Evaluation of plant behavior during the accident at Fukushima Daiichi Nuclear Power Station

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Abstract: The Great East Japan Earthquake that occurred at 14:46 on March 11, 2011, caused all off-site power to be lost at Fukushima Daiichi Nuclear Power Station (NPS), but the emergency diesel generators (EDGs) started up, and the electric power necessary for reactor safety was maintained. At 15:27 the first tsunami was observed, which far exceeded the design basis of the power plant and caused the loss of almost all safety functions of core cooling and containment. As a result, the reactor core was damaged in Units 1 to 3, and hydrogen explosions destroyed the reactor buildings (R/Bs) of Units 1, 3 and 4. Furthermore, since the spent fuel pool (SFP) cooling was also lost, external water was injected into the SFPs.

In Units 1 and 3, since depressurization of primary containment vessel (PCV) through the vent from suppression chamber (S/C) was completed, release of radioactive materials was controlled. On the other hand the PCV vent was not successful in Unit 2. Monitoring data rose sharply before noon on March 15 when Unit 2 PCV pressure dropped considerably and steam was seen coming from Unit 2 R/B. Winds blowing toward the north-northwest direction prevailed that day and rain fell in that direction at night, so it is likely that the contamination in high contamination zones around the plant resulted from a release of radioactive materials from Unit 2 R/B on March 15. Considering the field surveys and the design of the PCV, it is expected that the leak might have occurred at the seal of the PCV top head flange. In addition, as a result of evaluating the release of radioactive materials, the vent operations and the explosions at the R/Bs were not considered a major cause of contamination.

Keyword: core damage; MAAP; hydrogen explosion; release of radioactive materials

1 Introduction

This paper gives an overview of plant damage at Fukushima Daiichi due to the Great East Japan Earthquake and the huge tsunami on March 11, 2011 and the plant behavior during the accident of core melt of Fukushima Daiichi Nuclear Power Station (NPS) Units 1 to 3 using the Modular Accident Analysis Program (MAAP) [1], which contains fully-integrated modular models for primary system thermodynamics, core heat-up, degradation, melting, fission product release and so on, and the hydrogen explosion of R/Bs for the Fukushima Daiichi NPS Units 1, 3, and 4. Lessons learned from the accident and countermeasures enacted by Tokyo Electric Power Company (TEPCO) are also reported.

2 Overview of the Fukushima nuclear accident response

2.1 Great East Japan Earthquake

The main shock of the Great East Japan Earthquake that occurred at 14:46 on March 11, 2011, was a devastating earthquake of magnitude 9.0 (the fourth largest ever recorded in the world [2]). The earthquake caused massive slippage in the southern trench offshore of Sanriku and to a lesser extent in the northern area offshore of Sanriku and in the trench offshore of Bousou. The earthquake was caused by the movement of several seismic source regions offshore of: Sanriku, Miyagi Prefecture, Fukushima Prefecture and Ibaraki Prefecture (Fig.1). The focal area of the earthquake stretched from offshore of Iwate Prefecture to offshore of Ibaraki Prefecture, approximately 500 kilometers in length and about 200 km in width, with a maximum slip of more than 50 meters.

Though past seismic ground motion and tsunamis caused by individual source regions had been assessed, TEPCO, as well as the Headquarters for Earthquake Research Promotion (the Japanese government's earthquake investigation and research institution) had

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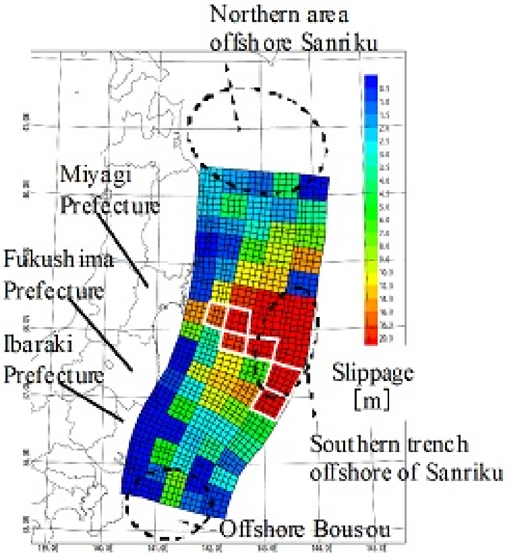

Fig.1 Tsunami wave source.

not expected that earthquakes would occur with the concurrent movement of all of the above regions.

The observed seismic motions at the Fukushima Daiichi NPS's R/B base mat partially exceeded the maximum acceleration used as the design basis seismic ground motion, Ss, the guideline for seismic safety assessment, however, it was largely below the design limits. On the other hand, the March 11 tsunami greatly exceeded the design basis, with the height evaluated as approximately 13 meters, which was more than twice the height resulting from evaluation based on the assessment method applied by the Japan Society of Civil Engineers (Onahama Peil - local construction datum level - O.P. +5.4 ~ 6.1 m).

2.2 Impact of the earthquake on the power station

Although off-site power was lost due to the seismic motion, the emergency diesel generators (EDGs) started successfully and supplied emergency power to the NPS. Also high pressure injection systems including the isolation condenser (IC) and the reactor core isolation cooling (RCIC) were in operation as expected without any abnormalities. Judging from the plant parameters, it was believed that there were no abnormalities with the integrity of reactor coolant system boundaries or associated equipment.

Seismic resistance of the main facilities that is important for reactor safety was assessed using earthquake response analysis based on observed earthquake data and it was confirmed that all calculated values were below the evaluation criteria as shown in Table 1.

Table 1 Seismic response analysis results for Fukushima Daiichi Units 1 to 3 main equipment

Unit MPa

Equipment		Unit 1		Unit 2		Unit 3	
		Calculated Value	Assement critical value	Calculated Value	Assement critical value	Calculated Value	Assement critical value
Reactor core support structure		103	196	122	300	100	300
Reactor pressure vessel		93	222	29	222	50	222
Main steam system piping		269	374	208	360	151	378
Reactor containment vessel		98	411	87	278	158	278
Shutdown cooling system	pump	8	127				
	piping	228	414				
RHR	pump			45	185	42	185
	piping			87	315	269	363
Other*		105	310			113	335

*Other listed equipment subject to assessment:
(Unit 1) Isolation condenser system pipes
(Unit 3) High pressure coolant injection system (HPCI) steam pipes

Furthermore, Fukushima Daiichi Units 1 to 6 were visually inspected to the greatest extent possible. Within the scope of those checks, items important to safety and even facilities of low seismic class were almost completely unaffected by the earthquake. From the results of these investigations, it is presumed that the earthquake itself did not affect the nuclear power plant's safe operation.

Meanwhile, at Fukushima Daini NPS, the emergency cooling system pumps which automatically started up after reactor scram, also operated with no abnormalities until the tsunami hit. The plants achieved cold shutdown safely with no core damage. Subsequent facility inspections found no damage to the functional performance of safety-critical equipment except for damage by the tsunami. Thus, it is considered that the earthquake had no impact on the functionality of safety-critical systems.

2.3 Direct damage to the Fukushima Daiichi NPS from the Tsunami

At Fukushima Daiichi NPS, the tsunami run-up reached the ground level of major buildings (O.P.+10 m on Units 1 to 4, O.P.+13 m on the Units 5 & 6), and it is recognized that the flooded areas covered the entire major building area. The flood height on Units 1 to 4 was approximately O.P. +11.5 m to 15.5 m, and flood depth approximately 1.5 to 5.5 m. On the side of Units 5 and 6, the flood height was approximately O.P. +13 m to +14.5 m, and flood depth approximately 1.5 m or less.

It was confirmed that flooding by the tsunami induced damage to building entranceways, EDG intake louvers and aboveground equipment hatches. Sea water also entered the EDG room and power panel room located on the underground floor. Since the tsunami was far higher than the ground level of the emergency seawater system pumps (O.P. +4 m), the tsunami caused these pumps (installed outdoors) to be submerged, resulting in loss of safety system function (Fig.2).

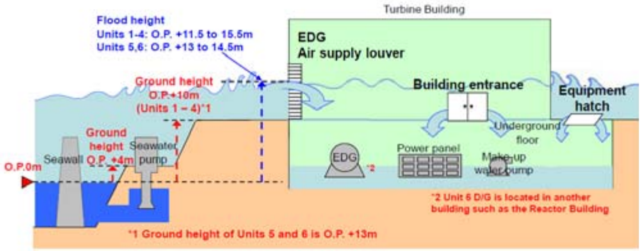

Fig.2 Path of inundation into major buildings (Fukushima Daiichi NPS).

Subsequently many power panels were inundated and all EDGs in operation were shut down except for Unit 6. This caused the loss of all AC power (station black out (SBO)) and resulted in the loss of all cooling functions using AC power. Furthermore, due to flooding of the cooling system seawater pumps, the heat removal function of transferring decay heat from the reactor to seawater was lost. In addition, Units 1 and 2 lost DC power concurrently with the tsunami's impact. On the other hand, DC power at Unit 3 withstood the tsunami and the core cooling systems were able to deliver water to the reactor core, but subsequently these core cooling systems stopped - mostly due to the depletion of DC power.

As for Fukushima Daiichi Units 5 and 6, since one of Unit 6's EDGs was functioning and feeding its electric power to Unit 5, water could be injected into the core for both Units 5 and 6. The heat removal function was thereby restored and cold shutdown of these units was achieved (Table 2).

Table 2 Damage to Fukushima Daiichi NPS (Power Source-related)

	1F-1	1F-2	1F-3	1F-4	1F-5	1F-6
Off-site power source	×				×	
EDG	×	△	×	△	△	○
Emergency high-voltage power panel (M/C)	×	×	×	×	×	○
Normal high-voltage power panel (M/C)	×	×	×	×	×	×
Emergency low-voltage power panel (P/C)	×	△	×	△	×	○
Normal low-voltage power panel (P/C)	×	△	×	△	△	×
DC power source	×	×	○→△	×	○	○
Seawater pump	×	×	×	×	×	×

○: Operable
△: EDG main unit not damaged by water, but inoperable due to M/C and related equipment being submerged
×: Inoperable

Furthermore, because of a total station blackout, there were limited communications measures and lighting in the main control rooms (MCRs). Out in the yard, tsunami-induced debris and residual water, as well as the risk of being hit by another tsunami, made working conditions even more difficult.

2.4 Direct damage to the Fukushima Daini NPS from the Tsunami

At Fukushima Daini NPS, although the entire seaside area of O.P. +4 m was flooded (flood height approximately O.P. +7 m), there were no watermarks of the tsunami run-up breaching the slope to the O.P. +12 m major buildings area. Since the damage was less than that of Fukushima Daiichi NPS, the difficulties of accident response were entirely different (Fig.3).

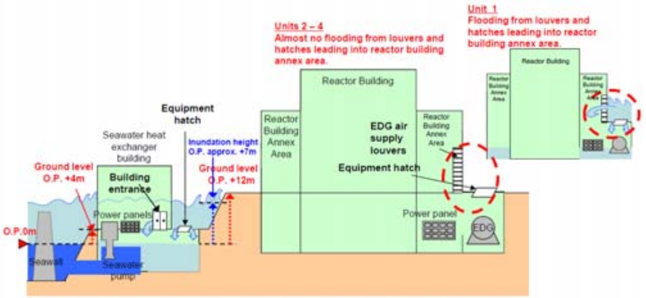

Fig.3 Path of inundation into major buildings (Fukushima Daini NPS).

At Fukushima Daini NPS, the tsunami caused the loss of emergency seawater system pump facilities at Units 1, 2 and 4. This prevented residual heat from being removed to the sea. However, since off-site power remained available for all units, it was possible to use alternate low pressure water injection systems such as the Make-up Water Condensate System (MUWC). MCRs' monitoring and operating functions were also maintained (Table 3).

Table 3 Damage to Fukushima Daini NPS (Power Source-related)

	2F-1	2F-2	2F-3	2F-4
Off-site power source	○			
EDG	×	△	○	○
Emergency high-voltage power panel (M/C)	△	○	○	○
Normal high-voltage power panel (M/C)	○	○	○	○
Emergency low-voltage power panel (P/C)	△	△	△	△
Normal low-voltage power panel (P/C)	○	○	○	○
DC power source	△	○	○	○
Seawater pump	×	×	△	×

○: Operable
△: EDG main unit not damaged by water, but inoperable due to M/C and related equipment being submerged
×: Inoperable

Analysis has shown that the difference in the tsunami heights at Fukushima Daiichi NPS and Fukushima Daini NPS was caused by the degree of superposition of tsunami waves occurring in different epicentral areas (Fig. 4).

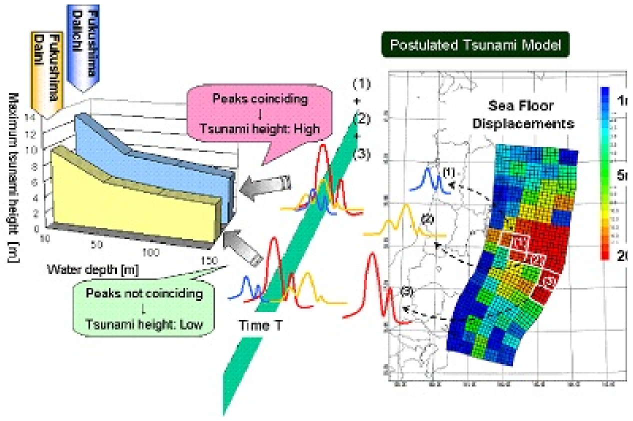

Fig.4 The superposition analysis results of tsunami (image).

3 Plant behavior of Fukushima Daiichi NPS units

In this section, the plant behavior during the accident, the MAAP analysis and the hydrogen explosions in the R/Bs for the Fukushima Daiichi NPS Units 1 to 4 are described in detail. Also analyses are being done for Fukushima accident by various organizations [3-5].

3.1 Unit 1

The earthquake caused an automatic reactor scram at Unit 1. Due to the loss of off-site power, the main steam isolation valves (MSIVs) closed automatically and the reactor was isolated. Reactor pressure dropped immediately after the scram then increased after the closure of MSIVs. The IC automatically started up upon receipt of the high reactor pressure signal. Reactor pressure was then controlled within the pressure range by manual operation of valves to start and stop the IC because the IC was to be operated so as not to exceed the reactor pressure vessel (RPV) cooling-down rate.

At 15:37 on March 11, all AC and DC power were cut by the tsunami onslaught. Accident management measures for supplying power from adjacent units had been prepared against delays in AC power restoration or unavailability of DC power. However, during the accident, power could not be restored promptly due to loss of power fed from offsite transmission lines, widespread inoperability of EDGs and inundation of onsite power panels.

Although almost all safety functions were lost due to the tsunami at this time, it was very difficult to confirm the condition of plant equipment. Moreover, since the instrumentation for confirming plant condition became inoperable, it was difficult to recognize what actions were required.

Although the procedures for maintaining reactor water level using the IC at the time of SBO had been prepared, the IC did not function because the valves were closed after the loss of DC power caused an isolation signal. Moreover reactor depressurization could not be performed, therefore reactor water injection using low-pressure pumps was impossible. As a result, reactor water level fell and the core was damaged (Fig.5). When DC power supply was temporarily restored after 18:00 on March 11, an attempt was made to open the IC valves, and according to the MAAP analysis, reactor water level was already lower than the top of active fuel (TAF). So, it is unlikely that the IC function was effective. After 21:00, although the reactor water level was indicated as higher than TAF, later investigation shows that the reactor water level gauge had already malfunctioned by this time.

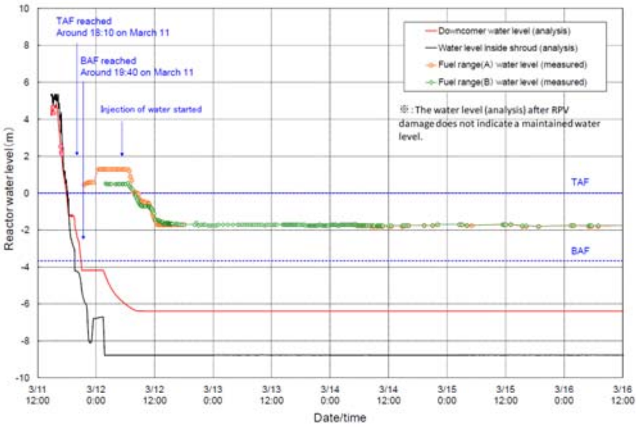

Fig.5 Trend in reactor water level (Unit 1).

After 20:00 on March 11, it was confirmed that reactor pressure was about 6.9 MPa [gauge] and before 03:00 on March 12, it decreased to about 0.8 MPa [gauge] (Fig.6). According to the MAAP analysis, the RPV was damaged before 02:00 on March 12 and almost all of the molten core had fallen onto the pedestal beneath the RPV.

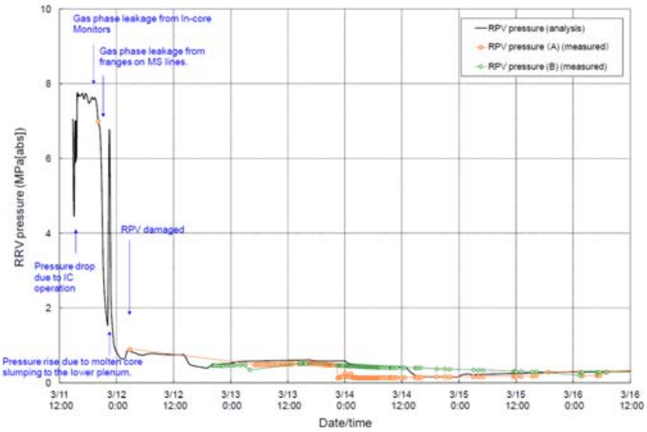

Fig.6 Trend in reactor pressure (Unit 1).

On the other hand, dry-well (D/W) pressure was confirmed as 600kPa [abs] for the first time around 00:00 on March 12. Considering the maximum operating pressure, 427kPa [gauge], this was excessive even in the situation of an accident (Fig.7). This could happen if there was a direct leak from RPV to PCV. So it is believed that the core damage caused a failure in the in-core instrumentation piping and the leakage from the flange sections of such parts at the safety relief valve (SRV) pipe beds. Thereby, it is presumed that reactor pressure fell before the RPV was damaged. Not long after, D/W pressure increased to 840kPa [abs], which means that RPV pressure and D/W pressure were equalized at the time.

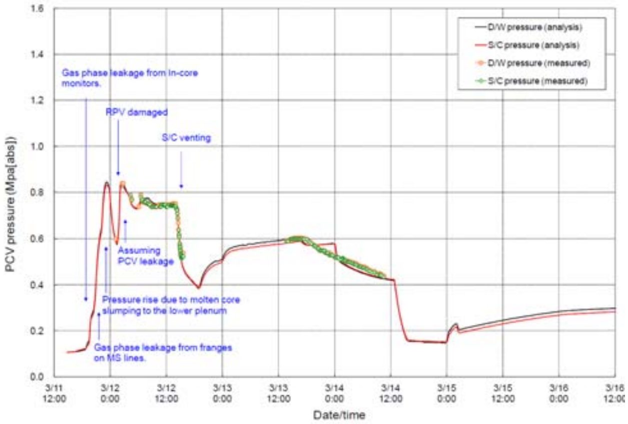

Fig.7 Trend in PCV pressure (Unit 1).

Water was injected into the reactor by fire engines after core damage, thereby suppressing progress of molten core concrete interaction (MCCI). Concrete erosion depth estimated by MAAP analysis was about 70 cm. After confirmation of D/W pressure, preparation for S/C vent operation was initiated. Because all the power supplies had been lost, field operation was necessitated and there were many difficulties in conducting the operation. After checking the completion of local resident evacuation, the air operated (AO) bypass valve along with the hardened vent line was opened after 10:00 on March 12 and the radiation dose rate near the main gate increased temporarily (Fig.8). After 14:00 on March 12, the S/C vent valve was opened and D/W pressure was decreased, however the radiation dose rate near the main gate did not increase. So, it is estimated that vent at Unit 1 did not release a large amount of radioactive materials that could have contributed to the contamination.

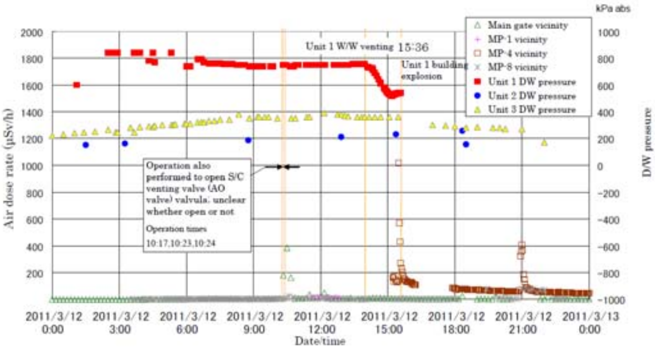

Fig.8 D/W pressure and monitoring data (March 12).

A hydrogen explosion occurred in the R/B topside at 15:36 on March 12. Although the cause of the explosion was not immediately determined, it is estimated that when the core fuel was damaged, hydrogen was generated as a result of zirconium-water reaction. This hydrogen then leaked out via the PCV to the R/B and finally the hydrogen exploded. In the explosion at Unit 1, all walls of the 5th floor were blown off and the ceiling collapsed onto the 5th floor of the R/B (Fig.9). Since the structure of the 5th floor walls of Unit 1 were of steel-frame construction and not reinforced concrete construction, it is presumed that the walls were damaged in the early stage of the explosion.

Another possibility is that the hydrogen might have escaped from the PCV vent line via the standby gas treatment system (SGTS) line into the R/B. However, there was a flow control damper which could have prevented hydrogen back-flow and the entire R/B was severely contaminated, which would not be expected if the vent gas passed through the SGTS filter. Therefore the majority of hydrogen must have leaked directly from the PCV into the R/B. From the PCV design information, it is presumed that the main route which hydrogen in the PCV transferred to the R/B was via the seal of the PCV head flange.

Fig.9 Appearance of Unit 1 R/B after explosion.

3.2 Unit 2

The earthquake caused an automatic reactor scram at Unit 2 and the reactor was isolated. RCIC was started up manually in accordance with operating procedures and injected water into reactor. SRVs were automatically operated and stabilized reactor pressure. Although the RCIC stopped due to a high reactor water level signal, it was manually restarted again at 15:39 on March 12. All AC and DC power were blacked out by the tsunami onslaught as was the case with Unit 1 and instrumentation became inoperable. Although the RCIC was restarted before the tsunami onslaught, it was impossible to control due to the loss

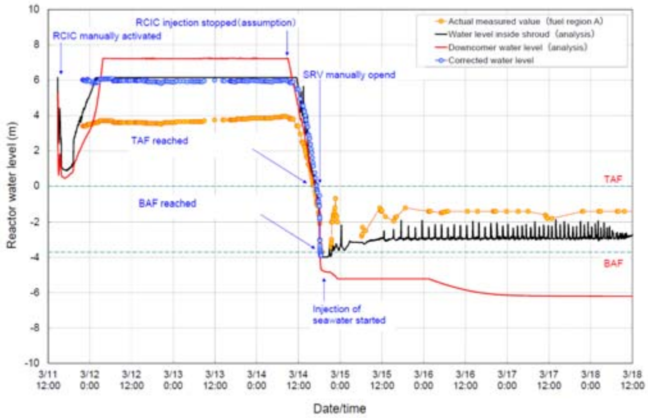

Fig.10 Trend in reactor water level (Unit 2).

of DC power supply. Until 02:55 on March 12, operators were unable to confirm the RCIC operation, however, the RCIC continued its operation without any operator control for about three days and the reactor water level was maintained (Fig.10).

Under normal conditions, the RCIC stops upon receipt of a high reactor water level (Level 8) signal but in Unit 2 after the tsunami this signal never came because of the loss of all electrical power. This situation enabled continuous RCIC operation using a two phase flow turbine driven mechanism. In this situation, since high enthalpy coolant flowed out of the RPV, it could be explained that reactor pressure was maintained below SRV actuation set point (Fig.11).

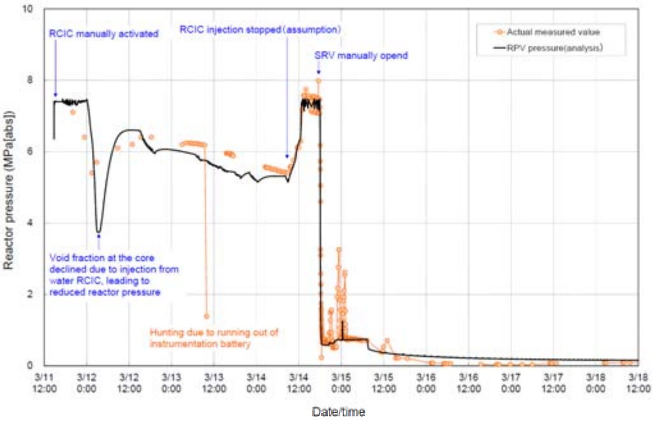

Fig.11 Trend in reactor pressure (Unit 2).

Moreover, measured D/W pressure was lower than that expected for this kind of accident. Since the tsunami water was confirmed to have entered the torus room of Unit 4 which is a similar plant to Unit 2, the assumption of water ingress to the torus room was applied in Unit 2 D/W pressure calculations. As a result, the behavior of measured D/W pressure has been reproduced by MAAP analysis (Fig.12).

At around 13:00 on March 14, the Technical Support Center (TSC) of Fukushima Daiichi NPS judged that the RCIC had lost its function considering the reactor water level drop. Although the reactor was depressurized by SRV using electricity from car batteries to power the actuator and fire engines began water injection into the reactor, the core cooling was apparently insufficient and the reactor core was damaged. After core damage, hydrogen which was generated as a result of zirconium-water reaction caused the D/W pressure to increase rapidly.

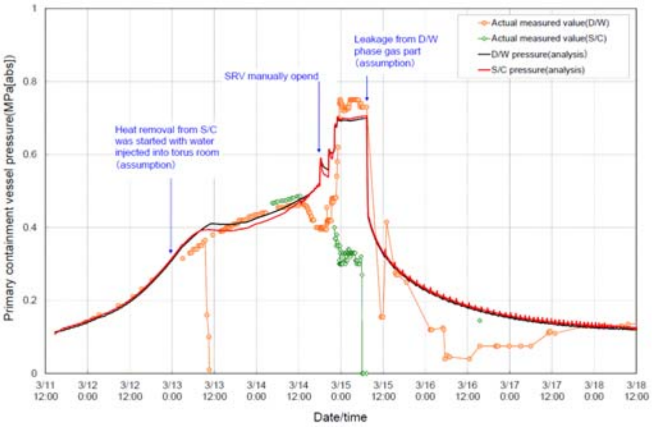

Fig.12 Trend in PCV pressure (Unit 2).

After 21:00 on March 14, the AO bypass valve along with the hardened vent line was opened and the radiation dose rate near the main gate increased temporarily (Fig.13). However, it is unknown whether the rupture disk, which was installed along with the vent line, was opened in this operation.

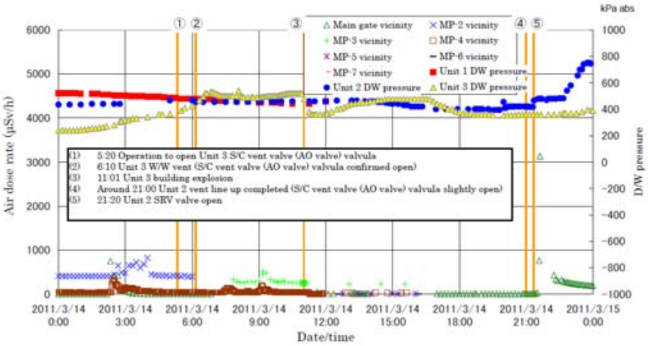

Fig.13 D/W pressure and monitoring data (March 14).

An impact sound and vibrations occurred at around 06:14 on March 15. At nearly the same time, S/C pressure decreased and it was reported that pressure was 0 kPa [abs]. These confusing condition readings led to the consideration that S/C damage had occurred. However, from seismometer observation records, it was determined that the large vibration and sound was caused by the explosion at Unit 4 at 06:12.

Since S/C pressure significantly differed from the D/W pressure from the night of March 14, an error was assumed to have occurred in the S/C pressure instrumentation. An investigation conducted days later confirmed that the S/C pressure indicator had dropped off the scale at that time, thereby it was judged to have been the result of an instrumentation malfunction.

After 07:00 on March 15, Unit 2 D/W pressure dropped considerably while being out of operation, and monitoring data near the main gate increased sharply (Fig.14). Since winds blowing toward the north-northwest direction prevailed that day and the contaminated areas had rain on that day, it is possible that the contamination in high contamination zones was the result of the radioactive releases from Unit 2 R/B on March 15. Considering the design of the PCV, it is thought that the leak might have occurred at the seal of the PCV top head flange.

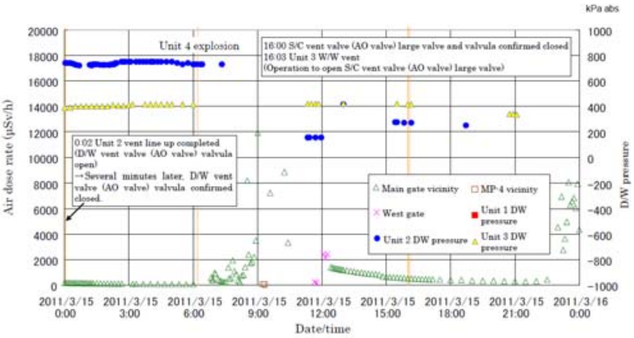

Fig.14 D/W pressure and monitoring data (March 15).

After core damage, a considerable quantity of hydrogen was generated in the PCV and gas including hydrogen leaked into the R/B. It is presumed that a hydrogen explosion did not occur because the gas was released from the blowout panel (BOP) which had been blasted off by the shock of the hydrogen explosion at Unit 1.

3.3 Unit 3

The earthquake caused an automatic reactor scram at Unit 3 and the reactor was isolated. The RCIC was started up manually to inject water into the reactor in accordance with operating procedures. SRVs operated automatically and stabilized reactor pressure.

After the tsunami onslaught, all AC power was blacked out but DC power was retained. Reactor water level was maintained thanks to the activation of the RCIC and HPCI (Fig.15). After the RCIC stopped, the HPCI started automatically due to a low reactor water level (level 2) signal, and the reactor depressurized to about 1 MPa [abs]. This phenomenon was the result of the operator's action to ensure continuous operation of the HPCI in order to maintain a stable reactor water level. In this situation, continuous steam supply to the HPCI turbine enabled the reactor to depressurize (Fig.16).

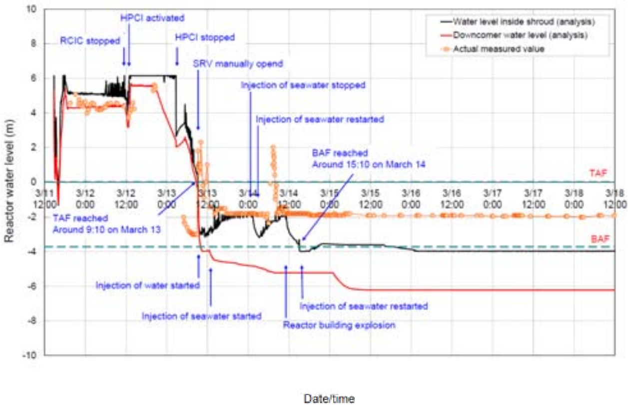

Fig.15 Trend in reactor water level (Unit 3).

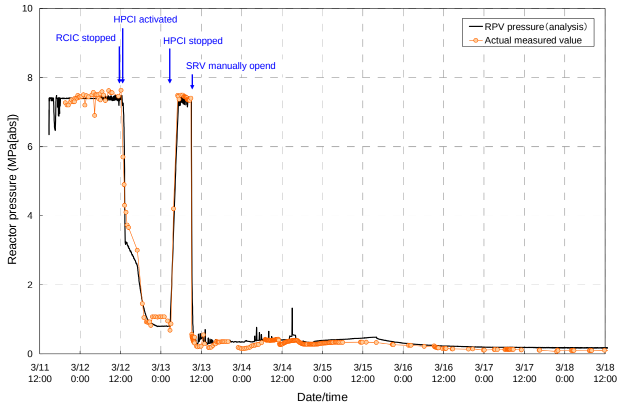

Fig.16 Trend in reactor pressure (Unit 3).

The HPCI was manually stopped at 02:42 on March 13 because of concerns over equipment failure in the situation that the reactor pressure decreased to the level of automatic system isolation, however this did not eventuate. The reactor water level dropped gradually and operators attempted to inject water into the reactor. Although the reactor depressurized afterwards and water was injected by fire engines, core cooling was not sufficient to prevent core damage.

Since D/W pressure exceeded the maximum operating pressure, S/C vent was carried out several times to avoid PCV failure. The fact that D/W pressure responded consistently to vent operation, means that it is likely that PCV integrity was maintained or that damage was minor at that time (Fig.17).

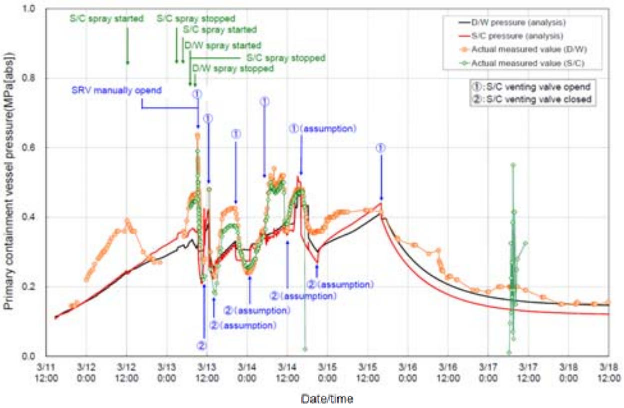

Fig.17 Trend in PCV pressure (Unit 3).

In addition, although monitoring data near the main gate increased temporarily from the direct radiation of the radioactive plume at the time of the first vent, a significant increase of monitoring data was not confirmed for the later vents (Fig.18). So, it is assumed that the vent did not release a large amount of radioactive materials that could have contributed to the contamination.

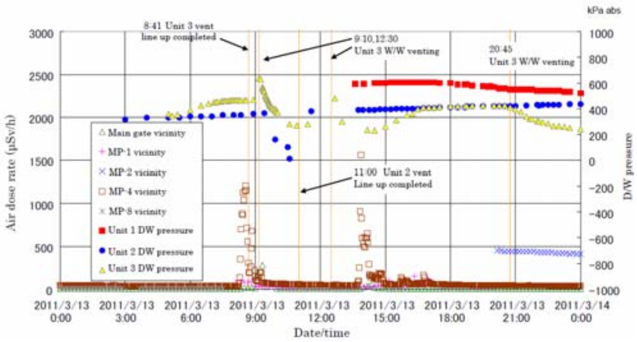

Fig.18 D/W pressure and monitoring data (March 13).

Since it was believed that hydrogen could accumulate within the R/B as was the case at Unit 1, measures to release hydrogen from the R/B were considered. These measures included "opening the BOP" and "perforation in the R/B roof." These were not ultimately performed because they would require work at high elevation, with no lights, in a high radiation area where there was a high risk of sparks causing an explosion. Regrettably, a hydrogen explosion occurred at 11:01 on March 14 (Fig.19).

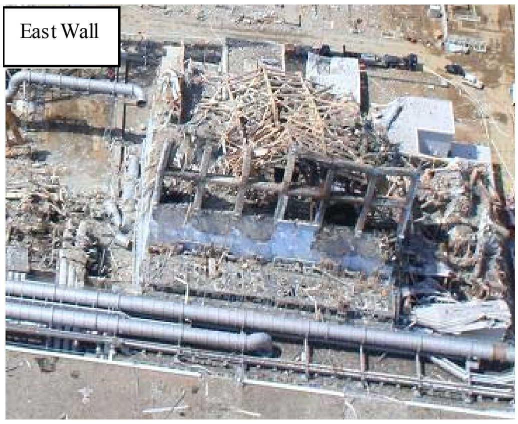

Fig.19 Appearance of Unit 3 R/B after explosion.

Similar to the Unit 1 explosion, hydrogen leakage via the PCV was judged to be the main route (Fig.20). This is supported by the results of investigations into Unit 3 SGTS filter radiation level, which is much lower than within the R/B. This means that the amount of vent gas that passed through the SGTS filter was limited if at all. From the PCV design information, direct leakage from the PCV to the R/B is expected to have occurred at the seal of the PCV head flange or equipment hatch.

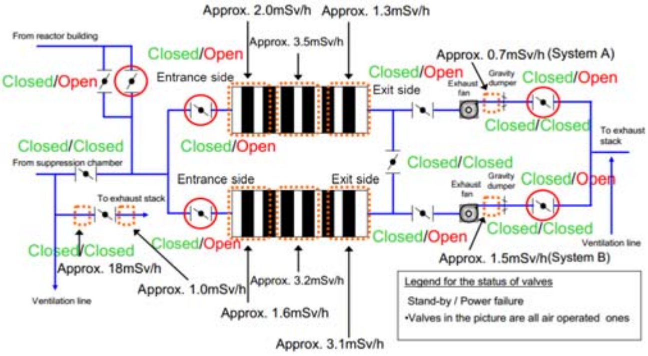

Fig.20 Measurement of radiation dose of SGTS filters at Unit 3 (conducted on December 22, 2011).

3.4 Unit 4

Unit 4 was under outage for periodic inspection when the earthquake occurred. All fuel had been removed from the reactor to the SFP. All AC and DC power was lost due to the tsunami arrival around 15:30 on March 11. SFP cooling and feedwater functions were also lost. Operators confirmed SFP water temperature was 84ºC at 04:08 on March 14.

On March 15, a hydrogen explosion occurred in the Unit 4 R/B (Fig.21), which not only made cooling water injection into the SFP difficult but also prompted concern about the status of fuel stored in the Unit 4 SFP. On the next day, March 16, TEPCO employees flew over the Unit 4 SFP in a Self-Defense Force helicopter and confirmed that the water level was being maintained as expected. By subsequent analysis, it turned out that the water of the reactor well flowed into the SFP through the pool gate and the water level was maintained even higher than originally expected. Cooling water injection at Unit 4 using concrete pump trucks began on March 22. Furthermore, a nuclear species analysis of the pool provided no data that indicates fuel damage.

Fig.21 Appearance of Unit 4 R/B after explosion.

In Unit 4, although there was no possibility of hydrogen generation from the reactor and the SFP was not exposed, a hydrogen explosion occurred. From the radioactive dose measurement at Unit 4 SGTS filters, it was found that the radiation dose level of the downstream filter was higher than those of the upstream filters (Fig.22). So the PCV vent gas from Unit 3 was judged to have flowed into the Unit 4 R/B through the SGTS piping which was inter-connected at the bottom of the common exhaust stack. Different from other Units, the SGTS design of Unit 4 had no dampers which would close when AC power was lost. Furthermore, from the survey results below it is presumed that the explosion first occurred near the exhaust duct on the 4th floor of the R/B.

- the 5th floor of Unit 4 was pushed up
- the exhaust ducts are missing in the 4th floor
- many types of rubble on the 4th floor seems to be the wreckage of the ducts.

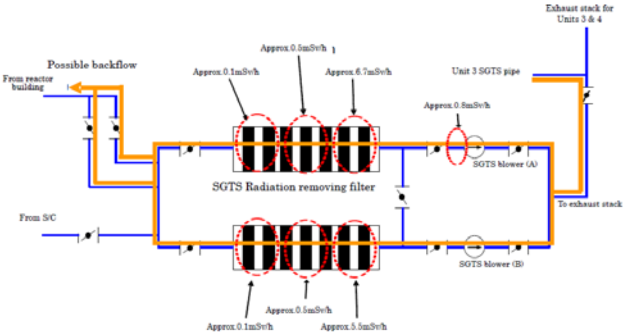

Fig.22 Measurement of radiation dose of SGTS filters at Unit 4 (conducted on August 25, 2011).

4 Atmospheric releases of radioactive materials

Evaluation of major events when radioactive materials were released into the atmosphere (Fig.23, Table 4) and the causes of high level contamination areas to the northwest of Fukushima Daiichi NPS are as follows:

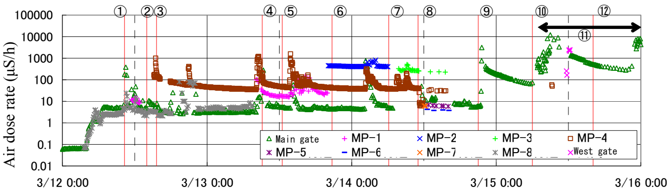

Fig.23 Monitoring data.

- The release of particulate radioactive materials at the time of vent was limited on the whole due to the scrubbing effect in the suppression pool and the amounts released were smaller in comparison to that from the R/B of Unit 2. So, TEPCO considers that the vent operation had minor impact on the total contamination load.
- Judging from the monitoring data at the time of the explosions of Units 1, 3 and 4 R/Bs, the amounts of release were quite small compared to that from Unit 2 R/B, and TEPCO does not consider this to be a major cause of the total contamination.

Table 4 Evaluation of the release of radioactive materials into the atmosphere

No.	Date/time	Unit	Event	Amount released (PBq)			
				Noble gases	I-131	Cs-134	Cs-137
①	March 12 after 10:00	1	Unknown*	3	0.5	0.01	0.008
②	March 12 after 14:00	1	S/C vent	4	0.7	0.01	0.01
③	March 12 15:36	1	Building explosion	10	3	0.05	0.04
④	March 13 after 09:00	3	S/C vent	1	0.3	0.005	0.003
⑤	March 13 after 12:00	3	S/C vent	0~0.04	0~0.009	0~0.0002	0~0.0001
⑥	March 13 after 20:00	3	S/C vent	0~0.003	0~0.001	0~0.00002	0~0.00002
⑦	March 14 after 06:00	3	S/C vent	0~0.003	0~0.001	0~0.00002	0~0.00002
⑧	March 14 11:01	3	Building explosion	1	0.7	0.01	0.009
⑨	March 14 after 21:00	2	Unknown*	60	40	0.9	0.6
⑩	March 15 06:12	4	Building explosion	--	--	--	--
⑪	March 15 after 07:00	2	Release from building	100	100	2	2
⑫	March 15 after 16:00	3	S/C vent	0~0.003	0~0.001	0~0.00002	0~0.00002
Total (including amount released which does not identify events)				Approx.500	Approx.500	Approx.10	Approx.10

*Both S/C vent or release from building can be considered, but event can not be specified.

- As shown in Fig.23, dose rates taken on March 15 show a rapid increase from several hundred to tens of thousands μSv/h near the main gate over several hours after 07:00 and then a decrease to approximately 1,000μSv/h at noon on the same day. The dose rate measured at 23:00 increased to close to 10,000μSv/h again. Considering the wind patterns on the day, it is believed that a large amount of radioactive materials were released continuously throughout this time period.
- Since Unit 2 PCV pressure decreased substantially between 07:00 and 11:00 on the same day and white smoke was seen coming from Unit 2 R/B (Fig.24), it is highly likely that Unit 2 was the source of the release.
- Radioactive release from the R/B of Unit 2 on March 15 in conjunction with winds to the north-northwest (Fig.25) and rain fall (Fig.26) had a major impact on the contamination. The reason for this amount of release is that the

Fig.24 Fukuichi live camera (around 19:00 on March 15).

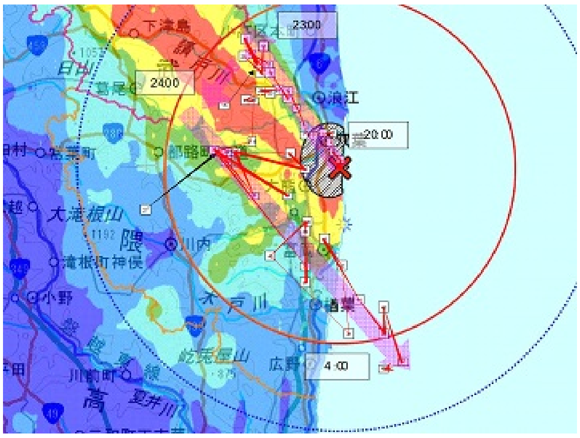

Fig.25 Path of plume released from Unit 2 after 20:00 on March 15.

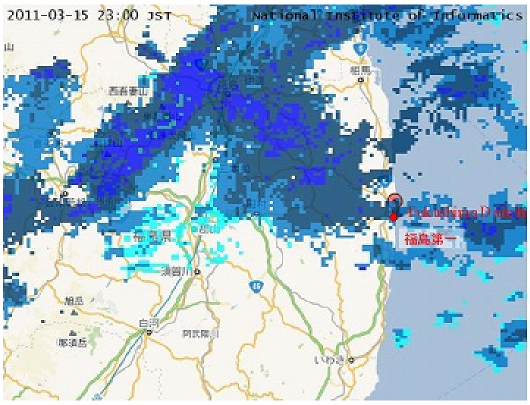

Fig.26 Rain clouds radar map in Fukushima Prefecture at 23:00 on March 15.

emissions from Unit 2 bypassed the suppression pool and there was therefore no scrubbing effect.

5 Lessons learned from Fukushima accident and countermeasures

In summary, the lessons learned from the Fukushima accident are as follows [6]:

1) During the earthquake, all reactors automatically scrammed and off-site power was lost. Considering the success of EDGs start-up and plant parameter trends, it is judged that no significant damage occurred due to the earthquake directly.
2) The design basis for tsunamis had been revised, however, a 13m high tsunami exceeded far beyond the design basis when it struck the power station. This historically gigantic tsunami damaged almost all power panels leading to the loss of all power supply.
3) Because of prolonged loss of AC / DC power and ultimate heat sink, all efforts to cool down the reactor core proved ineffective. This led to core melt resulting in a hydrogen explosion.
4) Since the Fukushima accident was far beyond design basis accident (DBA), even the systems and components prepared for accident management, such as water injection to reactors and/or PCV, instruments, illumination, and PCV venting all lost their functions.
5) The aftermath of the tsunami and explosions resulted in rubble being scattered throughout the yard. This seriously hindered the workers' recovery efforts.

Based on lessons learned above, TEPCO believes it is essential as countermeasures from a safety perspective to consider the response capability to resolve the accident even on the premise that the function of nearly all equipment in the power station is lost. Therefore, countermeasures after Fukushima accident from both hardware and software perspectives are being considered as follows:

1) Hardware countermeasures
   a. Buildings / Water-intakes
   - Tide wall, Reinforced water plates / Watertight-doors

   b. Water injection / Cooling
   - Enhanced water-tightness for pumps, Fire-engines
   - Precut cables / Connecting terminals

   c. Depressurization
   - N_2 cylinders, Batteries for opening valves

   d. Power supply
   - Mobile power supply, Spare portable batteries, Enhanced water-tightness

   e. Hydrogen accumulation prevention
   - "Top venting" of R/B, Opening BOP

   f. Infrastructure
   - Off-site power, Rubble removal, Communication system, Lighting, Radiation protection.

   g. Mid-to-long term items
   - Reliable / Filtered venting, Post-accident instrumentation, Improvement in reliability of high-pressure injection system
2) Software countermeasures
   a. Organization, Command and control, Roles and responsibilities, Resources
   b. Information sharing / Plant status recognition
   c. Transportation of resources
   d. Access control
   e. Radiological protection
   f. Public relations / Conveying information
   g. Cooperation with government

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