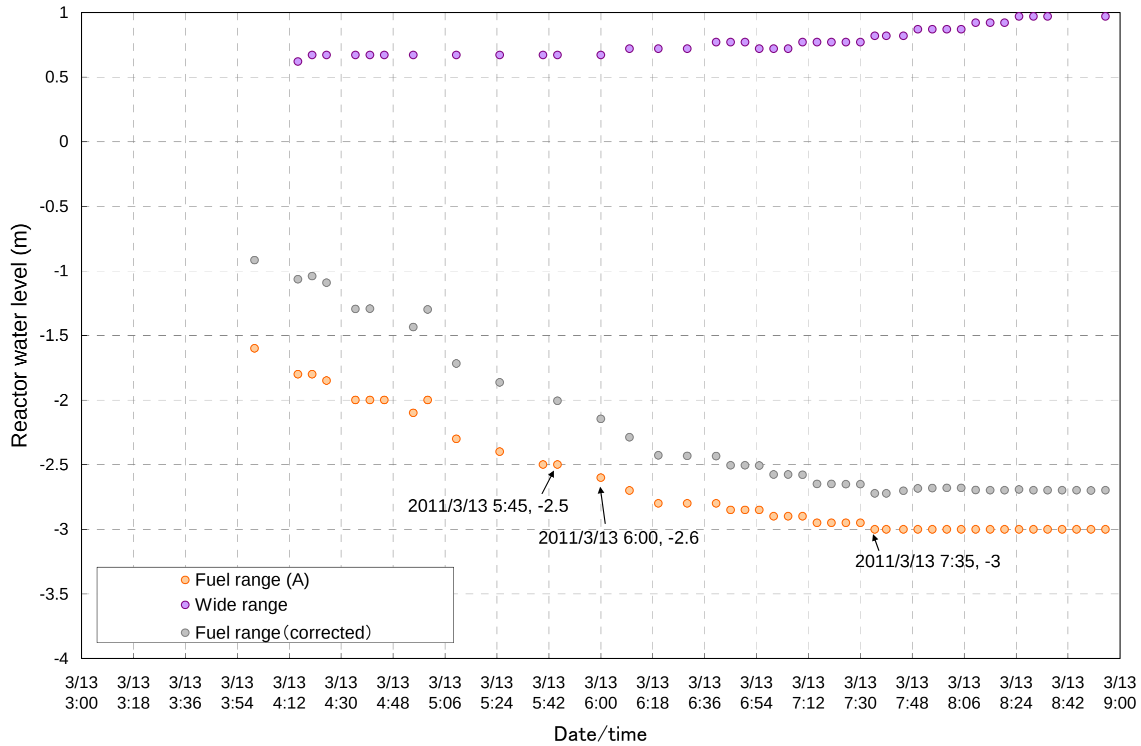


Figure 5 Reactor water level time chart.

4. Pressure behavior at depressurization

The pressure behavior at depressurization is given in Figure 6 (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 5. 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.)

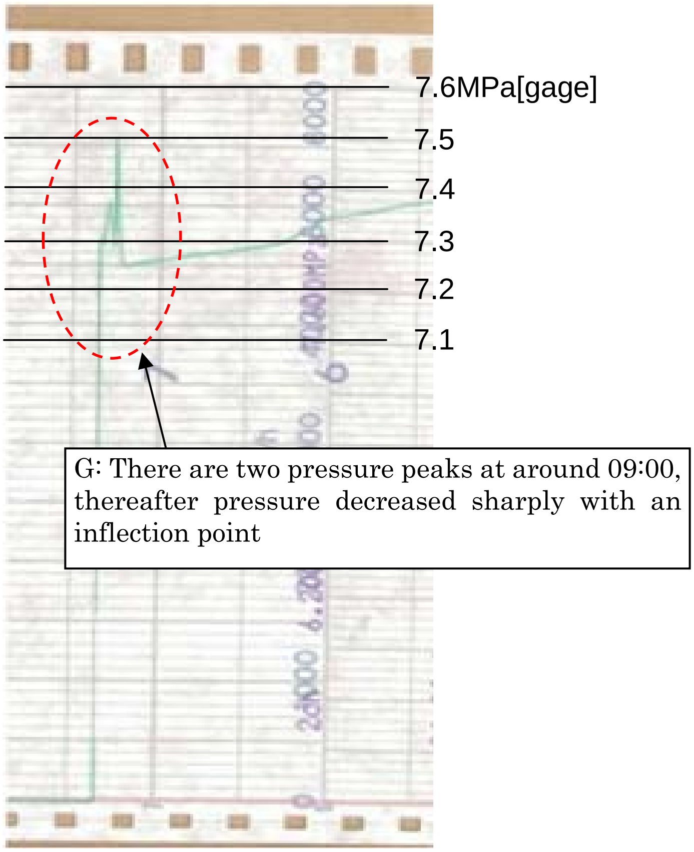


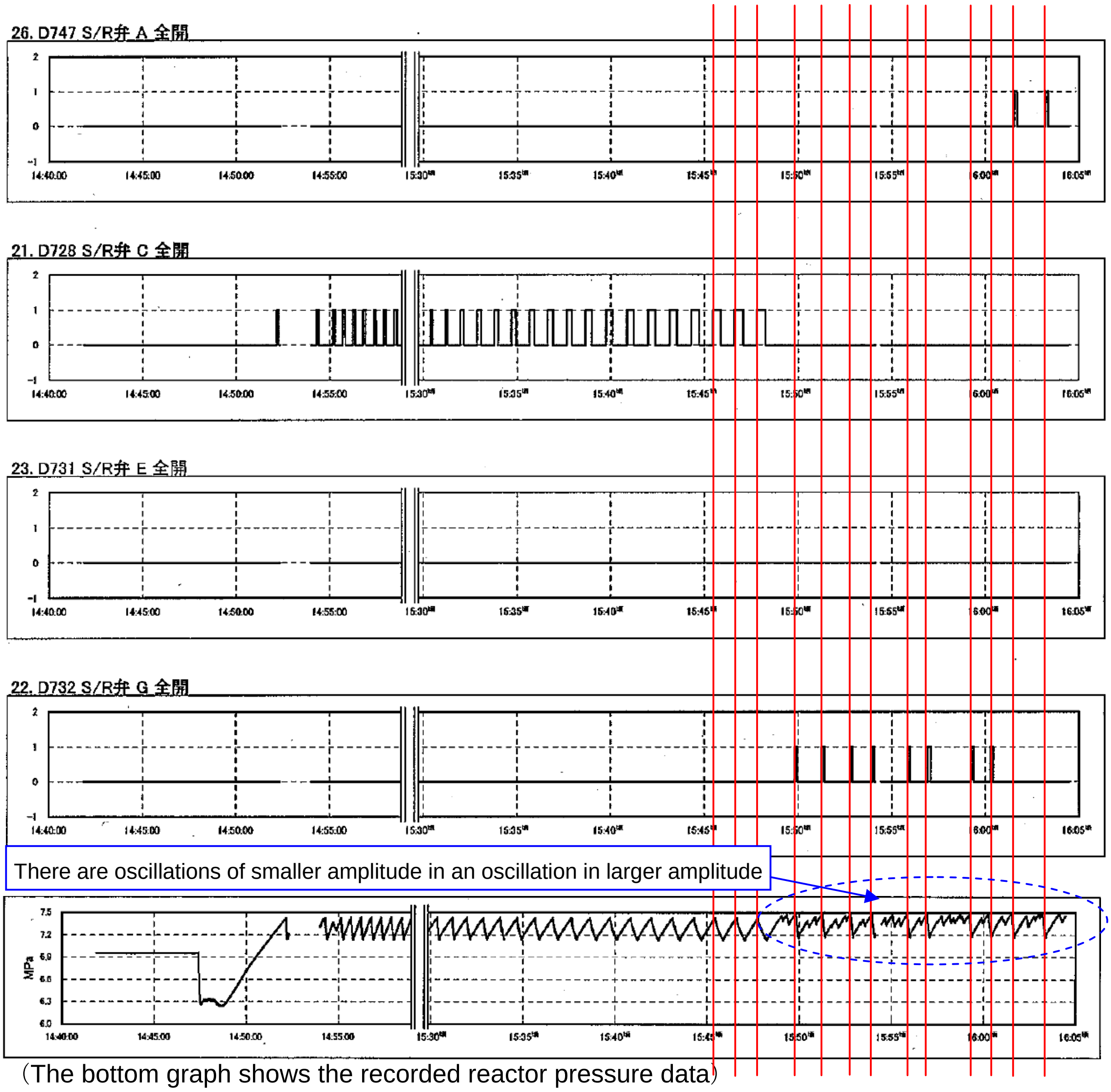
Figure 6 Reactor pressure time chart (narrow range)

5. Pressure oscillations during the time period D in Figure 4

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 7 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 4, 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 7 Records of the transient recorder.

6. Summary

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

- No pressure changes were seen in time period A, similar to those in time period B, despite the apparent fact that there was sufficient reactor pressure to open the SRVs.
- 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.