Chapter 2
Event Sequence of the Fukushima Daiichi Accident

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Abstract On March 11, 2011, the Great East Japan Earthquake and subsequent tsunami hit Fukushima Daiichi Nuclear Power Station. Flooding by the tsunami induced loss of AC and/or DC power for reactor cooling, hence the reactor water level decreased and fuel was exposed. Water reacting with high temperature fuel metal covering resulted in hydrogen generation and hydrogen explosion of reactor buildings. This accident caused radioactive release to the environment. In this chapter, an attempt has been made to understand in detail the mechanism of the accident progression for Units 1–3 that were in operation by utilizing results of computer simulations. It should be noted that, due to limited information and capability of the state-of-the-art severe-accident simulation tools, there are still unanswered questions, which should be tackled by academic research for improving and enhancing safety for the nuclear industry now and in the future.

Keywords Fukushima Daiichi nuclear power station・Severe accident・Accident progression・Great East Japan earthquake・MAAP simulation

2.1 Overview of the Accident

The Tohoku-Chihō-Taiheiyō-Oki Earthquake[1] (the Earthquake, hereafter) and ensuing tsunami, which occurred on March 11, 2011, led the Fukushima Daiichi Nuclear Power Station (NPS) to a situation far beyond design basis accidents and was even

[1] The earthquake is also often referred to in Japan as the Great East Japan Earthquake. In the Press Conference by Prime Minister Naoto Kan on April 1, 2011, it was announced that the Cabinet decided to officially name the disaster the Great East Japan Earthquake.

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further exacerbated by multiple failures assumed in developing accident management measures. Consequently, Units 1–3 ultimately experienced severe accidents; although they were successfully shut down, they lost functions related to cooling.

On March 11, 2011, Units 1–3 of Fukushima Daiichi NPS were in operation, while Units 4–6 had been shut down for periodic inspection outage. Due to the shock of the Earthquake that occurred at 14:46, the safety function of Units 1–3 was actuated by the seismic over-speed trip signal, which resulted in automatic shutdown of all reactors in operation at the time.

Due to the collapse of the electric tower connection to off-site, all power supply from off-site to Fukushima Daiichi NPS was lost, but the emergency diesel generators (EDGs) started up as expected, and the electric power necessary to maintain safety of the reactors was acquired.

Later, the tsunami hit the Futaba area of Fukushima Prefecture where Fukushima Daiichi NPS is located. It was one of the largest in history. Many of the power panels were inundated, and the EDGs, except for Unit 6, stopped, resulting in the loss of all alternating-current (AC) power and, consequently, loss of all the cooling functions using AC power at the site. As a consequence, core-cooling functions not utilizing AC power were put into operation, or, alternatively, attempts were made to put them into operation. These were the operation of the reactor core isolation cooling system (RCIC) in Unit 2, and the operation of the RCIC and the high-pressure injection system (HPCI) in Unit 3.

Units 1–3 had a different process, but in the end the loss of direct-current (DC) power resulted in the sequential shut down of core cooling functions that were designed to be operated without AC power supply. Then, due to water evaporation by decay heat and depressurization boiling, the reactor coolant in the reactor pressure vessel gradually decreased, which caused boil-dry of the fuel. Accordingly, water injection was attempted through an alternative water path by joining fire engines with the fire protection system and make up water condensate system (MUWC), but water could not be injected into the reactor vessels in Units 1–3 for a certain period of time.

Due to exothermic chemical reaction between steam and zirconium (Zr) included in the fuel cladding tube, $Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$, massive heat was generated, causing the fuel to melt and the generation of a substantial amount of hydrogen.

Subsequently, in Units 1 and 3, explosions, which appeared to be caused by hydrogen leakage from the primary containment vessel (PCV), destroyed the upper structure of their respective reactor buildings.[2]

2.2 Unprecedented Mega-Earthquake

The Earthquake on March 11, 2011 was of the biggest scale ever observed in Japan. Kurihara City in Miyagi Prefecture observed a maximum seismic intensity of 7 on the scale ranging between 0 and 7 defined by the Japan Meteorological

[2] Japanese BWR was designed to replace gas inside PCV with nitrogen to prevent hydrogen explosion inside PCV.

Agency (JMA),[3] and seven high tsunami waves were observed along the Pacific coastline from Hokkaido and Tohoku to the Kanto region.

It has been reported that the Earthquake occurred offshore of Miyagi Prefecture at a depth of 23.7 km where the Pacific plate sinks beneath the North American plate. The size of the source area extended from offshore Iwate Prefecture to offshore Ibaraki Prefecture, being about 500 km long (north to south), about 200 km wide (east to west), and with about 50 m in maximum slip. There was a massive slip observed in the southern trench side off the Sanriku coast and part of the trench sidel off Northern Sanriku coast to far south off the Boso Peninsula in Chiba Prefecture. Multiple regions, including offshore Central Sanriku, offshore Miyagi Prefecture, offshore Fukushima Prefecture and offshore Ibaraki Prefecture, moved simultaneously and the magnitude was 9.0 on the Richter scale at the hypocenter. A mega-earthquake of this scale was unexpected even in Japan, which is known to be seismically active.

It is worth noting that a mega-earthquake such as the Earthquake was not presumed in the national earthquake research projects engaged in by the majority of Japanese experts [1]. It was indeed a huge earthquake, the focal area of which covered a much broader area. Many unknown matters remain about the causes of such massive synchronized earthquakes. It is necessary, therefore, to monitor the research progress in Japan and overseas on the mechanism and to incorporate the latest knowledge about them in the consideration for design and operation of nuclear reactors.

The intensity of ground motions at Fukushima Daiichi NPS was at about the same level as those assumed in the seismic design, upon comparison of observed values and analysis results. Most of the frequency bands were below the values set for the seismic design, although some of the observed values for the reactor-building basement (the lowest basement floor) had exceeded the maximum acceleration corresponding to the design basis for earthquake ground motion (see Table 2.1). The reactor systems were found to be intact even with the impact of the Earthquake, from the observed plant operation status and the results of seismic

Table 2.1 Ground motion at Fukushima Daiichi NPS due to the earthquake on March 11, 2011

Unit #	Acceleration [gals]						Ratio of observed to max BDB		
	Observed			Maximum beyond design basis (BDB)					
	N–S	E–W	Vertical	N–S	E–W	Vertical	N–S	E–W	Vertical
1	460	447	258	487	489	412	0.9	0.9	0.6
2	348	550	302	441	438	420	0.8	1.3	0.7
3	322	507	231	449	441	429	0.7	1.1	0.5
4	281	319	200	447	445	422	0.6	0.7	0.5
5	311	548	256	452	452	427	0.7	1.2	0.6
6	298	444	244	445	448	415	0.7	1.0	0.6

[3] See http://www.jma.go.jp/jma/en/Activities/inttable.html

assessment using observed ground motions; the main equipment having important functions for safety maintained its safety functions during and immediately after the Earthquake.

2.3 Tsunami

The tsunami was designated as Mw 9.1 in an index for indicating the scale of tsunami [2, 3], and was the fourth largest ever observed in the world and the largest ever in Japan.

Replication calculations [2, 3] based on a wave source model, which utilizes data for fault lengths, fault widths, locations, depths, slip scales, etc., could reproduce the Earthquake well; the simulation results for tsunami tracks, inundation heights, tsunami bore levels, submerged areas, and diastrophism in the area from Hokkaido to Chiba Prefecture agreed well with the actual observation. The simulation results indicate that an especially large slip (about 50 m at maximum) occurred near the Japan Trench.

The estimated tsunami heights based on the estimated wave source were about 13 m at Fukushima Daiichi NPS and about 9 m at Fukushima Daini NPS. It was confirmed by the simulation that multiple waves overlapped and arrived at the coast due to the wide range of the epicenter area. Therefore, the main reason for this height difference was considered to be that the peaks of tsunami waves, which were generated in regions with large slips, estimated to be off Miyagi Prefecture and off Fukushima Prefecture, overlapped at Fukushima Daiichi but not as much at Fukushima Daini.

Many unknown matters remain about the causes of such massive tsunami. It is necessary, therefore, to monitor the research progress in Japan and overseas on tsunami generation mechanisms and to incorporate the latest knowledge on massive synchronized earthquakes with accompanying tsunami in design approaches.

The tsunami waves which hit Fukushima Daiichi NPS exceeded not only the 4-m ground level above O.P.[4] (hereafter described as 4 m ground level), where seawater pumps had been installed, but also the 10 m ground level, where key buildings had been constructed, and also flowed into the buildings through openings and other routes. Consequently, motors and electrical equipment were flooded, and important systems such as emergency diesel generators and power panels were directly or indirectly affected and lost their functions.

The wave force of the tsunami appeared to be strong enough to partially destroy openings of the buildings at the ground level such as doors, shutters, etc. These damages are considered due directly to the tsunami or to floating wreckage. Parts of heavy oil tanks, which had stood on the seaside area within the Fukushima Daiichi NPS, seemed to have been pulled away from their positions by wave force and buoyancy. But no significant damage was noticed on the building structures

[4] This stands for Onahama Peil, and means the height measured from the Onahama Port construction standard surface.

such as walls or pillars of key buildings. Furthermore, most of the breakwater and seawall banks stand as before, with no major impact having been confirmed, although part of northern breakwater with a parapet was damaged.

Regarding the arrival times of tsunami, the following findings have been concluded through analyzing continuous photographs and chronologically arranging the incidents at the time of the arrival at the site of the tsunami that accompanied the Earthquake.

- The tsunami, which affected various systems and equipment at the power plant, arrived at the Fukushima Daiichi NPS site sometime between 15:36 and 15:37, hereafter described as the 15:36 level.
- The tsunami maximum wave arrived from almost directly in front of the site with no major delay.
- Seawater system pumps located near the sea (4-m ground level) lost their functions mostly at the 15:36 level.
- Many systems and much equipment lost their functions in a limited time when there were no aftershocks,[5] indicating it was the tsunami that caused the losses of power.

2.4 Accident Progression for Units 1–3

The Modular Accident Analysis Program (MAAP) is a computer code used by nuclear utilities and various research organizations to simulate the progression of severe accidents in a light water reactor (LWR) [4]. The MAAP code cannot completely replicate the Fukushima Daiichi accident at the present time because of incomplete understanding about actual mechanisms and what the data indicate. Yet, the simulation is useful for checking the correctness of our understanding about severe accidents and constructing an integrated view of the accident; the discrepancy between simulation results and measurements gives valuable clues for further investigation. In this section, a summary of the accident progression of Fukushima Daiichi Units 1–3 is shown based on results recently obtained by validation studies for the MAAP code by comparing the simulation results with measured data. In this section as well, the accident progression is described by focusing on reactor water level and RPV/PCV pressure.

Fission-product (FP) atoms tend to have many neutrons compared to stable isotopes and are relatively unstable. Therefore, FPs decay to stable isotopes while releasing some energy. This energy liberated from FP is called decay heat. In a nuclear reactor, continuous removal of the decay heat is required even after termination of the nuclear fission reactions.

If decay heat cannot be removed, the water level in the reactor core decreases due to boiling. While it is better to maintain high pressure in RPV for sufficient

[5] There were 9 aftershocks in the Tohoku region until 15:25 after the main shock at 14:46. However, there was no further aftershock until 16:28.

steam supply, it becomes impossible to insert water into the reactor externally at a high-pressure condition. Therefore, the pressure should be decreased sooner or later, depending on what type of the low-pressure injection system it is equipped with.

During the early stage of an accident under the situation of loss of ultimate heat sink (LUHS), because there are no measures to release the energy contained in the reactor core, PCV pressure is considered to indicate the degree of accumulation of decay heat. After the core uncovering has started, the massive pressure increase indicates hydrogen accumulation in the core, and a high degree of generation of metal water reaction, because PCV of Boiling Water Reactor (BWR) Mark-I was designed to suppress by condensing the steam released from RPV. PCV venting is the only way to release the energy to the environment in such a situation; however, this means a break in the PCV boundary, which is designed to prevent FP release. Again, there is a problem in the use of a low-pressure water injection system under high PCV pressure, so the pressure must be decreased. For this depressurization actuation, PCV venting is important, as in case of failure of the venting attempt, massive fission product might be emitted to environment.

2.4.1 Unit 1

As a result of the analysis for Unit 1 by comparing simulation results by MAAP to actual measurements, Fig. 2.1 shows the reactor water level changes, while Figs. 2.2 and 2.3 show changes of the reactor pressure and PCV pressure, respectively. In these figures, MAAP simulation results are labeled as "(analysis)." In this section, accident progression for Unit 1 is described in accordance with the following accident chronology (Table 2.2).

In Unit 1, all the cooling capability was lost due to the tsunami. Therefore, Unit 1 fell into a severe condition within 3 or 4 h after the Earthquake. It was not until the next morning (March 12) that TEPCO could inject water into RPV. And then, PCV venting was conducted at 14:30 on March 12. After that, the hydrogen explosion occurred.

2.4.1.1 From the Earthquake to Tsunami Arrival

At Unit 1, two isolation condenser (IC) systems[6] were automatically activated due to the reactor pressure increase following the scram[7] caused by the Earthquake. After that, the two IC systems were manually shut down and then IC subsystem-A was started up. The reactor pressure was controlled by manually repeating the

[6] The isolation condenser (IC) system transfers residual and decay heat from the reactor coolant to the water in the shell side of the heat exchanger resulting in steam generation.

[7] The sudden shutting down of a nuclear reactor, usually by rapid insertion of control rods, either automatically or manually by the reactor operator. Also known as a "reactor trip".

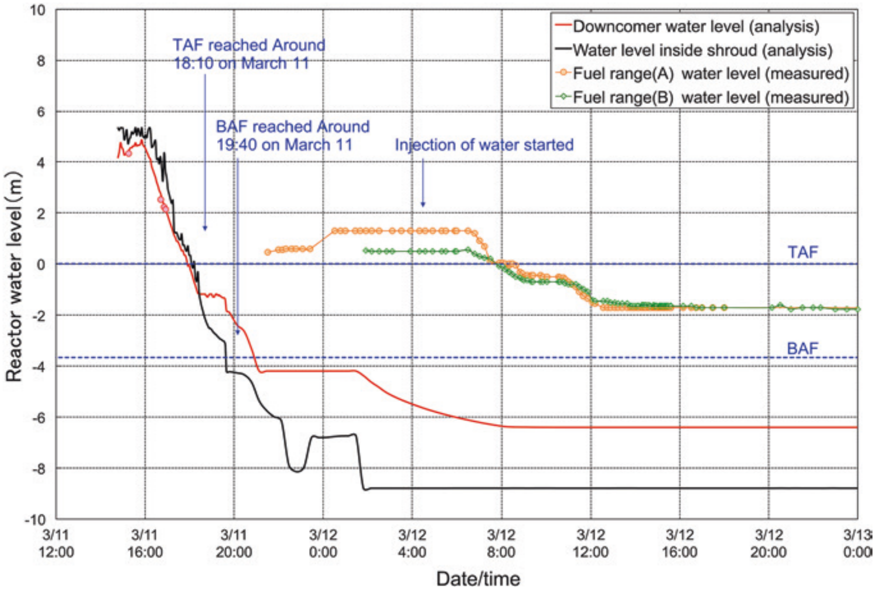

Fig. 2.1 Reactor water level change for Unit 1

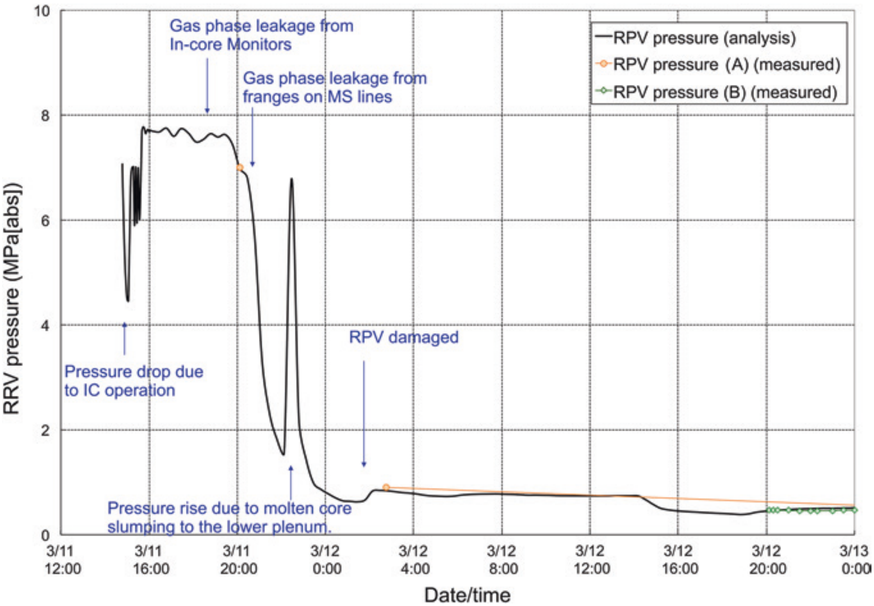

Fig. 2.2 Reactor pressure changes for Unit 1

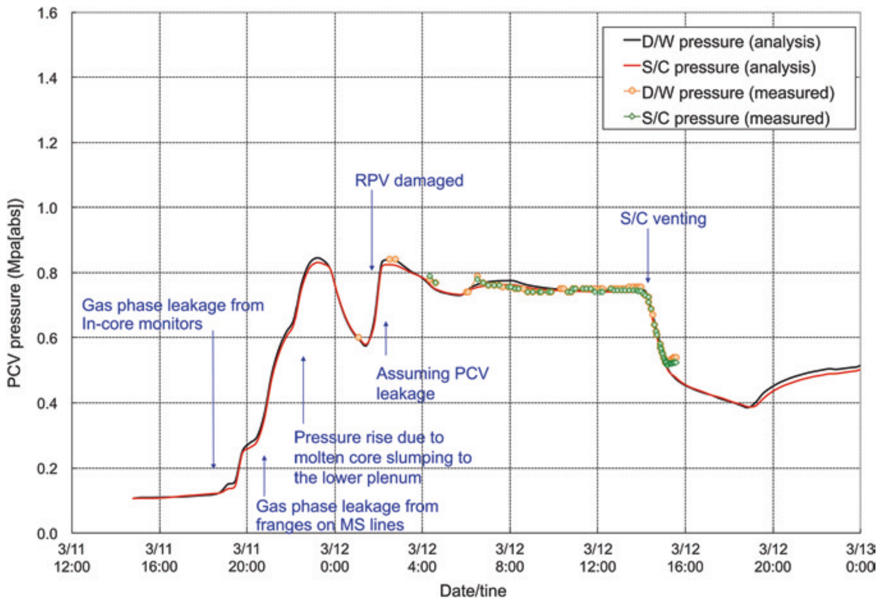

Fig. 2.3 PCV pressure changes for Unit 1

Table 2.2 Chronological accident description for Unit 1

Date	Time	Event	Section
3/11	14:46	Earthquake: reactor was automatically shutdown. Decay heat was continuously generated	2.4.1.1
		Loss of off-site power: DG was automatically started. Therefore, AC and DC power were available in this period	
	14:52–15:34	IC cooling: reactor was cooled by IC with start-stop operation so that RPV cooling down rate did not exceed 55 °C/h. Unit 1 was operated to achieve cold shutdown	2.4.1.1
	15:37	Tsunami hit: AC and DC were lost. IC was not in operation at this time	2.4.1.2
	After tsunami	RPV water inventory decrease due to no water injection	2.4.1.3
	18:10[a]	Core uncovering: Starting fuel heat up	2.4.1.3
	18:50[a]	Core damage started	2.4.1.3
	After 20:00	Containment vessel pressure increased	2.4.1.4
3/12	01:50[a]	RPV bottom damage: Corium (melted fuel) slumping to PCV pedestal	2.4.1.4
	14:30	Regarding the containment vessel vent, operation of AO valve of suppression chamber side was implemented at 10:17 am, and a pressure decrease was confirmed at 2:30 pm	2.4.1.5
	15:36	Reactor building explosions	2.4.1.6

[a]Time from MAAP calculation

start-up and shutdown of IC subsystem-A to maintain the pressure at a certain level. Maneuvering actions such as the starting up of the suppression chamber (S/C) in the cooling mode of the containment cooling system (CCS) were also being taken in parallel for a cold shutdown of the reactor. At 15:37 on March 11, 2011, however, all AC power supplies were lost due to the tsunami, followed by the loss of DC power supply.

Regarding the influence of the Earthquake, the issue of the possibility of a loss-of-coolant accident (LOCA) caused by the Earthquake was examined as described in Attachment 1–3 of Ref. [2].

2.4.1.2 From the Tsunami Arrival to Reactor Water Level Decrease

All cooling capabilities, including the steam-driven cooling system as well as motor-operated pump, were lost due to loss of control power, and all displays of monitoring instruments and various display lamps in the Main Control Room went out due to the loss of all AC and DC power. Approximately from 16:42 to 17:00 on March 11, 2011, part of the DC power supply was temporarily recovered, allowing the reactor water level to be measured for a while, which helped to confirm that it had decreased from the earlier level before the arrival of the tsunami. The level observed (by the wide range water level indicator) at 16:56 on March 11 was at the top of active fuel (TAF) +2,130 mm and had not decreased yet to TAF, although it was continuing to decrease (Fig. 2.1).

The analysis results shown in Fig. 2.1 suggest that the reactor water level reached TAF at about 18:10 on March 11, and the core damage started at about 18:50 (fuel cladding temperatures reached about 1,200 °C).

Even if the fuel starts to be uncovered, steam cooling prevents it from conspicuous temperature rises as long as sufficient steam is supplied from below. While decrease of the amount of steam generation due to decrease of water level progresses, once fuel claddings can no longer be cooled by steam cooling and their temperatures reach about 1,200 °C, large amounts of hydrogen are generated by water-zirconium reactions and the energy released from their oxidation reactions further raises fuel temperatures.

The situation continued that the IC operation could not be confirmed. When part of DC power supply was temporarily recovered, it was observed that the isolation valve outside the containment of IC subsystem-A was operable (the status display lamp was “Closed”). The shift operators took action to open the valve at 18:18 on March 11. The operators confirmed that the status display lamp changed from “Closed” to “Open,” and they heard the steam generating sounds and saw steam above the reactor building, but the amount of steam was limited and it stopped a while later. Due to the operators’ confirmation that steam generation had stopped and concern about the water inventory left in the IC shell side tank, at 18:25 the operators closed the isolation valve outside the containment on the return pipe. At 21:30 the operators took action again to open the isolation valve outside the PCV and confirmed the steam generating sounds and saw steam above the reactor building.

2.4.1.3 From the Reactor Water Level Decrease to PCV Pressure Increase

Reactor pressure of 7.0 MPa[abs] was measured at 20:07 on March 11 (Fig. 2.2), and drywell (D/W) pressure of 0.6 MPa[abs] at about 23:50; on March 12, D/W pressure of 0.84 MPa[abs] was measured at 02:30 and reactor pressure of 0.9 MPa[abs] at 02:45 (Fig. 2.3). In the meantime, although the exact timing is unknown, it was observed that at a certain time after 20:00 on March 11, the PCV pressure showed a sharp rise and the reactor pressure decreased despite no depressurization actions. BWR with MARK-I PCV is designed to suppress pressure increase by condensation at the suppression pool by steam from the reactor. Therefore, the sharp pressure rise is considered to be caused by gas leakage to the drywell.

A scenario was assumed in the analysis that steam had leaked from in-core instrumentation dry tubes or main steam pipe flanges due to temperature rise in the vessel caused by overheating of uncovered fuel and fuel melting.

When the fuel range water level indicators[8] recovered functionality at 21:19 on March 11 due to the temporary power supply, they showed that TAF was located at +200 mm, but the reactor water level indicators seemed to have already been defective. In this period, there would be no conceivable reason for an increase in water level because no water was injected to RPV. This detail is described in Attachment 1–2 of Ref. [2].

The meltdown accident progressed as follows: When heated to high temperatures, fuel melted down from the core to the lower plenum, and then further down to the bottom of the PCV by breaking through the reactor vessel.

2.4.1.4 From Containment Vessel Pressure Increase to Containment Venting Operation

At about 23:50 on March 11, the D/W pressure measured 0.6 MPa[abs]. Thereafter, the indicator continued displaying high values. At around 04:00 on March 12, the dose rate near the main gate of the NPS site started to show an upward trend, which may have resulted from radioactive materials leaked from Unit 1.

It is highly possible that the molten fuel dropped to the bottom of the reactor vessel and further to the bottom of the PCV before 19:04 on March 12, when fire engines started continuous water injection into the reactor. It is possible that the relocation of molten fuel to the PCV raised the PCV pressure and temperature even more. This scenario is related to the amount of the water injected by fire engines [2].

When the molten fuel cannot be sufficiently cooled, the concrete of the PCV floor is heated up above its melting point and core-concrete reactions start, which

[8] Fuel range water level indicators are designed for use in LOCA condition to monitor core uncovering. Hence, it is calibrated in atmospheric pressure. Narrow and wide water level indicators are designed for use in normal operation. They are calibrated in operating pressure condition.

dissolve the concrete. The core-concrete reactions generate non-condensable gases such as hydrogen, carbon monoxide, etc., resulting in a large impact on the containment pressure change and radioactive release behavior. But it is unknown to what extent core-concrete reactions actually occurred at that moment.

The D/W pressure was being maintained at about 0.7–0.8 MPa[abs], after reaching 0.84 MPa[abs] at about 02:30 on March 12, until PCV venting was successful. This fact of constant PCV pressure gives a strong suggestion that the PCV was leaking, because the PCV pressure should rise; when steam is produced due to water injection, PCV temperature rises, and gases are generated by core-concrete reactions, etc.

Fresh water was injected by fire engines from about 04:00 to 14:53 on March 12. But, since the fire protection system and make-up water system used for water injection are separated from the interior of the plant, part of the injected water had gone to other systems and equipment, not to the reactor. The analysis could yield consistent results with actual measurement data for containment pressures by assuming that the injection had not been enough to flood the core region and that only a fairly small amount of water, compared to the actual amount of discharged water by the fire engines, had been injected to the reactor.

2.4.1.5 From the Containment Venting Operation to Reactor Building Explosion

Three times at 10:17, 10:23, and 10:24 on March 12 the operation to open the small S/C vent valve was carried out from the main control room. There was no visible response in the D/W pressure,[9] while the dose rate near the main gate increased temporarily at 10:40. A while later, when a temporary air compressor was connected to open the large S/C vent valve and it was started up at about 14:00, an up-current of steam above the stack was observed by a live camera and the D/W pressure decreased from 14:30 until about 14:50. No dose rate increase was observed near the main gate and monitoring post-8 (MP-8).

After the opening operation of the large S/C vent valve, the D/W pressure decreased from 14:30 through about 14:50. Later at 15:36, hydrogen in the reactor building exploded and the roof and outer walls of the uppermost floor were damaged.

It can be considered that hydrogen gas generated mainly by water-zirconium reactions, which leaked together with steam and finally reached the reactor building, resulted in the hydrogen explosion. But its leak path, volume, explosion aspects, and ignition source are still unknown.

[9] S/C small vent valve is for easing the opening of S/C large vent valve while equalizing pressure by opening the small valve in case the large valve was difficult to open due to the pressure difference. Therefore, flow amount when opening the small valve is small.

2.4.1.6 From the Reactor Building Explosion to March 18

At 19:04 on March 12 after the reactor-building explosion, seawater injection was started by fire engines.

Water injection to Unit 1 and Unit 3 was halted once at 01:10 on March 14, when the water source used for these two units was depleted. Water injection to Unit 3 was resumed at 03:20 under critical conditions, when the water source was partly recovered by using an additional water supply, but water injection to Unit 1 was delayed. Water injection to Unit 1 and Unit 3 was again halted with the hydrogen explosion at Unit 3. Water injection to Unit 1 was eventually interrupted from 01:10 to 20:00.

Meanwhile, almost the whole core of Unit 1 dropped down to the lower plenum and most of that part dropped further to the containment pedestal, according to the analysis. There are many unknown matters concerning the location of debris, and the final status of accident progression.

2.4.2 Unit 2

As a result of the MAAP analysis for Unit 2, Fig. 2.4 shows the reactor water level changes, while Fig. 2.5 shows the reactor pressure changes, and Fig. 2.6 shows the PCV pressure changes. In this section, accident progression for Unit 2 is described in accordance with the following accident chronology (Table 2.3).

In Unit 2, despite the fact that both AC and DC power were lost due to the tsunami, RCIC continued operation without control for almost 70 h. However, Unit 2 fell into severe accident mode because of lack of water injection. PCV venting was never successful. Hydrogen explosion had not occurred, but FPs were released to the environment.

2.4.2.1 From the Earthquake to Tsunami Arrival

At Unit 2, the following operation steps were taken towards cold shutdown: start-up and shutdown of the reactor core isolation cooling (RCIC) system,[10] start-up of the residual heat removal (RHR) system[11] in the S/C cooling mode, etc. Unit 2 lost all power supplies due to damage by the tsunami at 15:41 on March 11. At Unit 2, as the RCIC system had been manually started up at 15:39 just before the DC power for control was lost, water injection to the reactor could continue after the tsunami arrival. This was the major difference between the situations of Unit 1 and Unit 2, i.e., at Unit 1 the IC had been shut down before the tsunami arrived, and therefore the IC could not be restarted upon loss of the control power supply, which resulted in a rapidly deteriorating situation.

[10] The RCIC system is a single train standby system for safe shutdown of the plant.

[11] The residual heat removal (RHR) system is typically a multiple-use system with modes of operation for low-pressure injection, shutdown cooling, suppression pool or containment sump cooling, and/or containment spray.

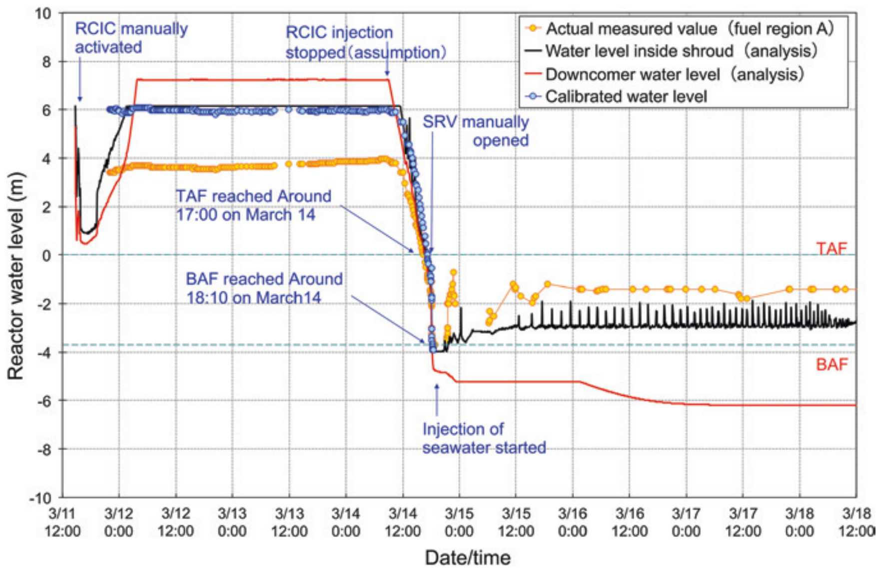

Fig. 2.4 Reactor water level change for Unit 2

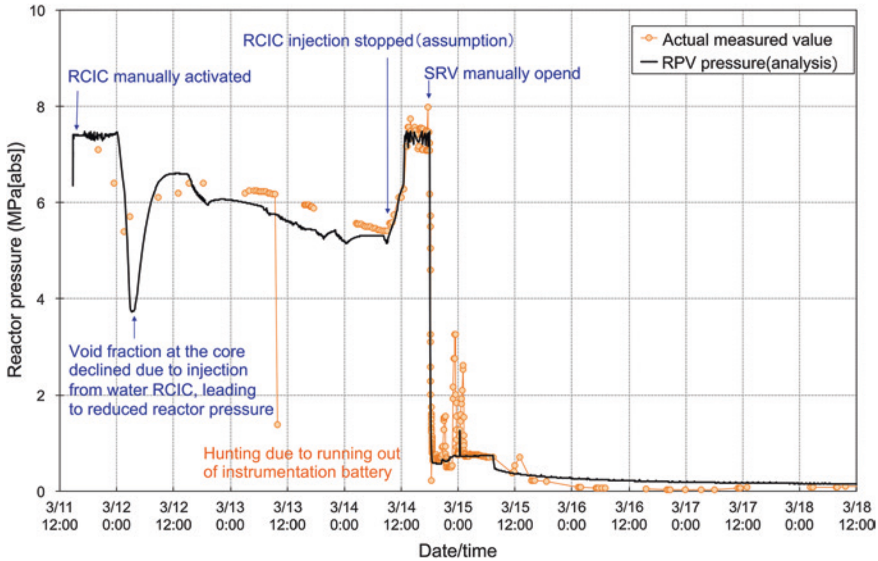

Fig. 2.5 Reactor pressure change for Unit 2

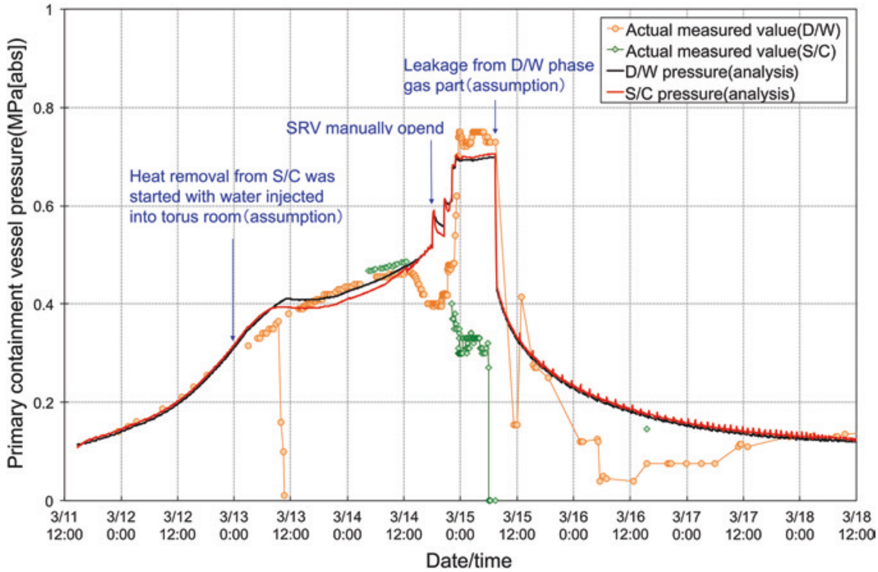

Fig. 2.6 PRC pressure changes for Unit 2

Table 2.3 Chronological accident description for Unit 2

Date	Time	Event	Section
3/11	14:46	Earthquake	2.4.2.1
		Loss of off-site power	
	14:50–15:41	RCIC injection: reactor was cooled by RCIC, even though RCIC was tripped several times due to RPV water level being too high	2.4.2.1
	15:37	Tsunami hit: AC and DC were lost. RCIC had been in operation for 2 min	2.4.2.2
	After tsunami	Reactor water level was increased and maintained by RCIC manual operation	2.4.2.3
3/14	9:00	RCIC operation was terminated due to some reason	2.4.2.4
	After RCIC termination	RPV water inventory decreased due to boiling	2.4.2.4
	17:00[a]	Core uncovering: starting fuel heat up	2.4.2.4
	18:02	Forced depressurization by SRV	2.4.2.5
	19:20[a]	Core damage started	2.4.2.5
3/15	After 7:20	PCV pressure deceased	2.4.2.6

[a]Time from MAAP calculation

2.4.2.2 From Tsunami Arrival to Reactor Water Level Increase

A possibility was hinted that the RCIC system was in operation, with no control power supply due to the tsunami, being driven by water-steam mixture, i.e., two-phase flow, which had been generated when the reactor water level increased to a level above the main steam line since water started being injected more than the amount of loss by steam; thus water was flowing into the steam piping, as in Attachment 2–1 of Ref. [2]. But no detailed behavior prior to the water level increase to the main steam line has been confirmed.

Reactor pressure was not at the level expected from normal RCIC operation during this period. In normal RCIC operation, reactor pressure would be maintained within the safety relief valve (SRV) activation and reset pressure, because the RCIC turbine cannot consume enough energy generated by decay heat; the rest of the steam should be released through SRV. Although the density of energy contained in water is less than steam, the density of mass is much larger than steam. Therefore, all of the decay heat was removed through the RCIC turbine line without SRV activation. This is the reason why reactor pressure varied in the range between 5 and 7 MPa. The changes in the reactor pressure in Unit 2 is further described in Attachment 2–1 of progress report [2].

In the analysis, the water injection rate was assumed to be 30 % of the rated value, which replicated the measured reactor pressure changes during the period while the RCIC was considered to be driven by two-phase flow. According to the results under this condition, the reactor pressure levels calculated during the time period prior to the water level increase up to the main steam line rose more slowly than the measured values. This raises the need to investigate the RCIC behavior after loss of power supply due to the tsunami (see Attachment 2–4 of progress report [2]).

2.4.2.3 From Reactor Water Level Increase to Loss of RCIC Functions

After the reactor water level increased by the consecutive operation of RCIC, no accurate water levels could be estimated, because the fuel range reactor water level indicators had reached their maximum limit of measurement. The reactor pressure, however, started to decrease after the RCIC started up. When it reached 5.4 MPa[abs] at 01:30 on March 12, the reactor pressure began to rise again (Fig. 2.5). In the time sequence, this pressure change had no relation to the switchover of water sources from 04:20 through about 05:00 on March 12, but can be explained by the (general) relationship between saturation temperature and pressure. It is expected that the accident progression can be better explained by identifying the amount of water injected by RCIC with which MAAP simulation reproduces the pressure rise observed at 1:30 on March 12.

Incidentally, the reactor water levels measured were higher than the “reactor water level high (L-8)” (upper limit of water level measurement) after correction of the reactor pressure increase and containment temperature increase (Fig. 2.4).

While the RCIC operation was continued with no control power supply, the reactor pressure is considered to have remained at lower levels than the level at normal operation for the following reasons:

- The reactor water level rose above L-8 because of no control of the RCIC valve apertures for adjusting steam flow rates.
- Decay heat energy was removed from the reactor by low quality two-phase flows.
- The water was injected by the RCIC at a lower flow rate than the rated value, because the RCIC turbine was operated by low quality two-phase flows.
- Thus, the energy in the reactor vessel was kept balanced without steam release by SRV operation required in the original design.

The reactor pressure varied in a downward trend again from about 06:00 on March 13 (Fig. 2.5). This can be understood as the effect of decreased decay heat with time. Thereafter, the pressure increased again after it was measured as 5.4 MPa[abs] at 09:00 on March 14 and reached 5.6 MPa[abs] at 09:35. MAAP could reproduce the gradual reactor pressure increase, assuming interruption of water injection by the RCIC system (but steam supply to its turbine continued) at 09:00 on March 14. The sharp change in the trend of the reactor pressure was considered to be a reflection of the change in the status of water injection by RCIC.

The containment pressure varied at lower levels than anticipated (Fig. 2.6), despite the fact that all the decay heat was stored in the S/C, because of the loss of the ultimate heat sink (LUHS). In the process of Unit 2's accident progression, it is considered that the SRV located in the transfer path of energy from RPV to PCV did not operate when the RCIC was in operation. This means the RCIC exhausted two-phase steam that had flowed into the S/C, accompanied by the energy equivalent to the decay heat energy. Therefore, the energy stored in the S/C must have raised the containment pressure. Some energy flow-out is required for lower than expected PCV pressure. As the scenario of this energy flow-out, tsunami-induced seawater inundating the reactor building is assumed to transmit energy and heat to the exterior from PCV through the S/C wall. Further investigation is discussed in Attachment 2–6 of progress report [2].

2.4.2.4 From Loss of RCIC Functions to Forced Depressurization by SRV Operation

Although it has not been clarified at what time the RCIC system shut down, the reactor water level started to decrease gradually after RCIC stopped, uncovering the core, and then it rapidly decreased due to depressurization boiling by opening the SRV. The core was completely uncovered and core damage started. After the reactor pressure increased due to RCIC system shutdown, it was maintained at about 7.5 MPa[abs] due to the SRV relief valve mode (Fig. 2.5) (the SRV(A) had been connected to temporary batteries and 7.5 MPa corresponds the actuation pressure). Thereafter, the reactor pressure sharply dropped upon opening the SRV manually and finally approached ambient pressure.

The reactor pressures and water levels were measured once the water level had gone below the maximum range of the fuel region reactor water level indicator, following the RCIC shutdown. Further, the reactor water levels and pressures could be reproduced with good accuracy. In the analysis, this was done by appropriate processing of the energy balance and property changes over the time span until the forced depressurization by the SRV, because the water in the reactor decreased monotonously, although it was being accompanied by pressure changes.

The measured values of PCV pressure changed downward from about 13:00 on March 14 after the RCIC system had stopped (Fig. 2.6). It can be considered to be a complex phenomenon due to heat continuing to be removed from the S/C by the seawater that flowed into the torus room, although no more energy was transferred to the S/C through the RCIC turbine.

2.4.2.5 From Forced Depressurization by SRV to PCV Pressure Decrease Initiation

About the same time when depressurization by the SRV was completed, water injection was started by fire engines. But the amount of water assumed in the present analysis turned out to be insufficient to correctly simulate the core water level (Fig. 2.4). Sufficient data on reactor water levels were not available, but their increasing trend after 21:00 on March 14 could be confirmed. This reactor water level increase, however, could have been caused by overestimating the real level due to water evaporation inside the reference water level side piping during the accident progression, as in Unit 1. The water level indicator became unable to show accurate values after all, although the timing when this happened is unknown. Therefore, the actual amount of injected water is considered to have been less, too, including its possible leakage from the injection lines of the fire engines.

The PCV pressure increased to 0.75 MPa[abs], thereafter, due to hydrogen generation and SRV opening, etc. The D/W pressure increases were observed at about 20:00, 21:00, and 23:00 on March 14, probably the effects of hydrogen generation.

At Unit 2 preparation was underway for the S/C venting and for attempting to release the valve several times, but no decisive evidence exists whether or not the rupture disc was opened. But it was at about 23:00 (measured pressure at 23:00 was 540 kPa[abs]) on March 14 when the D/W pressure exceeded the preset rupture disc operating pressure (528 kPa[abs]), even if the measured S/C pressure was not correct. In the meantime, a radiation monitoring car did record a sharp rise in dose rates at about 21:20 when the SRV opening operation was recorded. The occasional increase in reactor pressure around this time was at most about 1.5 MPa[abs] and non-condensable hydrogen gas is considered to have mixed with the discharged steam upon pressure decrease, because core damage is thought to have developed by this time.

2.4.2.6 From PCV Pressure Decrease Initiation to March 18

The measured PCV pressure was 0.73 MPa[abs] at about 07:20 on March 15, and then it decreased to 0.155 MPa[abs] at 11:25 on March 15. It is not clear when the pressure started to decrease, because the measured data are limited around this time period due to the temporary reduction in the workforce at Fukushima Daiichi NPS. Still, it is highly possible that this pressure decrease occurred during the morning, as suggested by the facts that (1) steam release from the Unit 2 blowout panel was confirmed in the morning on March 15, and (2) the dose rates measured by monitoring cars increased. The FPs released at this time are believed to have resulted in radioactive contamination in Iitate Village, etc., due to the effect of wind and rainy weather.

The containment atmospheric monitoring system (CAMS (D/W)) in the meantime showed a monotonous increase until around 06:00 on March 15 (63 Sv/h at 06:20) and then a lowered value (46 Sv/h at 11:25) after an interruption of data recording for about 6 h. The PCV pressure decrease would explain the dose rate decrease in the PCV, by the FP release from it. The CAMS (D/W) recorded a sharp rise to 135 Sv/h later at 15:25 on March 15. This indicates the possibility of drastic change inside the RPC and PCV.

The reasons for no hydrogen explosion at Unit 2 could possibly be hydrogen leakage from a blowout panel or ceiling holes, or a lower hydrogen generation rate at Unit 2 as compared to Units 1 and 3.

2.4.3 Unit 3

As a result of the MAAP analysis for Unit 3, Fig. 2.7 shows the reactor water level changes, while Fig. 2.8 shows the reactor pressure changes, and Fig. 2.9 shows the PCV pressure changes. In this section, the accident progression for Unit 3 is described in accord with the following accident chronology (Table 2.4). In Unit 3, owing to the survival of DC power, decay heat was removed by RCIC and HPCI. However, it fell into severe accident mode because of lack of water injection by HPCI. PCV venting was conducted by interoperation with reactor depressurization. Hydrogen explosion occurred about 1 day after depressurization.

2.4.3.1 From the Earthquake to Tsunami Arrival

Unit 3 was moving towards cold shutdown after the Earthquake by controlling the reactor pressure and water level, etc., through SRV and RCIC operations. But at 15:38 on March 11 all its AC power supplies were lost due to the tsunami. The DC power supply could maintain its function until the batteries were depleted though the function of the AC power supply was lost.

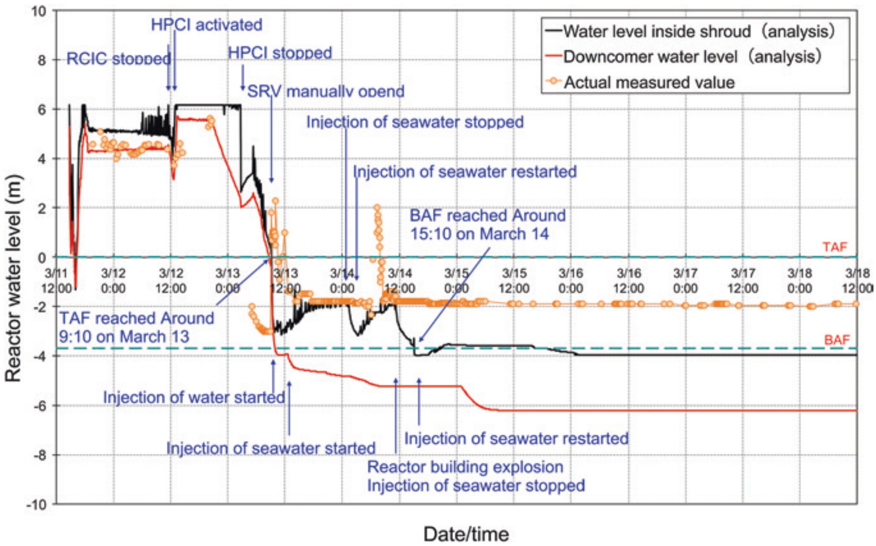

Fig. 2.7 Reactor water level changes for Unit 3

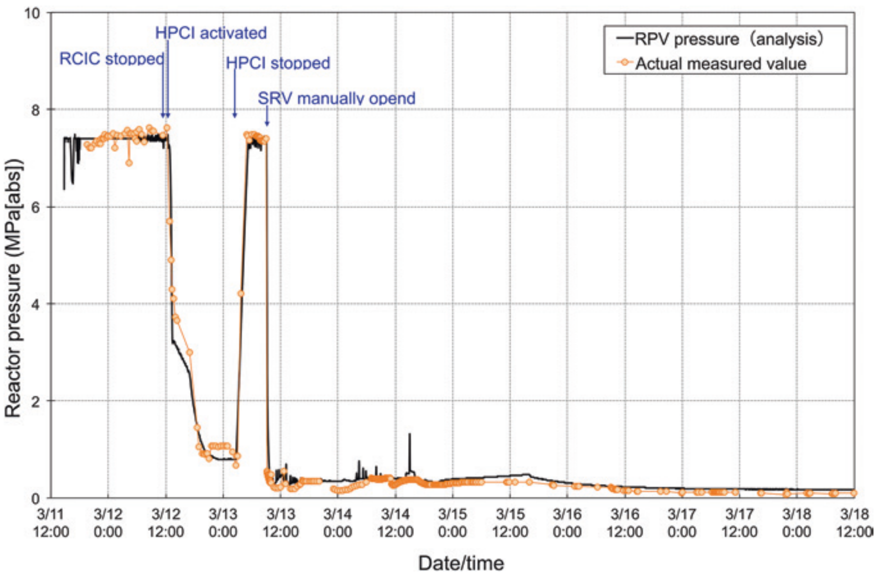

Fig. 2.8 Reactor pressure changes for Unit 3

2.4.3.2 From the Tsunami Arrival to RCIC Shutdown

The RCIC had stopped automatically at 15:25 on March 11 due to the high reactor water level before the tsunami arrived. As DC power supply was available at Unit 3,

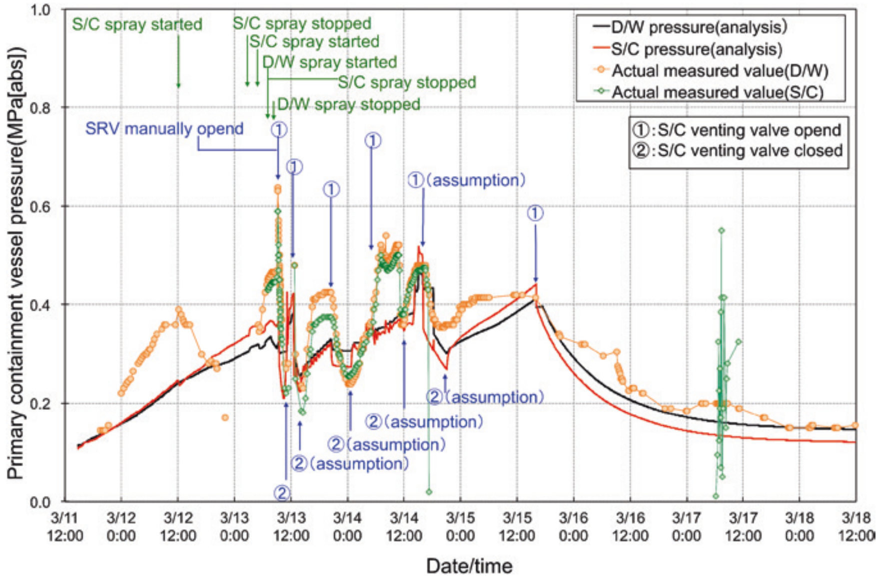

Fig. 2.9 PCV pressure changes for Unit 3

Table 2.4 Chronological accident description for Unit 3

Date	Time	Event	Section
3/11	14:46	Earthquake	2.4.3.1
		Loss of off-site power	
	14:50–15:37	RCIC injection: reactor was cooled by RCIC, even though RCIC was tripped several times due to RPV water level too high	2.4.3.1
	15:37	Tsunami hit: AC power was lost but DC power was available. RCIC was kept in operation with operator's control	2.4.3.2
	11:36	RCIC operation was terminated due to some reason	2.4.3.3
3/14	12:35	HPCI was automatically started due to RPV water level too low. RPV pressure decreased because HPCI consumed much steam	2.4.3.3
	2:42	HPCI manual shutdown: HPCI could not inject enough water due to lack of RPV pressure to drive turbine	2.4.3.4
	9:00	Reactor pressure sharp decrease by SRV manual open	2.4.3.5
	10:40[a]	Core damage started	
	11:01	Reactor building explosion	2.4.3.6

[a]Time from MAAP calculation

the RCIC was manually started at 16:03. The reactor pressure and water level were thus controlled by the SRV and RCIC. Since RCIC was designed for making up water loss by decay heat 15 min after shutdown, most of the time during plant operation, the amount of water injection was too large compared to decay heat. Hence, actuation and stop of RCIC was designed by increase and decrease of water level. Operators maintained reactor water levels by adjusting the flow rate set for flow controllers to allow gradual reactor water level changes. This was done by using the line configuration where water would pass through both the reactor injection and test lines so that part of the water could be returned to the condensate storage tank (CST) (water source for RCIC) in order to decrease the amount of water injection to the reactor even by consecutive operation. This would prevent automatic shutdown due to high reactor water levels, avoid battery depletion due to RCIC re-activation, and also ensure stable reactor water levels.

During this period the D/W pressure was increasing but the analysis results provided lower values of increase contrary to the situation of Unit 2; therefore the pressure behavior is assumed as follows.

- The RCIC turbine exhaust steam heated up the S/C pool water near the turbine exhaust pipe exit.
- The high temperature pool water was dispersed horizontally on the pool surface, thus producing thermal stratification in the pool water.
- This stratification caused a larger PCV pressure increase than the analysis (which assumed a uniform temperature increase of the pool water).

The RCIC stopped automatically at 11:36 on March 12 and thereafter its status of shutdown was confirmed on-site but its restart-up failed.

2.4.3.3 From RCIC Shutdown to HPCI Shutdown

The RCIC stopped automatically at 11:36 on March 12 and the reactor water level started to decrease. The High Pressure Coolant Injection System (HPCI)[12] started up automatically at 12:35 when the water level reached the low reactor water level (L-2). In addition, the diesel-driven fire pump (DDFP) was started up at 12:06 on March 12 for the S/C spray, since the S/C pressure had risen due to the exhaust steam from the SRV and RCIC.

Operators controlled the HPCI water flows by flow controllers using, as with the RCIC, the line configuration where water would pass through both the reactor injection and test lines so that part of the water was returned to the CST (water source of HPCI), which would prevent automatic shutdown due to high reactor water levels and avoid battery depletion due to re-activation, and also ensure stable reactor water levels. After the HPCI was started up, the reactor pressure started decreasing because the driving turbine consumed the steam.

The HPCI has a larger flow capacity than that of RCIC since the HPCI was designed to make up coolant flowing out from broken part in case of LOCA and consumes more reactor steam to actuate the HPCI turbine. As a result of these

[12] The HPCI system is a single-train system that provides a reliable source of high-pressure coolant for cases when there is a loss of normal core coolant inventory.

two facts, the reactor pressure decreased by operating the HPCI and reached about 1 MPa[abs] at about 19:00 on March 12. This reduced reactor pressure lowered the HPCI turbine rotation speed and the status continued so that it could stop anytime.

In addition, monitoring of the reactor water level became impossible at 20:36 on March 12 due to loss of the power supply for the reactor level indicators.

The reactor pressure, which had been stable at about 1 MPa[abs], started to decrease at about 02:00 on March 13. It became lower than the allowable HPCI operation limit and reached a situation in which the HPCI could stop anytime. The operator, therefore, manually shut it down at 02:42 in consideration of the preparation underway for reactor water injection using the DDFP.

2.4.3.4 From HPCI Shutdown to Reactor Depressurization

The DDFP was switched over from the S/C spray mode to reactor water injection mode, and the injection of water to the reactor was prepared, so that the main control room operators were notified of the information at 03:05 on March 13, shortly after the HPCI shutdown. The reactor pressure reversed to an increasing trend after the HPCI had been shut down, but the depressurization attempt by SRV manual open operation failed after all. The reactor pressure further increased and exceeded the DDFP discharge head, thus disabling the alternative water injection to the reactor. An attempt was made on-site to supply nitrogen gas to drive the SRV via the supply line, but it failed, because the valve on the supply line was an air-driven type and it could not be manually operated due to structural limitations. Further operation attempts also failed to start up the HPCI and RCIC: the HPCI failed due to battery depletion, and the RCIC failed because the turbine trip throttle valve was closed again by its trip mechanism.

The measurement of reactor water level was interrupted at 20:36 on March 12 due to loss of power supply. When it was resumed upon recovery of power supply at about 04:00 on March 13, the fuel range water level indicators showed about TAF-2 m.

Water injection by S/C spray was resumed by switching over the DDFP from the reactor water injection mode at 05:08 on March 13 in order to prevent pressure increases of the D/W and S/C. At 07:39 the spray lines were switched over from S/C to D/W and the S/C spray was terminated at 07:43.

At 08:41 on March 13, the large S/C vent valve (air-operated) was opened and the configuration of the venting line was completed except for the rupture disc.

At about 08:40 through 09:10 on March 13, the DDFP stopped the D/W spray and waited for the reactor depressurization by SRV manual open, and then switched to water injection to the reactor again.

The reactor pressure, in the meantime, reversed to increase by the HPCI manual shutdown at 02:42 on March 13 and reached about 7 MPa[abs] at about 04:30, and stayed thereafter for about 5 h at about 7.0–7.3 MPa[abs]. When battery connection work was ongoing for depressurization regardless of the manual operation of depressurization by operator, the reactor pressure decreased abruptly at about 09:00 on March 13 down to below 1 MPa[abs]. This depressurization might have occurred due to the actuation of ADS in accord with depletion of DC power and investigation of RPV and PRV pressure behavior. Further investigation related to this depressurization is discussed in Attachment 3–3 and 3–4 of progress report [2].

2.4.3.5 From Reactor Depressurization to Reactor Building Explosion

Following this rapid reactor depressurization, fire engines started freshwater injection from 09:25 through 12:20 on March 13, and later at 13:12 fire engines started seawater injection. The DDFP was also being operated in parallel, but water injection was considered mostly not to be working due to the pressure balance relation between the pump discharge pressure and reactor pressure.

Because of rapid reactor depressurization, the PCV pressure increased, the S/C pressure exceeded the rupture disc working pressure, and the D/W pressure was confirmed at 09:24 on March 13 to have decreased. This led to the conclusion that the PCV had been vented.

The reactor water level indicators showed hunting oscillatory behavior after the rapid depressurization at about 09:00 on March 13 and a certain constant level after 12:00 regardless of the amount of water injection. Similar to other units, it can be understood that the correct water level could not be shown due to water evaporation in the water level instrumentation tube.

The reactor water level which was kept at around the top of active fuel level following the HPCI shutdown at 02:42 on March 13 decreased, and fuel was overheated by the decrease in the amount of steam following the water level drop as in Unit 1, which resulted in the start of core damage. A large amount of hydrogen was generated by water-zirconium reactions when the core became uncovered and fuel cladding temperatures started to rise. The reason for the PCV pressure increase during rapid depressurization of RPV is assumed to be the effect of the accumulation of large amounts of hydrogen inside RPV. Therefore, it is considered that the core damage at Unit 3 had mostly progressed before the depressurization.

According to the chart records, the reactor pressure after the rapid depressurization at about 09:00 on March 13 showed a sharp rise to several MPa[abs] first at about 10:00 and again at 12:00, followed by a gradual decrease.

This pressure behavior may have some correlation to the SRV opening/closing operation for connecting batteries to the SRV for opening. But the pressure rise is steep for the value due to steam generation. The pressure increase can be confirmed to be considerably faster when compared with the pressure increase upon HPCI shutdown. Therefore, it is possible that the molten fuel dropping into the water pool at the bottom of RPV contributed to the pressure increase due to massive steam generation.

2.4.3.6 From the Reactor Building Explosion to Late March

Water injection by fire engines was continued after being interrupted at the time of the explosion at 11:01 on March 14 in the Unit 3 reactor building.

Water injection by fire engines was resumed at 15:30 on March 14 after the explosion. It was found that water injection to Unit 3 was interrupted again at 21:14 on March 14 in order to secure water injection to Unit 2 and that it was resumed at 02:30 on March 15.

Efforts were continued to keep the PCV vent valve open since it had been opened at about 09:00 on March 13 when the rupture disc opened upon reactor depressurization. But it was closed thereafter due to failure of the temporary generator for power supply, and the opening operation of PCV vent valve had to be repeated until March 20 to keep it open.

Unclear features remain concerning the D/W pressure: its changes when no PCV venting was recorded; and no pressure decrease when the PCV vent valve was confirmed to have been opened at 06:10 on March 14.

Steam was observed on several occasions, which might have leaked from the PCV: black smoke rising up at about 16:00 on March 21; and steam rising up from the west side of the building and above the building on March 29.

2.5 Present Situation of Cores and PCVs of Units 1–3

2.5.1 Unit 1

Water is being injected to Unit 1 from the Core Spray (CS) and feedwater system, as shown in Fig. 2.10. Water from the CS system is directly sent to the core and water from the feedwater system is sent to the lower plenum via the outer side of the core shroud. The reactor level is confirmed to be below TAF-5 m, based on the calibrated results of the water level indicators, that is, no sufficient water exists in the core region.

The status of Unit 1's core was estimated based on the above facts and aforementioned examination results, and is illustrated in Fig. 2.10. As can be seen in the figure, most of the molten fuel generated by the accident fell down to the lower plenum below the reactor pressure vessel and only a little fuel remains in the original core location. Most debris, which had fallen to the lower plenum, is believed to have reached the PCV pedestal. It is estimated that, after causing core-concrete interactions, the debris was cooled by injected water, decrease of its decay heat terminated the core-concrete interactions, and it now remains in the PCV.

At the in-containment investigation in October 2012, the level of residual water in the D/W was checked by cameras. It was about 2.8 m above the D/W floor (as of October 10, 2012).

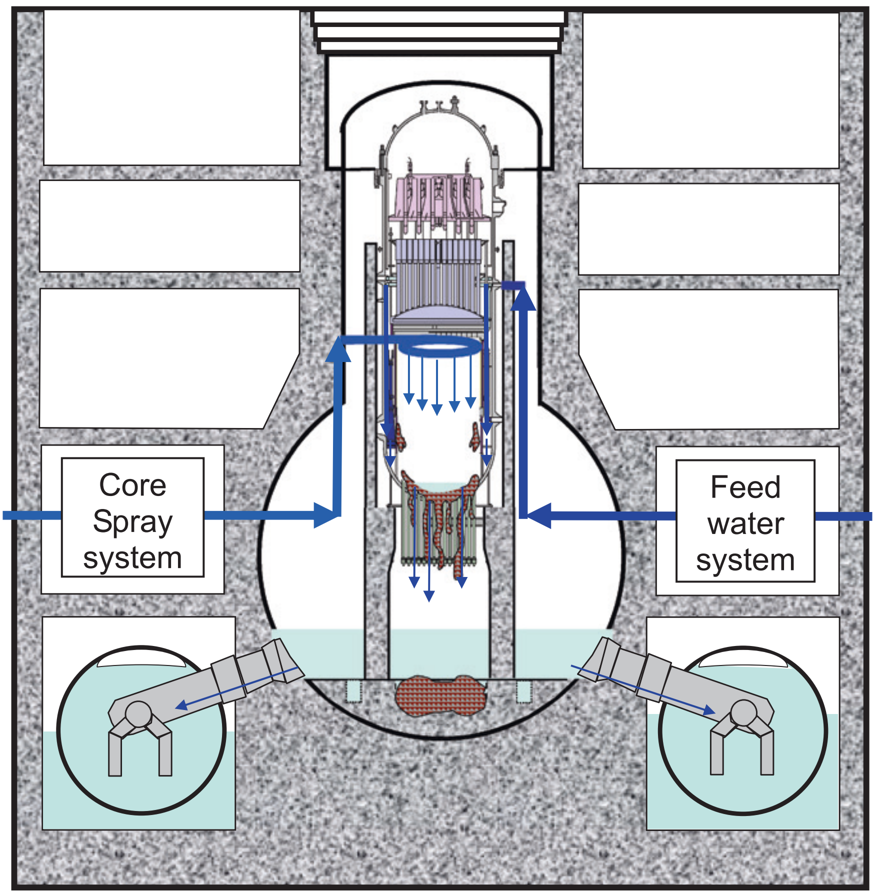

Fig. 2.10 Estimated conditions of the core and PCV of Unit 1

Concerning the status in the S/C, the nitrogen gas injection experiment in September 2012 demonstrated a mechanism that Kr-85 and hydrogen generated at an early stage of the accident had remained in the upper space of the S/C and they were discharged to the D/W via vacuum breakers when the S/C water level was pushed down. This means that the S/C is currently filled with water.

The location of liquid phase leakage was confirmed at the D/W bottom and vacuum breaker valve line due to the following evidence:

- Water flow from suction drainpipe which exhausted accumulated water to outside the D/W in November 2013.
- Water flow from vacuum breaker valve line connected for reducing the pressure difference between S/C and D/W in May 2014.

2.5.2 Unit 2

Water is being injected to Unit 2 from the CS and feedwater system, as shown in Fig. 2.11. Water from the CS system is directly sent to the core and water from the feedwater system is sent to the lower plenum via the outer side of the core shroud. Based on water filling to the condensing chamber on reference water level side piping shown by the water level indicators, the reactor water level is estimated to be below TAF-5 m, meaning there is not sufficient water for covering the core.

The estimated situation of the Unit 2 core, based on the above facts and aforementioned examination results, is illustrated in Fig. 2.11. As can been seen in the figure, part of the melted fuel generated in the accident fell down to the lower plenum below the reactor pressure vessel or to the PCV pedestal. Some of the fuel may remain in the original core location.

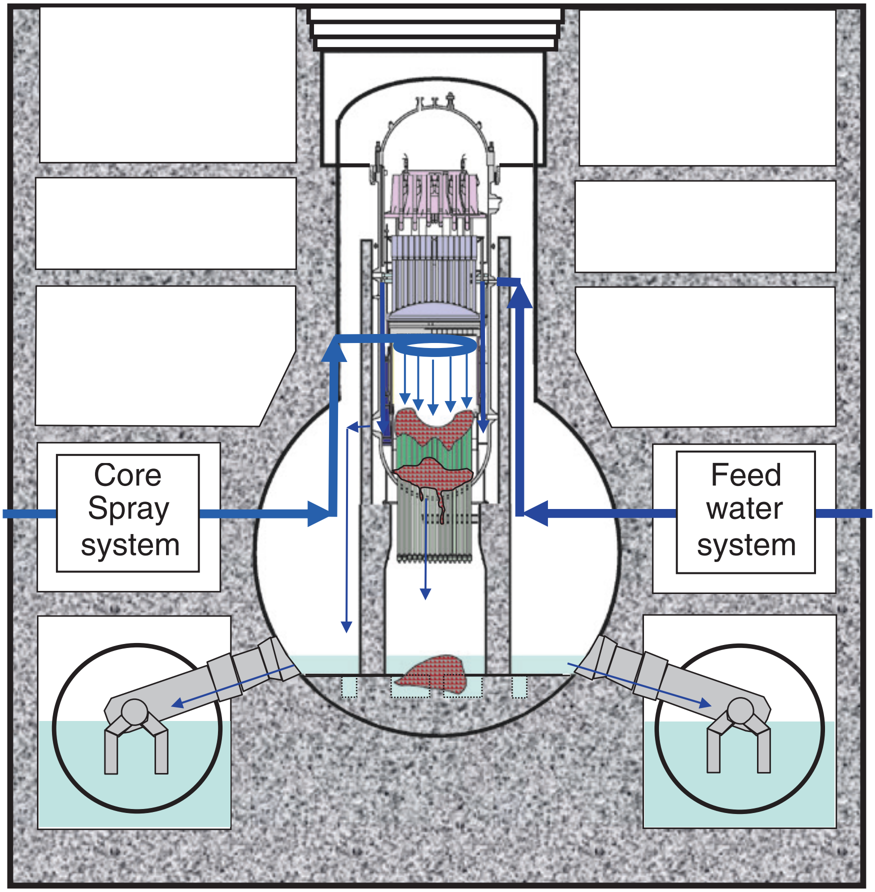

Fig. 2.11 Estimated conditions of the core and PCV of Unit 2

At the in-containment investigation in March 2013, the level of residual water in the D/W was checked by cameras. It was about 60 cm above the D/W floor (as of March 26, 2013).

The nitrogen gas injection experiment to the S/C conducted in May 2013 showed the S/C pressure of 3 kPag (as of May 14, 2013). This meant the S/C water level was at around the nitrogen gas injection inlet (O.P. 3,780 mm), because a certain water head should appear if the S/C was close to being full. When considered together with the low water level in the D/W, the water injected to the reactor is estimated to have flowed into the S/C via the vent lines from the D/W and leaked out to the reactor building from the bottom of the S/C, i.e., the current S/C water level can be estimated to be about the same level as the residual water level in the torus room.

The water leak paths from the S/C have not been located yet. But at least no leakage was confirmed at the S/C manholes, etc., when, for the internal investigation in the torus room in April 2012, robots accessed the corridor for visual checks; or at the lower ends of the vent tube, when they were checked at the internal investigation of the torus room in December 2012 and March 2013. Due to no damage at S/C top and low water level of D/W, leakage location of PCV is assumed to be at the S/C bottom.

2.5.3 Unit 3

Water is being injected to Unit 3 from the CS and feedwater system, as shown in Fig. 2.12. Water from the CS system is directly sent to the core and water from the feedwater system is sent to the lower plenum via the outer side of the core shroud. The reactor temperature was lowered to 70 °C as of November 11, 2011, which had been achieved by water injection from the CS system conducted from September 1, 2011 and the fuel debris in the CS water injection path, i.e., in the core, could be cooled.

The estimated situation of the Unit 3 core based on the above facts and aforementioned examination results is illustrated in Fig. 2.12. As can been seen in the figure, part of the melted fuel generated in the accident fell down to the lower plenum below the reactor pressure vessel or to the PCV pedestal. Some of the fuel may remain in the original core location.

No measured values are available so far concerning the D/W water level. But it could be estimated to be about 5.5–7.5 m above the floor by converting the S/C pressure to water head. The S/C pressure was obtained from its existing pressure indicators, not calibrated since the accident, so they are not highly accurate but they could be reliable as a trend to a certain extent because they have followed the pressure changes according to the water injection. In addition, leakage from around the expansion joint of PCV penetration of the main steam line D was confirmed. The elevation of this leakage is the same as the presumed water level inside the PCV, so most of the leakage from the PCV is assumed to be from this location.

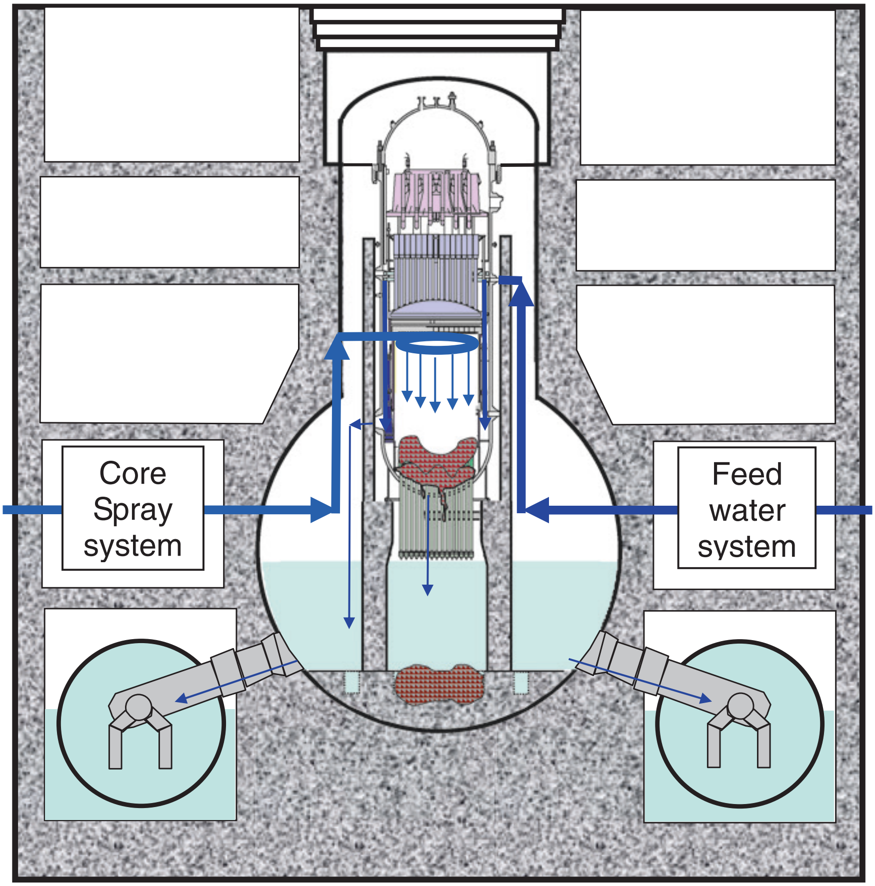

Fig. 2.12 Estimated conditions of the core and PCV for Unit 3

2.6 Spent Fuel Pool Cooling

Due to the impact of the tsunami, Units 1–6 and the common spent fuel pool (SFP) all lost cooling capacity. There was no emergency situation with the reactors, but the fuel energy deposition was large, and there was concern about the condition of the Unit 4 SFP that eventually led to the hydrogen explosion.[13] The day after the explosion (March 16), a TEPCO employee accompanied a Self-Defense Force (SDF) helicopter pilot, and according to the employee, the pool water level was maintained.

SDF helicopters sprayed water onto Unit 4, while firefighting units from the SDF, Tokyo Fire Department, and the National Police Agency hosed it down. Later, as

[13] SFP generally has fuels with small decay heat, therefore rapid accident progression is not considered. However, fission product released in case of fuel damage is large since there is no containment vessel for SFP.

a long-term stable measure for injecting cooling water, a large size concrete pump vehicle was used. (Cooling water injection into Unit 4 began on March 22.)

Dealing with the Unit 4 SFP was an extremely important turning point in preventing the spread of the disaster.

2.7 Plant Explosion

2.7.1 Units 1 and 3

It is assumed that when the fuel inside the reactor was damaged, hydrogen was generated as a result of zirconium-water reaction, which then leaked out and remained in the reactor building, finally resulting in hydrogen explosion.

The exact route by which the hydrogen escaped into the reactor building is unknown, but it is assumed that leak-proof seals on the head of the PCV and hatch joints where machinery and personnel enter and exit were exposed to high temperatures and may have lost their functionality.

Another possibility is that it may have escaped from the PCV vent line via the standby gas treatment system (SGTS) line into the reactor building, but the results of investigating the condition of the Unit 2 SGTS show that the volume of hydrogen that could travel this route is limited, and therefore, the major source of hydrogen for the explosion must have leaked directly from the PCV into the reactor building.

2.7.2 Unit 4

There are no indications of damage to the fuel in the SFP, and as the process of radiolysis of the water in the pool can only generate small amounts of hydrogen, the fuel inside the SFP is not being considered as a possible cause of the explosion.

The results of investigating conditions of the Unit 4 SGTS and the field investigation of conditions inside the Unit 4 reactor building lead to the hypothesis that the hydrogen that caused the explosion was the Unit 3 PCV vent gas that traveled through the SGTS pipes into Unit 4.

2.8 Concluding Remarks

There are still unclear issues and some observed phenomena that cannot be confidently interpreted. For example, the reason why the reactor core isolation cooling (RCIC) system of Unit 2 lost its function still remains unknown. Also, concerning earthquakes and tsunami, there are some issues for academic researchers to tackle, such as the mechanism of earthquakes of this historically huge scale occurring in the same district and causing massive tsunami.

Discovering root causes for loss of the safety equipment function improves knowledge about existing system functionality and thus enhances safety. Fuel removal and prevention of generating contaminated water are crucial for decommissioning Fukushima Daiichi NPS.

In order to cope with these issues, it is essential to grasp the damage mechanisms as well as the current situation of debris in the reactors and containment vessels (PCV). Even the issues not directly related to accident progression may provide clues to enhancing safety as a result of examining them.

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