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Reflections and Lessons from the Fukushima Nuclear Accident (Second Report)

Working Group on Fukushima Nuclear Accident
Sub-Committee on Fukushima Nuclear Accident
Comprehensive Synthetic Engineering Committee
Science Council of Japan

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Summary

In order to investigate the cause of the accident that began on March 11, 2011 at the Tokyo Electric Power Company (TEPCO) Fukushima Daiichi Nuclear Power Station, the Science Council of Japan (SCJ) set an investigation committee, the "Sub-Committee on Fukushima Nuclear Accident (SCFNA)" under the Comprehensive Synthetic Engineering Committee. The committee has published a record entitled "Reflections and Lessons from the Fukushima Nuclear Accident," wherein the members of the committee carefully investigated the background to the accident and the problems that emerged, and new concepts about nuclear safety.

There are still many items about the accident for which the details are not clear. It is important to discuss the reasons why the severe accident could not be prevented and the possibilities that there might have been other proper operations and accident management (AM) to prevent or lessen the severity of the accident than those adopted at the time. These discussions may be helpful to plan countermeasures against accidents in the future. Based on the above considerations, SCFNA decided to continue its investigation by setting up a working group called the "Working Group on Fukushima Nuclear Accident (WGFNA)".

The subjects investigated in the WGFNA have been:

- Validity of the countermeasures against seismic ground motion and tsunami taken before the accident
- Validity of the operations and AM toward the accident progression after the tsunami struck

More concretely, they are as follows.

- Unit 1: (1) validity of the operation of the isolation condenser (IC); (2) whether or not a loss of coolant accident (LOCA) occurred due to a failure of the cooling piping system by the seismic ground motion; and (3) the cause of the loss of the emergency AC power supply.
- Unit 2: the reason why a large amount of radioactive materials was emitted to the environment although the reactor building (RB) did not explode.
- Unit 3: the reasons why the operator stopped running the high pressure coolant injection system (HPCI).

・Units 1 to 3: validity of the venting operation.

These items were considered to be the key issues in these units that would have prevented progression to the severe accident.

The results of the investigation were put together as records of the SCJ in Japanese ([7],[8]). But the committee member authors thought it would be useful to spread the message of the lessons learned through the investigation to the international community as well. This report is the summary of the investigation described in the Japanese records ([7],[8]).

The investigation results for issues at the specific units are summarized as follows.

Unit 1

(1) Working of the isolation condenser (IC)

It is estimated that the isolation valves were almost completely closed due to the loss of all AC and DC power supplies caused by the tsunami flooding, and that IC did not work from that time. TEPCO had not made enough preparation against a long time loss of AC and DC power supplies. This is the primary reason why TEPCO could not prevent the loss of the function of the IC.

(2) Possible failure in the cooling piping system due to seismic ground motion

It is estimated that there was no loss of coolant accident (LOCA) in the pressure containment vessel (PCV) with a substantial effect, through comparing the observed and simulated results about the behavior of the pressure in the PCV which was measured for some period just after the earthquake. It is also estimated that there was no leakage of radioactive materials from the RB where the PCV was located to the air, since no alarm was given by the radiation monitors. It is concluded that there was no significant failure of cooling piping system due to the seismic ground motion.

(3) Possible cause of the loss of the emergency AC power supply

It is estimated that the tsunami reached Unit 1 at about 15:36:47. The electric current of the emergency AC power line A became zero, while that of line B decreased by one half, at 15:36:59, that is, about 10 seconds after the tsunami struck. Therefore, it is estimated that both lines A and B of the emergency power supply lost their function due to the tsunami.

Unit 2

(1) Understanding the situation in the whole unit

The reactor core isolation cooling (RCIC), a critical safety component sustained operations for an extended period of 70 hours, which was assumed to be sufficient to deliberate and to implement actions. But actually the staff of the main control room (MCR) and emergency response center (ERC) failed to vent the PCV and it took time to start alternative cooling by using a fire engine because the staff had difficulty to grasp the situation for the whole unit and their operations were disrupted by explosions of the Units 1 and 3 RBs.

(2) Damage to the PCV

The control valve on the vent line had closed, caused by the Unit 3 RB explosion, and it could not be reopened. Finally, the pressure was far over the critical design value, and a great amount of radioactive materials was released into atmosphere through a damaged part of the PCV.

(3) Complexities and relationships among units

The progression of the accident in Unit 2 was much affected by what was occurring in other units and the subsequent countermeasures. There is a serious problem for multiple units constructed in the same site. The staff were sometimes confused by the information coming from different units, for example, about the selection of items which should be tackled with the first priority.

Unit 3

(1) Sharing of information

Information was not shared among the staff of the MCR, ERC and TEPCO headquarters, and therefore, they failed to have action plans with any perspective on the total situation in Unit 3.

(2) Organizational structure

Organizational structure, in which only one person was responsible for all six units at the Fukushima Daiichi NPS, was inadequate, especially in emergency situations such as the accident.

(3) Timing of HPCI operation

In the early stage of the accident, no discussions were made about the timing at which the high pressure coolant injection (HPCI) had to be stopped.

Common issue to Units 1 to 3

(1) Venting

The Japanese way of thinking on venting was very different from that of US regulatory authorities and operators. Japanese stakeholders, through complacency and a lack of imagination, thought that the release of radioactive materials into the environment should be and could be prevented completely. There were serious problems in the preparedness for AM, including AM for related facilities. Therefore, once the accident began, the staff and the operators had big difficulties to tackle in, for example, the venting operation, and they could not prevent progression of the accident. There is a possibility that a successful wet venting in the early phase of the accident could have limited the radioactive material releases, if this problem had been sincerely considered beforehand by learning the latest knowledge from overseas.

Finally, the authors have drawn the lessons learned from the accident on the following items.

(1) Preparedness against seismic ground motion
(2) Preparedness against tsunami
(3) Preparedness against station blackout (SBO)
(4) Accessing information in an emergency
(5) Preparedness against a severe accident
(6) Education and training of operators

CONTENTS

Appendices

1. Introduction

The Tohoku Region Pacific Coast Earthquake and the following tsunami, which occurred on March 11, 2011, caused unprecedented devastation in Japan, especially to the Tohoku and North Kanto regions. This event has become known as the Great East Japan Earthquake disaster. Furthermore, the earthquake and tsunami seriously damaged the Fukushima Daiichi Nuclear Power Station (NPS), resulting in the meltdown of fuels in three reactor cores, the destruction of the nuclear RBs due to hydrogen explosions (this is called an "RB explosion" in the following) and large scale release of radioactive materials into the environment.

As for the accident at the Fukushima Daiichi NPS, many reports have been written, for example, by investigation committees of the Japanese National Diet [1], the Japanese National Government [2], the private sector [3] and TEPCO [4], and further, many reports have been made by members of academic societies.

SCJ also thought that it was important to investigate the accident from an academic viewpoint, and an investigation committee, "Sub-Committee on Fukushima Nuclear Accident (SCFNA)," was set up under the Comprehensive Synthetic Engineering Committee (CSEC) of SCJ. After two years of intense investigation, SCJ published its report entitled "Reflections and Lessons from the Fukushima Nuclear Accident" [5], in which the committee members carefully investigated the background to the accident, the problems that emerged in its course, and the new concepts about nuclear safety that resulted from it. The report is written in Japanese, and its summary has been translated into English [6].

There are still many items about the accident which are not clear in their details. For some items the judgments among committees [1–4] differ, and further investigation is necessary. Under the present situation that no one can approach the neighborhood of the damaged PCVs, it is difficult to get an accurate idea about what happened there. But it would be irresponsible to leave these items unclear for a long time because that makes it difficult to propose the right measures to prevent future accidents. And this uncertainty divides the public into two opinion groups on whether the reoperation of nuclear power plants (NPPs) in Japan is reasonable or not. It is important to distinguish what is clear from what is unclear, and for the latter, to draw the most probable scenario, fairly without any bias, based upon the information already available. It is also important to discuss why the severe accident could not be prevented and the possibility that there could have been other proper operations and accident management (AM) to prevent the accident or lessen its level of severity than those that were adopted at the time. These discussions may be helpful to plan countermeasures against future accidents.

From the above viewpoint, SCFNA decided to do further investigation by setting up a working group called the "Working Group on Fukushima Daiichi Nuclear Accident (WGFNA)". The members of WGFNA carefully read and compared the documents described in four reports [1–4]. They referred to other published reports, and further, made direct inquiries to the staff of TEPCO.

The sequences of events in the accident that occurred at Units 1 to 3 have been the focus for the investigation because consequences were severe in these units. The investigation was focused mainly on the technological aspects, while such items as the responsibility for the accident were out of the scope of the investigation.

The subjects investigated in WGFNA are the following.

- Validity of countermeasures against seismic ground motion and tsunami in place before the accident.
- Validity of the operations and accident management toward the accident progression after the tsunami struck.

More concretely, they may be described as follows.

- Unit 1: (1) validity of the operation of the isolation condenser (IC), (2) whether or not a loss of coolant accident (LOCA) occurred due to failure of the cooling piping system by the seismic ground motion, and (3) the cause of the loss of the emergency AC power supply.
- Unit 2: the reason why large amounts of radioactive materials were emitted to the environment although the RB explosion did not occur in Unit 2.
- Unit 3: the reason why the operator stopped running the high

pressure coolant injection system (HPCI).

・Units 1 to 3: validity of the vent operation.

These items were the key issues in these units to prevent the severe accident which occurred.

The results of the investigation were put together as records of the SCJ in Japanese [7&8]. But the committee member authors thought it would be useful to send the message of the lessons learned through the investigation to the international community as well. This report is the summary of the investigation described in the Japanese records [7&8].

The general aspects of the reactors in the Fukushima Daiichi NPS and sequence of events of the accident are briefly described in Appendices 1 to 3. It is recommended that readers review those descriptions before reading the main text.

2. Investigation of the Accident Progression in Unit 1 [7]

In Unit 1, the most important factors that affected the progress of the accident were:

(1) working of the isolation condenser (IC);

(2) possible failure in the cooling piping system due to seismic ground motion; and

(3) possible cause of the loss of the emergency AC power supply.

These items were investigated through intense inspections and debate in WGFNA. Details have been described as a record of the SCJ [7]. The summary of the record is shown in the following.

2.1 Working of the isolation condenser

Many kinds of cooling systems are prepared in order to cool reactors. But these systems cannot work without the AC power supply, that is, if a station blackout (SBO) occurs, they cease to function. In Unit 1, the AC power supply was lost due to facility damage caused by the seismic ground motion and tsunami flooding, and therefore, all these cooling systems could not work. But a special cooling system had been installed which did not need the AC power supply and its function was to remove the decay heat generated in the reactor. An isolation condenser (IC) is one such decay heat removal system, and it had been installed in Unit 1 in order to work in the shutdown condition when the reactor coolant system was isolated from the main steam condenser. The IC was designed to work for about 8 hours without any AC power supply and without any external water supply, although the Atomic Energy Commission (AEC) had suggested in 1977 that the device should be required to assure the cooling against the loss of the AC power supply only for a short time (but at least 30 minutes) (see Appendix A6). The suggestion showed that both the Japanese Government and the licensees did not think of the possibility of the long time loss of the off-site power supply.

This device has a "fail-safe" function where the isolation of radioactive materials in the PCV has to be guarded by closing the isolation valves installed on the flow line of the IC pipe in an emergency when the failure of the pipe, or the loss of the electric power supply for controlling the detection of failure, occurs. On the other hand, Units 2 to 6 each had an RCIC installed instead of the IC; the RCIC has the function of "fail-as-is" wherein the isolation valves stay as they are in the emergency.

The Tohoku Region Pacific Coast Earthquake occurred at 14:46, on March 11, 2011. And just after the earthquake, the reactor of Unit 1 scrammed, off-site power supply stopped, that is, the loss of off-site power (LOOP) occurred, and then the isolation valves of the main steam condenser were shut down automatically. But at the same time the emergency diesel generator (EDG) started working, and the IC also started working automatically and the reactor cooling was done by the IC. The operator tried three times to close and reopen the IC isolation valves in order to keep the cool-down rate within the described limit. This is described in the operation manual to prevent the generation of excess thermal stress in the reactor. It was found that the IC worked normally. And there was no evidence that any failure of the piping system occurred that could be regarded as the LOCA.

The first tsunami was observed in front of the seawall of the Fukushima Daiichi NPS at 15:27. The second tsunami of about 14-15 m height reached the Fukushima Daiichi facilities at 15:36 and the sea water flooded them, including the rooms where the distributing panel and EDG were located. The tsunami flooding tripped the EDG and all the AC and DC power supplies were lost in Unit 1.

The IC worked normally from just after the earthquake until the tsunami struck. When all the AC and DC power supplies were lost after the tsunami, the automatic closure of the IC isolation valves occurred because the fail-safe function worked. But actually the isolation valves were estimated to be almost completely closed, therefore, the IC did not work. Details about how the isolation valves behaved when the tsunami struck and why the IC did not work are described in Appendix A4. Further, details of the inquiries to TEPCO about the fail-safe design of the IC are described in Appendix A8.

Unfortunately, there were no persons at the seismic isolation building who noticed that the IC did not work. It was thought that the IC was working normally even after the tsunami, and that cooling of the reactor was being maintained. At about 23:50, about 8 hours after the tsunami, the director of the site recognized that the IC was not working. This is one of the reasons why operators were too late to prepare against the meltdown of fuels in the Unit 1 reactor core.

If the IC had been designed to have a function of "fail-as-is" as the RCIC in Units 2 to 6 had, it would have continued working even after the tsunami for about 8 hours, which would have resulted in a delay of the meltdown.

It is important that the concepts of the safety design and the operation manual are clearly understood by each operator and staff member.

Another important factor is the back fit problem which should have identified from the lessons of the Three Mile Island (TMI) and Chernobyl accidents. The US Nuclear Regulatory Commission (NRC) twice, i.e. in 2006 and 2008, presented to the Nuclear and Industrial Safety Agency (NISA) of Japan its order, called "Station Blackout and Advanced Accident Mitigation (B.5.b)", about making provisions against terrorism. In B.5.b, it was supposed that a nuclear power plant could be destroyed by a terrorist attack and that a SBO would happen. Further, the mitigation measures against such a situation were described in B.5.b. But NISA neglected to act on the order presented by the NRC, and it did not inform the National Government or the licensees in the electric power industry of the contents of B.5.b.

There is a possibility that the operator could have run the IC again by opening the isolation valves manually which had automatically closed just after the tsunami as a result of the fail-safe function and that the meltdown of the reactor core could have been prevented, if NISA had not hidden the information about B.5.b, and if the proper countermeasures proposed in the order B.5.b were adopted in all the NPSs in Japan.

The following items summarize the documents described in the record [7].

(1) The IC worked normally from just after the earthquake until just before the tsunami struck. This suggests that any failure of the piping system that could be regarded as the LOCA did not occur due to the seismic ground motion.
(2) The isolation valves had been almost completely closed when the loss of AC and DC power supplies occurred due to the tsunami. Because it was designed to have the function of fail-safe, this is the reason why the IC did not work after the tsunami struck.
(3) There is a possibility that the operators could have delayed the time to the meltdown by about 8 hours if the IC had been designed to "fail-as-is" as in the case of the RCIC installed in Units 2 to 6, and if it had worked even after the tsunami struck.
(4) The operators and staff members at the seismic isolation building did not recognize that the IC was not working for a long time, that is, for about 8 hours after the tsunami. If they had recognized this earlier, they could have prepared for cooling of the reactor by using a fire engine earlier.
(5) It is not certain whether they could have prevented the meltdown and the following RB explosion in Unit 1, even if some of the measures mentioned above had been adopted. But if they could have prevented the RB explosion, the following meltdowns in Units 2 and 3 and the following RB explosions in Units 3 and 4 could have been prevented.
(6) Both the NISA and TEPCO did not suppose the possibility of a long time SBO due to tsunami. They had not prepared against a severe accident systematically even though there was a chance to do it through the information presented in B.5.b in which countermeasures for the SBO are described. This might be the main reason why the severe accident could not be prevented.

2.2 Possible failure in the cooling piping system due to seismic ground motion

The point of discussion about the direct cause of the accident is whether or not the accident would not have happened if the tsunami had not come.

Excluding the National Diet report [1], the other three reports [2, 3, 4] stated that the direct cause of the accident was the loss of all the AC and DC power supplies due to the tsunami and the loss of the function to cool the nuclear reactors steadily. They concluded this through examining the data of the reactor pressure and the water level. On the other hand, the National Diet report stated that the direct cause of the accident was not limited to the tsunami, and it referred to the possibility of damage by the shaking of important equipment for the safety of the nuclear reactor; it did not deny the possibility of the small break LOCA caused by a pipe failure due to the seismic ground motion. It also stated that TEPCO was trying to present the accident as being smaller than the real situation.

(1) The specific points of each report

The Diet report [1] pointed out the possibility of an LOCA from the testimony of a TEPCO staff member, saying that "on the earthquake occurrence, he observed a leak of water on the 4th floor of Unit 1 reactor building". In order to investigate this problem, the Nuclear Regulation Authority of Japan set the "Examination meeting on the analysis of the accident at the TEPCO Fukushima Daiichi Nuclear Power Station," and from its findings obtained the conclusion, on August 30, 2013 that "this leak of the water was caused by the sloshing of cooling water from the spent fuel pool, and that it is supposed that the possibility of LOCA is extremely small" [9].

The Government report [2] stated that all the parameters such as reactor pressure, water level, temperature were recorded on charts automatically from the occurrence of the earthquake until the loss of AC and DC power supplies due to the tsunami and that the operators' actions just after the earthquake were consistent with these data. It also said that there was no question about the correctness of the parameters. The report concluded that "it is natural to think that there was no pipe failure by the seismic ground motion which affects the performance of the IC".

The private sector report [3] stated that "there is a record that the failure alarm of the IC piping came before and after the loss of power. But this could be caused by the loss of power of the failure detection circuit. It is desirable to do the dynamic analysis based on the result of measurement by the seismometer.”

The TEPCO report [4] also supposed that there was not any malfunction about the soundness of the piping system, judging from the charts of the main steam flow rate, PCV pressure/temperature, and PCV floor sump water level.

Analytical results about the small-break LOCA obtained by the Japan Nuclear Energy Safety Organization (JNES) were reported in the NISA report [10]. The NISA report did not point out the possibility of the small pipe failure. It stated that even a quite small leak (the leakage of the limit for which the continuation of operation is permissible (0.23 m^3/h leak)) was not thought to have happened. The report said that the possibility of the occurrence of LOCA was low enough judging from the actual containment pressure transient.

(2) The way of thinking about the leak quantity

Light water reactors have been designed from the beginning of their development to allow for water leaks from the hot and high pressure water/steam system. For example, in designing the capacity of the water supply system of the Shippingport reactor, the first commercial pressurized water reactor (PWR), it was expected that a miscellaneous leakage of 1500 gallons / day (leakage, miscellaneous flushing and filling) would occur in the opening and shutting of valves in addition to the decrease of water by sampling [11]. This value was obtained from the assumption of 1 gallon per minute to the amount per day (1 gallon per minute × 60 minutes × 24 hours = 1440 gallons per day). This design concept that an unknown leakage of 1 gallon per minute is permissible is still alive today in the design of boiling water reactors (BWRs).

This is "the leakage of the limit at which the continuation of operation is permissible (the leak corresponding to 0.23 m^3/h)" which is described in the TEPCO report [4] (1 gallon = 3.785 liters, 3.785 liters per minute × 60 minutes= 227 liters per hour = 0.23 m^3/h). That is, even if there was a leak below 1 gallon per minute, it is not regarded as a failure, but is a normal operating condition.

According to the above-mentioned NISA analysis [10], the pressure of the containment vessel rose more rapidly than the actually measured pressure, even if there was a leak of 0.23 m^3/h (corresponding to the leak area of 2 mm^2 in the liquid phase and 8 mm^2 in the steam phase).

Even if there was a leak before the tsunami arrived, the leakage could be less than 0.23 m^3/h, that is, the level of normal operation, and this is not called an LOCA.

In conclusion no LOCA occurred before the tsunami arrived.

(3) Conclusion

Comparing the actually measured containment pressure in the accident and the analysis result of NISA, it is concluded that there was no possibility of a small-break LOCA. That is, no LOCA had occurred because of the seismic ground motion before the tsunami struck.

2.3 Possible cause of the loss of emergency AC power supply

The report of the investigation committee of the National Diet [1] has pointed out that the time of the loss of emergency AC power at Unit 1, especially on the A line system, was earlier than the time of the first tsunami. The emergency AC power system is an important system for the safety of nuclear power plant in the case of the LOOP. If the emergency AC power was lost before the tsunami arrived, it could be concluded that the system was damaged by the seismic ground motion, and in such a case it is necessary to reevaluate earthquake resistant design for the emergency power supply system employed in nuclear power plants in Japan. Therefore, WGFNA selected this issue and has investigated it.

The other two investigation reports [2&3] did not mention the time of the loss of the emergency AC power. The TEPCO report [4] just mentioned the time without any discussion.

The WGFNA carefully examined the validity of the contents described in the report of the National Diet [1], based upon new evidence and information obtained by making inquiries to the staff of TEPCO.

(1) Time of tsunami

The record (http://www.tepco.co.jp/nu/fukushima-np/index10-j.html) of the wave height detector located 1.5 km off the coast indicated the highest peak of the tsunami (second stage in the second wave) was at 15:35.

The report of National Diet [1] has also pointed the same thing, but it says that the arrival time of the peak at the coast near Unit 4 was estimated as at 15:37. Further it says , based on the analysis of the photos taken by TEPCO, that the equipment of emergency AC power system in Unit 1 should be damaged a little later if it is assumed that the system was damaged by the tsunami. The report also mentioned testimony of a person who observed the tsunami arrival, but there was no evidence for the accurate time.

TEPCO said that it was not possible to decide the exact time from the photos because calibration of the camera timer was not done and the camera was lost.

In the WGFNA, the series photos taken by TEPCO were carefully investigated by comparing the profile of the record of tsunami wave 1.5 km off the coast with new data obtained from TEPCO. The eighth photo in the series showed when the tsunami peak reached the south pier of the Fukushima Daiichi NPS port. Then, from consideration of propagation speed of the tsunami, the tsunami peak was estimated to have reached Unit 1 at 15:36:47.

(2) Time of the loss of emergency AC power line A

There were two emergency diesel generators (EDG-A and EDG-B). There is no record about the time the EDG-A stopped in the TEPCO report. The daily operational report of Unit 1 indicated that line A was lost before line B. There was data equipment to record the transient phenomena automatically by a computer. But unfortunately the record terminated at 15:17, because the equipment was set to work for 30 minutes at an interval of 0.01 s after the scram instead of the 5-minute interval used before the scram.

The report of the National Diet [1] estimated that line A stopped about 1 or 2 minutes before line B based on the hearing made at the Fukushima site. Then the report estimated that line A must have stopped at 15:35 or 15:36, that is, before the tsunami struck.

From the above considerations the report of National Diet [1] concluded that the function of the emergency AC power at Unit 1, especially on the A line system, was lost due to the seismic ground motion before the tsunami struck.

(3) New evidence

TEPCO disclosed new evidence on May 10, 2013 consisting of the record of the transient phenomena taken at a 1-minute interval. This record showed that EDG-A and B were being normally operated with 7000V output at 15:36:59. The current of the metal-clad switch gear 1C (M/C-1C which is connected to EDG-A) decreased to zero between 15:35:59 and 15:36:59. The current of M/C-1D (to EDG-B) decreased to 66.16A at 15:36:59.

(4) Stop times of key devices

The stop times of key devices are estimated as follows by TEPCO (http://www.tepco.co.jp/nu/fukushima-np/index10-j.html)
and the National Government report made to the IAEA [12].

M/C-1C Unit 1: stopped at 15:35:59 to 15:36:59
M/C-1D unit 1 : decreased to 66.16A at 15:36:59
EDG-A and B in Unit 1: stopped after 15:36:59
EDG-A and B in Unit 1: stopped at 15:37
EDG-A in Unit 2: stopped at 15:37:40
M/C-2C Unit 2: stopped at 15:37:42
M/C-2D Unit 2: stopped at 15:40:39
All AC power lost in Unit 2: 15:41
All AC power lost in Unit 3: 15:38
All AC power lost in Unit 4: 15:38

From the above estimated values, it is obvious that the key devices in Units 1 to 4 stopped at nearly the same time after 15:36, successively within a short time of about 5 minutes.

(5) Analysis of tsunami propagation by simulation

Many research organizations and researchers have made simulation analyses seeking the reason why such large tsunami struck the Fukushima Daiichi NPS.

JNES published the simulation analysis results for the tsunami propagation in December 2011 [13]. In the Tohoku Region Pacific Coast Earthquake multiple earthquakes occurred from different seismic centers at slightly different times. The simulation results showed that the multiple waves interfered with each other and caused complex movements. This resulted in a large wave height at specific places. The simulation results corresponded well to the observed waves. In 2012, the Cabinet Office, Government of Japan, performed another simulation analysis [14], and in

2013, Satake, et al. [15] also performed a simulation analysis independently. All these simulations indicated that the tsunami was composed of multiple waves.

The analysis by JNES simulated well the peak (second stage of the second wave) of the observed data of the wave recorder 1.5 km off the coast, and the propagation time to reach Unit 1 was estimated as 1 min 40 s. Therefore, the peak reached Unit 4 at 15:36:40 almost the same as the time estimated by the WGFNA, 15:36:29 [7].

In the report of the National Diet [1], the propagation time was estimated as 3 min 8 s, much longer than any of the simulation results.

(6) Conclusions

a) The first tsunami reached Unit 1 at around 15:36:47.
b) Based on the new evidence, it was found that both EDG-A and B were normally working until 15:36:59. But the current of line A stopped at 15:36:59, and that of line B decreased to about one half at 15:36:59.
c) The daily operational report of Unit 1 indicated that line A was lost before line B, and there was testimony of a witness about this point. Also, the record of transient phenomena indicated the same thing.
d) Key devices in Units 1 to 4 lost their functions within 5 minutes after tsunami arrival. It is reasonable to estimate that the power supplies on both emergency AC power systems A and B were lost due to the tsunami.

2.4 Summary

The investigation into the accident progression in Unit 1 described in the record [7] is summarized as follows.

(1) Working of the isolation condenser (IC)

It was estimated that the isolation valves of train A were almost completely closed due to the loss of all AC and DC power supplies caused by the tsunami flooding, and that IC did not work from that time. TEPCO had not done enough preparation against a long time loss of AC and DC power supplies. This was the reason why TEPCO could not prevent the loss of the function of the IC.

(2) Possible failure in the cooling piping system due to seismic ground motion

It was estimated that there was no loss of coolant accident (LOCA) in the PCV with a substantial effect, based on comparing the observed and simulated results about the pressure behavior in the PCV which was measured from just after the earthquake. It was also estimated that there was no leakage of radioactive materials from the RB where the PCV was located to the air, since no alarm was given by the radiation monitors.

It was concluded that there was no significant failure of the cooling piping system due to the seismic ground motion.

(3) Possible cause of the loss of the emergency AC power supply

It was estimated that the first tsunami reached Unit 1 at about 15:36:47. The electric current of the emergency AC power line A became zero, while that of line B decreased by one half, at 15:36:59, that is, about 10 seconds after the tsunami arrived. Therefore, it was estimated that both lines A and B of the emergency power supply lost their function due to the tsunami.

3. Investigation on the Accident Progression in Unit 2 [8]

The RB explosion of Unit 2 did not occur while they did occur in Units 1, 3 and 4. But, in Unit 2, the PCV was exposed to extremely high temperature and high pressure for a long time after the RCIC did not work, and a great amount of radioactive materials was released from the damaged part of the PCV into the environment. Therefore, it is necessary to investigate the reasons why the operators failed in cooling the reactor and venting the PCV, and why they failed in preventing meltdown although they had enough time to do these operations. [8]

There were no remarkable differences among the descriptions in the reports of the investigation committees [1–4] for the analysis of Unit 2. But new information about the events in Unit 2, especially about the behavior of the rupture disk, about the leak of the radioactive materials, and about the ultimate strength of PCV have been obtained through hearing with TEPCO, details of which are described in Appendices A9, A10 and A11, respectively.

3.1 Working of the reactor core isolation cooling system (RCIC)

In Unit 2, the RCIC was one of the devices by which the reactor could be cooled under the condition of an SBO. A schematic drawing of the RCIC and its function are given in Appendix A5. Since the device was designed to "fail-as-is" and the isolation valves were opened just before the tsunami struck, it continued working after the tsunami arrived for about 70 hours. But the cooling potential decreased with time, and finally, the cooling function was lost at about 13:25 on March 14.

3.2 Venting operation for the primary containment vessel (PCV)

When the pressure of the PCV increases over a critical level, that is, the suppression chamber (S/C) pressure exceeds the operation pressure of the rupture disk in the venting line, it is necessary to decrease the pressure by releasing decay heat to the outside through venting. The staff in the seismic isolation building and operators in the MCR predicted this situation, and they had prepared for venting from an early stage. This meant that the vent valve had been opened beforehand. But the vent valve was closed due to the RB explosion in Unit 3 which occurred at 11:01 on March 14, and afterwards the operators experienced difficulty in reopening the valve manually. The problem of the vent is discussed in detail in the next chapter.

It is not clear whether the operator finally succeeded in reopening the valve or not. In conclusion, no rupture of the rupture disk occurred, and the venting operation failed.

3.3 Delayed start of alternative cooling by a fire engine

In the SBO, when the RCIC did not work, the alternative cooling method was the direct water injection into the reactor by a fire engine. But the pressure in the reactor pressure vessel (RPV) was so high, that is, about 7MPa, which was far over the discharge pressure of the fire engine, that it was necessary to depressurize the RPV beforehand by opening the safety relief valve (SRV) through which the steam would be released from the RPV to the S/C. This operation would result in a rapid increase of the pressure and temperature in the PCV, and venting of the S/C would be necessary to avoid failure of the PCV.

There was a debate from about 12:00 to 14:30 on the 14th about which action should be done first: opening the SRV or venting the S/C.

At first, the operators tried venting the S/C, but they failed to open the vent valve for the reason mentioned in 3.2. Next, they tried to open the SRV from about 16:30. At 18:02 they were able to open the SRV, and they succeeded to inject water by the fire engine at 19:06, but soon after that, they recognized that the gasoline to run the fire engine was exhausted. Finally, water could be injected into the reactor continuously from 19:57. But the pressure in the reactor was unstable, and repeatedly went up and down rapidly.

3.4 Meltdown of the reactor core

The level of the water in the reactor started falling at 13:25 on the 14th because of the loss of the RCIC cooling function. The exposure of the reactor core was estimated to start at about 16:30, and it was fully exposed at 18:22. Therefore, it was estimated that the meltdown of the reactor core started around this period. Further, a great amount of hydrogen gas was produced by chemical reaction of zirconium and water under very high temperature after the water injection by the fire engine.

At present there are many uncertain issues related to the meltdown of the reactor core, therefore, further investigation is necessary.

3.5 Release of radioactive materials into the atmosphere

TEPCO estimated that there was a great release of radioactive materials from the drywell of Unit 2 into the atmosphere from about 7:20 on March 15 [4]. Meltdown of the reactor core started in the evening of the 14th, and it continued through the night, which resulted in the generation of high temperature and high pressure steam and hydrogen gas in the RPV. They leaked through the wall of the RPV to the PCV. At about 18:00 on the 14th the SRV was finally opened, and the high temperature steam and hydrogen gas flowed rapidly into the S/C. As a result, the walls of the PCV were exposed to high temperature and high pressure at levels that were far over the critical values allowed in the design. At this stage, the venting should have been done as quickly as possible. But the operators failed in venting as mentioned above. Then, it was estimated that part of a PCV wall, probably the sealed part, was damaged by the high temperature steam and hydrogen gas, and they leaked through the damaged part into the atmosphere.

It was considered that the release of the radioactive materials before the morning of March 15 was due to the release by venting and hydrogen explosions of Units 1 and 3.

The problem of the release of the radioactive materials into the atmosphere is now under intense investigation by reverse analysis of the environment monitoring data [16]. There are still such unsolved problems as, for example, the reason why the great release was observed after March 15 and the possibility of high density radioactive materials floating in the accumulated water at the bottom of the turbine building of Unit 2 [17&18]. Further investigation is necessary to solve these problems.

3.6 Explosion at about 6:14 on March 15

In a very tense situation where the pressure of the PCV was far over the design value, a big impulsive sound and accompanying shock wave occurred at about 6:14 on March 15. And at nearly the same time the pressure sensor of the S/C showed zero. The staff and operators thought that the shock might have come from the explosion of the Unit 2 S/C, and that it might be dangerous for them to stay at the site. About 650 people moved to the Fukushima Daini NPS, while about 70 people stayed to maintain operations. But in the afternoon many of those who went to the Daini site returned to do their jobs.

Later it was found that the sound and the shock wave were due to the RB explosion in Unit 4, while the sudden decrease of the S/C pressure was due to trouble with the sensor. There was a big panic because these independent events occurred at nearly the same time, though incidentally.

The members of WGFNA made a hearing with TEPCO about the ultimate strength of PCV as shown in the following (Details of the hearing are shown in the Appendices 9 to 11):

{Question}：

The pressure of the PCV was far over the design value, that is, 0.48MPa[abs], finally it became 0.75MPa[abs] in the early morning of March 15. TEPCO has estimated that an explosion of the PCV was avoided but that the leak of the steam and hydrogen gas occurred through a sealed part of the PCV wall. Then the question is: What is the ultimate strength, or in other words, the maximum pressure or maximum temperature that the PCV can withstand？

{Answer}：

TEPCO considers that the PCV can bear a temperature of at most 200℃

and twice the design pressure. It is more probable that the leak was caused by the loss of the sealing capacity due to the high temperature rather than a failure of the PCV wall due to high pressure. TEPCO inspected the level of failure inside the torus room by using a robot on April 18, 2012. Inspection was done by a robot camera that sent video tape recorder (VTR) pictures. No serious failures such as large deformations, severe damage and leaks in the S/C torus and manholes could be found, although some parts of the heat insulation materials covering the pipe had fallen onto the floor [4].

3.7 The reason why the reactor building (RB) explosion was avoided at Unit 2

The reactor core started to be exposed to the gaseous phase at about 16:30 on March 14, and it was fully exposed at about 18:22. Then it was estimated that the meltdown of the reactor core started around this period and that a great amount of hydrogen gas was generated due to the chemical reaction of zirconium and water in the very high temperature atmosphere. This reaction caused further increase of temperature and pressure in the RPV, which resulted in the leak of the steam and hydrogen gas from the RPV to the PCV. Further, a great amount of steam and hydrogen gas moved into the S/C after the operator succeeded in opening the SRV at about 18:00, and the PCV walls were exposed to high pressure and high temperature. The steam and hydrogen leaked to the RB through the damaged sealed part of the PCV wall.

But, in the case of Unit 2, the RB explosion did not occur. Later it was found that the blow-out panel had dropped, affected by the RB explosion in Unit 1. Therefore, it was estimated that the hydrogen gas was emitted to the air through this path, and the RB explosion was avoided.

3.8 Effect of multiple units in the same site

The sequence of accident events in Unit 2 was deeply affected by those of other units located nearby.

- The Unit 1 RB explosion —> dropping of the blow-out panel of the Unit 2 RB —> avoidance of the RB explosion in Unit 2
- The Unit 3 RB explosion —> damaging the S/C vent line in Unit 2
- The Unit 4 RB explosion —>misunderstood as an explosion of the Unit 2 PCV —> evacuating operators and other staff members to the

Fukushima Daini NPS.

3.9 Summary

The following points summarize the documents described in the record [8] about the accident progression in Unit 2.

(1) Just after the earthquake, the reactor of Unit 2 scrammed, the off-site power supply was lost, and at the same time the EDGs started working. The operator opened the control valve of the RCIC manually, and it started working.

(2) After the tsunami struck, all the power supplies, both AC and DC, were lost. But, fortunately, the RCIC continued working for about 70 hours.

(3) There was a possibility that the meltdown of the reactor core might have been avoided if venting of the PCV and alternative core cooling by a fire engine were done during this period.

(4) But actually the staff and operators failed in the PCV venting and it took time to start the alternative cooling by a fire engine because the staff had difficulty to grasp the complete situation for the entire site and these operations were disrupted by the RB explosions in Units 1 and 3. Especially the control valve on the vent line had closed, affected by the Unit 3 RB explosion, and it could not be reopened.

(5) After the RCIC lost its cooling function, the temperature and the pressure in the RPV increased rapidly, and the meltdown of the reactor core started, which resulted in the generation of hydrogen gas.

(6) After the opening of the SRV, a great amount of the high temperature steam and hydrogen gas flowed into the S/C, which resulted in the rapid increase of temperature and pressure in the PCV. Finally, the pressure was far over the critical design value.

(7) A great amount of radioactive materials was released to the atmosphere in the morning of the 15th through the damaged part of the PCV.

(8) The impulsive sound and the shock wave at about 6:14 on the 15th were thought to be due to the catastrophic failure of Unit 2 PCV, and there were persons who moved to Fukushima Daini NPS. But later it was found that the shock was caused by the Unit 4 RB explosion, not by the catastrophic failure of the Unit 2 PCV.

(9) The reason why there was no RB explosion in Unit 2 is because the blow-out panel dropped as an effect of the Unit 1 RB explosion, and

hydrogen gas passed through the panel opening to the outside.

(10) The accident in Unit 2 was much affected by the RB explosion in Units 1, 3 and 4. This can present a serious problem when multiple units are constructed in the same site. The staff was sometimes confused by the information coming from different units, for example, about the selection of items which should be tackled with the first priority.

4. Operational Condition of High Pressure Coolant Injection System (HPCI) at Unit 3 [8]

In Unit 3, the reactor core was cooled by the RCIC, which was started by opening the isolation valves manually at 16:03 after the tsunami struck. It worked till 11:36 on March 12 (continuous operation time was 19 hours 33 minutes). About 1 hour after the RCIC stopped, the HPCI fortunately started and the reactor core was cooled continuously. But 14 hours later, the HPCI was manually (intentionally) stopped, and after that the reactor core was not cooled for a long time, and finally that resulted in the core meltdown. The WGFNA has investigated the reports of the investigation committees of the National Diet [1], the Japanese Government [2], the private sector [3] and TEPCO [4], and also referred to the supplementary documents written by the technical members of the government investigation committee [19]. All of these reports just mention the fact that the HPCI stopped, and they discuss neither the adequacy of the HPCI operation, nor the reason for the manual (intentional) stop of the HPCI. Only the report of the Government investigation committee [2] deeply discusses the insufficient preparation of an alternative water injection system. The WGFNA identified many items which were unclear and questionable, and directly asked the technical staff of TEPCO to reply to them.

4.1 Operational condition of HPCI during the accident progression

The HPCI injects a large amount of water into the reactor core (Appendix 12). Therefore, it is necessary to limit the water flow in order to avoid the rapid increase of water level which results in the stop of the HPCI. The restart of HPCI requires much electricity and the emergency battery is easily exhausted. To avoid this situation, the operator throttled the water flow by making a return line to the condensate storage tank (CST) as shown in Fig.

A12-1 (Appendix A12). During operation of the HPCI, the RPV pressure of Unit 3 remarkably decreased to 2.0 MPa [gage] at 17:30 on March 12, and the pressure varied between 0.8 and 1.0 MPa [gage] after 19:00.

The HPCI is designed to inject a large amount of water (682 t/h) for a short time with a high pressure condition (around 1.03 MPa [gage] to 7.75 MPa [gage]). Under this condition, the water in the CST will be exhausted within 3.7 hours. But in the actual conditions of the Fukushima Daiichi accident, flow rate of water was limited and rotation speed of the HPCI pump was very slow, which was outside the range set by the procedure guide. The water of the CST (2500 t) was expected to last for a long time.

The pressure was 0.820 MPa [gage] at 19:42 on the 12th, and after this the pressure was under 1 MPa [gage] till the HPCI stopped. Just after it stopped, at 2:44 on the 13th, the pressure decreased to 0.580 MPa [gage] [4].

TEPCO's view was as follows (Appendix A13, about the operation of HPCI at Unit 3):

"From 2:00 on the 13th, the pressure of the RPV decreased further from 0.8 - 0.9 MPa, and the rotation speed of the turbine also decreased further. So, it was feared that the turbine might be destroyed by abnormal vibration. The discharge pressure of the pump was also decreased and reached almost that of the reactor vessel. Therefore, the operators judged that the HPCI pump was not working effectively and that there would be no effective injection of water to the reactor."

The above comment indicates that TEPCO misunderstood that the HPCI was injecting water into the RPV as long as the turbine was operating. In Units 1 and 2, the reactor core water levels were measured from the night of the 11th. But in Unit 3, measurement of the water level was started at 5:00 on the 13th, just after the stop of HPCI. And by this time, the water level was already below the top of the active fuel (TAF). It would have been possible to find the loss of the HPCI function in an earlier stage if the water level had been measured earlier.

At 2:42 on the 13th, the operator on duty pushed the HPCI stop button on the control panel in the MCR of Unit 3. And he also closed the inlet valve of the turbine steam. This was written in the manual as the procedure for the HPCI stop.

By the action of "push the HPCI stop button," a magnetic valve was actuated and oil was dumped, oil pressure was released, then the stop valve of the HPCI steam line was closed. At this time the magnetic valve was operable. The inlet valve of the turbine steam line was a DC motor operated valve, and this valve was also operable.

At 2:45 on the 13th, the operator tried to open the SRV, but it could not be moved, in spite of the successful actions of the inlet and stop valves just 3 minutes before.

TEPCO's view was as follows (Appendix A13):

"At the time of the HPCI stop, the battery power had decreased considerably, and the SRV could not be operated. But there is still no analysis that gives the definite reason."

4.2 Adequacy of the operation to shut down the HPCI

After the HPCI stop, the operators tried to open the SRV and to decrease the pressure of RPV, then to remove the heat from the reactor core by injecting cooling water. But, the SRV could not be opened. The WGFNA investigated the adequacy of the operation to shut down the HPCI and to open the SRV.

The WGFNA asked TEPCO if it was possible to open the SRV and to decrease the RPV pressure before stopping the HPCI operation.

TEPCO's view was as follows (Appendix A13):

"After the HPCI start, the rotation speed of the turbine decreased with the decrease of RPV pressure, and it fell below the lower limit of the required operational condition. The HPCI was still working although the RPV pressure decreased to the level below which the HPCI essentially stops working, that is, it was isolated. If the SRV was opened in this situation, it would result in the further decrease of RPV pressure and the turbine vibration would become greater. Finally, fatal damage would occur in the turbine system. This damage would produce the spread of steam inside the RPV into the HPCI room. We were anxious that the radioactivity in the steam would hinder the work of the operators for recovery from the accident. This is the reason why we stopped the operation of the HPCI manually."

The WGFNA further asked TEPCO if this HPCI operational condition, the 0.8-0.9 MPa under 1.03 MPa, was a very dangerous situation which required an emergency stop of the HPCI, and if there were any symptoms in the vibration characteristics related to the emergency stop.

TEPCO's view was as follows (Appendix A13):
"From 2:00 on the 13th, the pressure of the RPV further decreased and the speed of the turbine rotation also decreased. The risk of HPCI damage increased more than ever. And, we also judged that the injection of water to the reactor core by the HPCI pump was not effective any more. Then, we judged that the immediate change of the cooling system from the HPCI to the diesel driven fire pump (DDFP) was necessary."

The WGFNA considered that, in the above condition, it was imperative to immediately stop the HPCI without decreasing the pressure of reactor by opening the SRV, in order to avoid the possible contamination by radioactivity. But it should have been checked before the HPCI stop whether the remaining amount of DC power was enough, or whether the operation of the DDFP was ready at that time. With this check, the transfer of cooling water from HPCI to DDFP could have been made smoothly.

4.3 Function of HPCI and amount of water injected by the HPCI

The WGFNA has taken up the following unclarified issues and made a direct inquiry to TEPCO.

(1) How much water was injected into the reactor core by the HPCI at the time just before the HPCI stop?
(2) How long would the CST retain its water?
(3) Would cooling by the HPCI be effective because the RPV pressure was kept very low just before the HPCI stop?

TEPCO's view was as follows (Appendix A13):
"TEPCO is now considering that the water supply to the reactor core was insufficient just before the HPCI stop. Estimated water flow rate was almost zero. The RPV pressure was kept low by the consumption of the steam from the reactor core to the HPCI turbine. The water level in the RPV was considered to be above TAF. Therefore, the reactor core was cooled at that time."

The WGFNA has also considered that the water flow to the reactor core was almost zero when reactor pressure dropped under 1.0 MPa [gage]. It was impossible to increase the water flow by decreasing the return line flow.

4.4 Communication about the operating states of HPCI

The Government report [2] pointed out the delay of communication as follows: "The operator on duty reported the situation of the SRV opening failure. The information was available to the chief of the MCR operators and the group members of the power generation team in the emergency response center (ERC), and they discussed the next actions. But in such a situation in which many events were momentarily changing, details of the information were not always reported to the group leader in the ERC. It was at 3:55 on the 13th, after the RPV pressure increased above 4 MPa [gage], that the information was shared among the ERC staff and the staff at TEPCO headquarters. The transfer of the information was apparently too late." (Government report p.184 [2-2])

The WGFNA asked TEPCO if there was any reasonable explanation for this delay.

TEPCO's view was as follows (Appendix A13):

"The MCR operators and ERC staff shared a common perception that the DDFP would be operated after the HPCI. But it took a little time for sharing, among all staff of the ERC, the information about the situation of the SRV and the operator's actions after the HPCI stop. The DDFP could not be operated soon after the HCPI was stopped, and in the meantime many attempts were taken by the MCR operators (for example, attempts to open the SRV and to restart the RCIC or HPCI). We do not consider the delay of communication affected the actions taken by the MCR operators. Actually, at that time, the situation was very complicated and communication tools were restricted. These are the reasons for the communication delay."

The WGFNA considered that communication was inadequate in spite of these difficult conditions, and that TEPCO failed to make a perspective action plan because of this information delay.

4.5 Summary

The WGFNA considered that reactor core cooling by the HPCI was not effective after 17:30 on March 12, when the RPV pressure was decreased around 2 MPa [gage]. Therefore, at the last stage of the HPCI operation it was inevitable that the HPCI should be manually stopped. But the failure of the DDFP to start after the HPCI stop was crucial for prevention of the severe accident.

The following important issues became clear about the HPCI operation.

(1) Information was not shared among the staff members of the MCR, ERC and TEPCO headquarters, and therefore, they failed to have any perspective action plans.
(2) Organizational structure, in which only one person was responsible for all six units at the Fukushima Daiichi NPS, was inadequate, especially in the emergency situation of the accident at this time.
(3) No discussion was made in the early stage of the accident about the timing at which the HPCI had to be stopped.

5. The Problem of the PCV Venting [8]

5.1 Effects of venting

The venting of the PCV in the Mark-I and Mark-II BWRs needs to be considered as of two types of actions, that is, the venting action before and the venting action after the core damage. The venting before the core damage has the purpose of cooling water in the suppression pool, which is the source of water for injection into the reactor core, by the RCIC or the HPCI, by depressurization boiling when the function of the residual heat removal system is lost.

However, here discussion focused on the venting after the core damage. It was done in order to restrain the increase of the pressure in the PCV, by discharging gas in the PCV, which included a great amount of radioactive materials, into the atmosphere.

There are two kinds of PCV venting in BWRs, that is, the wet venting and the dry venting.

The wet venting consists of discharging gas in the PCV into the atmosphere after passing it through the water in the S/C. When the temperature rise in the containment vessel is restrained and sub-cooling of the S/C water is sufficiently secured, radioactive materials in the PCV are scrubbed off by the water in the S/C, and the concentration of the radioactive materials in the gas discharged to the atmosphere is supposed to decrease to a few percent or less than that in the PCV. However, if the temperature rise in the PCV is not restrained and the water in the S/C is near the boiling temperature, the scrubbing effect becomes very small, and further, the direct leak of the gas from the PCV may occur through a part of the PCV damaged by overheating.

On the other hand, in the case of the dry venting, the high concentration of the radioactive materials in the released gas cannot be decreased and large scale environmental pollution will result because the dry venting discharges the gas in the PCV directly into the atmosphere without any scrubbing.

5.2 Time sequences of venting for each unit

The main processes (the time sequences) for the venting of each unit are well summarized in table form in TEPCO's "The Fukushima nuclear accident investigation report 〈the overview version〉" [4]. Here, in order to serve as a reference in reviewing the points and problems, some details from another report [20] were added.

There was no manual for the venting operation in the case of loss of all AC and DC power supplies as happened in this accident. Therefore, all the actions of the operators, such as trying to do the venting by temporally connecting an air compressor, were those of "adaptation to circumstances".

(1) Time sequences in Unit 1

March 11	around 17:50	Noticed radiation level abnormality for the first time. (Part of the fuel might be exposed above the coolant level)
	around 22:30	Substantial increase of radiation level (Evidence that IC was not functioning)
	during the night	Preparation for venting started
March 12	around 01:30	Proposed performance of venting to the Government and got approval
	02:45	Substantial decrease of pressure in the RPV (Evidence of RPV failure)
	09:04	Operators started to go to the place to perform venting
	09:15	The first group opened the PCV vent motor operated valve (MOV), but the second group had to give up opening the S/C vent air operated valve (AOV) as the radiation level was too high.
	10:17	Remotely operated the S/C vent AOV small valve (3 times, it was unknown if it worked).

		Concurrently reviewed the place to connect an air compressor temporarily.
	10:40	Monitoring post (MP) at the main gate indicated increase of radiation level
	around 14:00	Set the air compressor temporarily at RB entrance and started operation.
	14:30	Pressure decrease at drywell (D/W). Judged radioactivity release by venting

(2) Time sequences in Unit 2

March 11		Preparation for venting
March 12	17:30	The director of the site ordered preparation of a venting line.
March 13	11:00	Vent line configuration was completed except for the rupture disk.
March 14	11:01	Hydrogen explosion at Unit 3; valves closed as an effect. After that, many trials for the vent line recovery were done.
	13:25	Confirmed RCIC function loss.
	18:22	Recognized all fuel rods were exposed
March 15	00:16 and after	PCV pressure increase (The crisis)
	06:00	An impulsive sound
	11:25	Confirmed D/W pressure decrease

As for Unit 2, the venting was tried from before the core damage began. That is, the vent line was prepared to maintain the water injection function of the RCIC. However, TEPCO failed in the venting operation.

(3) Time sequences in Unit 3

March 11		Preparation for vent
March 12	11:36	RCIC stopped automatically
	12:35	HPCI started automatically
	17:30	The director of the site ordered preparation of a venting line.
March 13	02:42	HPCI stopped manually

around 03:00	Water injection by DDFP was impossible.
08:41	The vent line was completed except for the rupture disk.
09:08	Started rapid depressurization of the reactor by opening the SRV. After increasing at once, D/W pressure started to decrease.
09:20	Judged that venting had been performed

As for Unit 3, the venting was tried before the core damage started just as in the case of Unit 2. That is, the vent line was prepared to maintain the water injection function of the HPCI. However, the venting was performed only for the purpose of decreasing the containment pressure after the core damage.

5.3 Issues to be examined

(1) Positioning of the venting action

a) In general, since the 20-00s Japanese utilities have been adopting PCV venting strategies that delay venting as late as possible in order to avoid the release of radioactive materials to the atmosphere. In keeping with this strategy, a rupture disk, which does not rupture until the PCV pressure reaches the maximum allowable value in the design, is equipped on the vent line.

On the other hand, in the US, BWRs typically do not have rupture disks because the view is that it would prevent early venting, and that the emergency operating procedures require that the venting should be initiated before the PCV design pressure is reached [21].

b) In the US, there is a definite consensus that the first priority is to reduce the hydrogen concentration inside the PCV to prevent its explosion, and that a small release of radioactive materials to the atmosphere is unavoidable to that end if the core damage has occurred [21].

But in Japan, the procedure guidance was developed based upon the results of the PCV integrity test conducted by Sandia National Laboratories. And in the guidance the PCV pressure was allowed to increase to the twice of the design pressure before venting.

However, the likelihood of the leakage of the increased hydrogen gas in

PCV to the atmosphere was not adequately addressed [22].

c) It is thought in the US that a small release of radioactive materials is allowed to prevent a larger release. On the other hand, it seemed in Japan that even a small release could not be allowed since it was believed that such an accident would never happen that would result in the release of the large amount of radioactivity (this was derived from complacency and a lack of imagination [23]).

d) In the US, the decision to initiate venting is made by the shift manager, with consultation and advice from the site ERC [22]. On the other hand, the decision is made by the director of the site in Japan [22].

Actually, the ERC and the TEPCO headquarters staff got permission at 1:30 on March 12 from Mr. Masataka Shimizu, the president of TEPCO, to vent Units 1 and 2. And TEPCO got permission from NISA and Prime Minster Naoto Kan. Finally, at 6:50 on March 12 an order for venting was given by Mr. Banri Kaieda, the Minister of the Ministry of Economy, Trade and Industry based on the law [8].

e) Moreover, operators started venting after confirming the evacuation status of personnel as described below [8].

March 12, 06:33 Confirmed the evacuation status
08:03 Director of the site ordered venting to start at 9:00
08:27 Information that evacuation was not done from part of the site south area
09:02 Confirmed that all personnel had evacuated from the south area
09:04 Operators started venting

(2) Design issues

a) The wet venting is a valid safety means as long as the sub-cooling of the S/C water is well secured. The removal effect of the radioactive materials cannot be expected when the water is near the saturation temperature. That is, it is necessary to ensure the S/C water is below the sub-cooling temperature.

b) Failure of the PCV cannot be prevented only by PCV venting. It is necessary to combine another means such as the core or debris cooling by injecting water to restrain the rise of the PCV temperature. It is especially so for BWRs that there would be a possibility of leakage when the RPV is overheated by the decay heat, and the upper head of the PCV is exposed to very high temperature.

c) The loss of all AC and DC power supplies was not considered at the design stage.

d) Even though it was necessary to operate many valves, the deterioration of the operation environment due to the increase of radiation dose in the site area after core damage was not considered.

e) It was not possible to detect by a direct monitor whether or not the rupture disk ruptured and the venting succeeded.

(3) Lack of preparation for the AM

a) As for the venting operation to maintain the function of injecting water into the reactor core before the core damage occurred, TEPCO failed to do the venting operation in Unit 2, and it was done too late to attain the purpose in Unit 3.

b) Venting operation after core damage seemed successful in Units 1 and 3. But the effect was limited from the vent line as the leakage from other routes might have occurred by damage to the PCV by overheating.

c) Batteries, air compressors and so on were not prepared beforehand.

d) The operators were not well trained and they had difficulties to connect the vent lines at the time of the severe accident.

(4) Pointing out the problems

The problems (1) to (3) pointed out in this report were not deeply reviewed in the four accident reports [1-4]. Similar discussions to the present one are found in the ANS report [21] and the INPO report [22].

5.4 Summary

The way of thinking of Japanese utilities about venting was much different from that of the US utilities. Japanese stakeholders, through complacency and a lack of imagination had thought that the release of the radioactive materials into the environment should be and could be prevented completely. There were serious problems in the preparedness for AM and in that for the related facilities. Therefore, once the accident happened, the staff and the operators had big difficulties to tackle with, for example, the venting operation, and they could not prevent the accident from progressing. There is a possibility that they could have succeeded in the wet venting in an early phase of the accident to restrict the radioactive material release, if they had faced this problem sincerely beforehand by learning the latest knowledge from overseas.

6. Lessons Learned from the Investigation

Summaries of the investigation for each item were described at the end of each chapter. Here the authors look at the subjects from an overall viewpoint and express their opinions.

About Unit 1:

(1) The IC operation, and the success/failure of measures for the functional failure of the IC determined the sequence of events in Unit 1.

(2) It is critical for operating staff to have a broad understanding of the safety systems, and it is necessary to incorporate the various aspects of such systems into training and drills in everyday operation.

(3) A monitoring system to understand whether or not critical functions are at least operating under accident conditions should be in place.

(4) Assessments on vulnerabilities and integrity of nuclear plant systems against natural hazards (such as the earthquake and the tsunami in the 2011 Tohoku Region Pacific Coast Earthquake) should be made to determine the extent to which the minimum functions may be maintained under disaster conditions, and what would happen in the event of failure of the functions, in the formulation of AM measures.

About Unit 2:

(1) The RCIC, a critical safety component sustained operation for an extended period of 70 hours, which is assumed to be sufficient to deliberate about and implement actions. However, appropriate measures could not be implemented because the plant (unit) manager had no authorized power to carry them out, and also because onsite staff had not been provided with sufficient training.

(2) Consideration should be given to the relevance of concentrating

authorized power solely on the site director for multiple units in one site based only on the likelihood of a single event. How can simultaneous multiple events be addressed when only one person has the right of decision making in carrying out response measures?

(3) A monitoring system to gain the minimum understanding of the plant status in an accident should be in place.

About Unit 3:

(1) Although there was sufficient time to deliberate on appropriate strategies and implement actions, AM was not sufficient because the staff had to cope with simultaneous events in other units.

(2) The relevance of a system where the director of the site is solely responsible for the AM of multiple units in the same site should be discussed to develop strategies in this respect.

About the venting:

The basic approach towards venting in Japan differed greatly with that of the US – in Japan, there was a great reluctance against releasing radioactive materials to the environment. Moreover, because sufficient AM strategies were not in place, the plant staff held back from conducting venting. It is important to establish communications with the international community for sharing information on safety issues and AM strategies.

Through the investigations and intense discussion as shown in the previous chapters, the members of WGFNA could extract the following lessons.

6.1 Preparedness against seismic ground motion

Although nuclear plant systems maintained integrity when the earthquake occurred, one of the transmission line towers collapsed due to the ground collapse caused by the earthquake, which led to the extended loss of the external power supply.

6.2 Preparedness against tsunami

Because of the geographic conditions, nuclear power plants in Japan are sited only in coastal regions. Accordingly, not only anti-tsunami measures, but also solid AM measures that include response to tsunami-induced events should be established.

For a country prone to natural disasters like Japan, establishing solid safety and AM measures against the likelihood of not only tsunami but also various natural hazards is essential. A system on how evolving technologies should be utilized and incorporated into the nuclear safety system should be deliberated by all related parties, including the National Government, nuclear industries, and academia.

6.3 Preparedness against station blackout (SBO)

The extent to which AC and DC power supplies should be maintained for different conditions should be examined. The scope of implementation of the safety measures and specific AM measures that should be implemented on the support systems should also be considered.

6.4 Accessing information in an emergency

Under accident conditions, minimum information necessary for onsite decisions on AM measures should be acquired. At the same time, a framework for determining the scope of information necessary for evacuation, the ultimate safety measure of defense-in-depth level 5, and the method of collection and sharing such information should be considered.

6.5 Preparedness against a severe accident

Understanding of the defense-in-depth concept, the basic approach to effective severe accident management, should be shared by all related parties to establish a consolidated and effective framework on safety measures. (Appendix A7)

6.6 Education and training of operators

Safety education and training on the various aspects of AM measures, for operating staff, particularly, the shift supervisors responsible for onsite management are important.

Clear assignment of the roles, responsibilities, and duties, etc., is essential among the shift supervisors, unit head (responsible person for a power generating unit), director of the site (responsible person for the entire plants in the site including those with multiple units), the head and employees of the plant operator, the heads of the central government and the local government.

7 Concluding Remarks

In this report the authors, the members of the WGFNA, investigated and expressed their opinions on the technological points at issue, that is, the key points by which the accident could have been prevented, about Units 1 to 3 of the Fukushima Daiichi NPS.

These were:

- Unit 1: (1) validity of the operation of the isolation condenser (IC); (2) whether or not the loss of coolant accident (LOCA) occurred due to the failure of the cooling piping system by seismic ground motion; and (3) the cause of the loss of the emergency AC power supply.
- Unit 2: the reason why a considerable amount of radioactive materials was emitted to the environment although the RB explosion did not occur in Unit 2.
- Unit 3: the reason why the operator stopped running the high pressure coolant injection system (HPCI).
- Units 1 to 3: validity of the venting operation.

The summaries of the investigation were described at the end of each chapter. And finally, the authors have listed the lessons learned from the accident regarding the following items:

- Preparedness against seismic ground motion
- Preparedness against tsunami
- Preparedness against station blackout (SBO)
- Accessing to information in an emergency
- Preparedness against a severe accident
- Education and training of operators

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Nomenclature

ADS: automatic depressurization system
AEC: Atomic Energy Commission
AM: accident management
AOV: air operated valve
BDBA: beyond design basis accident
CS: core spray
CSEE: Comprehensive Synthetic Engineering Committee
CST: condensate water storage tank
DBA: design basis accident
DDFP: diesel driven fire pump
D/W: dry well
EDG: emergency diesel generator
ERC: emergency response center
HPCI: high pressure coolant injection
IC: isolation condenser
JNES: Japan Nuclear Energy Safety Organization
LOCA: loss of coolant accident
LOOP: loss of off-site power
M/C: metal-clad switch gear; specifically, the 6900 V switch board for high voltage circuit power
MCR: main control room
MOV: motor operated valve
MP: monitoring post
NISA: Nuclear and Industrial Safety Agency
NPP: nuclear power plant
NPS: nuclear power station
NRA: Nuclear Regulation Authority
NRC: Nuclear Regulatory Commission
P/C: power center; specifically, the 480V switch board for low voltage circuit power
PCV: primary containment vessel
PLR: primary loop recirculation system
RB: reactor building
RCIC: reactor core isolation cooling

RHR: residual heat removal system
RPV: reactor pressure vessel
SBO: station blackout
S/C: suppression chamber
SCJ: Science Council of Japan
SCFNA: Sub-Committee on Fukushima Nuclear Accident
SHC: shutdown cooling system
SRV: safety relief valve
TAF: top of active fuel
T/B: turbine building
TEPCO: Tokyo Electric Power Company, Inc.
TMI: Three Mile Island
WGFNA: Working Group on the Fukushima-Daiichi Nuclear Accident

Appendices

A1. Nuclear Power Reactors at Fukushima Daiichi NPS [A1-1]

Fukushima Daiichi Nuclear Power Station was one of the oldest NPSs in Japan in March 2011. It had six BWR plants and Unit 1 had started commercial operation in March 1971. The electric output, reactor model, primary containment model and other specifications are indicated in Table A1. Fig. A1 is a schematic drawing showing the main components of the Mark-1 type BWR.

Table A1 Specifications of plant units at Fukushima Daiichi NPS

Plant Number	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Unit 6
Electric Output (MWe)	460	784				1100
Commercial Operation	1971.03	1974.07	1976.03	1978.1	1978.04	1979.1
Reactor Model	BWR3	BWR4				BWR5
Containment Vessel Model	Mark-1					Mark-2
Emergency Core Cooling System	IC	RCIC				
	HPCI					HPCS
						LPCS

HPCS:High Pressure Core Spray System, LPCS:Low Pressure Core Spray System

A	Reactor building	3	Crane
B	Turbine building	4	Nuclear reactor
1	Condenser	5	Drywell of containment vessel
2	Turbine generator	6	Suppression chamber of containment vessel

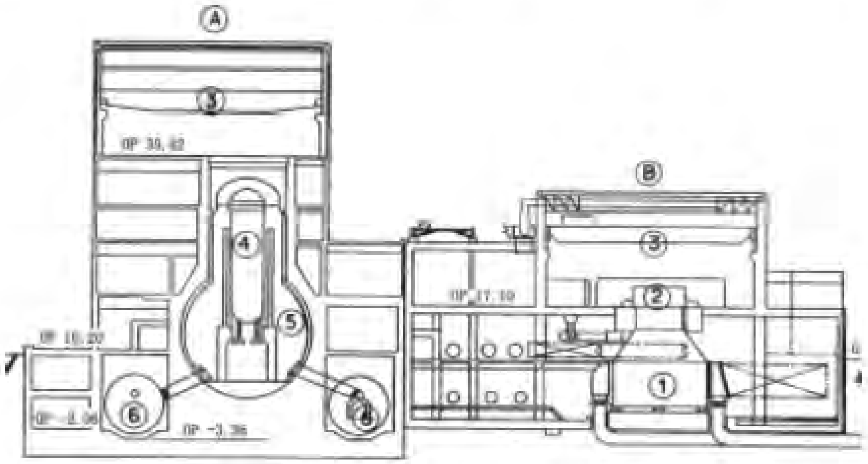

Fig. A1 Schematic of the Mark-I type BWR (Unit 2) [A1-2]

Core cooling systems of Units 1, 2 and 3

The core cooling systems that were equipped in each BWR were intended to provide cooling of nuclear fuels in an accident. In Unit 1 (BWR 3), the IC and the HPCI were provided and Units 2 and 3 (BWR 4) had the RCIC and the HPCI. In an accident with the loss of the normal fuel cooling function, the IC works to condense the steam in the RPV and to supply the generated water back into the RPV for cooling of the reactor core. Both RCIC and HPCI, which work by steam driven pumps using the high pressure steam in the RPV, inject the water from the condensate storage tank or from the suppression chamber (S/C) for the cooling of the reactor core. They work without AC power, though DC power is required to operate the valves. Further, for the cooling of the reactor core under the low pressure condition, the core spray system (CS) and the shutdown cooling system (SHC) were equipped for Unit 1, and the CS and the residual heat removal system (RHR) were equipped for Units 2 and 3. However AC power is needed to operate them and they could not work in the accident.

Plant status of the six reactors before the earthquake

On March 11, 2011, Units 1, 2 and 3 were in operation, and Units 4, 5 and 6 were shut down for periodic inspection. The fuel assemblies of Unit 4 had been transferred to the spent fuel pool since exchange of the shroud was underway during the periodic inspection. Fuel assemblies were in the RPVs of Units 5 and 6.

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A2. Sequence of Events of the Accident －General Aspect－[A2-1]

Occurrence of the earthquake

At 14:46 on March 11, 2011, a mega-earthquake struck northeastern Japan. Its moment magnitude scale was 9.0, making it the fourth largest earthquake ever recorded in the world's history. The earthquake occurred as the result of faulting on the boundary between the Pacific Plate and the North American Plate. The epicenter was about 130 km southeast of Oshika Peninsula with a depth of approximately 24 km. The size of the faulting zone was about 400 km long, and approximately 200 km wide. Fig. A2 shows the epicenter of the earthquake and the location of the five nuclear power stations (NPSs) in the area afflicted by the disaster.

Nuclear power plants within the afflicted area

In the afflicted area of the disaster, 15 BWR plants had been constructed. From north to south they were:

1 plant at Higashidori NPS of Tohoku Electric Power Co.;
3 plants at Onagawa NPS of Tohoku Electric Power Co.;
6 plants at Fukushima Daiichi NPS of TEPCO;
4 plants at Fukushima Daini NPS of TEPCO; and
1 plant at Tokai Daini NPS of Japan Atomic Power Co. (JAPC).

Most of the plants were brought to the cold shutdown condition within a several days. However, the tsunami caused damage leading to the reactor accident with the meltdown of fuels for three units at the Fukushima Daiichi NPS.

Effect of the earthquake on the Fukushima Daiichi NPS

The three operating Units 1, 2 and 3 were shut down automatically on detecting the earthquake at 14:46 on March 11, 2011. However, all off-site electric power for Units 1 to 6 was lost through damage caused by the earthquake. Then the EDGs started and the decay heat of the nuclear fuels was removed by the core cooling system until the time that the tsunami struck. The core cooling systems started automatically or were started manually. They were the IC for Unit 1 and the RCIC for Units 2 and 3.

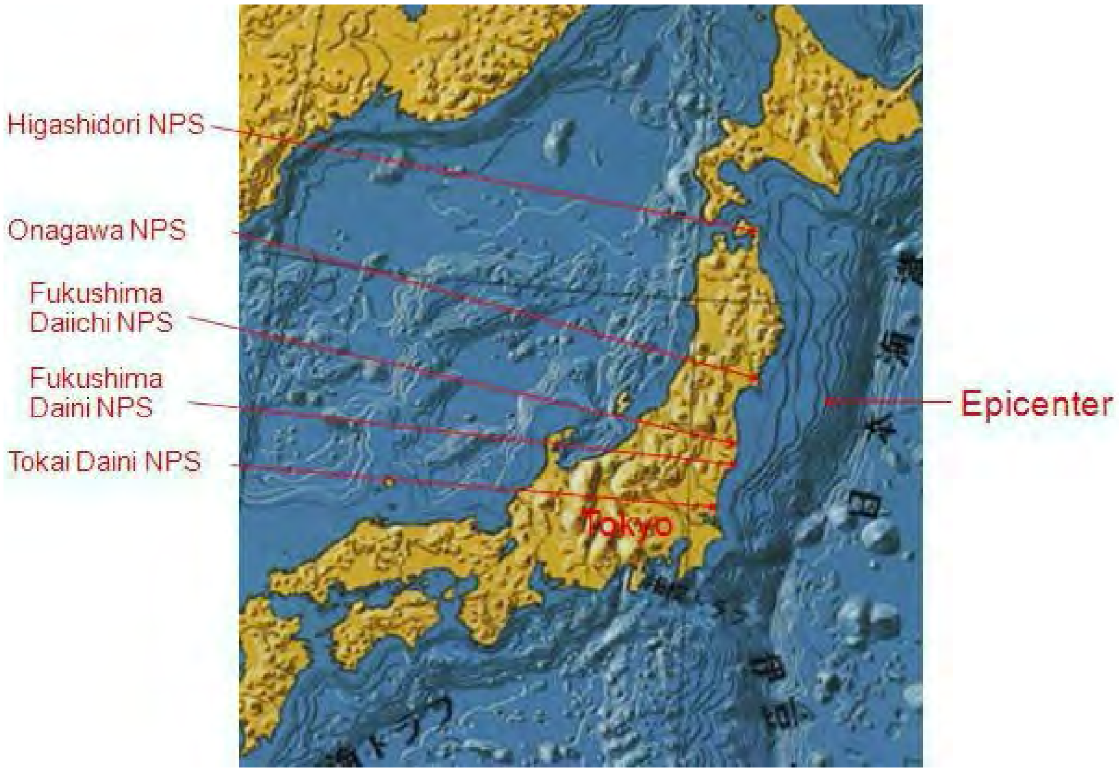

Fig. A2 Epicenter of the earthquake and location of the five nuclear power stations

Cause of the external (off-site) **AC power loss at Fukushima Daiichi NPS**

The electric power was supplied through six lines for Units 1 to 6. For Units 1 and 2, the electricity was transmitted from the Shin-Fukushima Transformer Station through Okuma Nos. 1 & 2 lines to the normal high voltage switchboard of Units 1 and 2 via the switchyards for Units 1 and 2. Further TEPCO's nuclear line from Tohoku Electric Power Co. was connected as a reserve to the normal high voltage switchboard of Unit 1. Due to the earthquake, several parts of the circuit breakers at the switchyards for Units 1 and 2 were damaged, resulting in the actuation of the circuit breakers at the Shin-Fukushima Transformer Station. As for the TEPCO nuclear line, the connecting cables to the metal-clad switch gear (M/C) of Unit 1 were damaged and failed. As for Units 3 and 4, the Okuma Nos. 3 and 4 lines were connected to the normal high voltage switchboard of those units. The line cables touched the tower, due to the violent seismic movements, resulting in a short circuit and they failed. Further the normal high voltage switchboard was inundated later by the tsunami. These events resulted in the actuation of the circuit breakers at the Shin-Fukushima Transformer

Station. As for Units 5 and 6, the Yonomori Nos. 1 and 2 transmission lines were connected to the normal high voltage switchboard of those units. Due to the violent seismic movements, the line cables touched each other, resulting in the actuation of the circuit breakers at the Shin-Fukushima Transformer Station. Further one tower of the transmission line connecting to the switchyards for Units 5 and 6 collapsed. These events resulted in the loss of all external (off-site) power supplies to Units 1 to 6.

Arrival of the tsunami

At about 40 minutes to one hour after the first earthquake on March 11, seven waves of large tsunami struck the coast of Tohoku and Kanto. The first wave of tsunami reached the Fukushima Daiichi NPS at 15:27, and the second which was the largest tsunami reached there at 15:35. The 15 m high tsunami got over the 10 m high sea wall and entered RBs and turbine buildings (T/Bs). The cooling sea water pumps were 4.1 m above the sea level and were inundated. The EDGs, M/C, power centers, and so on at the lower level of the T/Bs were also inundated.

Function loss of major machines and components

Emergency diesel power generators

There were 13 EDGs installed at the Fukushima Daiichi NPS. They were intended to supply the power to each unit through the M/C. Each unit had 2 (A and B) EDGs except Unit 6 which had 3. Among them, 10 EDGs were sea water cooled and 3 EDGs (Unit 2B, Unit 4B and Unit 6B) were air cooled. After the tsunami struck, all sea water cooled EDGs lost their function, while the 3 air cooled ones were still available. For Unit 1, EDGs 1A and 1B located in the first basement of the T/B were inundated and lost their function. For Unit 2, EDG 2A located in the first basement of the T/B was inundated and lost its function. EDG 2B located on the first floor of the common spent fuel pool building was available, though the M/C was inundated and its function was lost. For Unit 3, EDGs 3A and 3B located in the first basement of the T/B were inundated and lost their function. For Unit 4, EDG 4A was under periodic inspection. EDG 4B located on the first floor of the common spent fuel pool building was available, though the M/C inundated and the function was lost. For Unit 5, EDGs 5A and 5B located in the first basement of the

T/B were available, though the connected components were inundated and their function was lost. For Unit 6, EDGs 6A and EDG 6C located in the first basement of the RB were available, though the sea water pump necessary to cool the EDGs was inundated and its function was lost. EDG 6B located on the first floor of the diesel generator building was available and the function to supply power was available, too.

Metal-clad switch gear and power centers

The M/C is the 6900 V switch board for high voltage circuit power, and the P/C is the 480 V switch board for low voltage circuit power. There were 15 setups each for the M/C and the P/C. They had three kinds of operations for normal, for emergency and for common (shared) use. Due to the earthquake, the M/C and the P/Cs lost the function for normal and for common use since the off-site power was lost. Due to the tsunami, 12 among 15 setups for the M/C for emergency use were inundated and lost the function, and 9 among 15 P/Cs for emergency use were inundated and lost the function.

Emergency cooling sea water pumps

The emergency cooling sea water pumps are equipped to supply sea water to the heat exchanger of the containment cooling system (CCS) for Unit 1 and the residual heat removal system (RHR) for Units 2 to 6. After the tsunami struck, the emergency cooling sea water pumps stopped by the loss of AC power to Units 1 to 5, and the function of the CCS and the RHR was lost.

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A3 Sequence of the Events in Units 1 to 3 in the Accident [A3-1 to A3-3]

The summaries of the accident sequences in Units 1 to 3 which are referred to in this document are shown in the following.

Unit 1
Friday, March 11, 2011
14:46 Loss of offsite power and reactor scrammed.
14:47 EDG started.
Some workers confirmed leaking water from an upper floor near the IC equipment.
14:52 Both IC trains started.
15:03 Operator stopped both IC trains to maintain the cool down rate of the reactor.
15:17 Operator restarted train A-IC.
15:19 Operator stopped train A-IC.
15:24 Operator restarted train A-IC.
15:26 Operator stopped train A-IC.
15:32 Operator restarted train A-IC.
15:34 Operator stopped train A-IC.
15:37 EDGs tripped (SBO), loss of DC power.
18:18 Indicators showed both outboard IC valves closed, operator started train. A-IC by opening the DC motor operated valves MO-3A and MO-2A.
18:25 Operator could not confirm the IC operation and he stopped train A-IC to secure the IC.
21:30 Operator restarted train A-IC by opening the MO-3A.
21:51 Dose rate in the RB confirmed to be too high for entry.
23:00 High dose rate observed in front of RB entrance gate.
23:50 High D/W pressure observed.
Saturday, March 12, 2011
00:06 Preparation for PCV venting started.
02:45 Operator observed low reactor pressure.
04:00 Water injection started by a fire engine (continued intermittently).
08:03 Director of the site ordered venting to start at 09:00.
09:04 Start of PCV venting operation, operator dispatched to manually open containment vent valves in the RB.

09:15 MOV of PCV vent partially opened.
09:24 Operator tried to manually open the PCV vent AOV in the S/C.
09:30 PCV vent AOV could not opened; the high dose rate in the S/C prevented the operator from staying there.
10:17 Operators attempted to open AOV remotely.
14:00 Temporary air compressor was connected and opening of the S/C AOV was started.
14:50 PCV pressure decreased, PCV venting confirmed.
15:36 Explosion in Unit 1 RB.

Unit 2
Friday, March 11, 2011
14:46 Loss of offsite power.
14:47 Reactor scrammed and EDGs started.
14:50 RCIC started.
14:51 RCIC stopped by high water level (L8).
15:02 Operator started RCIC.
15:28 RCIC stopped by L8 set point.
15:37 Water cooled EDG tripped.
15:39 Operator restarted RCIC.
15:41 Air cooled EDG tripped (SBO), loss of DC power, RCIC manipulation lost.
21:50 MCR reactor water level measurement re-established and water level above TAF was confirmed
Saturday, March 12, 2011
02:55 RCIC was declared operating.
05:00 RCIC intake lineup to S/C from CST completed.
15:30 480 V low-voltage grid was reenergized.
15:36 Explosion in Unit 1 occurred, 480 V low voltage gird failed.
Sunday, March 13, 2011
08:10 MOV of PCV vent partially opened.
11:00 Large S/C AOV opened, PCV venting failed.
Monday, March 14, 2011
03:00 Temporary air compressor connected to instrument air system to keep large AOV open, PCV venting was not successful.
11:00 Alternative sea water injection line assembly completed.

11:01 Explosion in Unit 3 occurred, alternative sea water injection line was damaged. Large AOV in the S/C closed.
12:30 ERC made decision to postpone RPV depressurization.
13:00 RCIC was declared inoperable.
14:43 Sea water injection through core spray line re-established.
16:20 RPV water level decreased to TAF.
16:21 Large AOV in the S/C reopened, PCV venting failed.
16:28 Operator decided to depressurize RPV via SRV, RPV did not depressurize.
16:34 Attempt to open SRV failed.
18:00 SRV opened, RPV depressurized.
19:05 Sea water injection via fire engines commenced.
19:20 Sea water injection stopped.
19:54 Fire engines refueled, sea water injection restarted.
Tuesday, March 15, 2011
00:01 D/W vent AOV opened, PCV pressure did not decrease.
06:14 Explosion in Unit 4 occurred, S/C pressure dropped to vacuum pressure.
09:00 Highest radiation reading was made at main gate.

Unit 3
Friday, March 11, 2011.
14:47 Reactor scrammed on seismic trip set point.
14:48 Loss of offsite power, EDG started.
15:05 Operator started RCIC.
15:25 RCIC stopped by L8 set point.
15:38 EDGs tripped (SBO).
16:03 RCIC restarted manually. Operators started load-shedding of equipment to conserve DC power.
Saturday, March 12, 2011
11:36 RCIC tripped.
12:06 S/C spray started by DDFP.
12:35 HPCI started automatically by L2 set point.
Sunday, March 13, 2011
02:42 Operator stopped HPCI manually. DDFP line up was changed from S/C to RPV.

03:38 Attempted to open SRV manually, but SRV did not open.
04:00 RPV water level measured under TAF, core was already uncovered.
05:08 S/C spray restarted by DDFP.
07:43 DDFP spray line up was changed from S/C to D/W.
08:35 MOV of PCV vent partially opened.
08:41 Large S/C AOV opened for PCV venting.
09:08 RPV pressure decreased, cause of this pressure drop was unknown.
About 09:10 DDFP stopped.
09:20 Operator observed PCV pressure decreasing, PCV venting succeeded.
09:25 Borated freshwater injection into RPV started.
11:17 Large AOV in the S/C found closed.
12:20 Freshwater depleted, RPV injection stopped.
12:30 Large AOV reopened for venting.
13:12 Sea water injection started.
19:00 Air compressor replaced. Large AOV in the S/C reopened.
Monday, March 14, 2011
11:01 Explosion in Unit 3, sea water injection into RPV stopped.
13:05 Sea water injection line work restarted.
19:20 Sea water injection stopped when fire truck ran out of fuel.
After that RPV injection and PCV venting were operated intermittently.

Environmental measurements and public protective actions
Friday, March 11, 2011
15:42 Nuclear disaster emergency declared based on Article 10 of Nuclear Disaster Act.
16:36 Nuclear disaster emergency declared based on Article 15 of Nuclear Disaster Act.
19:03 Nuclear emergency declared by the National Government.
20:50 2 km zone evacuation order issued by the local government.
21:23 3 km zone evacuation and 3-10 km zone shelter order issued by the National Government.
Saturday, March 12, 2011
05:44 National Government ordered evacuation of 10 km zone.
15:29 Site radiation levels were 1015 μSv/h.

16:27 Abnormal site boundary radiation level (569 μSv/h) reported based on Article 15 of Nuclear Disaster Act.
18:25 National Government ordered evacuation of 20 km zone.
Sunday, March 13, 2011
09:01 Abnormal radiation level (882 μSv/h) reported.
14:15 Abnormal radiation level (905 μSv/h) reported.
Monday, March 14, 2011
02:20 Abnormal radiation level (751 μSv/h) reported.
02:40 Abnormal radiation level (650 μSv/h) reported.
04:00 Abnormal radiation level (820 μSv/h) reported.
09:12 Abnormal radiation level (518.7 μSv/h) reported.
21:35 Abnormal radiation level (760 μSv/h) reported.
Tuesday, March 15, 2011
06:50 Abnormal radiation level (583.7 μSv/h) reported.
08:11 Abnormal radiation level (807 μSv/h) reported.
09:00 Main gate radiation reading was 11,930 μSv/h (highest value).
11:00 Prime Minister issued an order for residents in the 20-30 km zone to take shelter indoors.
16:00 Abnormal radiation level (531.6 μSv/h) reported.
23:05 Abnormal radiation level (4,548 μSv/h) reported.

References

[A3-1] Tokyo Electric Power Co., Inc.:, Final Report of Fukushima Nuclear Accident Investigation Committee, Tokyo （June 20, 2012）. (in Japanese)
[A3-2] Government of Japan, Nuclear Emergency Response Headquarters: "Report of the Japanese Government to the IAEA Ministerial Conference on Nuclear Safety — The Accident at TEPCO's Fukushima Nuclear Power Stations," Tokyo, (2011).
http://www.iaea.org/newscenter/focus/fukushima/japan-report
[A3-3] IAEA, Description and Context of the Accident, Fukushima Daiichi Accident Technical Volume 1/5, IAEA STI/PUB1710, August (2015).

A4 Fail-safe Mechanism of IC Valve and How It Worked When the Tsunami Struck

Fig. A4 shows a schematic diagram of the IC and its piping system installed in Unit 1 [A4-1]. Two IC trains named A and B were installed to cool the reactor core. Each of them has four isolation valves 1A to 4A and 1B to 4B, respectively. Just after the earthquake, both trains started working at the same time. This meant that all the valves were opened automatically as a result of the fail-safe function. But since the cooling capacity was too big to keep the cooling rate within the prescribed limit, that is, 55℃/hour, the operator closed the isolation valve, 3B, which meant that the B-train did not work afterwards. Then the operator repeated closing and reopening isolation valve 3A of the A-train three times by following the suggestion in the operation manual. This was done to keep the cooling rate within the prescribed limit. These operations were done to prevent the generation of the excess thermal stress. The operations and the behaviors of the IC described above suggested that the IC was working normally and there was no evidence which showed a failure of the piping system as could be regarded as an LOCA.

Just before the tsunami struck the operator had closed valve 3A. When the tsunami arrived, the sea water came to the underground floor of the T/B in Unit 1 where the distributing panel and EDGs were installed. And both the AC and DC power supplies were lost.

There was a complicated problem associated with the fail-safe function of the IC. In the following only the behavior of the valves in the A-train are explained because the B-train has the same function. In the train the control signals for the fail-safe function were driven by the DC power supply, and the AC power supply was necessary to open and close valves 1A and 4A which were located inside the PCV, while the DC power supply was necessary for valves 2A and 3A located outside the PCV. If both AC and DC power supplies were available and the isolation signal was sent, all the valves would have been closed automatically as a result of the fail-safe function. But, when the sea water flooded the distribution panel, the order of the function loss of the AC and DC power supplies was unknown. In the first case, if the DC power supply had failed first and the AC power supply was available for a while, the valves 1A and 4A would have been closed while 2A and 3A were kept open, just as they were before the tsunami struck. In the second case, if the AC power supply had failed first and the DC power supply was available for a while, the valves 2A and 3A would have been closed while 1A and 4A were kept open.

Members of the Atomic Energy Society of Japan (AESJ) have analyzed the behavior of these valves in detail. The following are results of the AESJ analysis [A4-2]:

・Just before the tsunami struck, valve 3A was closed by the operator.

・Just after the tsunami struck, signals to close all the valves were sent, and as a result, valves 1A and 4A were almost closed.

・Therefore, the IC was not working from just before the tsunami arrived.

・Later, in the evening of the 11th , the operator reopened valve 3A, but the IC did not work substantially.

The AESJ report also described the behavior of the B-train valves. Valves 1B and 4B were considered to be almost open even after the tsunami struck, that is, even after AC and DC power supplies were lost. Therefore, there was a possibility that the B-train could have worked by reopening valves 2B and 3B by getting a DC power supply using a portable battery.

References

[A4-1] Government of Japan, Nuclear Emergency Response Headquarters: "Report of the Japanese Government to the IAEA Ministerial Conference on Nuclear Safety — The Accident at TEPCO's Fukushima Nuclear Power Stations," Tokyo, (2011).
http://www.iaea.org/newscenter/focus/fukushima/japan-report

[A4-2] Investigation Committee, Atomic Energy Society of Japan (AESJ): "The Fukushima Daiichi Nuclear Accident," Final Report of the AESJ Investigation Committee, Springer, 2015.

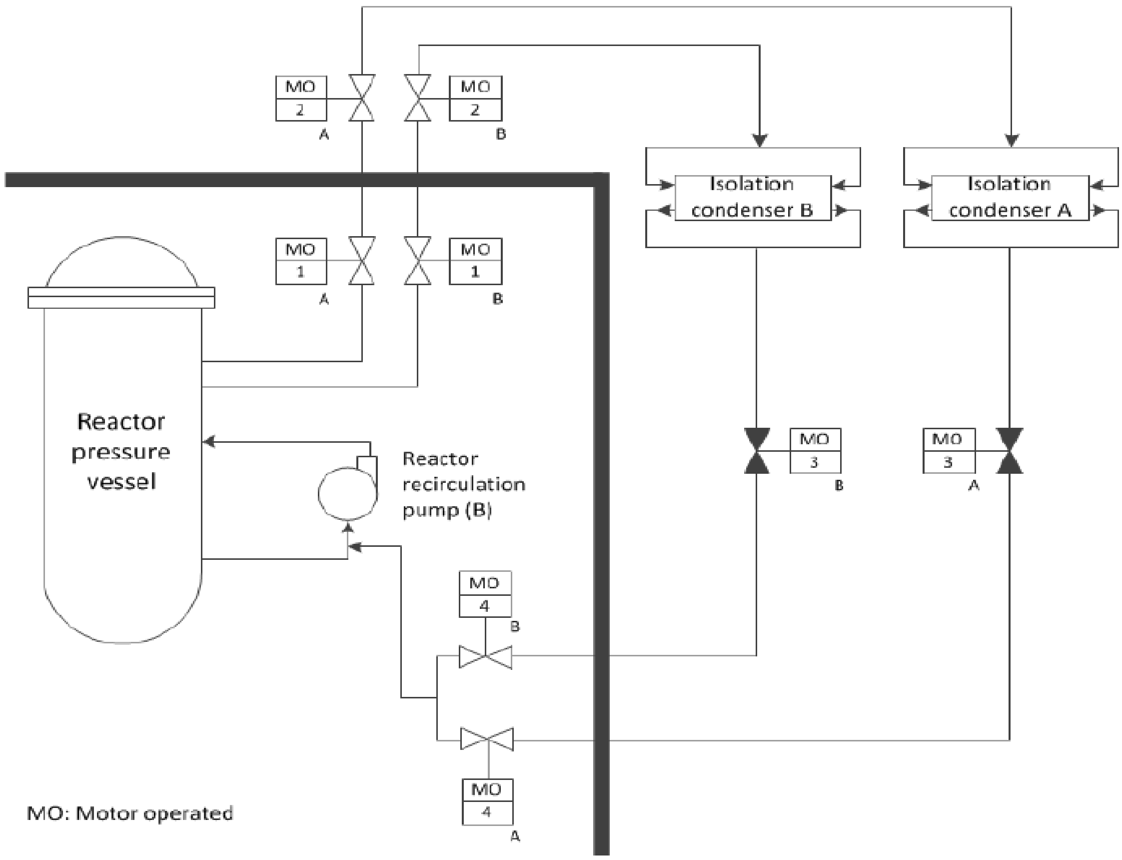

Fig. A4 Schematic of Isolation Condenser (IC) [A4-1]

A5 Reactor Core Isolation Cooling System (RCIC) [A5-1]

The RCIC is the device by which water is poured into the reactor outside the shroud of the reactor core under high pressure without any power supply. It is done by using the turbine pump driven by the steam flow generated by the large pressure difference between the RPV and the S/C. Since S/C could not be cooled in the situation of the SBO, the temperature and the pressure increased gradually, and the pressure difference became small and the turbine pump lost its function after working about 70 hours.

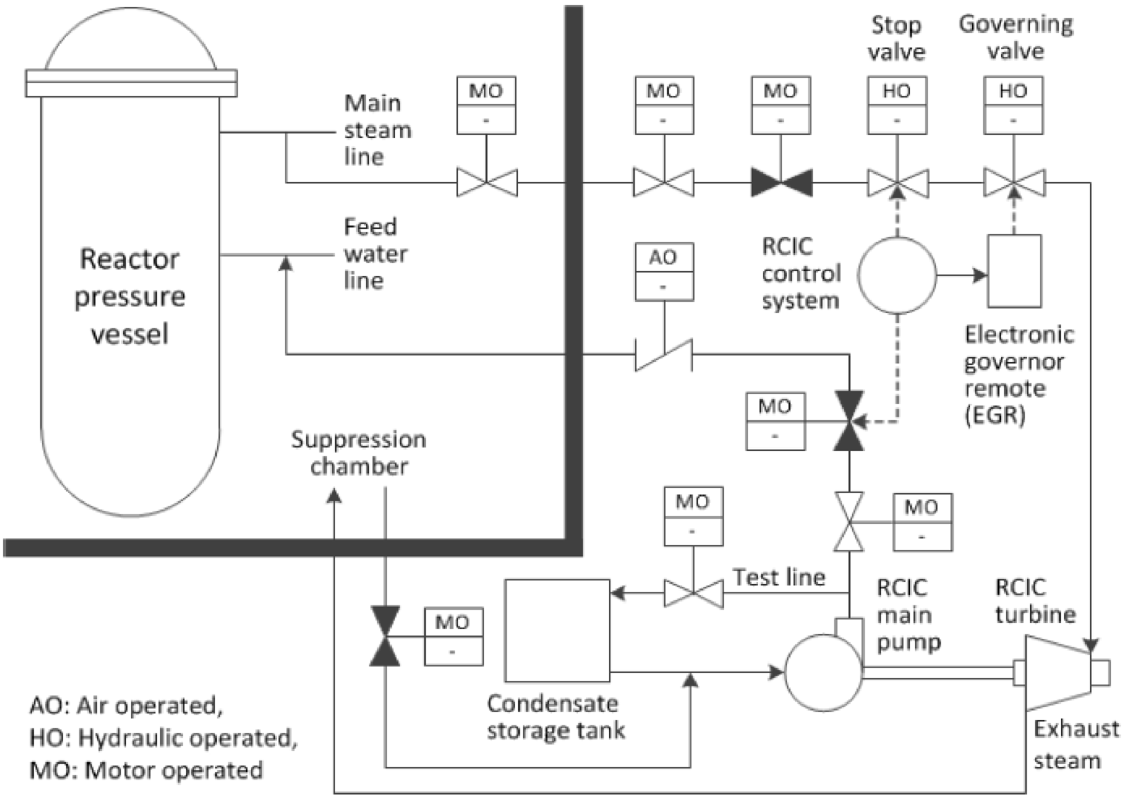

Fig. A5 Schematic of Reactor Core Isolation Cooling System (RCIC) [A5-2]

References

[A5-1] M. Fuchigami, N. Kasahara, and Y. Hatamura, "What Happened at the Fukushima NPS?" Technical Commentary on the Report of the Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of TEPCO by the Cabinet Secretariat of the Government of Japan, Nikkan Kogyo Shinbun Co. Ltd., Tokyo (Dec. 25, 2012). (in

Japanese)
[A5-2] Government of Japan, Nuclear Emergency Response Headquarters: "Report of the Japanese Government to the IAEA Ministerial Conference on Nuclear Safety — The Accident at TEPCO's Fukushima Nuclear Power Stations," Tokyo, (2011).
http://www.iaea.org/newscenter/focus/fukushima/japan-report

A6 Responses to the Total AC Power Loss Event [A6-1]

Total power loss is the status where all external and in-plant emergency AC power supplies are lost. To secure a power supply, in June 1977, the Atomic Energy Commission (AEC) reviewed the Regulatory Guide for Reviewing the Safety Design of the Light Water Nuclear Power Reactor Facilities and required for the first time in Guideline 9 the "Design Consideration for Loss of Power" whereby a "nuclear power station should be designed safely to shut down a nuclear power reactor and secure cooling after shutdown when all power supplies are lost for a short time." The Nuclear Safety Commission (NSC) said the practice of defining 'short time' in the expression "when all power supplies are lost for a short time" had been 30 min or less since 1977, and the requirement for the loss of all power supplies meant the battery and the water injection capacities, etc., should be sufficient to maintain the cooling function when all power supplies were lost for 30 minutes.

It has been interpreted that Units 1 to 6 satisfied the Regulatory guide for Reviewing the Safety Design of the Light Water Nuclear Power Reactor Facilities because the IC in Unit 1 and the RCIC and SRV in Units 2 to 6 had cooling abilities for at least 30 minutes without AC power supplies.

Reference

[A6-1] Investigation Committee, Atomic Energy Society of Japan (AESJ): "The Fukushima Daiichi Nuclear Accident," Final Report of the AESJ Investigation Committee, Springer, 2015.

A7 Prevention of Severe Accidents at Nuclear Power Plants [A7-4]

Summary of the documents about severe accident described in the reports of Investigation Commissions of National Diet [A7-1], **Government** [A7-2] **and Private Sector** [A7-3]

The Diet Investigation Commission [1] emphasized the vulnerabilities in severe accident management that did not consider external events (e.g., earthquakes and tsunami, etc.), human events (e.g., terrorist attacks, etc.) and the extended SBO, but was limited only to internal events (e.g., erroneous operations). Because severe accident management was not regulated and left to the voluntary discretion of the operators, the effectiveness of the measures diminished. The report also pointed out that the regulatory body did not reinforce measures for ensuring defense-in-depth although they were aware that the requirement in Japan was only up to defense-in-depth Level 3 against the international standards of Level 5. An additional flaw pointed out was neglecting to reflect in the Japanese regulatory framework, "Station Blackout and Advanced Accident Mitigation (B.5.b)" requiring provision of safeguards and trainings for SBO, issued by the US NRC after the 9.11 terrorist attack though this was well recognized by the Japanese authorities. However, the Diet Investigation Commission report did not extensively discuss factors related to the severe accident to define clearly what future severe accident measures should be. Instead, it simply stated, "regular monitoring and updates on accident management must be implemented on the basis of the lessons learned on accidents, global trends on safety standards and the application of state-of-the-art technologies, in order to maintain the highest standards and the highest technological levels globally" (Article 3 of Recommendation 6 "Reforming Laws Related to Nuclear Energy").

As with the Diet Investigation Commission, the Government Investigation Committee [2] emphasized the significance of severe accident management that includes external events. In the recommendations, it points out the necessity of a comprehensive risk analysis and severe accident management in (4) "Analyses on Accident Prevention Measures and Disaster Preparedness" of 1. "Analysis of Key

Issues" - "nuclear operators should conduct comprehensive risk analysis encompassing the characteristics of the natural environment including external events, of not only earthquakes and their accompanying events but also other events such as flooding, volcanic activities or fires, even if their probabilities of occurrence are not high, as well as internal events having been considered in the existing analysis. Nuclear regulators should check the operators' analysis." In the formulation of severe accident measures based on comprehensive risk analysis - "In order to ensure and maintain nuclear safety at nuclear power stations, vulnerabilities against a wide range of internal and external events should be identified for each facility through comprehensive safety assessment, and effective severe accident management measures that include assumption of core damage caused by events exceeding design basis should be developed. The effectiveness of such severe accident management should be evaluated through the PSA or other means." The issues pointed out are relevant, however, extensive examinations on these issues were not made in the report. In addition, the report was formulated on the premise that the operators must take initiatives in severe accident management with the regulatory authorities confirming the adequacies of the measures taken by the operators.

The Independent Investigation Commission from the private sector [3] also pointed out the inadequacies in severe accident management, claiming that the reason for the shortfall in promoting severe accident management in Japan was because nuclear regulatory control placed emphasis on the hardware aspects as structural strength, which hindered the establishment of quantitative risk assessment. However, no specific recommendations were made on the future enhancement of nuclear safety.

Reports on investigations and analyses of the Fukushima accident from different perspectives have been prepared by various organizations, including TEPCO.

Defense-in-depth levels of IAEA

(1) The IAEA has applied the concept in the design of nuclear power plants with a goal to prevent harmful consequences of radiation to people and the environment, to provide protection against and mitigate harmful consequences, and determined the following five levels of defense

(defense-in-depth-specific functions, design and procedures).

Table A7 shows the goals of each defense-in-depth level and essential means for achieving the goals.

(2) Plant conditions given consideration in the design are roughly classified into “operating conditions” and “accident conditions,” with the former sub-classified as “normal operation” and “anticipated transients,” and the latter as “design basis accident” and “design extension conditions (DEC)”. Defense measures for the four operating conditions correspond to

Table A7 Defense-in-Depth Levels in IAEA

	Defense -in-Depth Level	Goal	Essential Means	Related Plant Conditions
Design Basis	Level 1	Prevention of abnormal operation and failures	Conservative design and high quality in construction & operation	Normal operation
	Level 2	Control of abnormal operation and detection of failures	Control, limiting and protection systems, and other surveillance features	Transient condition to abnormal state (Anticipated Operational Occurrences, AOO)
	Level 3	Control of accidents within design basis	Engineered safety features and accident management procedures	Design basis event (A single, anticipated initiating event)
Beyond Design Basis	Level 4	Control of severe conditions including prevention of accident progression & mitigation of severe accident consequences	Complementary measures & accident management including defense of containment vessel	Redundancy failures Severe accident Design extension conditions
Emergency Response	Level 5	Mitigation of radiological consequences of significant release of radioactive materials	Off-site emergency Response	Disaster prevention

a) **Level 1** is oriented towards the prevention of abnormal operations and failures. Appropriate quality level and engineered safety features (e.g., application of redundancy, independence and diversity) are incorporated for a sound and conservative design, construction, maintenance and operation of nuclear plants.

b) **Level 2** is aimed at the control of abnormal operations and detection of failures. Deviations are detected and prevented to inhibit any abnormal development from anticipated events during operation.

c) **Level 3** provides control over design basis accidents. In the event of failure of Level 2 in preventing development of AOO (anticipated operational occurrences) and anticipated initiating events, Level 3 provides control over progression to severe consequences and ensures safety shutdown.

d) **Level 4** ensures control of severe plant conditions, including accident development and mitigation of severe accidents, protection of confinement, as well as ensures that radioactive materials release is kept as low as achievable.

e) **Level 5** covers functions in mitigation of radiological consequences of significant release of radioactive materials, which requires emergency centers with appropriate equipment and on-site and off-site emergency response plans.

References

[A7-1] National Diet Report: The National Diet of Japan Fukushima Nuclear Accident Independent Investigation Commission, The Official Report of the Nuclear Accident Independent Investigation Commission (The National Diet of Japan); (July 5, 2012). (in Japanese)

[A7-2] Japanese National Government Report: Final Report of Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company. (2012), (in Japanese)

[A7-3] Rebuild Japan Initiative Foundation: The Fukushima Daiichi Nuclear Power Station Disaster: Investigating the Myth and Reality, Rebuild Japan Initiative Foundation, Tokyo (March 11, 2012). (in Japanese)

[A7-4] Committee on the Prevention of Severe Accidents at Nuclear Power Plants: "Preventing Recurrence of Severe Accidents at Nuclear Power Plants," Report by the Committee on the Prevention of Severe Accidents at Nuclear Power Plants, (April 22, 2013).

[A7-5] Basic Safety Principles for Nuclear Power Plants 75-INSAG-3 Rev. 1 INSAG-12,(1999)

A8 Hearing with TEPCO (1) about Fail-Safe Design of IC

WGFNA made inquiries to TEPCO about the fail-safe design of the IC in Unit 1, and made a hearing with TEPCO on July 12, 2013. Details of the Q&A are shown in the following.

{Q1-1} The AESJ report [A8-1] stated that "The IC system containing the IC is not the emergency core cooling system (ECCS) that is activated in the event of loss of core coolant, but heat removal equipment utilized to condense steam generated in the reactor when the condenser in the turbine system is not available, and considered as safety equipment. " What is TEPCO's position regarding the IC in Unit 1?
{A1-1} The ECCS is a general term for the devices by which damage of the reactor core can be prevented by cooling the reactor core through injecting the water into the RPV, when the LOCA occurs. In the case of Unit 1, they are HPCI, core spray system (CS) and automatic depressurization system (ADS).

The IC is the "emergency" condenser which is used when the normally used main condenser cannot work for any reason. The IC is not the device to be used as ECCS, that is, it is not the device to use in the LOCA which occurs by failure of the piping system. But it is regarded as safety equipment because it has a function of cooling the reactor when the main condenser cannot be used.

{Q1-2} After the earthquake and before the tsunami, the operator repeated closing and opening the isolation valve of the IC a few times. Does TEPCO regard this operation as "normal"?
{A1-2} The decay heat is removed by the main condenser in normal use after shutdown of the reactor. But in the present accident the main condenser did not work because all the main steam isolation valves (MSIVs) closed due to the loss of the AC power supply caused by the earthquake damage, and the cooling pump, i.e., water circulation pump, for the main condenser stopped.

Then IC automatically started working by the pressure increase in the reactor caused by the shutdown of all MSIVs. The operator controlled the isolation valve of the IC manually in order to control the pressure. This operation is the one described in the operation manual for an accident, although it is not the one for the normal state where the main condenser is used.

{Q1-3} Had the operators experienced training beforehand about this operation?
{A1-3} The operators had received educational training according to the operation manual of the IC in an accident. As actual operations they were trained to open or close the isolation valve of IC regularly as a part of regular tests during the regular inspection period or the operating period. More concretely speaking, the operators tried to open and close each of the four isolation valves in A and B trains one by one at the time of a regular test in order that the steam from the reactor might not flow into the IC, and they confirmed that the valves could open and close normally.

After the earthquake and before the tsunami arrived, the operator in the control room could control the pressure of the reactor by controlling the isolation valve correctly. This is considered to be the result that the operator understood the function of the IC through the educational training and on the job training (OJT).

{Q1-4} Did the steam flow out from the exhaust hall called "pig's nose" through the IC operation?
{A1-4} As mentioned above, the steam does not flow out in the regular tests. But when the IC is working normally, that is, the steam flows into IC from the RPV and condenses into the water, the steam produced from the coolant water will flow out from the pig's nose.

In TEPCO we did not confirm the flow of the steam from the pig's nose directly, but we think that the IC worked normally before the tsunami through observation of changes of the plant parameters, that is, the changes in the RPV pressure according to opening and closing of the isolation valve.

{Q1-5} Were other cooling systems working or not in this period?
{A1-5} After the reactor scrammed due to the earthquake and before the tsunami, other cooling systems than the IC, that is, ECCS were not working because we knew that we could control the reactor pressure by controlling the decay heat removal through opening and closing manually the isolation valve of the IC and because we also knew that the water level in the RPV

was stable. We also confirmed that HPCI could start working automatically during that period.

But after the tsunami struck all the cooling systems including the IC lost their functions due to the loss of all AC and DC power supplies.

{Q2-1} When the tsunami struck, all AC and DC power supplies in Unit 1 were lost, and the IC had to be relied upon to cool the reactor because no other cooling systems could work without AC and DC power supplies. Had TEPCO supposed this sort of situation could happen beforehand?

In other words, had a scenario been prepared to use the IC as a safety system on the same level as the ECCS?

{A2-1} In TEPCO we did not suppose the loss of all the power suppling including the DC supply which was just like the situation that happened in the present accident. And therefore, we did not prepare any manuals nor do any training against this sort of situation. This is not only for the IC, but also for all other components in the ECCS.

In the present accident, we had difficulty to understand how the IC was working because the indicator lights showing the IC working state turned off and other instruments in the MCR lost their functions. Further, we had difficulty to understand whether or not the IC was working because that information depended on the order of the loss of AC and DC power supplies that were connected to the control signal and the driving forces of the isolation valves, respectively (see Appendix A4).

{Q2-2} Had operators received any training for this sort of situation?

{A2-2} Regarding training about the IC, we responded to that in our answer {A1-3}. We did not do any training for the situation supposing the loss of all AC and DC power supplies.

{Q3} Besides Unit 1 of the Fukushima Daiichi NPS, the IC was also set in Unit 1 of the Tsuruga NPS of the Japan Atomic Power Company (JAPC). According to the AESJ report [A8-1], the IC was used two times in the past 10 years at the Tsuruga NPS, and operators were trained to use the IC through OJT and educational training with a small scale simulator. There was no description about this sort of training in the report of the Cabinet Secretariat of Japan [A8-2]. Is this because the positioning of the IC was different between the NPSs of TEPCO and JAPC?

{A3} Regarding training about the IC, we responded to that in our answer {A1-3}. The operators could control the RPV pressure, that is, remove the decay heat, by using the IC until the tsunami struck. But we did not do any training for the situation supposing the loss of all AC and DC power supplies.

References

[A8-1] Investigation Committee, Atomic Energy Society of Japan (AESJ): "The Fukushima Daiichi Nuclear Accident," Final Report of the AESJ Investigation Committee, Springer, 2015.

[A8-2] Japanese National Government Report: Final Report of Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Company, 2012. (in Japanese)

A9 Hearing with TEPCO (2) about the Events in Unit 2

WGFNA made inquiries to TEPCO about the events that occurred in Unit 2, and made a hearing with TEPCO on February 22, 2014. Details of the Q&A are shown in the following.

{Q1} There is a description about the venting in the TEPCO report [A9-1, p164] As follows: "From about 20:00 on the 14th to about 6:00 o'clock on the 15th, during which no decrease of the pressure was observed in the PCV, that is, in both the D/W and S/C, the operators tried to recover the vent line in the PCV, and finished composing the vent line in the S/C at about 21:00 on the 14th. But the pressure did not reach the one at which the venting was set to occur."
What was the critical pressure set for the venting?
{A1} The critical pressure was the one at which the rupture disc would work, that is, it would rupture. In the case of the Unit 2 PCV, the pressure was 0.42 MPa [gage], that is, about 0.528 MPa [abs]. At about 21:00 on the 14th when the vent line was composed, the pressure of the D/W was about 0.42 MPa [abs] and it was below the critical pressure.

{Q2} On the other hand, we found the following description in the report of the Independent Investigation Committee [A9-2, p32]: "In Unit 2, the effort for the venting was successively done as well as that for the decompression. The pressure of the D/W became 0.54 MPa at 22:00 on the 14th, and it exceeded the pressure at which the rupture disc was set to work. By that time, it was considered that one of the two vent lines starting from the S/C was available. But the pressure in the D/W was continuously increasing even after it exceeded the critical value, and it became 0.740 MPa [abs] at 23:35 on the 14th. On the other hand, the pressure in the S/C had a decreasing tendency although that in the D/W was increasing. And therefore, the operators recomposed the vent line from the D/W instead of using the one from the S/C. But, in conclusion, it is not certain whether the venting was actually done or not."
Then the questions are:
{Q2a} What is the reason why the rupture of the rupture disc did not occur when the pressure of the D/W exceeded the critical value at which it was set

to rupture => Answer: See {A2} ① below.

{Q2b} Why the rupture disc did not work, that is, the rupture of the rupture disc did not occur although the wet vent from the S/C was ready and the pressure got over the critical value for rupture? How did you set the design pressure for rupture disc, and how much is the variance of the design pressure? Or is this not the matter of the rupture disc but that of the vent valve? That is, was the vent valve not open? => Answer: See {A2} ① below.

{Q2c} What are the design pressures of the S/C and D/W? And what is the designed vent pressure for each? => Answer: See {A2} ② below.

{A2}

① The composition of the vent line was completed by slightly opening the S/C vent valve, a small valve, at about 21:00 on the 14th. But the D/W pressure continued increasing, it exceeded the critical value for the rupture disc to work, 0.427 MPa [gage]=0.528 MPa[abs], at about 22:50, and it reached about 0.7 MPa[abs] at about 23:30. We consider that this was because the slightly opened vent valve had closed again.

At the moment, it has not been confirmed whether the rupture disc worked or not. This is a matter to be investigated further.

There is a code for the rupture disc "JIS B 8226-3:2011, rupture disc type safety equipment," wherein the general allowable variances for the rupture pressure are shown in table 2 of chapter 3. In TEPCO we adopted the inverse dome type rupture disc as the standard one for the vent line, though we did not always confirm all the designs. According to the JIS table, the allowable variances are within 5%, and the upper and lower limits were set within 10%, respectively, in the actual construction.

② The design pressure for both the S/C and D/W was set at 0.38 MPa[gage] in Unit 2. (The maximum allowable pressure was 0.427 MPa[gage].) The working pressure of the rupture disc in Unit 2 was the same as the maximum allowable pressure of the D/W.

References

[A9-1] Tokyo Electric Power Co., Inc.:, Final Report of Fukushima Nuclear Accident Investigation Committee, Tokyo (June 20, 2012). (in Japanese)

[A9-2] Rebuild Japan Initiative Foundation: The Fukushima Daiichi Nuclear Power Station Disaster: Investigating the Myth and Reality, Rebuild Japan Initiative Foundation, Tokyo (March 11, 2012). (in Japanese)

A10 Hearing with TEPCO (3) about the Leak of the Radioactive Materials

WGFNA made inquiries to TEPCO, about the leak of the radioactive materials, and made a hearing with TEPCO on February 22, 2014. Details of the Q&A are shown in the following.

{Q1} About the leakage (1) from the RPV to the PCV and (2) from the PCV to the environment, please show us how you analyzed the time when the significant leakage occurred and the route through which the radioactive materials leaked, with the change of the pressure of the RPV and PCV, respectively.
{A1} We answer questions (1) and (2) for Units 1 to 3 separately.

Unit 1:

(1) In Unit 1, the reactor cooling function was lost at an early stage because the power supply for driving the valves of the IC was lost due to the tsunami. Therefore, we estimate the temperature of the reactor core became high enough to melt the fuels from midnight of March 11 to the early hours of March 12. We estimate that the melted fuels caused the failure of the bottom of the RPV, and that they fell down to PCV. But when we look at the change of the pressure of the RPV from about 7 MPa[abs] at about 20:00 on March 11 and that of the PCV from 0.6 MPa[abs] at 23:50 of the same day to about 0.9 MPa[abs] (RPV) and 0.84MPa[abs] (PCV), respectively, at about 3:00 on March 12, it is considered that the leakage from the RPV started before the failure of the pressure boundary of the reactor cooling system occurred due to the melted fuels. In the analysis done by TEPCO, we assumed that the pipe of the nuclear instrumentation system (that is, the pressure boundary of the reactor cooling system formed at the reactor core) and/or the gasket of the main steam release valve were the candidates where the leakage occurred. On the other hand, according to the report by the Sandia National Laboratory, the possibility of creep failure of the main steam pipe is pointed out. But at the present time it is not clear when and through which route the leakage happened.

(2) In Unit 1 the final heat sink was lost, and the decay heat accumulated in the PCV boundary, and then, the pressure of the PCV monotonically

increased. Further, the leakage of the gas, including the inert gas from the RPV occurred, and therefore, the pressure of the PCV increased, becoming extremely high. In TEPCO's analysis we assumed that the leakage started at about 3:00 on the 12th to simulate the measured pressure change in PCV. But, as shown in the answer {A2} in the following, although there are some candidate routes for the leakage that can be considered, it is not clear at the present time when and through which route the leakage occurred.

Unit 2:

(1) In Unit 2, the RCIC was operating for three days although all the AC and DC power supplies were lost after the tsunami struck. Meanwhile, cooling the reactor core was continued through injecting water by the RCIC. Because the reduction of the pressure was realized during the period when the water in the reactor core were above the critical level, we estimate that there were not any remarkable leakages at high pressure from the pressure boundary of the reactor coolant system other than the small one occurring normally through the PLR mechanical seal.
We think that the leakage from the pressure boundary of the reactor coolant system occurred afterwards as the progress of the subsequent accident. But we could not estimate the definite time when the leakage occurred by the measured pressure and it is also unclear through which route the leakage occurred.

(2) In Unit 2 the PCV pressure changed at lower level than that estimated by the accumulation of the decay heat, although the final heat sink was lost. We estimate that this is because the part of the decay heat was removed by the external cooling due to the penetration of the tsunami water into the torus room where the S/C was set. The PCV pressure started to decrease from about 13 o'clock of 14th. We analyzed the reason why this reduction of the pressure occurred [A10-1], and we evaluate that the PCV was sound at that moment.

Afterwards as the accident worsened, the PCV pressure increased. But it started to decrease in the morning of the 15th, and nearly at the same time we observed steam blowing out through the blow-out panel. Also it was confirmed later that the steam gushed out from around the shield plug on the 5th operation floor of the PCV, just beneath which the top head flange of the PCV was located. Therefore, we estimate that a large scale leakage occurred at this time through the top head flange of the PCV. But we do not deny other possibilities.

Unit 3:

(1) In Unit 3, since the DC power supply was available although the AC power supply was lost due to the tsunami, injecting water into the reactor was continued by controlling the RCIC which started working first, then the HPCI. But since the HPCI had lost its ability to inject enough water before it was stopped manually, we estimate that the failure of the reactor core started before the decompression of the RPV occurred at about 9:00 on the 13th.[A10-1]

Therefore, the pressure of the RPV in Unit 3 was similar to that in Unit 1, that is, it was high enough to cause the leakage. But we can estimate, through the observation of the change of the measured RPV pressure shown in the strip chart (Fig. A10-1), that there was no serious leakage.

The Government report [A10-2] pointed out that the decompression itself could be due to the failure of the pressure boundary of the reactor coolant system. But in TEPCO we think, through the consideration done in the above report [A10-1], that it is not the failure of the pressure boundary but it could be the decompression because the automatic decompression system worked.

We estimate that the leakage occurred as the accident progressed. But we could not estimate the definite time when the leakage started using the measured change of the pressure since the RPV had been decompressed.

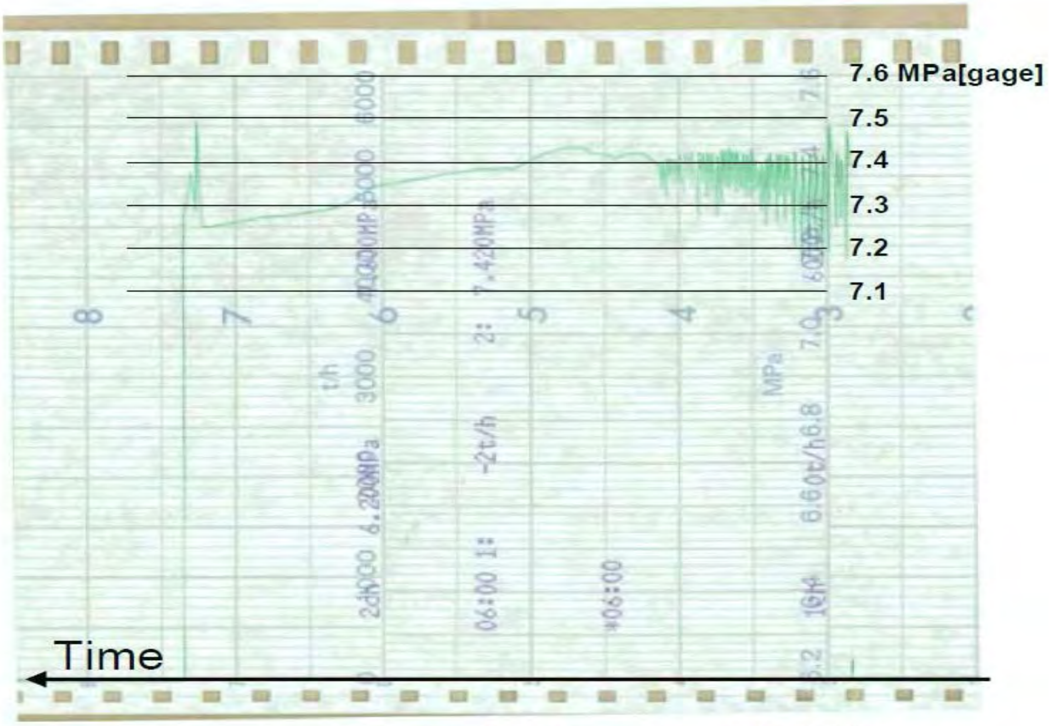

図２　原子炉圧力チャート（狭帯域）

Fig. A10-1 Chart of the reactor pressure (narrow band)

(2) Unit 3 was in a serious state since the final heat sink was lost. But, in contrast with the case in Unit 2, the pressure of the PCV changed at a higher level than that estimated by the accumulated decay heat. We estimate that this is because the temperature of the top surface layer of the stratified water in the S/C became high. We further estimate that the PCV was sound until the decompression of the RPV occurred since the pressure in the PCV decreased to the level estimated by the decay heat after the operation of spray cooling for the S/C.

Further, we think that the rupture disc on the vent line of the PCV opened just after the decompression of the RPV, and the venting was successful. Therefore, we could not suppose the leakage from the PCV.

On the other hand, for example on March 15, we confirmed that the large amount of the steam gushed out from the top of the RB, around the top head flange of the PCV. Then we think the leakage occurred from the top head flange around the 15th.

{Q2} In TEPCO it was regarded that the leakage occurred through the sealed parts of the joints, that is, the degradation of the sealing materials due to the high temperature exposure. Please provide data about the sealing materials used in the leakage route and their heatproof temperatures over which the degradation occurs.

{A2} About the sealing materials used for the possible leakage routes and their heatproof temperatures, we show the data for the flange part in the following.

Flange part (top head, hatch, air lock)

As the sealed parts, there are the top head flange, hatches for the devices and air locks. O-rings made of silicone were used for each. Fig. A10-2 shows the heatproof temperature for silicone rubber. This figure was obtained through past research where the PCV was modeled by a small model device and the relation between the pressure and the heatproof temperature was obtained. The figure shows that the heatproof temperature decreases with increase of the pressure and that it ranges from 225 to 300℃ within the pressure range below 20 kgf/cm^2.

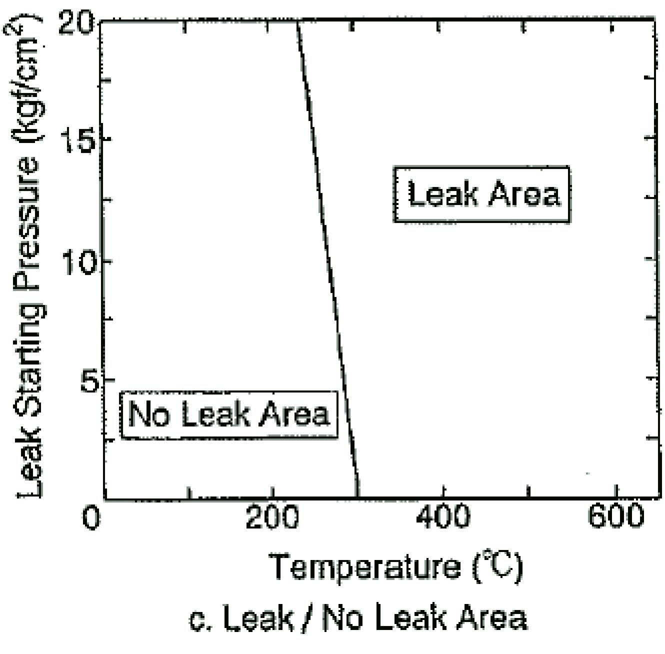

Fig. A10-2 The relation between the pressure and the heatproof temperature of the silicone rubber. [A10-3]

References

[A10-1] Tokyo Electric Power Co., Inc.: Final Report of Fukushima Nuclear Accident Investigation Committee, Tokyo (June 20, 2012), (in Japanese)

[A10-2] Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of Tokyo Electric Power Co, Inc.: Interim Report, Cabinet Secretariat of the Government of Japan, Tokyo (2011), (in Japanese)
[A10-3] K Hirao et al., "High-temperature leak-characteristics of PCV hatch flange gasket," Nuclear Engineering and Design 145 (1993), 375-386.

A11 Hearing with TEPCO (4) about the Failure Strength of PCV

WGFNA made inquiries to TEPCO, about the failure strength of the PCV, and made a hearing with TEPCO on February 22, 2014. Details of the Q&A are shown in the following.

{Q1} The pressure of the PCV in Unit 2 increased well over the design pressure, and finally it had a maximum of about 0.75 MPa. At that time the catastrophic failure of the PCV was feared, but it is understood that the large scale failure was avoided actually, and that the decompression occurred by the leakage through the sealed parts. Is this understanding correct?
What is the proof pressure over which the failure of the PCV occurs? In another words, how is the safety margin estimated for the design pressure?
{A1} As for the failure strength over which the failure of the PCV occurs, we refer to the research done in the past about the resistance evaluation of the PCV [A11]. The critical values of the strength and openings of the top head flange and hatched parts, and heatproof temperature of the seal material were obtained by experimental and analytical studies. In TEPCO we think that the resistance of the PCV could be assured at most to 200℃, and twice the design pressure.

We estimate that the leakage from the PCV was caused by the loss of sealing ability due to the high temperature rather than the mechanical operation of the high pressure.

Reference
[A11] M. Goto et al., “Study for Ultimate Capacity of Typical BWR Containment Vessel in Japan,” Proceedings of ICONE3 (1995).

A12 High Pressure Coolant Injection System (HPCI) [A12-1]

The HPCI is the emergency core cooling system installed in all units (Fig. A12). It is driven by the high temperature and high pressure steam the same as in the case of the RCIC. By using the HPCI, it is possible to inject water into the RPV even if the RPV is at a high pressure. Since the amount of injected water is large, the HPCI is expected to be the trump card when such a serious accident happens as an LOCA. The HPCI was operated only for Unit 3 in the case of the Fukushima accident.

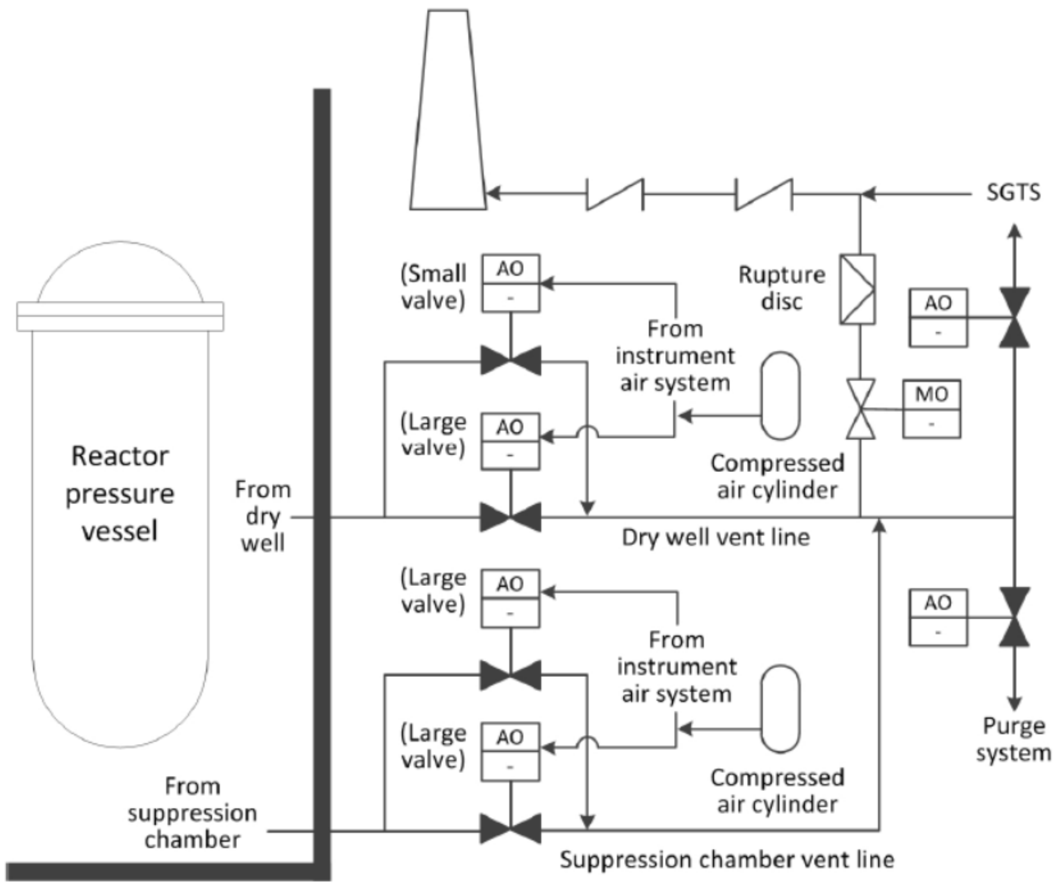

Fig. A12 Schematic of High Pressure Coolant Injection (HPCI) System [A12-2]

References

[A12-1] M. Fuchigami, N. Kasahara, and Y. Hatamura, "What Happened at the Fukushima NPS?" Technical Commentary on the Report of the Investigation Committee on the Accident at the Fukushima Nuclear Power Stations of TEPCO by the Cabinet Secretariat of the Government of Japan, Nikkan Kogyo Shinbun Co. Ltd., Tokyo (Dec. 25, 2012). (in Japanese)

[A12-2] Government of Japan, Nuclear Emergency Response Headquarters: "Report of the Japanese Government to the IAEA Ministerial Conference on Nuclear Safety — The Accident at TEPCO's Fukushima Nuclear Power Stations," Tokyo, (2011).
http://www.iaea.org/newscenter/focus/fukushima/japan-report

A13 Hearing with TEPCO (5) about the Operation of the HPCI at Unit 3

WGFNA made inquiries to TEPCO about the operation of the HPCI, and made a hearing with TEPCO on February 22, 2014. Main points of the Q&A are shown in the following.

{Q1} Was it possible to open the SRV and to decrease the pressure of the reactor before stopping the HPCI operation?
{A1} After start of the HPCI, the rotation speed of the turbine decreased with the decrease of reactor pressure, and it was below the lower limit of the required operational condition. The HPCI was still working although the RPV pressure decreased to the level below which the HPCI essentially stop working, that is, it would be isolated. If the SRV was opened in this situation, it would result in the further decrease of RPV pressure and the turbine vibration would become more severe. Finally, fatal damage would occur in the turbine system. This damage would produce the spread of steam inside the RPV into the HPCI room. Radioactivity from the steam would prevent recovery from the accident. This is the reason why we stopped the operation of the HPCI manually.

{Q2} The pressure was 0.8-0.9 MPa which was lower than the lower limit pressure of 1.03 MPa above which HPCI can work. Was it such a dangerous situation for the HPCI operational condition as to require an emergency stop of HPCI? Were there any symptoms such as significant vibration which suggested the need for an emergency stop?
{A2} From 2:00 on the 13th, the pressure of the RPV decreased further from 0.8 - 0.9 MPa, and the rotation speed of the turbine also decreased further. So, it was feared that the turbine would be destroyed by vibration. The discharge pressure of the pump was also decreased and reached almost that of the RPV. Therefore, the operators judged that the HPCI pump did not work effectively and that there would be no effective injection of water to the reactor core. Then, it was judged that the immediate change of the cooling system from the HPCI to the DDFP was necessary.

{Q3} How much water was injected into the reactor core by the HPCI at the time just before the stop? How long would the CST keep its water? Is it possible to think that the cooling by the HPCI was effective because reactor pressure was kept very low just before the HPCI stop?

{A3} TEPCO is now considering that the water supply to the reactor core was insufficient just before the HPCI stop. Estimated water flow rate was almost zero. The RPV pressure was kept low by the consumption of the steam from the reactor core to the HPCI turbine. The water level in the RPV was considered above TAF. Therefore, the core was cooled at that time.

{Q4} When and who decided the stop of the HPCI operation?

{A4} The operator on duty judged the necessity to change the cooling from the HPCI to DDFP, because the RPV pressure decreased further, and rotation speed of HPCI turbine decreased. And, the operator on duty has a right to stop the HPCI as a practical procedure. Before stopping the HPCI, the MCR operator and ERC staff shared their common perception that the DDFP would be operated after the HPCI.

{Q5} Was there any reasonable explanation for the delay of communication between operators on duty and the staff at TEPCO headquarters?

{A5} The MCR operators and ERC staff shared the common perception that the DDFP would be operated after the HPCI. But it took a little time for sharing this information, among all the staff of the ERC, and also the information about the situation of the SRV and operator's actions after the HPCI stop. The DDFP could not be operated soon after the HCPI was stopped, and in the meantime many attempts were taken by the staff of the power generation team in the ERC (for example, attempts to open the SRV and to restart the RCIC or HPCI). We do not consider the delay of communication affected the actions taken by the operators. Actually, at that time the situation was very complicated and communication tools were restricted. These are the reasons for the communication delay.

{Q6} Why could the SRV not be operated in spite of the successful actions of the inlet and stop valves just 3 minutes before?

{A6} At the time of the HPCI stop, the battery power had decreased considerably, and the SRV could not be operated. But still there is no analysis as to the reason.

{Q7} What was the status of the test line just before the HPCI stop? Was the valve in the test line still open? If it was open, would the water flow to the reactor core increase by closing the test line?
{A7} At 20:36 on the 12th, electric power was lost and the water level meter was not used. We could not check the water level of the reactor core. We did not notice the closure of the valve in the test line. Operators tried to increase the water flow of HPCI to reactor core. But this action was not effective. So, TEPCO considers that even if the valve was closed, the necessary amount of the water flow had not been kept.