Impacts of the earthquake on Unit-1

1. Overview of the incident and subjects for examination

Units-1 to 3 of the Fukushima Daiichi Nuclear Power Station successfully scrammed at the earthquake and reactors were in the process toward cold shutdown. It is of TEPCO's evaluation that all units experienced the station black out (SBO) upon arrival of the tsunami, lost all their cooling capabilities and finally reached the status of a severe accident, since all power supplies including the DC power sources could not be recovered in time. In other words, it is TEPCO's judgment that the direct cause of the accident was the tsunami.

However, the Fukushima Nuclear Accident Independent Investigation Commission of the National Diet of Japan (hereinafter referred to as the "Diet Investigation Commission") pointed out in its report that a possibility could not be negated of a small loss of coolant accident (LOCA) at Unit-1. Its grounds for considering this possibility were in the following three points:

- Contractor workers noticed water leakage in the isolation chamber (IC) room on the 4^{th} floor of the reactor building;
- Pipe leaks below $0.3cm^2$ could not be negated according to the Japan Nuclear Energy Safety Organization (JNES) report; and
- Shift operators did not hear the sounds of the main steam safety relief valves (SRVs) working.

An examination has been done to see logically, starting with these three points, whether such a LOCA could have happened.

The Diet Investigation Commission's report also pointed out a possibility that the emergency diesel generator (A) (DG (A)) might have lost its function, not due to tsunami, but due to the earthquake, on the ground, based on the statement of a shift operator, that DG (A) might have lost its function before arrival of the tsunami.

This examination has been done using the information newly available, when the existence of data on the transient recorder was discovered in April 2013. The data included the one-minute-cycle information from before the earthquake until the transient recorder stopped due to the tsunami. This newly found set of data is used for examining the DG (A) behavior.

2. Possibility of a LOCA

The Diet Investigation Commission report stated that a possibility of a small LOCA could not be excluded on the basis of the three cited grounds: the workers' observations, the evaluation result and the operator's statement; but it did not present a logical scenario, which explained these three points. In the following chapters, each of these is examined.

The first subject is the water leakage in the IC room on the 4th floor of the Unit-1 reactor building. According to the Diet Investigation Commission report, it was near the hatch of the opening of the large object carrying-in entrance in the southwest area on the 4th floor of Unit-1 reactor building where the water leakage had been confirmed and the water had been leaking from an elevated position on the east wall (the spent fuel storage pool was on the other side of this wall).

The actual positional relations on the site can be estimated as illustrated in Figures 1 to 3 from the statements of Person B, who confirmed water leaking from the nearest position, and Person A, who confirmed water leaking in the direction of Person B. As can be seen in Figure 1, Person B stood immediately next to the hatch of the opening of the carrying-in entrance, was able to see the IC in front of him, and confirmed water leaking from the upper right. Person A, on the other hand, as can be seen in Figure 2, was hiding between the IC and containment vessel, from where he confirmed water leaking from his upper left in the direction toward Person B. Statements of these two people concerning the leak position (arrows) illustrated in Figures 1 and 2 are consistent. Therefore, it seems certain that the water was leaking from an elevated position of the east wall, as shown in Figure 3. According to a document *1) of the Nuclear Regulatory Authority (NRA) of Japan, Person A stood between the IC (A) tank and IC (B) tank. In whichever position he was confirming the water leakage at the time, there is no difference in the direction of the water leakage.

*1) Handout document 1-1, Situation of water leak on the 4th floor of Unit-1 at the Fukushima Daiichi Nuclear Power Plant (hearing results), The second deliberation session concerning the analysis of the accidents at the Fukushima Daiichi Nuclear Power Plant,, Nuclear Regulatory Authority of Japan

As clearly understood, the water leakage was confirmed not from the IC itself but from some other direction. It is difficult to assume the water leaked was the steam, which flowed into the IC, or the condensate for return.

On the east wall, from where water was leaking, there were pipes and ducts, as shown in Figure 4. Among them, those pipes which could have contained water or steam were the overflow prevention chamber (①) and the IC steam venting line (②). Other multiple pipes (③) are for electric cables and contain no fluid in them.

The overflow prevention chamber was connected to a duct which took in air from the surface of the spent fuel pool and discharged it to the outside. In the case that water of the spent fuel pool flowed into the duct, this overflow prevention chamber was installed to receive the water first and then drain it via a drain line. But at the time of an earlier earthquake, an incident had been experienced in which water of the spent fuel pool flowed into a duct due to sloshing, the water was too much to be drained by the drain line, part of that water flowed further into another duct downstream, and leaked outside the radiation control area. Based on this lesson, modification work had been done to isolate the overflow prevention chamber and the duct downstream by a diaphragm.

The IC steam venting line had a role to prevent water hammers in the IC steam line. To this end, steam was constantly circulated during normal plant operations in order to warm the steam line. Once the IC started up, this venting line was isolated by a valve and no more steam was circulated. Although it is not known whether the IC was operating when the water leaked, because it is not known when the water leakage was observed, but at any rate the leakage from this path does not last long, i.e., a LOCA scenario does not exist on this path.

The fluid of the IC steam venting line was steam, and no liquid water leaked but high temperature steam of high pressure would have blown out even if a pipe break occurred. The statements are quite different from this situation. The on-site investigation conducted in later days found no pipe damage on this line, either. The overflow prevention chamber was completely destroyed so had not kept its original shape, perhaps due to the hydrogen explosion. However, from the following reasons, the water confirmed leaking on the 4th floor could be assumed to have come to the overflow prevention chamber from the spent fuel storage pool and leaked out for some reason.

- Water overflowed by sloshing from the spent fuel storage pool has been confirmed on the 5th floor.
- The spent fuel storage pool water could have flowed into the duct through its opening when the water reached that elevation by sloshing.
- The background reason for installing an overflow prevention chamber was to receive water, which could not be drained sufficiently via the drain line if a large amount of water had flowed into the duct.

It can be concluded, therefore, that the possibility of a LOCA having caused the water leakage in the reactor building, which the Diet Investigation Commission pointed out in its report based on the workers' statements, actually has no connection with a LOCA.

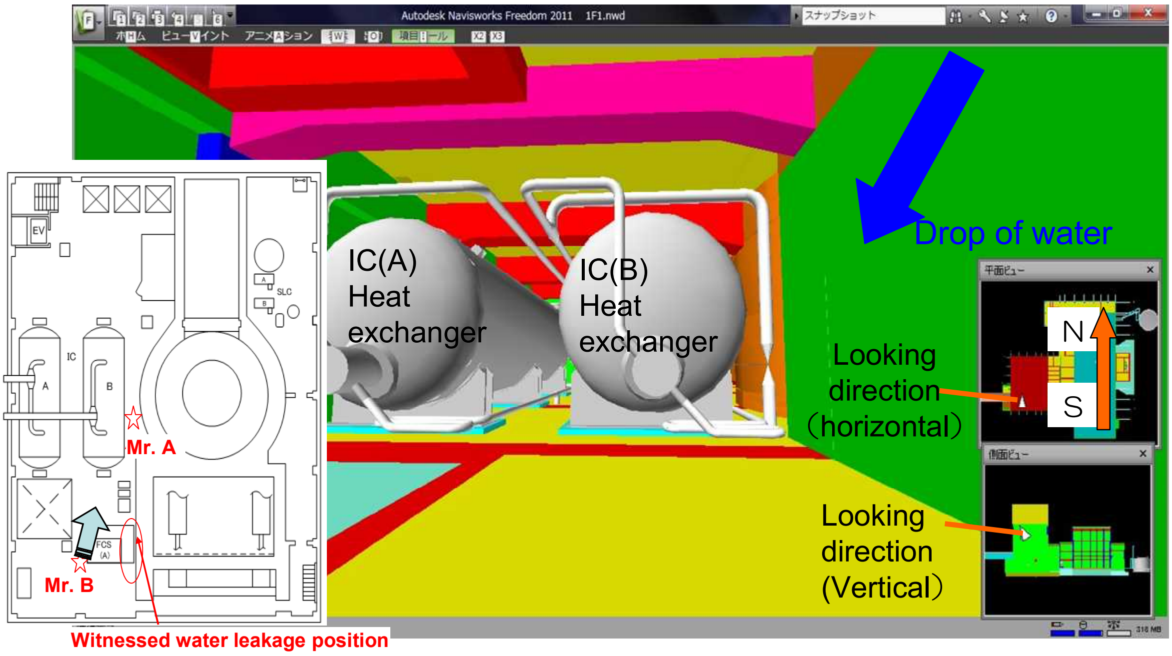

Figure 1 Situation of Person B at the time

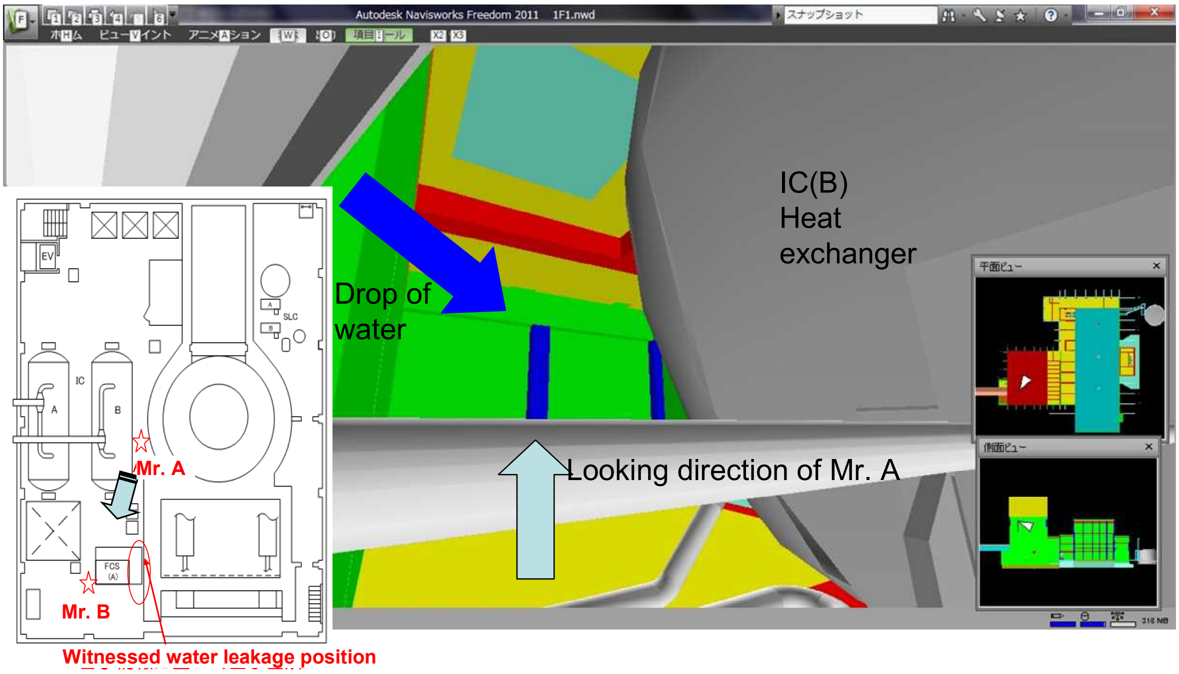

Figure 2 Situation of Person A at the time

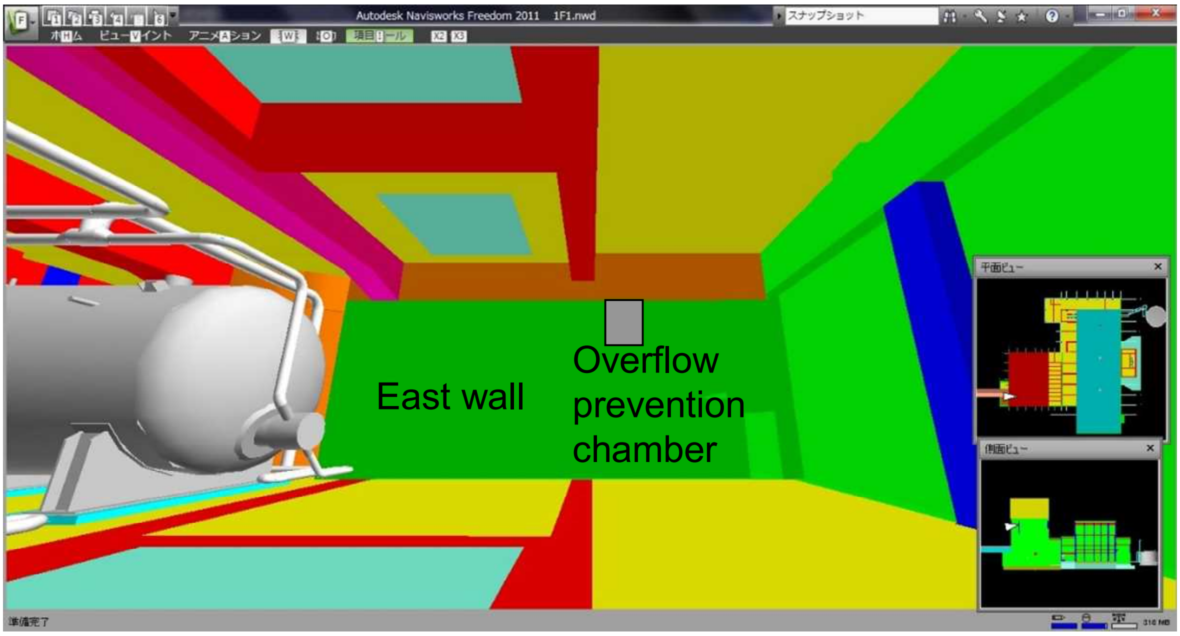

Figure 3 Position of water leak

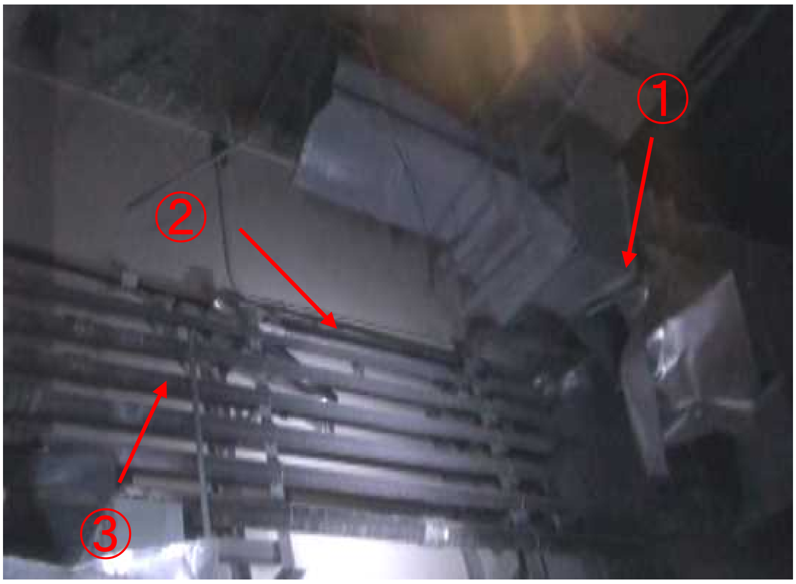

Figure 4 Pipes on the east wall

The second subject to examine here is the leak from the pipe break of less than 0.3cm^2, which JNES attempted to evaluate. It is true that leaks less than a certain scale cannot be negated from only the changes of plant behavior, because small leaks do not affect the plant behavior much. However, the Diet Investigation Commission assumed a small leak of less than 0.3cm^2 as its prerequisite if a leak existed. Further, the Diet Investigation Commission deduced that the SRV had not worked, because it could not obtain statements on the SRV working sounds. If the deductions were correct, it means that the SRV could not release steam, either. Therefore, it is examined below whether these two incidents could occur simultaneously.

The reactor pressure can be considered to have been continuously increasing even after arrival of the tsunami, if the plant behavior measured and the MAAP (Modular Accident Analysis Program) results were taken into account, and it could have reached far above 12MPa as of 17:00 on March 11th regardless of leaks, as can be seen in Figure 5. If so, the reactor vessel could have ruptured. But in reality no such symptoms have been noticed. In other words, the two incidents, i.e., a leak from a pipe break less than 0.3cm^2 which JNES assumed cannot be negated, and the SRV did not work, cannot happen simultaneously from physical viewpoints.

Based on the considerations above, a new scenario was assumed, which could meet the condition of no SRV working. The new scenario assumed that the leak area had enlarged after it became impossible to measure the plant parameters in the wake of the tsunami. In this case, the leak area had to have enlarged to a area big enough to release steam by about 16:00 on March 11th, when the reactor pressure was to approach the SRV working pressures. The steam production rate decreases monotonously in accordance with the decrease of decay heat. Therefore, once the leak area is enlarged enough to stop the pressure increase, steam discharge becomes more dominant than steam production. As a consequence, the reactor pressure starts to decrease as shown in Figure 5.

In TEPCO's MAAP results (made available on March 12th, 2012), a leak hole of 1.4cm^2 was assumed to have been generated at about 18:50 on March 11th. This area of leak turned out not to be big enough to release sufficient steam even with the amount of steam produced at about 18:50 on March 11th. Only by combining intermittent SRV working, could the reactor maintain a stable pressure at about 7.5MPa. This means that, as long as the MAAP results are considered, the leak area could not be less than 1.4cm^2 even at about 17:00 on March 11th, and the scenario cannot be concluded valid without a fairly larger leak area.

In the MAAP results, the reactor pressure started to decrease at about 19:40 on March 11th, by a leak 1.4cm^2 in area, and MAPP reproduced the pressure of 6.9MPa at 20:07 on March 11th. So, if the pressure decrease started much earlier and the leak area was much bigger, the pressure at 20:07 on March 11th could not be 6.9MPa, but it must have been much lower. In other words, the pressure decrease after about 19:40 on March 11th must have been faster than the MAAP results. This is inconsistent with the measured values of reactor pressure.

A series of MAAP analyses was conducted with leak area as the parameter by assuming a small leak after the tsunami arrival in order to examine the above scenario (Figure 6). In the analyses, the leak was set as having started one hour after the scram. The analysis results showed that the reactor pressure had increased and reached the level high enough to activate the SRVs if the leak area had been less than 7cm^2. The leak area, therefore, must be bigger than 7cm^2 in order to satisfy the assumption "the SRVs did not work." On the other hand, the analysis results showed that, if the leak area had been bigger than 7.5cm^2, the SRVs certainly had not worked, but the reactor pressure had decreased quickly and the pressure 6.9MPa[gage] at 20:07 on March 11th could not have been reproduced. The MAAP analysis has shown that a small LOCA did not occur which was consistent with the reactor pressure of 6.9MPa[gage] measured at 20:07 on March 11th under the condition of no SRV activation.

It can be concluded from the deliberations above that the three points noted by the Diet Investigation Commission as hinting at a LOCA had no connection with a LOCA and that, should they have been caused by a LOCA, they could not have occurred physically at the same time.

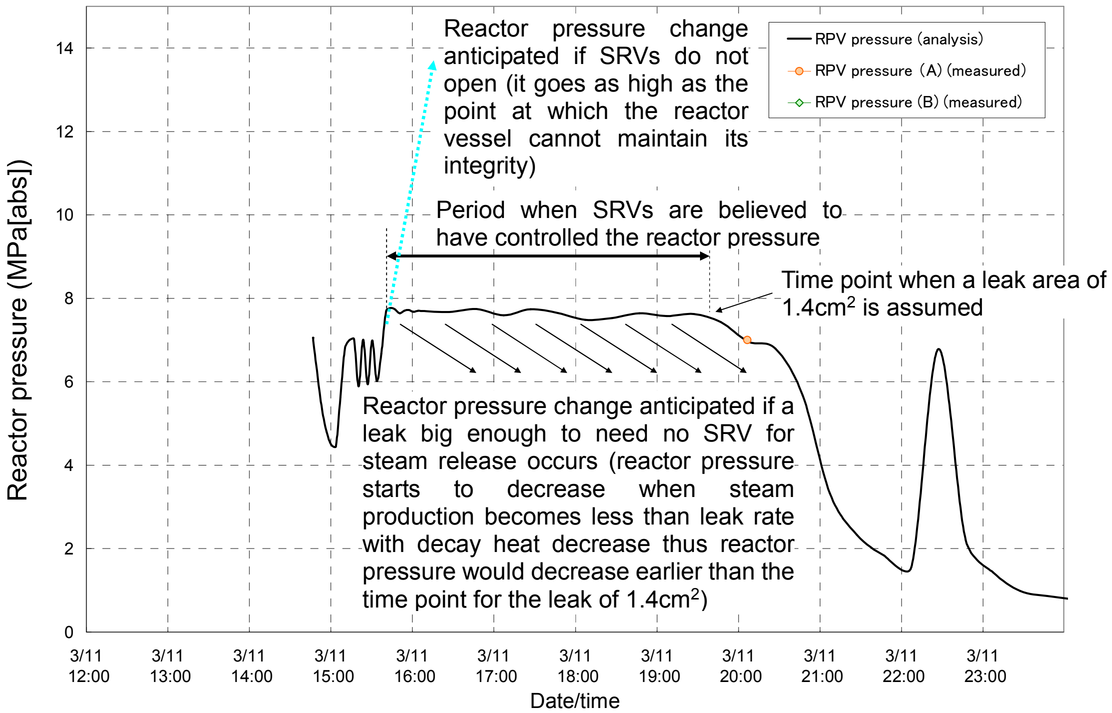

Figure 5 Reactor pressure change of Unit-1

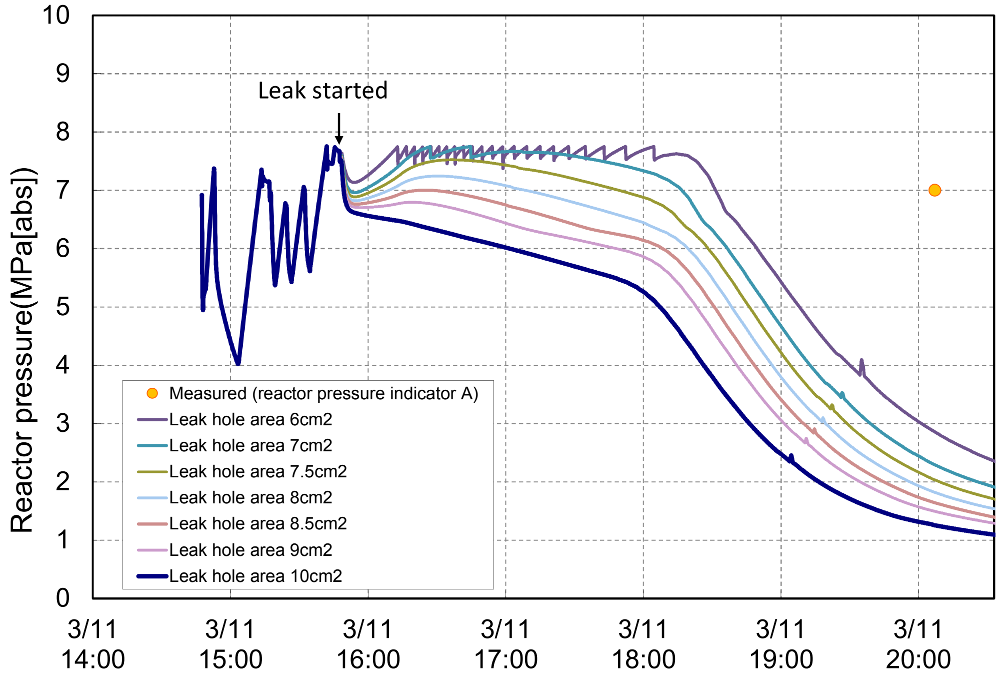

Figure 6 Reactor pressure change as a function of leak hole area

3. IC maneuvering actions by operators before arrival of the tsunami

IC maneuvering actions by operators before arrival of the tsunami and their relation with the plant behavior have been examined as below.

Figure 7 presents the reactor pressure changes and the IC maneuvering actions by the operators. At 14:47 on March 11th, the earthquake occurred and Unit-1 was scrammed by the “large seismic acceleration” signal. The reactor pressure decreased a little at the time of the scram, but started to increase thereafter due to steam production by decay heat. IC (A) and IC (B) were automatically started up at 14:52 when the reactor pressure reached the preset level for automatic IC start-up. It should be noted that the preset pressure for automatic IC start-up was lower than the SRV working pressures and therefore SRVs did not work when the ICs were started up.

After IC (A) and IC (B) started up, the reactor pressure started to decrease by their cooling effects and pressure was cut to 5MPa in about 10 minutes. This means that the coolant temperature in the reactor dropped about 20 deg C in about 10 minutes, because the saturation temperature of reactor coolant is about 285 deg C in normal operations with about 7MPa, while about 265 deg C when the pressure drops to about 5MPa. This temperature change rate exceeded the upper limit of the rate allowed for normal cooling at reactor shutdown, which is 55 deg C per one hour. For negating the possibility of a leak causing at the rapid pressure decrease, and for reducing the cooling speed (temperature decrease rate) and controlling the reactor pressure, the operators manually shut down IC (A) and IC (B).

The pressure started to increase again and reached about 7MPa. Thereafter, three times the operators repeated manual start-up and manual shutdown. In all actions, the pressure increase and decrease were under the operators' control.

From the above deliberations, it is considered that the operators thought of the possibility of a LOCA at the beginning but negated it based on the plant behavior upon IC start-up and shutdown. It is not extraordinary for the operators of Unit-1 to be concerned about leaks from the reactor pressure change because they are trained, by operation simulators, etc. to always take operating actions considering the possibility of leaks.

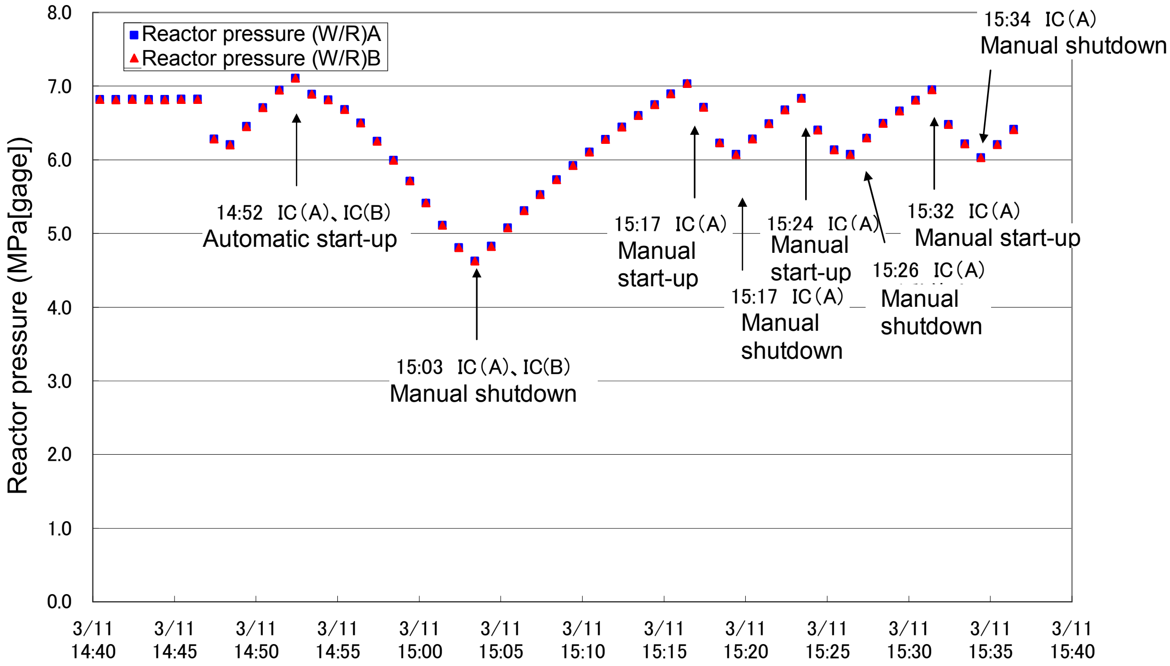

Figure 7 Reactor pressure change prior to tsunami arrival, and operators' IC maneuvering actions.

4. Causes of the loss of functions of emergency diesel generator (A)

The Diet Investigation Commission pointed out in its report that the DG (A) had lost its functions by the earthquake. The grounds thereof were the following, as cited from its report.

- The record said it was at 15:37 when the emergency diesel generator (B) (DG (B)) lost its functions.
- The operator stated that DG (A) had stopped before that (2 to 3 minutes at the longest)

- Therefore, DG (A) stopped before 15:35.
- By that time (15:35) the tsunami had not reached the site yet.

Concerning this point, a new file on the transient recorder was found in April 2013 and could be investigated. The file contained the information on the plant behavior until the tsunami arrived, although the information was limited to only the one-minute cycle. This could clarify the behavior of the bus line voltage and diesel generators upon arrival of tsunami.

The transient recorder is a system to record plant behavior in 10ms intervals before and after the transient once a transient incident occurs for some reason. For Unit-1, the information from 5min before the earthquake to 30min after it had been left but the information at the time of the tsunami arrival as not in 10ms intervals because the tsunami arrived at the site more than 30min later. However, the transient recorder has a separate complementary option for recording the information in a longer cycle. The Unit-1 transient recorder had an option to record one-minute-cycle data.

There is a big gap between the amount of information in the 10-ms-cycle and the one-minute-cycle. Figure 8 compares the voltage changes of bus lines C and D using these two data sets at around 14:48 on March 11th, when DGs started up upon loss of the external power supply. The 10-ms-cycle data show the voltage fluctuations and drops of bus lines as well as the subtle difference in start-up timings of DG (A) and DG (B). However, the information in the one-minute-cycle during this time period is available only for one time point at 14:48:59 (marked in the circle in Figure 8). Neither the bus line voltage loss nor the successful start-up of DGs can be explained from this single piece of information. From this background, the one-minute-cycle data were considered meaningless in analyzing transient behavior.

It has been found, however, that relevant information could be extracted regarding the time sequence of bus line voltage losses and DG operations. This is because the transient recorder keeps one-minute-cycle data, which are outside between 5min before a transient (the earthquake) to the time beyond 30min after the transient as the original system function, specifically to the time immediately before the transient recorder itself lost its functions due to the tsunami arrival. The data beyond 30min after the transient are not recorded in the 10-ms-cycle data.

Figure 9 presents voltage changes of bus lines and DGs. Voltage changes of bus lines A, B, C and DG (A) are plotted at the top, while voltage changes of bus line D and DG (B) are plotted at the bottom. First to note is that the voltage of bus lines A and B, which were not connected to DGs, dropped to zero upon loss of the external power supply. It can also be confirmed that DG (A) and DG (B) started up following the loss of the external power supply, because their voltages rose from zero to about 7,000V. Bus lines C and D were connected to DG (A) and DG (B), respectively, and therefore they maintained their voltages by receiving electricity from each DG even after loss of the external power supply. As mentioned earlier, no information is visible in one-minute-cycle data concerning the voltage drops upon loss of external power supply and voltage gains upon DG start-up. When the data around 15:37 when the tsunami arrived at the site are looked into, the voltage drop of bus line C down to zero can be seen (in the one-minute-cycle data chart the voltage dropped between 15:35:59 and 15:36:59). On the other hand, voltages of bus line D, DG (A) and DG (B) were maintained at about 7,000V as of 15:36:59 and it is after 15:37 when they lost their functions. It should be noted that the DGs can maintain their voltage by themselves even if the recipient lost its voltage.

Finally, Figure 10 shows the current changes of DG (A) and DG (B). The increase of currents at the DG start-up and at the time of containment cooling system (CCS) start-up for suppression pool water cooling can be confirmed from the figure. Looking at the changes at the time of tsunami arrival, it can be seen that the voltage of DG (A) connected to bus line C dropped to zero, and so did the current as well. At the same time, some decrease in current on bus line D can also be recognized, which maintained the voltage of about 7,000V. This can be presumed as due to the loss of its load such as the loss of functions of seawater pumps, which were installed in low elevation areas of the site.

Based upon the deliberations above, the tsunami impacts on power sources can be presumed to have proceeded from the seaside as in the following sequence and the loss of power supplies was reconfirmed to have been caused by tsunami.

Tsunami arrived

Loss of functions of seawater pumps, etc.

Loss of function of bus line C

Loss of functions of bus line D, DG (A) and DG (B)

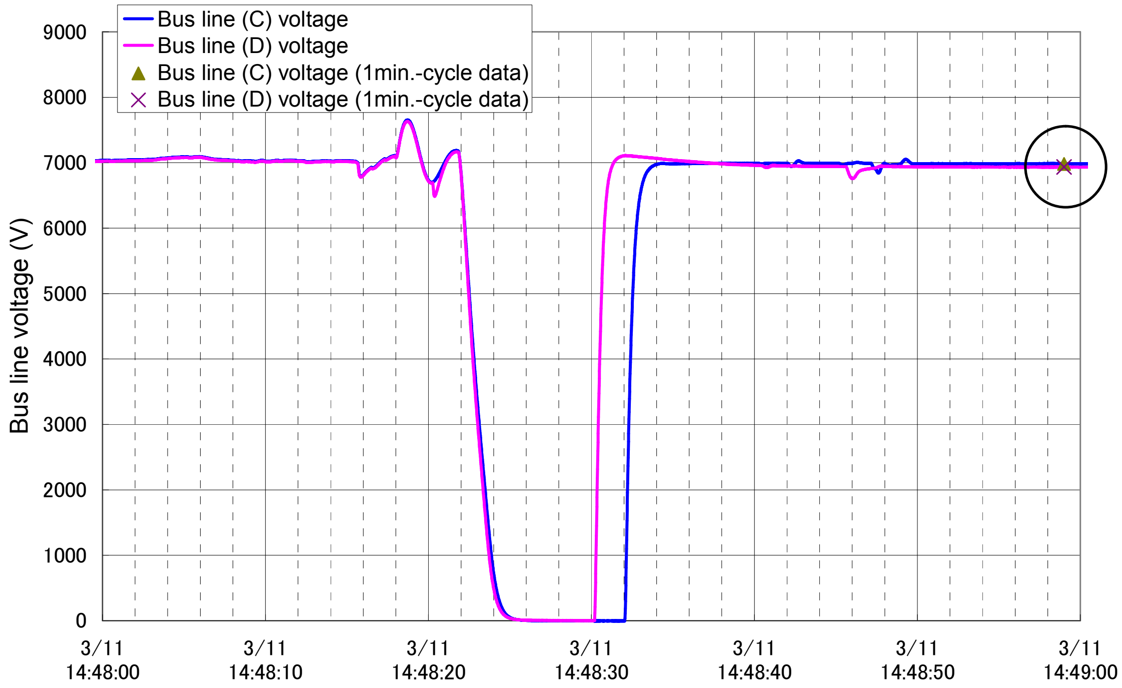

Figure 8 Comparison of 10-ms-cycle data and one-minute-cycle data by transient recorder

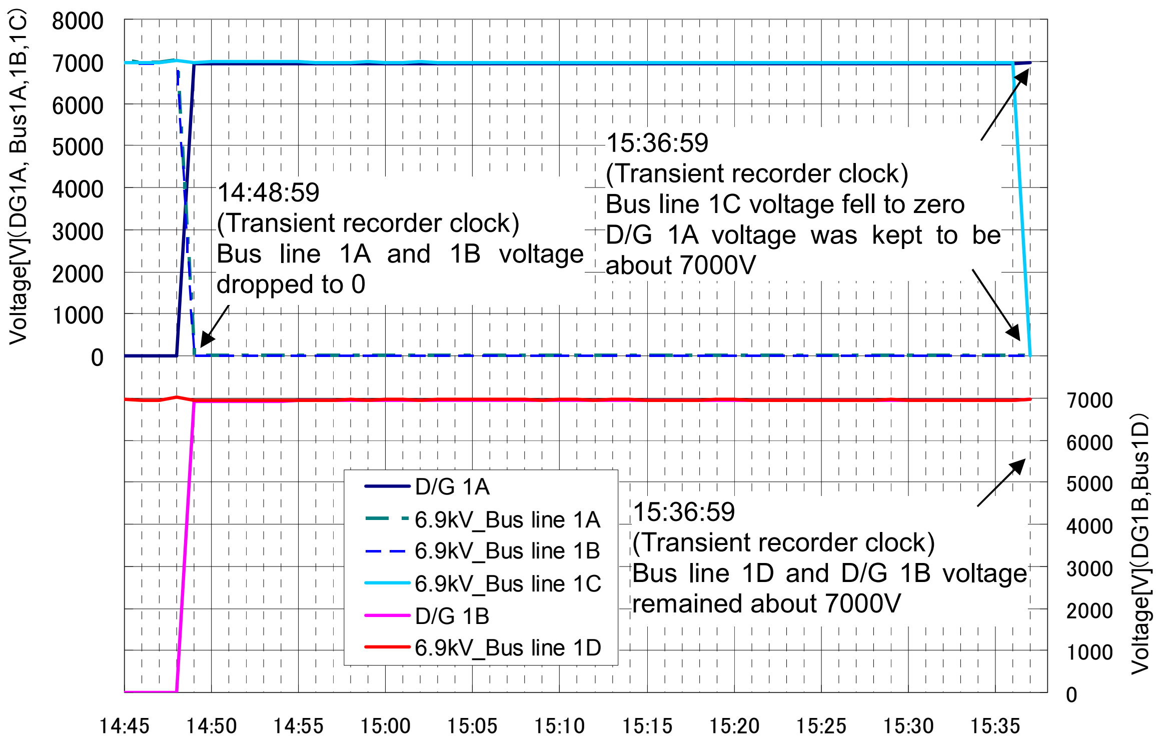

Figure 9 Voltage changes of bus lines and DGs

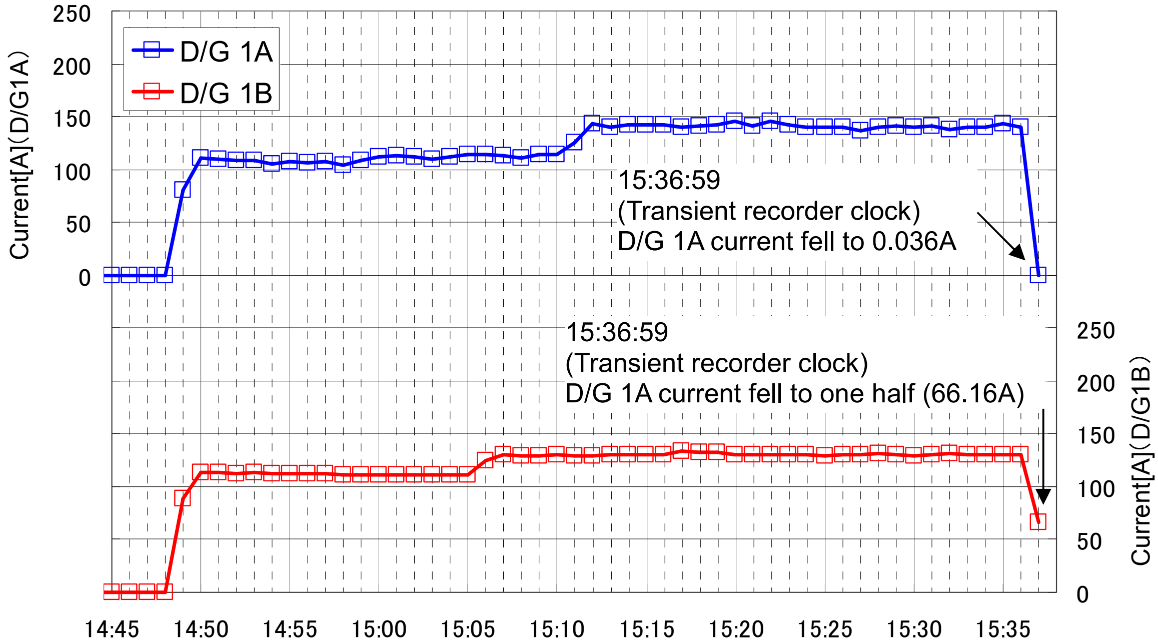

Figure 10 Changes of DG (A) current and DG (B) current

5. Summary

The possible impacts of the earthquake on causing a LOCA or the loss of DG functions have been examined for Unit-1. Concerning the LOCA, it has been concluded that pipe breaks causing leakage of a scale affecting the accident development currently assumed did not occur. Concerning the loss of DG functions, it has been shown that this was not caused by the earthquake, since the recorded data clarified that it followed time-wise the loss of functions of seawater pumps, which are considered to have been caused by the tsunami.