Chapter 2
Fukushima Daiichi Unit 1, 2 and 3 Accidents

2.1 Outline of Fukushima Daiichi Nuclear Power Station

As of March 11, 2011, the day the Great East Japan Earthquake hit the area, there were five nuclear power plants comprising a total of 15 units installed along the Japanese coast facing the Pacific Ocean, ranging from the Tohoku to the Kanto areas. They are, from north to south, Higashidori Nuclear Power Station (hereinafter "NPS") of Tohoku-Electric Power Co., Inc. (1 unit) in Aomori Prefecture, Onagawa NPS of the same company (3 units), in Miyagi Prefecture, Fukushima Daiichi NPS of Tokyo Electric Power Co., Inc. (hereinafter "TEPCO") (6 units), in Fukushima Prefecture, Fukushima Daini NPS of the same company (4 units), also in Fukushima Prefecture, and Tokai Daini NPS of The Japan Atomic Power Company (1 unit), in Ibaraki Prefecture (Fig. 2.1).

Of these five nuclear power plants, four NPS, i.e., Onagawa, Fukushima Daiichi, Fukushima Daini, and Tokai Daini, reported damage caused by tsunami as a result of the Great Eastern Japan Earthquake. Of these, Onagawa and Fukushima Daini were still receiving power from external sources after the earthquake and tsunami. At Tokai Daini, although all external powers were lost, two emergency diesel generators were able to operate and provide electricity.

Except Fukushima Daiichi, all power plants had electric power to use. Or rather, simply because electricity was available, the operating staff's efforts were not wasted – they were able to stop the reactors, and they succeeded in safely cooling down the reactors. The damage brought by tsunami were wide and varied. The skill of the operating staff of all these power generating stations could only be judged as "commendable" for not causing any severe accidents despite various hazards. They proved that the claim of opponents to nuclear power that "human beings cannot control nuclear power" is absolutely wrong. People can control nuclear reactors so long as electric power is available. It is akin to saying that animals can live so long as water and food are available.

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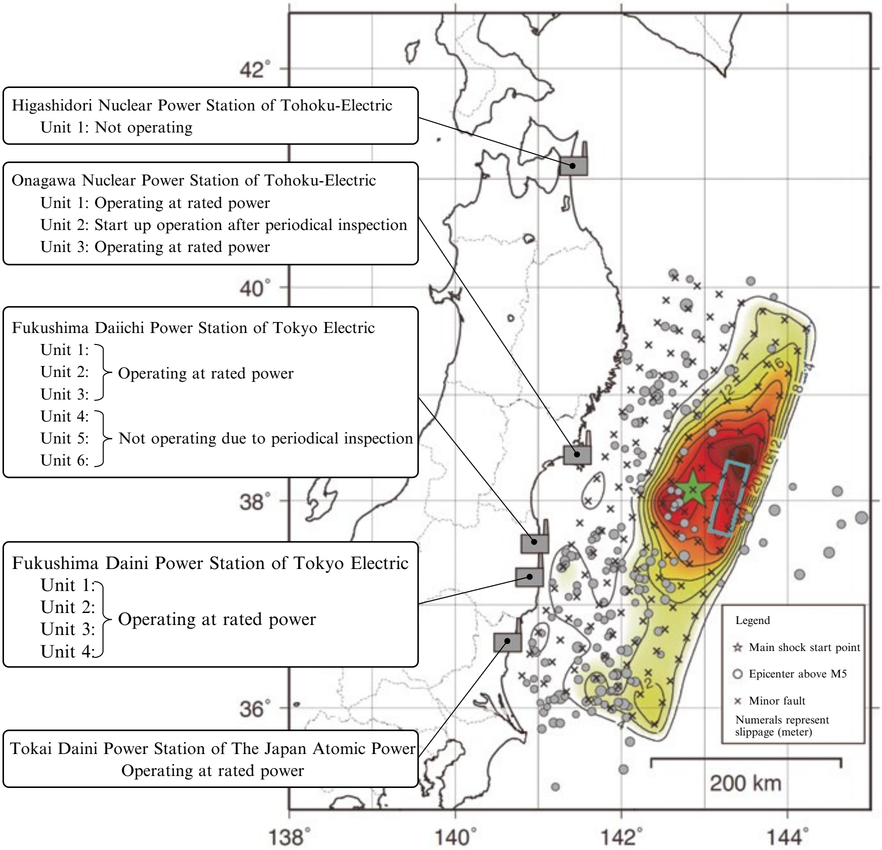


Fig. 2.1 Map showing relative locations of Great East Japan Earthquake and nuclear power stations on the Pacific coast of the Tohoku and Kanto areas (prior to earthquake) (Source: Meteorological data added with author's notes)

The tragedy occurred at Fukushima Daiichi, where electricity was lost. The difference from Onagawa, Fukushima Daini and Tokai Daini was that the external electricity supply was stopped for as long as 10 days due to the tsunami. Without electricity, the extraordinary effort of the power station's staff was unfortunately no more than a grasshopper's horn, a desperate, only symbolic attempt. Core melts and explosions occurred at four of the six reactors of Fukushima Daiichi, causing emergency evacuations of residents in the vicinity due to the fear of radiation.

I will attempt technical verifications and descriptions of how the Fukushima accident, particularly the core melts and hydrogen explosions, occurred.

Fukushima Daiichi NPS is situated approximately 220 km north-northeast of Tokyo covering portions of the towns of Ookuma and Futaba in the middle of Fukushima Prefecture's stretch along the Pacific coast, where the mainland of Japan, Honshu, is arching out its belly toward the Pacific Ocean accompanied with soft continuing hills. The plant is located on a hill of about 35 m above the sea level, and occupies an area of approximately 3.5 million square meters, extending about 3 km north-to-south and about 1.5 km east-to-west in the shape of a semi-circle. A pair of breakwaters extends in a triangular shape reaching approximately 0.7 km from the shore, and a dock and a wharf are provided inside the area guarded by the breakwaters.

Of the six reactors, Units 1–4 are located on the south side of the plant site, placed in the order of Units 4, 3, 2 and 1 from the south. Units 5 and 6 are located slightly apart from them on the north side, placed in the order of Units 5 and 6 from the south (Fig. 2.2).

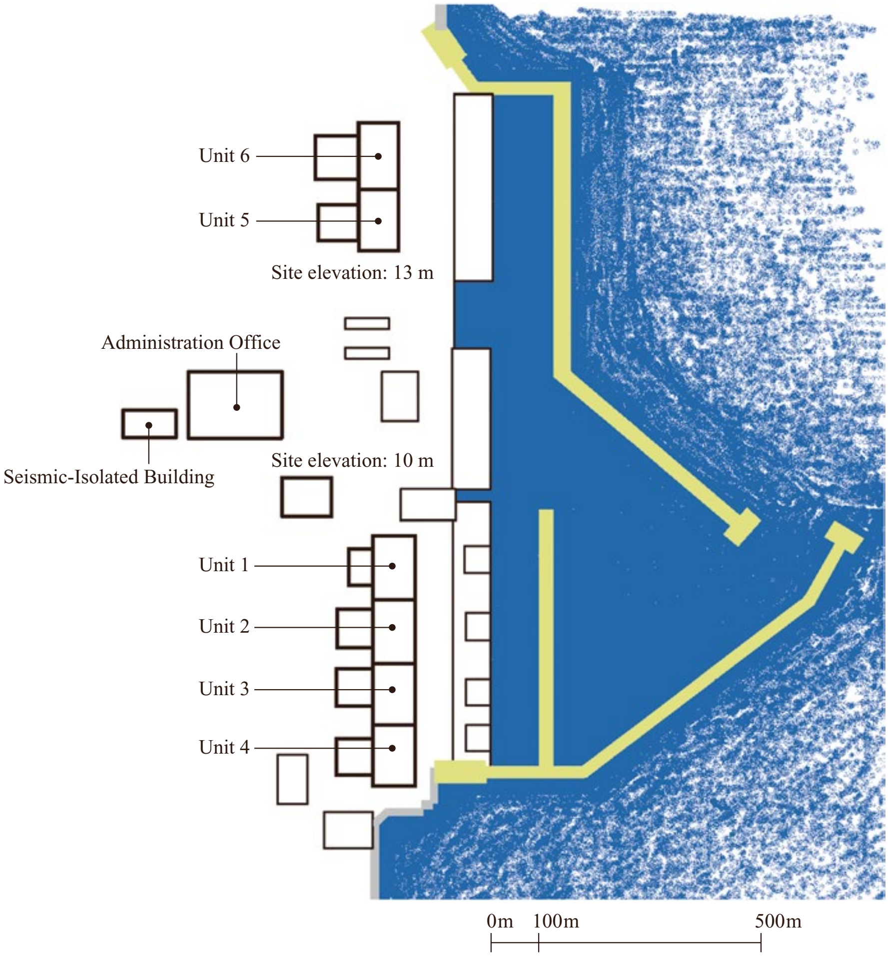


Fig. 2.2 Fukushima Daiichi NPS layout (Source: TEPCO data, with author's notes)

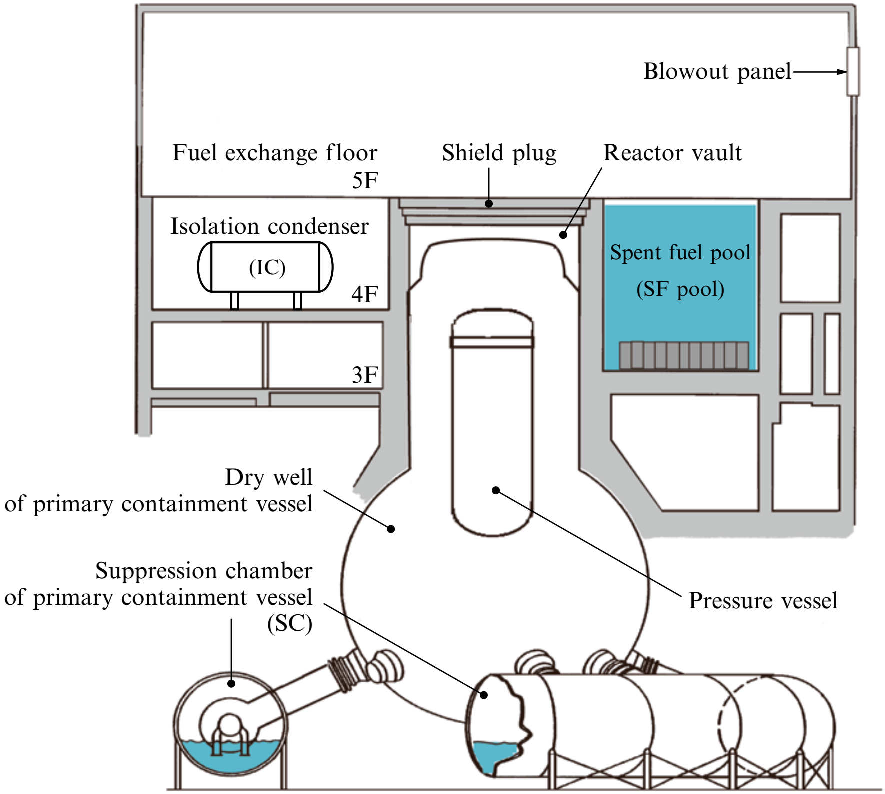


Fig. 2.3 MARK-I primary containment vessel (Source: from TEPCO's "Fukushima Nuclear Accident Report")

The electrical output of Unit 1 is 460 MW while those of Units 2–5 were all 784 MW each. Their reactors are Boiling Water Reactors (BWR) and are each installed in a containment vessel equipped with a pressure suppression pool (or suppression chamber/"SC"), which is essentially a donut-shaped water pool, named MARK I (Fig. 2.3). Unit 6 is a 1,100 MW BWR and its containment vessel is a MARK II type, different from others, but the explanation of its detail will be omitted because it has no bearing to the accident.

The major buildings (reactor building, turbine building, etc.) of the power station are located at 10 m above sea level in the case of Units 1–4, and at 13 m in the case of Units 5 and 6. They are built on the ground produced by cutting the soil of a hill of about 35 m above sea level down to a lower level on purpose. As there are various criticisms regarding the selection of the height of the power plant site above sea level, I will explain the reasoning for it in Sect. 5.3. The sea water pumps that played an important role in the cooling of the reactors were all located close to the shore and placed at 4 m above the sea level. As a consequence, they were all destroyed by the tsunami.

So that is the outline of the power station that seems to be necessary in studying the Fukushima accident.

2.2 Initiation of the Accidents – Earthquake and Tsunami

When the earthquake occurred on March 11, 2011, three out of the six reactors, i.e., Units 1–3, were operating while Units 4–6 were not operating because of periodic inspections.

An earthquake with a wide epicentral area, extending from off the coast of Iwate Prefecture to off the coast of Ibaraki Prefecture, occurred at 2:46 p.m. to initiate the Great East Japan Earthquake. According to a seismological record, the earthquake, which had a magnitude of 9.0, spread from the epicenter in the Sanriku coast at 2:46 p.m. to the entire sea area mentioned above, followed by numerous tremors including 8 earthquakes of level 5 or above on the Japanese seismological scale during a period of approximately 40 min until 3:25 p.m. (Table 2.1). It was a huge earthquake, without precedent in official records.

Because of this earthquake, all seven feeder lines to Fukushima Daiichi became unusable due to damaged breakers and collapsed transmission towers. In layman's terms, the power station suffered a power outage due to damage to the transmission wires. In professional terms, it is called external power loss.

The earthquake induced a big tsunami that hit a broad coastal area extending from Aomori to Ibaraki. About 45 min after the earthquake, i.e., at around 3:27 p.m., the first wave, approximately 4 m high, hit Fukushima Daiichi, and the second wave arrived at around 3:35 p.m. This second wave was so high that it well exceeded the tide gauge; according to a TEPCO estimation, it was approximately 13 m high. Units 1–4 were all covered by tsunami.

Although our common image of tsunami is that it approaches us at a great speed, scientists tell us that it is more like a high tide with a very deep expanse. Therefore, once it arrives, it stays in the same place for a while. In other words, the damage caused by tsunami is not caused by wave actions of water but rather by immersion in a pool of dammed-up water. Thus, a building hit by tsunami will be completely filled with water and mud, so that the mechanical equipment inside the building will become completely useless once they are engulfed by tsunami.

Most of the mechanical equipment installed in the basement as well as on the first floor of the power station became fully immersed in water by tsunami and became useless. We can see how extensive the tsunami was from the fact that most of the emergency diesel generators, more precisely 12 out of 13 diesel generators, provided for use in case of an external power outage, became unusable because the generators or related devices were covered by water. It was not just that. Since the power distribution panels were also installed either in the basement or on the first floor, most of them got immersed in water and became unusable. This meant that

Table 2.1 Earthquake and aftershocks in the Tohoku area of the Pacific Ocean

No.		Time of occurrence					Epicenter location	Dep	Mag	Maximum seismic intensity[a]
		Yr	Mon	D	H	Min				
1	Main shock	2011	3	11	14	46	Sanriku coast	24	9	7
2		2011	3	11	14	51	Fukushima coast	33	6.8	5 Lower
3		2011	3	11	14	54	Fukushima coast	34	6.1	5 Lower
4		2011	3	11	14	58	Fukushima coast	35	6.6	5 Lower
5		2011	3	11	15	6	Iwate coast	29	6.5	5 Lower
6		2011	3	11	15	7	Ibaraki coast	20	6.5	4
7	(Outside area)	2011	3	11	15	8	Izu (Shizuoka)	6	4.6	5 Lower
8		2011	3	11	15	8	Iwate coast	32	7.4	5 Lower
9		2011	3	11	15	12	Fukushima coast	39	6.7	5 Lower
10	Max aftershock	2011	3	11	15	15	Ibaraki coast	43	7.6	6 Upper
11		2011	3	11	15	18	Ibaraki coast	41	4.7	5 Lower
12		2011	3	11	15	25	Sanriku coast	11	7.5	4
13		2011	3	11	15	29	Sanriku coast	15	6.9	3
14		2011	3	11	15	59	Fukushima coast	50	6.8	3
15		2011	3	11	16	14	Ibaraki coast	25	6.8	4
16		2011	3	11	16	17	Fukushima coast	20	6.5	4
17		2011	3	11	16	28	Iwate coast	17	6.6	5 Upper
18		2011	3	11	16	30	Fukushima coast	27	5.9	5 Lower
19		2011	3	11	17	12	Ibaraki coast	32	6.6	4
20		2011	3	11	17	15	Fukushima coast	32	6.5	3

Source: Extracted from Meteorological Bureau's website
[a]Figures indicate those of Japanese seismic intensity scale (7 is the maximum scale)

even if the external electric power was restored, it was not easy to run the machines. As you can see the tsunami's strike on the electrical facilities was a double punch. The hardship of the operating staff started with this hard reality.

Now, back to Units 1–4. In the end, in addition to the loss of external electric power supply, the emergency power supply and DC (battery) power supply were also lost, so that the power station fell into a real emergency, losing all electricity supply. It's not just the machines that stopped to operate. All indicators stop to provide their readings, warning signals, and even lighting in the operation control room was lost. The control rooms in the windowless buildings of the nuclear power station were pitch dark.

This total power outage continued for approximately 10 days, until a temporary power system was installed on or around March 20 to restore electricity. As a result, the condition of the power plant slowly began to be restored. The restoration of electricity finally allowed the power station to turn the corner of the emergency.

In essence, the accident occurred when they lost electricity and, with the return of electricity, they began to see the light ahead. All the key subject matters of this book, including the core melt, explosions and emission of radioactive substances, happened during the dark period when no electricity was available. This makes us realize that the first cause of the accident at Fukushima Daiichi NPS which led to the disaster was the tsunami, but the second cause was that the total power outage lasted for 10 days.

The total power outage for an extended period of time was a main cause – one that is as significant as the earthquake and the tsunami.

Column Brilliant Performance of Fukushima Daiichi's Operating Staff

Digressing a little here, I wish to mention that there was one emergency diesel generator that survived by a stroke of luck. The operating staff who controlled Units 5 and 6 that day used this sole surviving generator to maintain the two nuclear reactors at cold shutdown by managing the scarce electricity available from this sole generator. I believe that this was indeed a commendable maneuver, because Units 5 and 6 were still generating decay heat although they were not operating, as they were under periodic inspections when the accident occurred. With this fact alone, it is clear that the operating skills of Fukushima Daiichi's operating staff were on par with those of Onagawa and Fukushima Daini – at world-class level.

This fact is well noted by the IAEA's investigation team who visited Fukushima after the accident and reported by the overseas mass communication services. Strangely enough, the Japanese news media failed to report that the accident could have been prevented only if the electric power supply was available, even though the power station was hit by the tsunami.

Moreover, the extraordinary effort of Fukushima Daiichi's staff was not appreciated very much as the Kan administration branded TEPCO as being responsible for the accident. This was despite the fact that the operating staff who gallantly stayed to battle the situation at the site under further deteriorating condition after the explosion of Unit 4 were hailed as the "Fukushima 50" by reporters overseas. As a witness to history, I would like to memorialize permanently this successful and gallant fight of the staff of Fukushima Daiichi.

2.3 Outline of the Accident

First, let me give you the outline of the Fukushima accident (Table 2.2).

On the morning of March 12, the core of Unit 1 melted, and the hydrogen explosion occurred in the reactor building at around 3:30 p.m. It was the first step of the disaster. With this explosion, we lost all hope of cooling down Unit 2. The cable prepared for connecting a power supply-car to the power distribution panel and

Table 2.2 Summary of the Fukushima Daiichi accident

	Unit 1	Unit 2	Unit 3	Unit 4
Earthquake attack	Mar/11 2:46 p.m.			
Tsunami attack	Mar/11 3:35 p.m.			
Core melt	Mar/12 about 4 a.m.	Mar/14 about 10 p.m.	Mar/14 about 10 a.m.	
Damage timing (structural)	Mar/12 3:36 p.m. (reactor building)		Mar/14 11:01 a.m. (reactor building)	Mar/15 6:14 a.m. (reactor building)

luckily survived the tsunami in order to feed electricity to a high pressure injection pump was now damaged by the explosion. This made it difficult to restore the electric power needed for cooling.

The reactor core of Unit 3 also started to collapse around 1:00 a.m. on March 13, and on March 14, hydrogen explosion occurred in its building. As a result of the core melt of Unit 3, i.e., because of the hydrogen gas flow from Unit 3, an explosion occurred in Unit 4 as well on March 15.

Around 10 p.m. on March 14, the core of Unit 2 melted, but barely escaped an explosion. This was because the explosion of Unit 1 blew off the blowout panel of the reactor building of Unit 2 and allowed the hydrogen gas to be exhausted. On the other hand, the radioactive substances that leaked out directly from the containment vessel severely contaminated the surrounding environment.

Speaking of radiation, the radiation level measured in the vicinity of the main gate fluctuated quite significantly and looks complicated at first glance, as shown in Fig. 2.4. However, by a closer observation of the graph, it can be seen that the background radiation dose increased with the core melt, and also some irregular increases can be observed occurring quickly due to vent operations, etc. With a more precise analysis, one can see further that the background radiation level increased twice.

The first radiation level rate increase that was caused around 4 p.m., March 12 was due to the core melt in Unit 1. The venting in Unit 1 occurred around 10 a.m., March 12, so that said increase has nothing to do with the venting. It seems that the radioactive substances which had been entrapped in the fuel rods were directly discharged due to the core melt from the building although it was only a minute amount. As a result, approximately 4 μSv/h of radiation were recorded in the vicinity of the front gate of the power station. This is not a radiation level that mandates an evacuation of residents. This condition continued until March 15 despite the emission of radioactive substances due to other venting events or the explosion in Unit 3.

However, the direct emission of radioactive substances started with the damage of the containment vessel of Unit 2 on the morning of March 15. Because of this direct emission, the radiation dose rate in the vicinity of the front gate jumped up almost 100 times to approximately 300 μSv/h (Fig. 2.4). This is a radiation level that mandates an evacuation of residents.

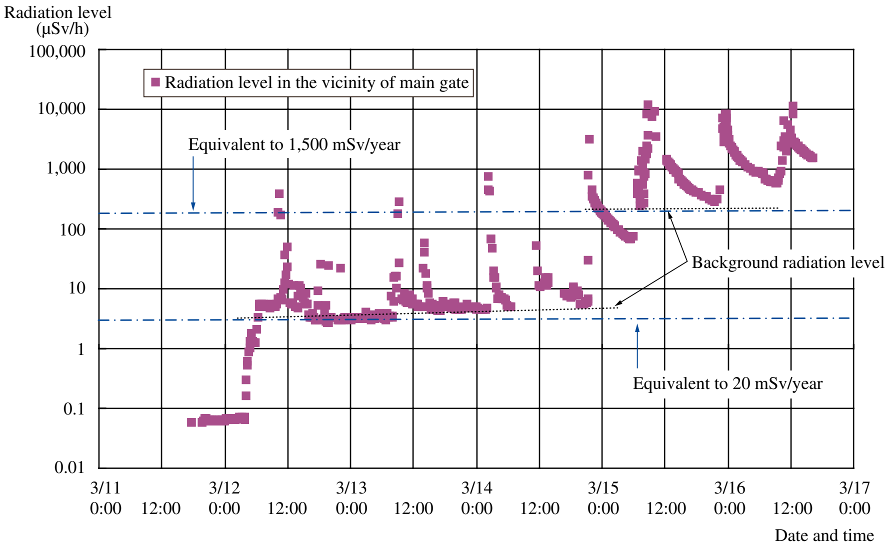


Fig. 2.4 Radiation level change in the vicinity of the front gate of Fukushima Daiichi NPS (Source: from TEPCO's "Fukushima Nuclear Accident Report")

However, the actual evacuation had already started as early as midnight of March 11. It was an emergency evacuation and was not based on any evacuation plan or preparation. The fact that SPEEDI (System for Prediction of Environmental Emergency Dose Information) was not implemented at that time shows well how haphazardly the evacuation was done as was criticized by the mass media. This lack of preparation for evacuation not only caused confusion and frustration among the evacuees but also caused up to 60 people to die at seven hospitals and long-term care facilities related to the evacuation [1]. I will discuss the evacuation issue again in Chap. 4 of Part II in relation to the radiation emission issue.

One other thing we must not forget is the extravagant operation for cooling of the spent fuel pool ("SF" pool) of Unit 4, i.e., the aerial water spray by the JSDF's helicopter, the use of the Tokyo Fire Department's fire trucks designed for high-rise building fires, etc. That was an incident separate from the reactor accidents, more specifically the core melt and the hydrogen explosion, that are the objects of this book.

By March 20, temporary power was made available to the accident site. The restoration of lights to the once pitch dark accident site came to accelerate the handling of accident. The decay heat that caused the core melt and hydrogen explosion dropped down to well below 1 %. So long as the cooling of the core continued, the possibility of new unexpected surprises would be lower. There was finally some breathing room. As electricity became available and the water used to cool the core melt changed from sea water to fresh water, a new concern was what to do with the waste water discharged from the core melt and accumulated in the basement of the reactor facility. It was April 5 when we received complaints from South Korea and other neighboring nations for releasing low level contaminated water.

At this point, the difficulty the power plant staff was facing was enormous. Several hundred staff members were living as a group in a contingency planning building called “Seismic Isolated Building” that withstood the earthquake and tsunami. They slept on the floor with no change of clothes, and worked around the clock they were not quite prepared for. The food they ate was all cold preserved food.

And yet, they endured. I believe that those who worked at the power station, were the ones who recognized the graveness of the accident most and were most concerned about it. Most of them lived in the same community and stayed at the power station although their families had evacuated. During that period of time, almost no communication was possible between them and their families. It was approximately 2 months after the incident that signs of improvement came to be seen when the government and TEPCO jointly issued the first amendment to the “Roadmap towards Restoration from the Accident at Fukushima Daiichi Nuclear Power Station (May 17, 2011).”

If I were to write the story of all the difficulties the staff went through, it would easily fill a separate book, but it will deviate from the purpose of this book, so I won’t say anything further. The IAEA’s accident investigation team, which visited the site on May 24, offered the staff praise: “The on-site response by dedicated, determined and expert staff, under extremely arduous conditions, has been exemplary and resulted in the best approach to securing safety given the exceptional circumstances.” As those who are familiar with power stations, they no doubt could not avoid making such an observation.

By June, with the help of U.S. and France, a recirculating cooling facility was completed on the site. The pipeline facility for removing the radioactive substances from the accumulated waste water so that the water can be recycled as cooling water was finally completed in a rush. With the completion of this facility, it became readily possible to cool the reactor and the temperatures surrounding the power plant began to drop gradually. As a result, the amount of radioactivity released from Units 1–3 dropped substantially, and it is reduced to about one one-hundred millionths of what it used to be at the time of the accident now 3 years later.

I suppose that it was after the interim report of the government on the accident, which came out around the spring of 2012, or about a year after the accident, when the decommissioning issue came to be talked about. Concerning the TEPCO’s decommissioning plan, which took 4 years to formulate and will take 40 years to complete, I have been asked what I think of it by various people in the media as I have an experience of decommissioning the JPDR (Japan Power Demonstration Reactor) of the Japan Atomic Energy Research Institute about 20 years ago. I will be rendering my opinion about it in Part II, Chap. 7, so that I will stop my outline description of the accident right here.

2.4 Case of Unit 1

Unit 1 was completed and started to operate in March 1971. It was the third BWR built in Japan. It was the time when there was a boom in the construction of nuclear power stations in the United States, the world leader in the field of nuclear power generation, and most of the design and manufacture of their key components were done by General Electric (GE).

JPDR of Japan Atomic Energy Research Institute which succeeded in atomic power generation for the first time in Japan was also made by GE in 1963. The second oldest in Japan was Unit 1 of Tsuruga NPS of The Japan Atomic Power Company, which [was aimed for commercial atomic power generation for the first time] in Japan. That was also made by GE. The design of Unit 1 of Fukushima Daiichi is almost identical to those of other BWRs in use today but its electric output is approximately 460 MW, which is slightly smaller than the others.

If I were to point out the characteristics of Unit 1, it relies more on mechanical devices, as often seen in old machines. In that sense, it is a power station born in the midst of evolution. Comparing it to newer power stations is like comparing a manual shift automobile to an automatic shift automobile of today. However, it has no essential difference from the newer models in the basic performance, as manual shift automobiles are to automatic shift models. I see not a few operators feel attached to Unit 1 as if they love manual shift cars.

I wanted to write this because there are people who claim in know-it-all attitudes that Unit 1 is 40 years old and that's why it caused the accident. The accident was caused by tsunami and has nothing to do with the age of the power station.

2.4.1 Isolation Condenser (IC) Problem

Another feature of Unit 1 is that it has isolation condenser (ICs). The ICs, which are criticized because they did not work in the accident, are emergency cooling devices utilizing the natural circulation system used only for three older BWRs including Fukushima Daiichi Unit 1.

The Reactor Core Isolation Cooling System ("RCIC") is used instead of ICs for all units after Unit 2. In that sense, Unit 1 is an old type of nuclear reactor. Although I will be explaining about RCIC in relation to Unit 2 later, please remember for the time being that both ICs and RCIC are safety devices for the purpose of cooling the core when the reactor is separated (isolated) from the turbine as in the case of this accident.

Let me make here a simple explanation of ICs. As shown in Fig. 2.5, the essence of an IC is a simple heat exchanger for cooling purposes, which is located at a position higher than the reactor. It is a cooling circuit based on the principle of natural circulation in that the steam rising from the reactor is cooled and condensed to return to water as it passes through the heat exchange tube. It is a highly reliable

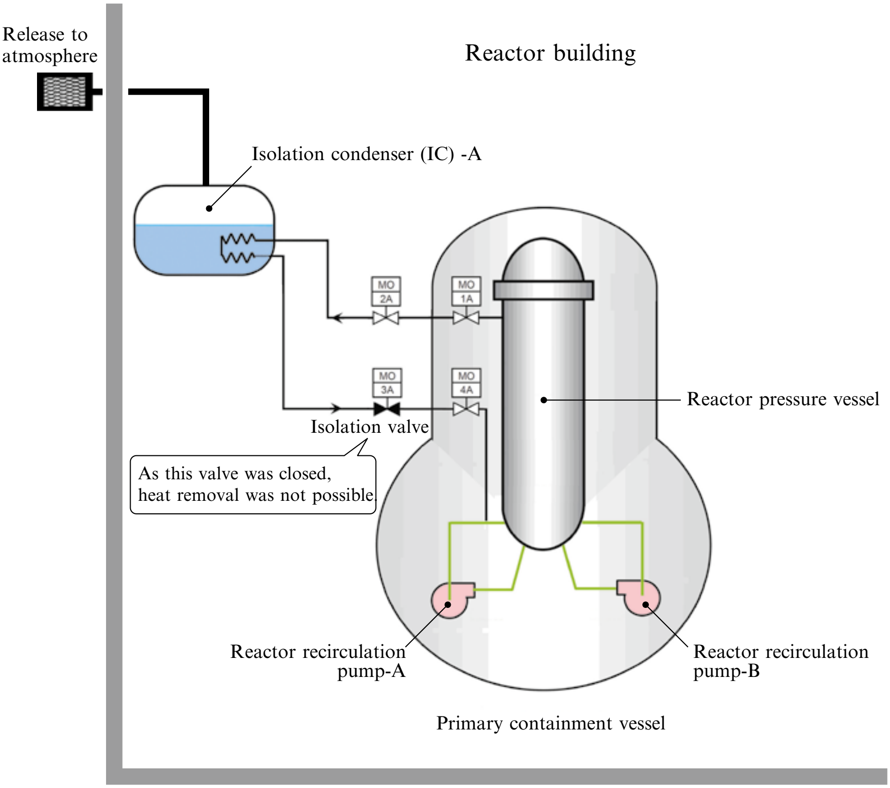


Fig. 2.5 System diagram of Unit 1 isolation condenser

device using gravity so that if this IC worked as we expected, the core melt and hydrogen explosion of Unit 1 would not have occurred and the accident would have been much smaller.

It is so designed that as much as 100 tons of water is stored on the secondary side of IC's heat exchanger, so that it can continue to cool the reactor for 8 h continuously when the reactor stops. Of course, the cooling period can be easily extended by simply replenishing the water. Unit 1 was equipped with two ICs, i.e., A and B.

Although I will be explaining later why the ICs did not work as expected, the problem is that neither the Site Response Headquarters nor the Head Office Response Headquarters of TEPCO were aware of the fact that the ICs were not working and simply took it for granted that the ICs were working. I suppose that this misunderstanding amplified the accident. It seems that the main concern of TEPCO headquarters immediately after the tsunami hit was focused on Unit 2, whose output power is larger and whose reactor water level and operating status of RCIC were unknown at the time, and they paid little attention to Unit 1, thinking that it was safe, as its output is smaller and has natural circulation cooling ICs.

The reason that these ICs of supposedly higher reliability did not work is that the isolation valve (MO-3A), which is located where the piping that connects the reactor with ICs pass through the containment vessel, was closed.

There are many valves related to ICs. Each valve's status during the accident, i.e., whether the valve worked or not, is still in the midst of discussion. Since it deviates too far from the purpose of this book to discuss each of them in detail, I will focus my discussion of the performance of ICs focused on the status of MO-3A valves which the operator controlled.

Why then was this MO-3A valve closed?

The reactor was automatically shut down as the earthquake hit the power station at 2:46 p.m., March 11. With it, the power outage occurred and the main steam isolation valve was closed automatically. However, decay heat continued to be generated even though the reactor was shut down. As the main steam isolation valve was closed, the steam generated by decay heat had no place to go so that it ended up causing the reactor pressure to rise. At 2:52 p.m., 6 min after the reactor's shut down, the ICs automatically kicked in as designed, having received the reactor pressure high signal. Unit 1 then switched to the cooling by ICs.

The cooling speed is typically very fast immediately after ICs are kicked in. This is because the cool water that has been kept in the cooling tube of ICs rush into the reactor all of a sudden. I personally experienced it during my days at JAERI witnessing how IC of JPDR works; it really cools the reactor well immediately after it is kicked in. I heard that they used to conduct emergency trainings at Tsuruga NPS using IC from time to time during the cooling process after scheduled reactor shutdowns, but it looked that this was the first time for the operators of Fukushima Daiichi Unit 1 to experience this.

At 3:03 p.m., 10 min after the IC operation started, they suspended the IC cooling because they thought that the cooling speed was too high. They used the particular MO-3A valve to stop it. This was not a wrong operation. The operation rule states that the cooling speed of the reactor shall not exceed 55 °C/h. At the particular instance, the operating staff had no idea as to whether a tsunami would attack them later so that they simply obeyed the rule. It was the standard procedure to do so.

Not much later, the temperature and pressure of the reactor began to return to normal, the operating staff kept only one of the IC systems operating, and operated the isolation valve (MO-3A) on the condenser return piping on and off in order to control the cooling speed of the reactor manually. It seems that this operation was done several times. It was quite unfortunate that the tsunami came immediately after the MO-3A isolation valve was closed by the operating staff. The electric power of Unit 1 was totally lost by tsunami. The electric power to operate MO-3A was gone. Thus, the ICs became inoperable.

As I mentioned above, there have been many things said about the status of IC of Unit 1 after the accident. I have my own thought about it, but that is not the purpose of the book, i.e., the analysis of the core melt, so that I do not wish to discuss about it here.

However, it is still true that whether the ICs worked or not was detrimental in the occurrence of the core melt. It was a critical issue of grave consequence that determined the life and death of the reactor. The operating staff must have known that. However, what attacked them was earthquake, tsunami and total blackout due to power failure. It would be too harsh to demand perfect performance for the operating staff on all matters such as emergency operating performance and accurate information recording and transmission. If only they had a portable generator or a battery, MO-3A could have been opened. If they had such preparation, the operating staff could have been more attentive. I will be discussing this in Chap. 6 of Part II.

The stoppage of ICs made a night-and-day difference in the Fukushima Daiichi accident. Their late recognition of the IC stop was the biggest mistake they made. However, crying over spilt milk does not move us forward. Let us move on now, admitting that the core cooling of Unit 1 is lost forever as the IC function is lost by the attack of tsunami.

2.4.2 Fuel Temperature Rise

The second wave that flooded the power station arrived at 3:35 p.m. The ICs became inoperable about 50 min after the earthquake.

However, it was very lucky for Unit 1 that the ICs operated for at least this period of 50 min. It is because the decay heat which used to be about 7 % of the rated power immediately after the reactor shut down was reduced to about 2 % in 50 min. In other words, the size of the decay heat that triggers the core melt was reduced to 2 % at the starting point. It means that a large advantage was given to the operating staff at the start, so that the time to the core melt was substantially elongated in comparison with the case of TMI.

Unfortunately, TEPCO failed to take advantage of this luck. It is because they did not realize that the critical device, the ICs, were not operating. If they were aware of it, there were ways to take advantage of it. Many things could have been done since the radiation level of the site was low enough so long as they could manage the darkness.

Since IC is a simple natural circulation circuit, the reactor can be cooled even without electricity, so long as the valve is open. That's why the commander and his staff at the site headquarters did not pay too much attention to Unit 1 assuming that the ICs were operating. That was their critical mistake.

I assume that it was around 10–11 p.m. of March 11 when they noticed that the radiation level inside the reactor building rose sharply when Unit 1 was in a critical condition.

According to TEPCO's analysis, the reactor's water was empty about that time. However, this conclusion can be discounted slightly. It is because the γ-ray that is emitted from the fuel rods do not function as the source of the decay heat as it disperses to the outside of the core when the reactor water level drops and the fuel rods become exposed above the water level.

The discussion of this reason takes a lot of words and deviates from the main subject so I will not discuss it here, but it contains some important matters in considering the nuclear reactor accident so that it will be written as at the end of this chapter as Appendix 2.1. You are welcome to look at it if you are interested in.

Now, let us summarize what transpired with respect to Unit 1's core after the ICs ceased to operate.

The ICs stopped about 1 h after the reactor's shut down. The magnitude of the decay heat is approximately 2 % of the rated power, or more specifically, approximately 30 MW. With this thermal energy, the water in the reactor core is heated to produce steam, resulting in an increase of the reactor pressure. When the pressure rises about 10 %, the safety relief valve opens automatically to discharge the steam to the containment vessel, and restores the reactor pressure back to about 7 MPa. When the pressure returns to normal, the valve closes. This steam blowout-and-stop cycle repeats itself again and again after the isolation condensers ceased to function.

This steam blowout by the safety relief valve is essentially the cooling of the reactor by evaporating the water kept inside the reactor. It can be compared to an octopus eating its own arms in order to survive. It cannot last long. It consumes the water in the reactor and keeps lowering its water level. On the other side, the temperature and pressure of the sump water in the containment vessel where the steam is dumped increase as the amount of the dumped steam increases.

Let's make a simple calculation. The water evaporation by this heat is calculated as approximately 75 tons/h. According to TEPCO's calculation, the water level that used to be approximately 5 m above the core dropped to the upper portion of the core 3 h later (about 6 p.m., March 11), and reached the bottom of the core about 5 h later (about 8 p.m.) (Fig. 2.6). Since this is a simple calculation of the water level drop due to steam generation, it is slightly exaggerated as I mentioned before, but it can be trusted as a ballpark calculation. As the time required from the water level to drop the length of the core (approximately 4 m) was approximately 1.5 h, the water level drop speed at the core was approximately 2.7 m/h, or 4.5 cm/min.

Now let us look at the fuel status when the water level has dropped to the middle of the core, in order to compare it with the TMI accident.

The water inside the reactor was only boiling calmly during the period when the safety relief valve was closed. The fuel rods at this moment were like bathers in a sauna bath just like the fuel rods of the TMI accident when the block valve of the pressurizer relief valve was closed. Since the evaporation speed of steam is roughly 1.5 cm/s or so (Appendix 2.2), it was a sauna without any breeze. However, when the pressure increased and the safety relief valve was open, the steam vented from the reactor so that the fuel rods were cooled somewhat. While the portion of the fuel rods that was exposed above the water level was sometimes heated by the sauna and sometimes cooled by the steam flow, its temperature must have gradually risen as the water level dropped further.

It must be that the fuel cladding tubes exposed above the water level began to be oxidized and covered by a thin oxide film on the surface. I assume that the inside of the softened cladding tubes must have adhered to the pellets and formed oxide film as well. I believe it is safe to assume that it was no different from the status of the TMI accident but the fuel status of Unit 1, whose decay heat was less than that in

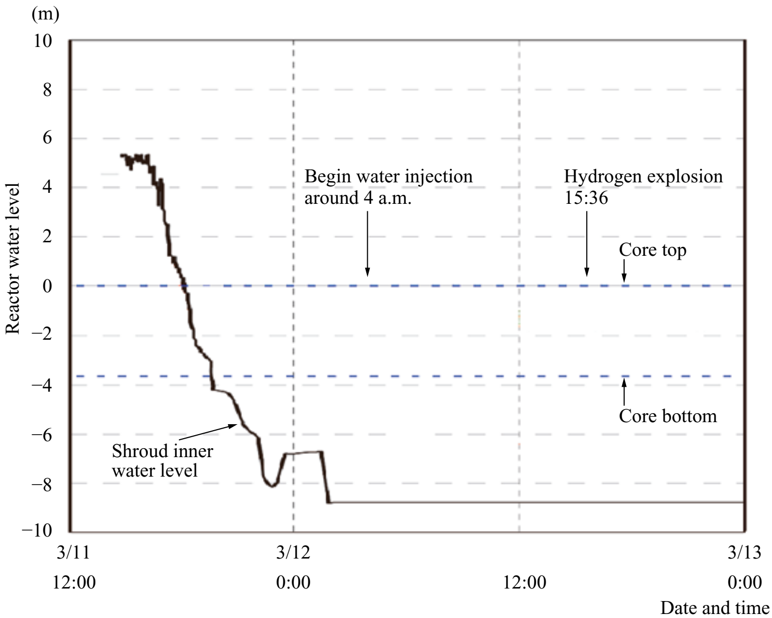


Fig. 2.6 Unit 1 water level change (analysis data) (Source: from TEPCO "Fukushima Nuclear Accident Investigation Report")

the case of TMI, was in a status between [II] and [III] of the model diagram (Fig. 1.5) of Sect. 1.4.

In case of TMI, the status of the fuel rods was at [IV] as the decay heat was high. That was when the reactor coolant pump began to run. Hence, the core collapsed. Please refer to Sect. 1.5. A large amount of cool coolant water flowed into the core, the fuel rods broke up into pieces, the core collapsed, and the core melt occurred. However, in case of the Fukushima accident, it was about 7 p.m. when the water level dropped to a half, but the pump did not run due to the power outage, so that water did not flow into the core. Therefore, neither fuel rod breakdown nor core collapse occurred. The fuel rods tenaciously held the status of either [II] or [III] of Fig. 1.5.

This condition continues. However, the further the water level of the core dropped, the length of the portions of fuel rods below the water became shorter, so that the water evaporation amount reduced, and the degree of overheating in the upper portion of the core increased proportionately. In other words, the amount of heat used for evaporation declined, and while that to raise the steam temperature increased. Consequently, the fuel temperature in the upper portion of the core rose by that much. The status of the fuel rods probably shifted gradually from [III] to [IV].

By midnight of March 11, the water level of the reactor was completely lost. Although the decay heat generated in the core needs to be subtracted somewhat, due to the increased heat dissipation by radiation with the temperature of the fuel rods.

From this point on, the situation requires us a comprehensive study on the status of the fuel rods the temperature of which continues to rise while they keep emitting radiation heat, of the temperature increases of the internal components of the core and the surrounding structures such as the core structure, the reactor pressure vessel,and the containment vessel exposed to the radiation. The temperature evolution of each component is determined by the give and take balance of the radiation heat, in addition to the core melt.

As the water level drops to a half of what it used to be, the TMI accident is no longer useful as an example to learn from. From this point on, it is a voyage without a nautical chart, and there is no way out but to think carefully about the condition of the core on our own in order to find what happened. As I laid out, there are so many things to think about.

Incidentally, the most complex case of core melt among those of Units 1–3 is that of Unit 1. Therefore, I wish to temporarily stop the analysis of Unit 1 here, and do the analysis of the core melts of Unit 2 and Unit 3 which are closer to the example, i.e., TMI, first and then resume the Unit 1 analysis based on those examples. I believe the explanation will be easier for me and it will be easier for the readers to agree with my thought as well.

2.5 Case of Unit 2

Unit 2 was completed and commenced operation in 1974, 3 years after Unit 1. The main difference between the two units is that the output is 460 MW in Unit 1, and 784 MW, or approximately 70 % larger, in Unit 2. As the output increased, so did the physical size of each facility, but the design concept itself did not change much.

If we are forced to find major differences, the differences are, as I mentioned for Unit 1, that the reactor core cooling system with respect to isolation cooling (cooling when the reactor is isolated from the main turbine and condensers) was changed from IC to RCIC, and that many of the control systems were converted to electric type. Another marked difference is that most of the equipment, which were made by GE in case of Unit 1, were switched to Japanese makes such as those made by Hitachi and Toshiba. However, you should understand that there is no difference between Unit 1 and Unit 2 as to the core structure, which is the key subject of this book.

2.5.1 Reactor Core Isolation Cooling System (RCIC)

Although Unit 2 was affected by the power loss and the reactor was shut down as a result of the earthquake, the cooling process was started by the operating staff using the Reactor Core Isolation Cooling (RCIC). RCIC is a cooling system used when the reactor is isolated as mentioned above, same as the ICs used in Unit 1.

The difference between RCIC and IC is that, while IC uses natural circulation for cooling, RCIC uses a steam turbine driven pump for cooling, so that it needs to be controlled electrically.

The RCIC is capable of maintaining its own mechanical power because the steam used for driving the pump is generated by the decay heat of the core and does not depend on electric power. While the RCIC can control the water level, it requires DC (battery) power for the control. The balance between merits and demerits is a delicate one. Unfortunately, the scale tipped in the wrong direction in the accident. The battery was flooded and the system became uncontrollable.

Let me explain how RCIC works.

In case of a normal reactor shutdown, the steam generated by the decay heat is discharged to the turbine condenser to be cooled by a large amount of seawater. However, in case of this accident, the circulation water pump for pumping up seawater was disabled not only by the power outage but also by the damage caused by the tsunami, so that there was no way to discharge the steam to the turbine condenser. That's where RCIC comes in.

The RCIC pump has two water sources: the suppression chamber ("SC"), which is a very large water sump located in the lower part of the containment vessel, and the condensate storage tank. However, as the water of the condensate storage tank was never used in this accident since the switching was made on the early morning of March 12, only the SC will be considered as a water source in the following discussion. Let's look at Fig. 2.7.

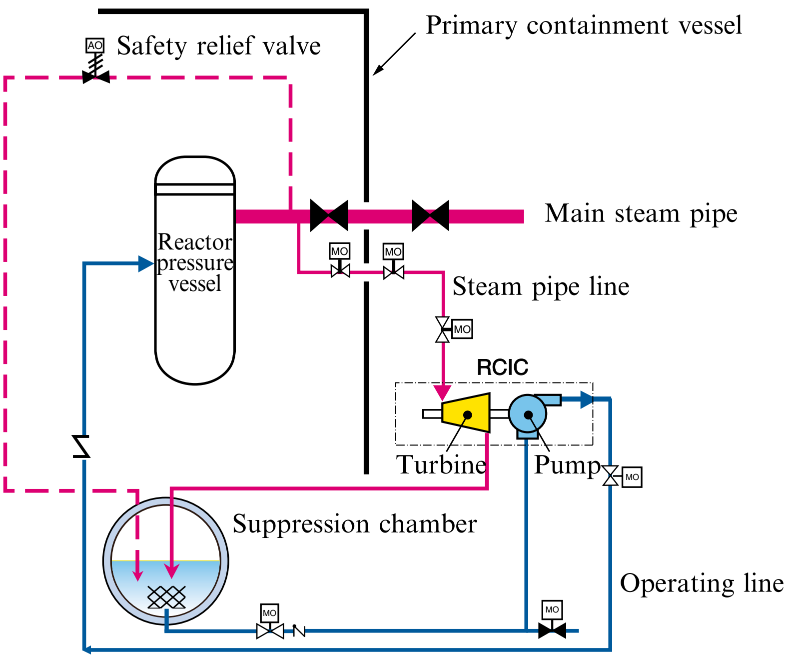


Fig. 2.7 Reactor Core Isolation Cooling (RCIC) system diagram

The water from the pump enters the reactor pressure vessel via the water supply piping and replenishes the water lost by the decay heat. A battery is needed to control this supply amount to maintain the water level of the reactor properly. On the other hand, the steam generated by the decay heat enters the SC again after having propelled the turbine that drives the RCIC pump and having been condensed back to water.

In other words, the reactor cooling by RCIC forms a closed loop circuit by using the water of the SC, i.e., the sump of the containment vessel, as the cooling water, while returning the steam generated in the reactor back to the same SC. In other words, the reactor cooling using RCIC is [a circulation cooling] by means of the SC water of the containment vessel, and so there is a net zero effect on the water balance. That means, however, that the cooling capacity (capability) is governed by the quantity of the SC water. The SC water amount that can be stored in the Mark-I type containment vessel is approximately 3,000 tons. If we assume that RCIC can be used until half of that amount of water is evaporated, it will be able to cool the reactor for 5 days or so.

By the way, most of the reactors of Fukushima Daini NPS and Onagawa NPS used this RCIC for the core cooling after their reactors were shut down during the Great East Japan Earthquake. Although the operating staff had a very tough time due to the damage caused by tsunami, they were eventually able to achieve cold shutdown status on all of those reactors.

As can be seen from this example, reactors can be cooled so long as water injection from RCIC can be continued. Since the decay heat is only about 7 % of the rated output, the temperature of the fuel rods do not rise. The temperature of the fuel rods is about the same as that of the cooling water, i.e., 300 °C or so, so that it is far removed from the world of fuel melting and oxide films forming on the cladding tube. It is safe for us to think that a core melt does not occur so long as the RCIC is functional ((a) of Fig. 2.10).

At around 3:35 p.m., Unit 2 was also hit by the tsunami. The tsunami flooded the battery and made it impossible to control the RCIC. However, all of the main units of RCIC were installed on the reactor building which was saved from the tsunami, and it was lucky that the turbine that drives the pump continued to run without the help of the control power and kept supplying water to the reactor.

A TEPCO report states that it was confirmed that the reactor water level was 3,400 mm above the core as of about 10 p.m. on March 11, and that the operating staff confirmed that the RCIC operating in the blacked-out site at around 3 a.m. on March 12. That must have been a heartening report for TEPCO. The people at the site may have hailed, "OK, we can make it!"

What should be noted is that the water level of plus 3,400 mm that was confirmed on the night of March 11 was kept unchanged until around 10 a.m. of March 14, as evidenced on the TEPCO's water gauge record (Fig. 2.8). This means that the RCIC pump kept running without control for 3 days since the accident. This is a total surprise, because an isolation cooling facility like RCIC is normally designed for a power outage of 8 h. A machine designed to run 8 h kept running for three complete days in a poor environment without control. We are badmouthed because

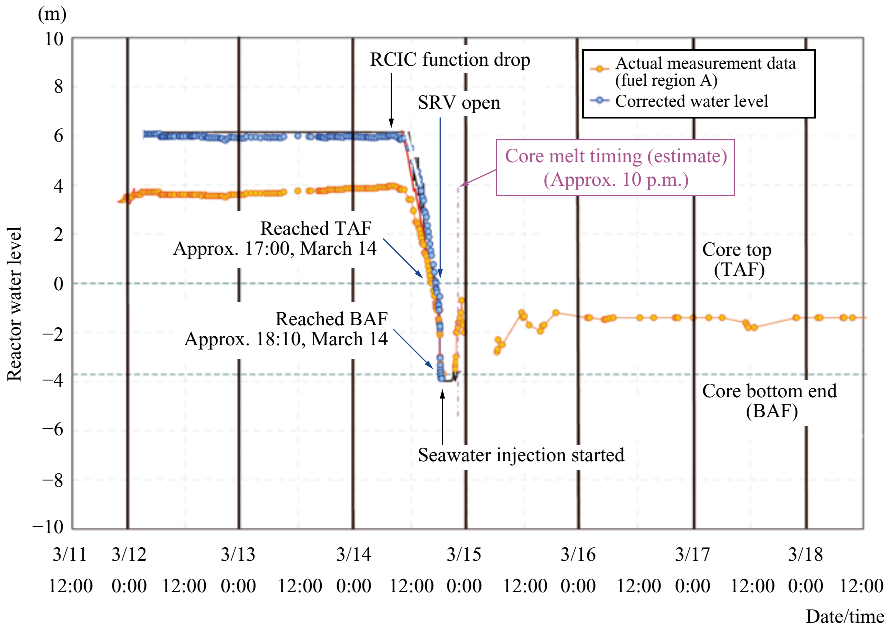


Fig. 2.8 Unit 2 reactor water level change (measured data) (Source: from TEPCO "Fukushima Nuclear Accident Investigation Report")

of the accident, but our safety devices at the power plant stood up for their names. They worked better than they were expected. Incidentally, this 8 h design criteria is common to all nations around the world, except for a few exceptions.

According to the report, this plus 3,400 mm water level amounts to plus 6,000 mm if the error of the water gauge due to the accident is compensated for. Although I will not elaborate on the reasoning, I trust this compensation is correct. If the water level was actually plus 6 m, it exceeds the top of the steam-water separator, so that it is reasonable to expect that the quality of the separated steam was poor and contained water. I suppose that the rotary blades of the RCIC drive turbine were substantially damaged by the water content of the steam.

The reactor water level started to drop after 11 a.m. of March 14. The report states that the power plant manager judged that the RCIC had ceased to function, noting the extreme drop of the water level, at 1:25 p.m. on March 14. I suppose that the RCIC pump stopped at around 11 a.m. (Appendix 2.3).

From that point on, the decay heat of the reactor was removed by water evaporation, and the reactor's water level started to drop because of it. In other words, the core cooling condition of Unit 2 became the same as that of Unit 1. It is safe to say that the core melt problem of Unit 2 started around 11 a.m. on March 14.

Coincidentally, an explosion occurred in the reactor building of Unit 3 at 11:01 a.m. on March 14. Because of this explosion, the temporarily installed water hose and fire engines prepared for the purpose of feeding water to Unit 2 were damaged and became unusable. In addition, the operating device of the vent valve prepared for pressure relief of the containment vessel became unusable as well, so that the pressure venting of Unit 2 became difficult. As the on-site task force team of Unit 2 was busy coping with these matters, the water injection to the core was delayed until 8 p.m. of the same day.

This delay caused the core melt, which I will be discussing later.

Let's get back to the discussion of the core. When the RCIC pump stops, the water injection to the core stops, so that the status of the fuel rods become a cooling state as if they are bathing in a sauna bath. This causes the core water to evaporate, the fuel rod temperature to rise, and the oxidation of the cladding tubes to start in no time.

As we look at Fig. 2.8, the water level, which used to be plus 6 m at 10 a.m., March 14, reached exactly to the bottom of the core, i.e., minus 4 m by 6 p.m. of the same day. The cooling water is totally gone from the core by around 6 p.m.

Let's make sure if this understanding is correct by checking the data from 11 a.m., when the RCIC stopped, to around 6 p.m., when all the water of the core is gone. As far as we can see from Fig. 2.8, the core water level decreased very smoothly without any unexpected change. The reactor pressure (Fig. 2.9) started to rise at around 10 a.m. because of water evaporation, and was kept at around 7.5 MPa constantly by means of the operation of the safety relief valve from a little after 2 p.m. until approximately 6 p.m. All the data look as expected with no special deviation.

The fact that no irregularity can be found in the reactor's pressure data means that the core was cooled to a certain degree until 6 p.m., and no problem such as a core melt occurred. We assume so because, if core melting occurred, there must

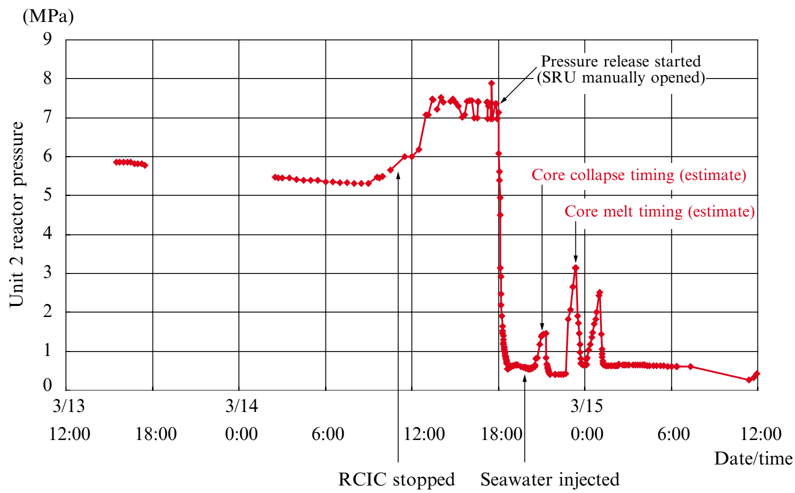


Fig. 2.9 Unit 2 reactor pressure change (measured data) (Source: from TEPCO "Fukushima Nuclear Accident Investigation Report")

have been an acute core water level change due to the enormous heat caused by the zirconium-water reaction. It also must have caused an abrupt reactor pressure rise by the generation of hydrogen. The fact that there was no abrupt change as such proves that there was no core melt until 6 p.m.

Although this may sound very obvious, it has a very important meaning. It means that core melt did not occur even though there was no water in the core and it was exactly like heating a bath with no water in it. This is a fact that was clarified for the first time in this Fukushima accident, and it was a new finding that was not experienced in the TMI accident. This, of course, is data that should be utilized in reactor safety from now on.

Now, we know that the water level was down to the lowest part of the core by 6 p.m. I have a view that the fuel temperature increase due to the water level decreased was not so high, probably reaching only up to 1,000 °C at most, because the decay heat had reduced to about 0.4 %, different from the case of the TMI accident, and also because there was a heat dissipation of breezy intermittent steam flows due to the safety relief valve. The state of the fuel rods was probably the [I] or [II] stage of Fig. 1.5 at most.

The core has not started to melt by this time, i.e., the early evening of March 14. The core melt has yet to start at this point.

2.5.2 Sea Water Injection and Core Melt

At 6:02 p.m., the safety relief valve was fixed to an open position to lower the reactor pressure.

At 7:54, the water injection to the reactor was started using fire engines.

The combination of these two operations triggered the core melt.

The title of this section is the core melt. In order for the core melt to occur, two conditions must hold simultaneously, i.e., that the fuel rods are at a red-hot state and that a large amount of water is available, as described in the conclusions I and II of Sect. 1.7. Please keep these in your mind as you read the following.

Before we get into the main discussion, let us make some calculations that are needed for assessing the situation.

As I described in Sect. 1.4, the size of the decay heat that was a partial cause of the core melt within 2 h after the shutdown in case of the TMI accident was approximately 1 %, and the rate of temperature rise of the fuel rods due to this heat was a little over 0.74 °C/s. In case of Unit 2, the decay heat had dropped further to about 0.4 % as it had been a full 3 days after the shutdown. If we assume that no water was in the core, so that no heat was being removed at the time, the rate of temperature rise of the fuel rods was about one third of that of TMI, or 0.2 °C/s, or 12 °C/min, or approximately 700 °C/h.

At 6:02 p.m., the operating staff lowered the core pressure forcibly by firmly setting the safety relief valve to the open position. The reactor pressure had dropped sharply from about 7.5 MPa to about 0.5 MPa. The time needed for the pressure drop was probably 30 min or so.

Due to this pressure drop, the water in the lower part of the reactor began to "decompression boil." Decompression boiling is a kind of self-boiling phenomenon caused by a decrease of the saturation temperature associated with a drop in pressure. The consumption of cooling water by this decompression boiling can be substantial. According to my ballpark calculation, the decompression boiling caused approximately 30 tons of water that was below the core to evaporate. Those of you who are interested may review the calculation provided at the end of this chapter (Appendix 2.4).

Thus, the water level dropped to approximately 1 m below the core.

In addition, it is assumed that the core fuel that had been kept at around 1,000 °C in a sauna-like condition up to that point was cooled by the steam generated by decompression boiling and the temperature dropped to around 150–160 °C, or close to the saturation temperature of water.

In other words, the fuel rod temperature dropped because of the decompression boiling. If seawater was injected into the reactor immediately after the completion of the pressure reduction at this time, the core melt would not have occurred. That is because zircaloy covered by oxide film does not react with water if the temperature is low. If the zirconium-water reaction does not occur, a core melt will not occur even if the fuel rod splits up and fall down, because such fuel debris will be cooled by water ((c) of Fig. 2.10).

Please recall the PBF-PCM test described in Sect. 1.3, the communication path, and the agglomeration of cooled fuel debris found on top of the TMI core.

Unfortunately, it was as late as 7:54 p.m. when seawater finally arrived at the core. It was approximately 2 h after the pressure reduction started. It can be easily estimated from the ballpark calculation we did a while ago that the temperatures of most of the fuel rods must have reached around 1,500 °C by then.

The surface of the fuel rods sticking out in a red-hot state above the water surface must have been covered by oxide films, and the inside of the oxide films must have been filled with zircaloy, i.e., the cladding tube material, which was softened, partially melted, and formed agglomerations here and there. Then came a flush of cold water. If the seawater was sprayed from the top of the core, the oxide film would have been quenched and broken down, causing the fuel rods to split into pieces, so that the core must have collapsed judging from the precedents of PBF and TMI. The core could have collapsed instantly into a pile of debris. But it didn't turn out that way.

The water was not sprayed from the top of the core, but was fed from the piping on the side wall of the reactor pressure vessel. Besides, it was a tiny flow from a fire engine. A portion of the seawater that streamed downward along the wall may have evaporated but the majority of it must have accumulated into the bottom part of the reactor pressure vessel serving to raise the rector water level.

Checking with a fire station, I found out that a fire engine pump takes 3–5 min to discharge the water contained in its 2 ton tank. Since this amounts to 24–40 tons/h, it takes about an hour to replenish the water lost by decompression boiling.

Please look at the reactor pressure change diagram of Fig. 2.9. A small but sharp pressure increase can be observed at around 9 p.m. of March 14. Around 9 p.m. corresponds to about 1 h after time the water injection started. This is about the time

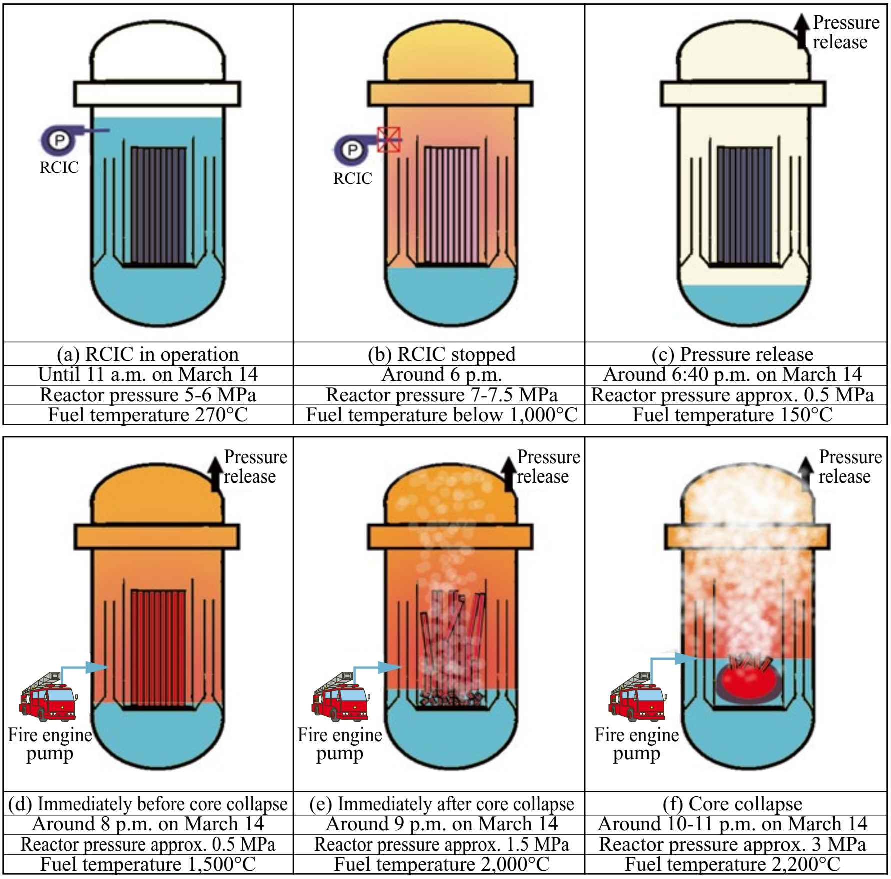


Fig. 2.10 Progress of Unit 2 core status (model diagram)

the reactor pressure vessel's water level is estimated to have reached the core bottom. I assume that it is about the time when a certain amount of zirconium-water reaction occurred as the water level reached the bottom of the hot fuel rods ((e) of Fig. 2.10).

I imagine that the water that contacted zirconium partially boiled, splashed around, and evaporated. Hot fuel rods, on the other hand, split into pieces as they contacted cold water, and the molten zircaloy reacted with water to generate hydrogen. I imagine that this generation of hydrogen caused a temporary reactor pressure increase of about 1.5 MPa.

However, the reaction was not so large as to cause the core to melt. The reason was that the amount of water available for the reaction was insufficient.

In the TMI accident, it took only about 2 min for the core to melt in the TMI accident. Although the primary coolant pump was operated for only 19 min, it is thought that approximately 28 tons of coolant was injected into the core within less than a minute because a large amount of coolant stored in the piping was injected by a large capacity pump. With this large amount of water gushing in, it is believed that the core was, thus causing the top portion of the core to break into pieces and ending up in an overall collapse of the core, as well as causing the zircaloy left in the core to oxidize altogether to generate a large amount of hydrogen.

On the other hand, in the case of Unit 2, water was supplied in a small stream from a fire engine. Since the pumping speed from a fire engine is typically 24–40 tons/h, it was only one sixtieth of the rate of water supply in the case of the TMI accident. If not enough water is supplied, an oxidation reaction cannot occur. Thus, the core melt did not occur in a short period of time as in the case of TMI. A further supply of seawater was needed in order to cause the core melt to occur.

Please keep in mind that what is meant by a core melt here is a first violent reaction between water and the mixed molten substance in the core and amounts to about 30–40 % of the total zircaloy. The reaction between water and the remaining zircaloy is assumed to have occurred later from time to time depending on the circumstance.

Let us do some brush-up now. We have learned that the heat that causes the core to melt is not decay heat but rather an enormous amount of reaction heat generated by the oxidation reaction between water and the zirconium used as the cladding tube material. However, in order to cause this reaction to occur all at once, both a high fuel rod temperature and as well as a large amount of water are needed. The amount of water supplied by the fire engines was not sufficient to cause the reaction to occur all at once.

Let us make a calculation from a different angle. The total amount of hydrogen generated by Unit 2 is estimated as 460 kg by TEPCO. Let us use 500 kg as the approximate number in our calculation. Since the molecular weight of hydrogen is 2 and the same for water is 18, it takes 9 water to generate 1 hydrogen in the weight ratio. In order to generate 500 kg of hydrogen, it requires at least 9 times of it, i.e., 4.5 tons of water. As I am not sure how much of the total injected water contributes to the reaction, let me be conservative and assume that 50 % of it contributes to the reaction; then the required water would be approximately 9 tons. In reality, the required quantity is probably more than that. That much amount of water requires at least 15–30 min to be supplied from a fire engine.

The above is only a rough estimate but is enough for you to realize that it takes a substantial length of time for Unit 2 to develop a core melt, different from the case of the TMI accident where it was caused by a large amount of water supplied in one quick shot.

Actually, the evidence is in the reactor pressure diagram of Fig. 2.9. The reactor pressure curve made sharp temporary rises three times between 9 p.m. of March 14 through the early morning of March 15. Although I cannot be too certain because the time scale is rough, I can only assume that these irregular pressure rises are caused by violent hydrogen gas generation due to zirconium-water reactions. I also assume that the core melt of Unit 2 occurred three times intermittently between the evening of March 14th through the morning of the 15th.

The time needed for the first peak to occur is the time required for replenishing approximately 30 tons of water, the amount of water lost by the decompression boiling. As can be seen from Fig. 2.9, the fact that the first pressure rise occurred approximately 1 h after the water injection is convincing proof.

Let us estimate the core condition based on these pieces of circumstantial evidence. The fuel rods cooled down for a while due to the steam discharge caused by the forced decompression that started at 6:02 p.m. on March 14, but it took a total of 3 h for the seawater to be delivered to the bottom of the core – a 2 h delay in the delivery and another hour to be delivered to the destination. During this period of time, the fuel rod temperature rose to approximately 2,000 °C.

The fuel rods still stood straight up like forest trees, however. Then comes in the seawater pumped in by the fire engine. As the cold seawater from the fire engine started to flood the lower part of the core, a violent boiling occurred and the sloshing seawater, violently sloshing because of the boiling, quenched the surface of the fuel rods. I am sure that this caused the oxide film of that part to break up, causing the fuel rods to disintegrate and collapse. In other words, a partial core collapse occurred.

In the meanwhile, the debris of the broken-up fuel rods was piled up on the core plate. There is no question that some of the agglomerations of high temperature zirconium, which were protected by the oxide films formed here and there, streamed out through cracks formed by the breakup and caused oxidation reactions as they met with water. There is no question that, as a result of this heating, localized melting occurred in the lower part of the core and generated hydrogen as well. This hydrogen is the cause of the first rise in pressure.

I suppose that the fuel rods that collapsed because of the loss of support still remain there, holding their shapes from the middle to the top of the core. There must have been an egg-shell made of the mixed molten substance in the vicinity of the core bottom to protect the molten core from making direct contact with the water.

This area is where we can make various speculations and conjectures. It is a world of chaos. I think you should use your imagination freely to picture it. It can be seen from Fig. 2.9 that such a chaotic world lasted for a few hours.

I suspect that, after a couple of hours of such a chaotic condition, the fuel rod temperature's rising, and the water level of the lower part of the core rising again to a sufficient height, the direct contact between water and the fuel rods restarted. This is when the full-scale core melt started. Sharp reactor pressure rises that reached 2.5–3 MPa are recorded twice between the late evening of March 14th through the early morning of the 15th. There is no question that large zirconium-water reactions occurred.

The second reaction was around 10 p.m. The radiation dose rate in the vicinity of the front gate jumped up sharply just about this time. I estimate the time of the core melt of Unit 2 to be the midnight of March 14, although I cannot determine the exact time ((f) of Fig. 2.10).

2.5.3 *Hydrogen Gas Generation and Radioactive Release*

Now, let us look at the condition up to this point from the perspective of the pressure change of the containment vessel (Fig. 2.11). The containment vessel comprises a space called a dry well ("DW") that surrounds the reactor vessel and a doughnut shaped part called a suppression chamber ("SC"). The DW and SC are connected by an interconnecting pipe. The SC contains a large amount of water and there is a vacant space above the water. The steam that is discharged from the safety relief valve is sent directly to the SC and is cooled by the SC water to return to water.

Next, let us think about hydrogen gas discharged from the reactor. The hydrogen gas discharged from the DW passes through the interconnecting pipe, the SC water, and enters into the SC vacant space. The vacant space has a normally closed vent piping. In the middle of the vent piping provided is the rupture disk in question. In case of an emergency, the gas that enters the SC can be guided to rupture the rupture disk to escape to the atmosphere via the stack by opening the vent piping.

That is the explanation of the Mark-I type containment vessel. Although the DW is also equipped with vent piping, it will not be discussed here because it has nothing to do with the accident in question.

Incidentally, each of the DW and the SC is equipped with a pressure gauge. The two gauges normally indicate about the same pressure. Since both of them indicated same pressures until midday of March 14, we have no problem in trusting them (Fig. 2.11).

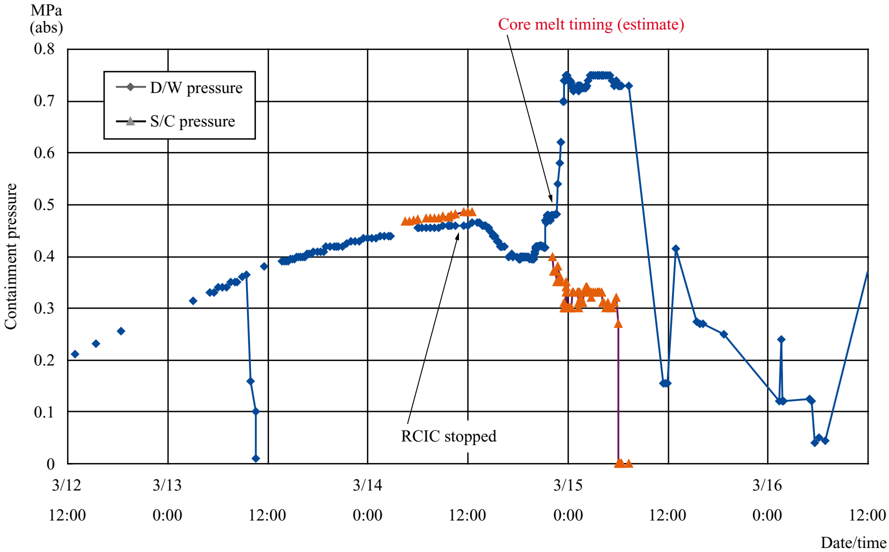


Fig. 2.11 Unit 2 containment vessel pressure change (measured data) (Source: from TEPCO "Fukushima Nuclear Accident Investigation Report")

However, only the data of the DW was available since then until after 10 p.m. of the same day. To our chagrin, when the SC pressure was restored at around 10 p.m. that day, its indication was entirely opposite to the DW pressure and became unmeasurable from around 6 a.m. the following day. This is a problem. Both of these data are not perfect for explanation, but I will be using the DW data as the correct containment vessel pressure data in the following explanation, but I suspect that both gauges were damaged by sharp pressure rises.

The reactor pressure (Fig. 2.9) gradually started to rise approximately 2 h before the RCIC pump stopped, i.e., about 9 a.m., and the containment vessel pressure (Fig. 2.11) started to drop around 1 p.m. This shows the fact that the RCIC pump began to run abnormally, and the steam quantity consumed by the pump (for reactor heat removal) began to drop. As a consequence, the reactor pressure tends to rise, while the containment vessel pressure tends to drop due to the reduction of steam quantity entering the SC water.

At around 2 p.m., the reactor pressure rose to approximately 7.5 MPa and steam began to blow out intermittently from the safety relief valve. The DW pressure tends to decrease slightly at this point. This is believed to be caused by the reduction of the mass flow, because the gaseous phase flow became dominant with the drop of the water level. When the water level was high, the liquid flow had been dominant, even if there was no change in the reactor pressure. We can see that the containment vessel was discharging a large amount of heat from the fact that the containment vessel's pressure was reducing despite the fact that mass and energy were flowing in (Fig. 2.12).

The DW pressure indication slightly upward starting around 8 p.m., but at 10 p.m., it began to turn sharply upward from 0.4 to 0.8 MPa. This sharp rise represents the harshness of the hydrogen generation due to the core melt. In case of Unit 2, the DW volume of the containment vessel is approximately 4,000 m^3. In order to raise the pressure of this volume by 0.4 MPa in one stroke, a humongous amount of gas is required – 16,000 m^3 of gas, if converted into atmospheric pressure.

Since hydrogen gas is generated from the molten core, the temperature is about same to that of the molten core, i.e., 2,000 °C. If a volume of 16,000 m^3 is to be filled with hydrogen gas of this temperature, approximately 200 kg of it is necessary (Appendix 2.5). That amounts to approximately 40 % of the total amount of hydrogen generated by Unit 2 as discussed in Sect. 2.5.2. This sharp pressure increase can only be explained by the hydrogen gas generation. To put it in another way, the existence of this pressure rise is the evidence of the core melt time.

By the way, the design pressure of the containment vessel is approximately 0.4 MPa. However, it is confirmed by various tests that it can withstand pressures about twice that pressure from the standpoint of structural strength. Having said that, however, I am impressed that it withstood the high temperature hydrogen gas of approximately 0.8 MPa.

Now, the question is the temperature of the containment vessel. There is no such data. TEPCO has calculated the containment vessel temperature at this time to be 150–170 °C. The hydrogen gas release occurred from around 9 p.m., after having

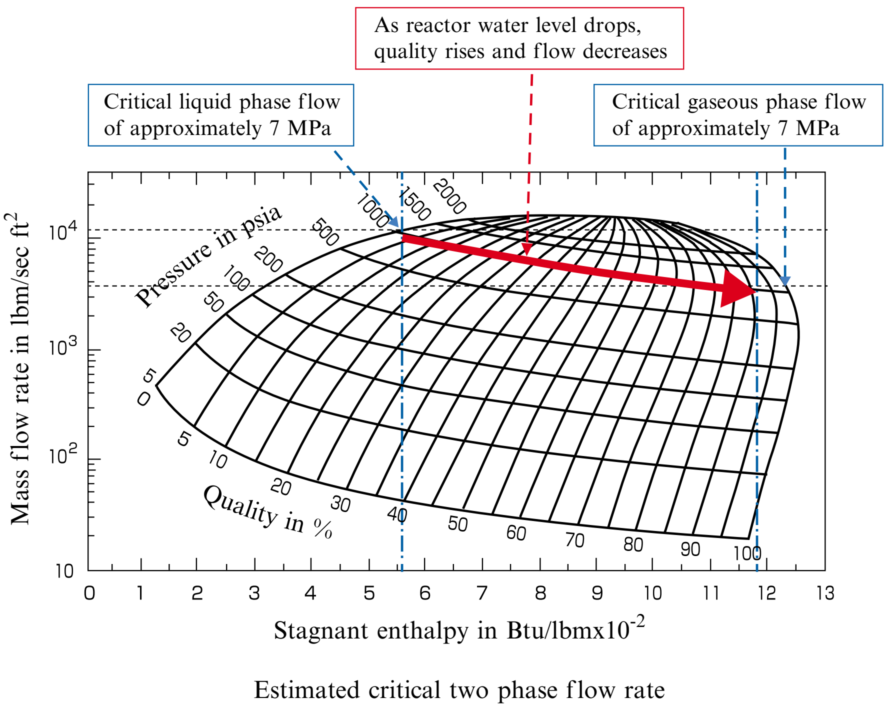


Fig. 2.12 Mass velocity and quality (Source: Fauske, H. K., "Two-Phase Critical Flow," Paper presented at the M. I. T. Two-Phase Gas-liquid Flow Special Summer Program, 1964)

this preheating. I estimate that the temperature of the upper portion of the containment vessel must have been at least the reactor saturated steam temperature, i.e., 300 °C or even higher.

With such a high temperature, what is concerned is thermal expansion. If the bolts that are used to fasten the lid of the containment vessel elongate due to thermal expansion, the fastening of the lid gets loosened and the pressure that is added there will make a gap. Thus the top lid of the containment vessel was pushed up by the pressure. Hence it allowed the hydrogen gas to leak. The TEPCO report says that there was some deterioration of the sealing material due to high temperatures, and I suppose that was possible. However, a slight amount of leakage through the seal cannot explain a huge amount of hydrogen gas discharge. I estimate that the lid was lifted up at least a few millimeters to allow the hydrogen gas to blow out from the periphery of the lid. In other words, the top lid was lifted up by the inner pressure.

Please look at Fig. 2.3. There is a small space of about 300 m^3 called "reactor vault" above the containment vessel. On top of it, there is a large shield plug made of concrete which is removed in case of work such as refueling. The size of the plug is approximately 13 m in diameter and 2 m in thickness, and it weighs approximately 600 tons. A large crane is needed to remove it.

The hydrogen that leaked out by pushing up on the lid of the containment vessel blows out into the space of the reactor vault. Although the reactor vault space connects to a larger space beneath it, the communicating space between them is narrow so that it is difficult for the large volume of hydrogen that blew out sharply to be released into the lower space.

The reactor vault pressure rises with the hydrogen gas blowout. This is where many people fell into a pitfall in their thought processes.

What is the pitfall? It is the assumption that a 600-ton concrete plug will be as solid and immobile as the floor. Let's see if that is true by making a simple calculation. The specific weight of concrete is approximately 2.3 so that the weight per unit area of a concrete object with a thickness of 2 m is about same to that of a water column with a height of 5 m. This can be interpreted as only 0.05 MPa. In other words, if the reactor vault pressure exceeds 0.05 MPa, the pressure acting on the entire area of the bottom of the shield plug can lift this huge shield plug (ref. to Sect. 2.6.5).

Most of us think that the shield plug is so heavy that it is immobile, so that they simply assume that the hydrogen that entered into the reactor vault goes through a contact surface between the shield plug and the floor. This is wrong. The small amount of flow that could pass through a narrow gap in the contact surface cannot produce a hydrogen explosion. A gap of at least a few millimeters would be needed.

Rather, the pressure of the containment vessel's DW with a volume of 4,000 m^3 – the source of the pressure – is as much as 0.8 MPa. A very small amount of blowout of hydrogen from the containment vessel is enough to raise the reactor vault pressure to 0.05 MPa. I imagine that the reactor vault pressure rose to a value much higher than 0.05 MPa and stayed there for a while to keep the shield plug pushed up. During that period, the hydrogen gas from the containment vessel leaked out and spread to the entire fuel exchange floor. The flow stopped when the reactor vault pressure dropped and the force to raise the shield plug was lost.

Incidentally, as a result of the explosion that occurred in Unit 1 on March 12, the reactor building of Unit 2 had lost the blowout panel provided on the sealed wall of the fuel exchange room, thus leaving a big opening. Consequently, the hydrogen gas that blew out from the reactor vault leaked out to the outside of the reactor building through this opening. It was about 10 p.m., which coincided with the time when the DW pressure of the containment vessel indicated the maximum value (approximately 0.8 MPa).

Although it is only my personal view, I believe that hydrogen gas leaked out in this case most likely as a plume (columnar smoke) from a bonfire from the reactor vault to the outside via the blowout panel. As a consequence, hydrogen did not remain in the reactor building and that's why the building was saved from an explosion. The reason I thought of a plume for this case was that I knew that the hydrogen gas was very hot and hot smoke from a bonfire tends to flow as a plume.

Figure 2.4 shows the radiation level in the vicinity of the main entrance gate of Fukushima Daiichi immediately after the accident. Although the detail of this will be explained later, please note the changes from around 6 p.m. on March 14 through the end of March 15.

We notice two radiation level peaks at around 10 p.m. on March 14 and at 6 a.m. on March 15. Since there were no significant events during this period pertaining to Units 1 and 3, which had already had explosions, we can determine that these two peaks must be the radiation emissions from Unit 2.

The first peak occurred at 10 p.m. which coincides approximately with the core melt timing. As I explained before, the large amount of hydrogen gas that was generated simultaneously with the core melt leaked out to the fuel exchange floor by lifting the lid of the containment vessel and the shield plug and emitted out to the atmosphere through the blowout panel.

The second emission peak occurred at around 6:14 p.m. on March 15, which is noted on the TEPCO's report as an occasion of a sharp drop of the containment vessel pressure, dropping beyond the lowest measuring capability of the SC pressure indicator. I suppose it cannot be denied that the second peak was caused by the radioactive substances being discharged through the broken hole of the containment vessel. Please pay attention to the fact that it took 5–6 h for the DW pressure to come down. While the second emission was also a direct emission from the containment vessel, the radiation concentration is higher because of the progress of melting.

Both the first and second radiation emissions were direct emissions from the DW. Different from the cases of Unit 1 and 3, the radiation concentration was very high as it was not the radiation washed by the SC water. As it was not the discharge via the stack, the radioactivity was not diluted by the wind. It was discharged to the ground, so that the density was naturally higher. With these two radiation emissions from Unit 2, the radiation level surrounding the power plant rose and made the forced evacuation mandatory. I will be discussing this in Chap. 4 of Part II.

The containment vessel pressure after the first discharge was showing significant pressure readings in both the DW and the SC, so that it is assumed that no major damage was suffered in the containment vessel during this time period. However, after the second discharge, the DW pressure reading dropped extremely so that it is evident that the containment vessel was damaged. Therefore, it is estimated that the radiation emission was higher and the radiation dose value was higher the second time than the first time.

That concludes the explanation of the core melt and the radiation emission of Unit 2.

2.5.4 Section Conclusion

This has been a long explanation. Let me summarize at this point the core melt and the hydrogen gas emission in the case of Unit 2.

Although Unit 2 lost all electric power because of the tsunami, the RCIC pump, using decay heat, survived, cooling the reactor for 3 days. However, the RCIC pump finally was stopped by exhaustion at around 11 a.m. on March 14, and all means of cooling the reactor were lost.

Having lost all means of cooling, the reactor's decay heat was removed by water evaporation, so that the reactor's water level started to drop. As the water level dropped, the fuel rod temperature started to rise because of insufficient cooling. At 6 p.m. or so, the reactor water level dropped to the bottom of the core. However, the fuel rod temperature did not rise so much because the fuel rods were cooled due to the heat dissipation effect of breezy intermittent steam flows to the safety relief valve: I suppose it was below 1,000 °C, according to my ballpark calculation.

At about the same time, at 6:02 p.m., the safety relief valve was set and kept to the open position in order to lower the reactor pressure. As a result, high pressure steam continued to be released through the safety relief valve, and the reactor pressure dropped sharply from about 8 MPa to 0.4–0.5 MPa. As a result of the autonomous boiling caused by this pressure drop, the temperatures of the fuel rods dropped to around the water saturation temperature (150–160 °C).

If the seawater injection by the fire engine started at this point, the accident situation could have been substantially different. This is because a cooled cladding tube does not cause a zirconium-water reaction.

Unfortunately, the seawater injection by the fire engine started at 7:54 p.m., or 2 h later. During that time, the fuel rod temperature rose at least 1,500 °C.

It was approximately 1 h later, or around 9 p.m., when the injected seawater contacted the red-hot core. This delay was the time needed to fill the vacant space beneath the core, created by the decompression boiling, with seawater. The contact between high temperature zircaloy and water caused an oxidation reaction and generated a large amount of hydrogen gas. The reactor pressure rose sharply during this short period of time.

The oxide film that covered the hot cladding tube surface was quickly cooled, shrank, and broke apart, thus causing the fuel rods to break into pieces and the core to collapse. I am quite sure that a pile of debris of the collapsed fuel rods mounded on the core plate. However, since the water quantity was small, this reaction did not melt the entire core.

I believe the full-scale core melt occurred around 10 p.m. This delay was the time needed to replenish the seawater spent in the first reaction and for the seawater to start infiltrating into the agglomerates of debris. The contact between high temperature fuel debris and seawater initiated the zircaloy-water reaction. I am certain that this reaction started around 10 p.m. from the indicator of the reactor pressure gauge shown in Fig. 2.9, the DW pressure change among the containment vessel pressure changes shown in Fig. 2.11, and the sharp rise of the radiation dose shown in Fig. 2.4.

Heated by the light, hot hydrogen gas, the upper part of the containment vessel becomes hot. The bolts used for fastening the top lid elongated due to thermal expansion, thus reducing the force for fastening the top lid of the containment vessel, and the top lid is pushed up by the increased inner pressure. Hydrogen gas blows out through the gap formed as described above and fills the reactor vault space above the containment vessel. Since the reactor vault space is small, the pressure quickly rises and pushes up the shield plug on top of the vault. The shield plug thus lifts up and the hydrogen gas flows into the fuel exchange room through the gap formed by the lifting. Although it sounds like a long process, the time needed must have been relatively short.

It is conceived that, as a result of this first reaction, the bottom of the agglomerates of debris became partially molten and a thin egg-shell that serves as the bottom of the pot was gradually formed in the shape of a bottom of a pot. The inside of it must have been filled with a hot mixed molten substance consisting of uranium, zirconium and oxygen mixed in a non-uniform state.

The second and third pressure increases shown in Fig. 2.9 represent the reaction between the mixed molten substance and water caused by the seawater that flowed in across this pot-like boundary. It is imagined that the debris temperature rose even higher because of the combination of the reaction heat and the decay heat. That is the reason so that is why the second and third reactions were larger. That was the status of the core from midnight through 2 a.m. The reason that two pressure rises occurred was probably that the seawater supply from the fire engine was not large enough to cause the entire mixed molten substance to react all at once.

Because of the hydrogen gas generated in the second reaction, the containment vessel pressure jumped up to 0.8 MPa. That is twice as large as the design pressure. The hydrogen gas used for raising the pressure was generated from the molten core, so that it was very hot. It must have been somewhere near 2,000 °C, judging from the melting point of the mixed molten substance of uranium, zirconium and oxygen.

That is the outline of the core melt and hydrogen gas generation of Unit 2.

Although I realize that there are various estimates as to the molten core, I think that the core of Unit 2 still remains in the reactor pressure vessel judging from the curriculum vitae of the accident that water always existed at the bottom of the reactor pressure vessel. Another reason is that no significant change was observed on the reactor data since the late evening of March 14 when the molten core appeared.

The performance of the core melt is essentially the performance of a substance in a stewing pot. Since what was in the pot was the three-element mixed molten substance comprising of high temperature fuel and zirconium, each time water was added, a reaction took place, a thin skin was formed, uranium dioxide melted, and the molten part gradually grew in size. At the same time, the entire surface must have increased in thickness and became a hard shell.

Judging from the fact that the entire volume of the fuel rods is about half the core volume, I estimate that its final size is 3–4 m in diameter and 2 m in height and its shape is that of a semi-egg-shaped muffin.

I cannot find any data that shows that the molten core flowed outside of the reactor pressure vessel. It is not impossible that some amount of the mixed molten substance may have dropped through the cracks of the egg-shell but even if it dropped, it would have come into contact with the water below it and formed small balls. We have learned from the TMI accident that once the egg-shell is formed, it prevents any further chemical reaction from occurring. Therefore, we will probably find those small balls, cooled by the water beneath the core, having formed agglomerates of a certain kind of alloy and lying on the bottom of the reactor pressure vessel.

I presume that, if the molten core surrounded by the egg-shell still exists today as a mass of about 2 m high, the inside of it is still melted due to the decay heat although the exterior is cold. According to my calculation, the decay heat is still probably between 100 and 200 kW 3 years after the accident. However, it is heating inside a shell of a limited volume. It can be compared to having several hundreds of electric heaters turned on continuously in a tiny enclosed room of 4.5 *jo* (approximately 80 ft^2).

That will instantaneously cause a fire if that was a wooden Japanese house, but the egg-shell we are talking about is surrounded by thick walls made of three-element alloy. You can imagine a casting piece. The outside of the wall is cooled by cooling water but the core portion is still molten. The thick wall has cracks through which remaining radioactive refractory gaseous substances are leaking little by little. The radioactive substances are cooled by the cooling water so that most of them are solidified and deposited in the water at the bottom of the reactor pressure vessel. That is how I am imaging the status of the molten core at the moment (ref. to Fig. 2.13).

That concludes my summary explanation of Unit 2.

Let me list the new findings and their reasons from the Unit 2 accident in comparison with the findings from the TMI accident.

I. Neither a core collapse nor melting occurred for approximately 2 h until the water injection started, even though the fuel rods were without cooling and in a red-hot state because the water level dropped below the core. The heat under said condition was dissipated by radiation, which we experienced for the first time in a nuclear accident (Fig. 2.14). This will be discussed further in Sect. 2.7.

II. When the cool seawater was injected and reached the bottom of the core, the fuel rod splitting and the core collapse occurred, and the high-temperature zirconium caused oxidation by seawater, which in turn caused the core melt. This is the same process as the TMI core melt.

III. A large amount of hydrogen was generated as a byproduct of the core melt. A sharp rise of the containment vessel pressure thus developed resulted in the lifting of the top lid of the containment vessel, which allowed the hydrogen gas to leak via the gap produced by the lid lifting, which in turn allowed the hydrogen gas pressure to lift up the shield plug, thus allowing the hydrogen gas to enter the reactor building and leak to the outside environment via the blowout panel.

IV. As a consequence, radioactive substances from the molten core were directly emitted to the atmosphere, and the radiation level in the surrounding areas of the nuclear power plant rose to levels far exceeding the IAEA's evacuation advisory dose of 20 mSv/y.

V. It seems that Unit 2 would not have had a core melt if water was injected into the core just after the pressure was reduced.

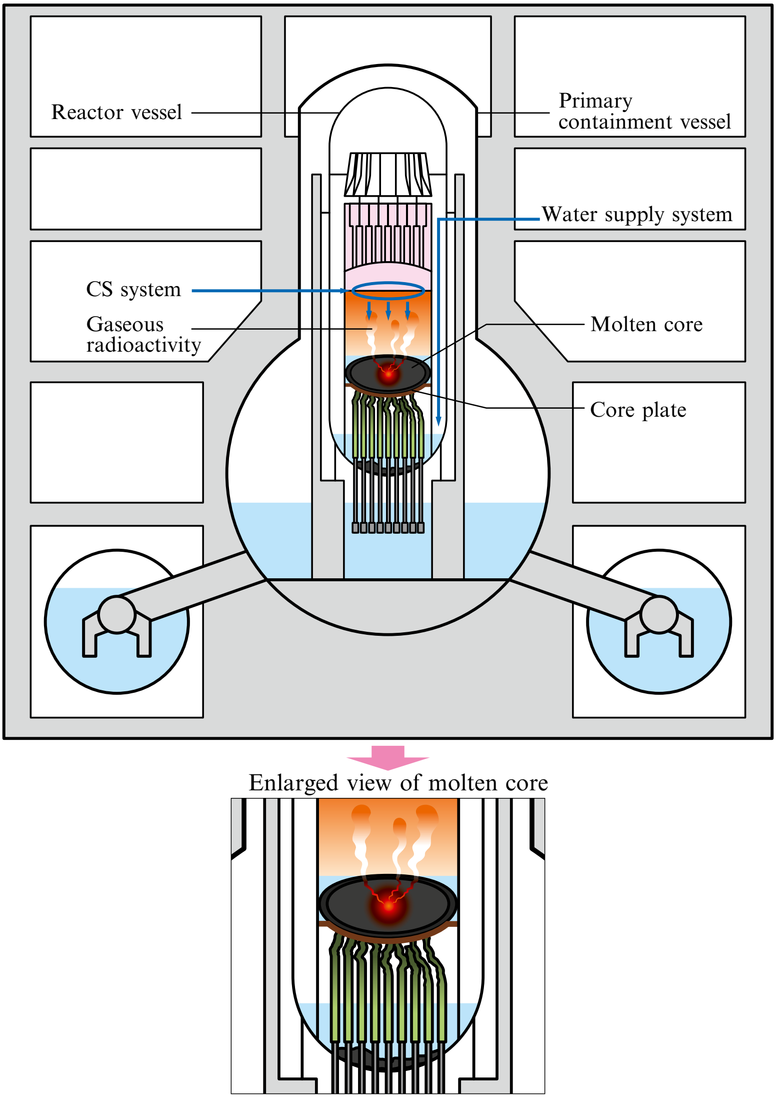


Fig. 2.13 Imaginary view of current status of molten core (Unit 2)

2.6 Case of Unit 3

Unit 3 is also a BWR of 784 MW capacity equipped with a MARK-I containment vessel. There may be some differences in the details, but it can be regarded as a sister reactor of Unit 2, as it is designed in a similar manner as far as the reactor and the containment vessel are concerned.

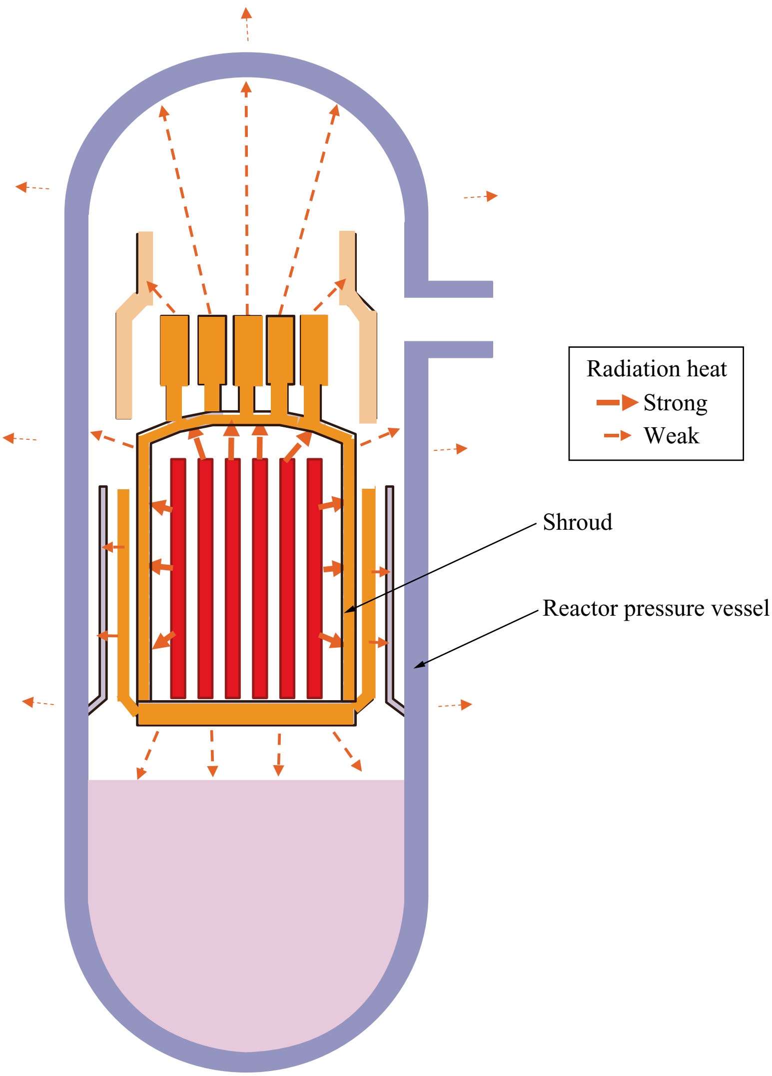


Fig. 2.14 Explanatory diagram of core heat dissipation by radiation

However, there is a major difference in the ways accidents occurred in Units 2 and 3. First, no explosion occurred in Unit 2, but the reactor building of Unit 3 was destroyed by an explosion. The containment vessel was damaged due to the failed venting in Unit 2, Unit 3 succeeded in venting and hence the containment vessel was kept intact. As a consequence, while that from Unit 2 was a direct release from the containment vessel, the radioactive emission from Unit 3 was released after being decontaminated by the SC water so that it was incomparably smaller relative to that of Unit 2.

It was lucky for Unit 3 that a portion of the DC power source survived the tsunami so that its RCIC could be controlled properly. Although things looked like they were going smoothly as the containment vessel vent was implemented as planned and the water injection by the fire engine was also working relatively smoothly, the core melted and a hydrogen explosion occurred in the reactor building at around 11:00 a.m., March 14.

Then why did the core of Unit 3, where everything seemed to be working smoothly, melt, resulting in an explosion earlier than that of Unit 2? Finding the answer to that question is the theme of this section.

To our luck, a portion of the DC power survived the tsunami, so that a certain amount of data during the accident is available to us. The data include the reactor pressure and the water level shown in Fig. 2.15 and the containment vessel pressure shown in Fig. 2.16. We will follow the path that led to the melt and the explosion based on these data. I will be asking you readers to look at these two charts again and again.

However, I must warn you that my explanation will tend to be lengthy as I have to deal with a lot of data available to us. The reason I do so is because I believe precise explanations of all the data is necessary in order to achieve the credibility of my explanation of what happened. However, I also realize that a voluminous explanation may make difficult to grasp the outline of the accident. Faced with this dilemma, I decided to explain the accident of Unit 3 by dividing it into the following five time periods:

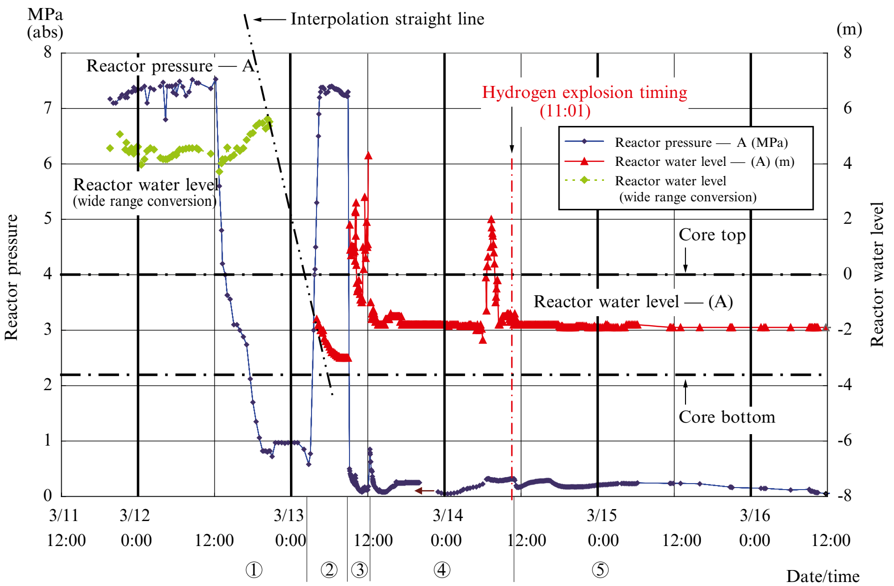


Fig. 2.15 Unit 3 reactor pressure and water level changes (measured data). Note: Time periods ① through ⑤ of the figure match with ① through ⑤ of 2.6.1 of the text (Source: from TEPCO "Fukushima Nuclear Accident Investigation Report")

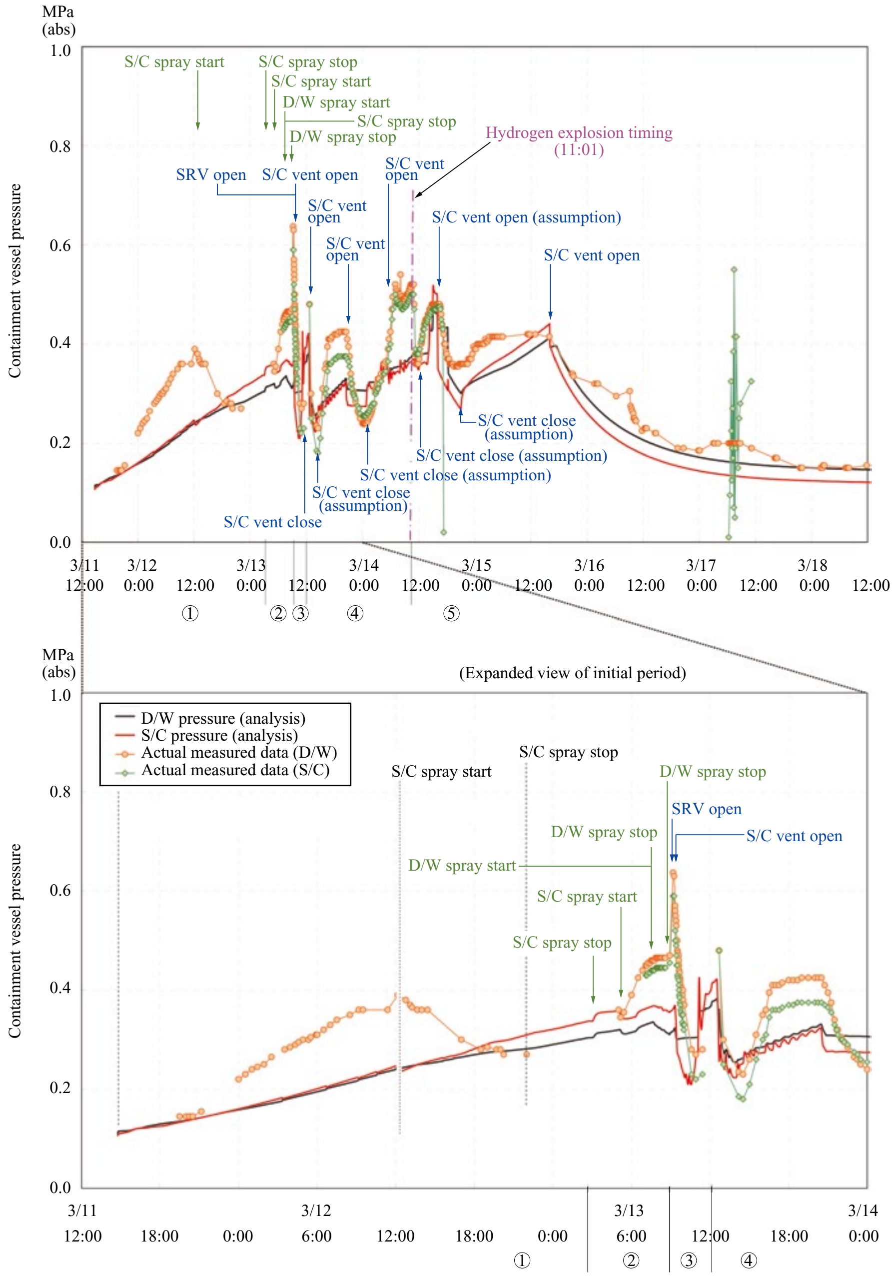


Fig. 2.16 Unit 3 containment vessel pressure change. Note: Time periods ① through ⑤ of the figure match with 2.6.5(5) of the text (Source: from TEPCO "Fukushima Nuclear Accident Investigation Report")

① Operating period of RCIC and HPCI
② Core temperature rise after HPCI stoppage
③ Start of core collapse
④ Seawater injection and core melt
⑤ Explosion of reactor building

At the end of the description of each period, we will confirm the state of the fuel rods and the core before entering into the explanation of the next phase. Please make sure to check the conclusion of each of Sects. 2.6.1 through 2.6.5.

As you read through, it is important for you to pay attention to the fuel rod (core) temperature, reactor water level, and cooling water injection status. The core melt occurs when the fuel rods in a red-hot state meet a large amount of cooling water, and hydrogen generation occurs simultaneously with the core melt.

Now is the time our up-hill battle begins.

2.6.1 Operating Period of RCIC and HPCI (① 4 p.m. on March 11–2:42 a.m. on March 13)

2.6.1.1 Operating Period of RCIC (4 p.m. on March 11 – Around Noon on March 12)

After losing electric power as a result of the tsunami attack, Unit 3 switched over to cooling via RCIC. This transition went smoothly as DC power was available.

Let us look at the data at the time of the accident of Unit 3. The reactor water level and pressure (Fig. 2.15) was kept completely stable until around noon on March 12. This is what makes Unit 3 different from Unit 2, and it was because the RCIC's flow adjustment was properly conducted as the DC power was alive. This part of the operation was beautifully done. When I first saw this data, I even jumped to conclusions that it must be an automatic operation.

The containment vessel pressure (Fig. 2.16) was rising slowly due to the steam release from the safety relief valve, etc., but it was quite a normal change. Everything looks fine.

However, at around noon on March 12, the all-important RCIC went into an automatic stop. The reason for that is not written in the TEPCO Report, and it is still written as "cause unknown" in the "Summary of Fukushima Nuclear Accident and Nuclear Safety Reform Plan" published by TEPCO now at the time of writing this manuscript. I am not happy about this lack of explanation.

I heard a rumor that the electric power was exhausted, but I wonder if that can be true. Since the power source of RCIC is the decay heat, the exhaustion of the DC power cannot explain the stopping of the pump. In fact, Unit 2's RCIC ran for 3 days without electric control, so that there is no reason why Unit 3's RCIC to stop only after 1 day. If it was caused by the electric circuit, it is a design fault. The cause analysis of such a minute point can lead to safety improvements in the future. This is what nuclear safety personnel should be aware of.

As RCIC stops, the water level of the reactor which lost water supply can only go down. As the reactor water level drops, the high pressure water injection system (HPCI) automatically kicks in. Although the reactor water level returns to a normal for a while, the reactor pressure begins to drop sharply as the water is supplied from the cold condensate storage tank. The rest will be described in the next sub-section.

Incidentally, the containment vessel spray from the SC started at around the same time as the stoppage of RCIC. This spray was stopped at around 2 a.m. of the following day. This is the reason why that the containment vessel pressure dropped during this time period. As this is not relevant to how the accident proceed, it is enough only to mentioned here.

Now, until about this time, i.e., around 11:30 a.m. on March 12, when the RCIC pump stopped, the fuel rods and the core were intact ((a) of Fig. 2.17).

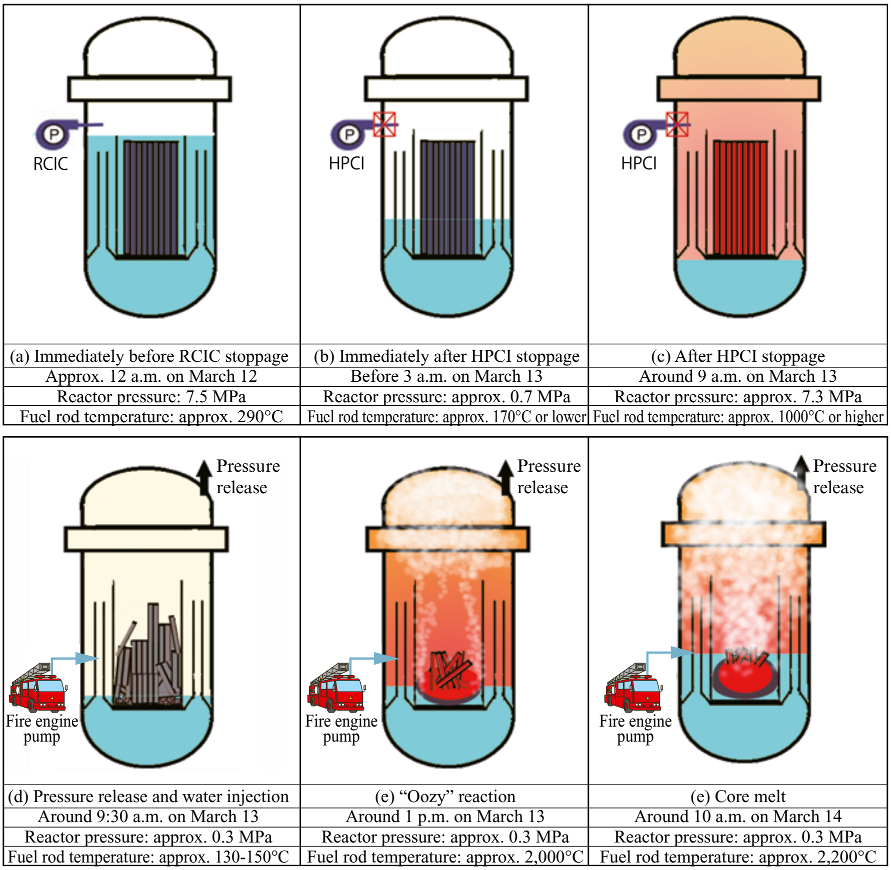


Fig. 2.17 Progress of Unit 3 core status (model diagram)

2.6.1.2 Operating Period of HPCI (Around Noon on March 12–2:42 a.m. on March 13)

The advantage of Unit 3 was that its DC power survived. The core water level begins to drop sharply due to evaporation after the water injection cooling was stopped as a result of the RCIC stoppage. Receiving a warning signal of low core water level 1 h later, the high pressure coolant injection (HPCI) pump was turned on. It was 0:35 p.m. and it functioned properly as designed. The power source of this pump is also the decay heat.

The HPCI pump is designed to inject the cold water of the condensate storage tank – the temperature must have been approximately 20 °C – into the core directly. Unfortunately the capacity of the HPCI pump is so large that it overcooled the core. As a result, the reactor pressure dropped excessively, causing the HPCI driving steam pressure to drop, thus causing in turn the pump's speed to drop, and making the pump to be in such an unstable condition that it might stop at any time.

This situation can be easily understood in the variation of the reactor pressure as indicated in Fig. 2.15. The reactor pressure dropped sharply after noon on March 12, which was when the HPCI pump started to operate, and the pressure which used to be 7.5 MPa dropped to below 1 MPa by 6 p.m. By contrast, the reactor water level rose to its maximum of plus 6 m, almost reaching the top of the steam-water separator. Obviously this is an excessive cooling condition due to an excessive supply of cold water. The pump drive torque must have dropped substantially as a result.

The sharp drop of the reactor pressure accompanied with the HPCI operation caused a misreading of the reactor water level gauge. If boiling occurred in the reference condensing water chamber,[1] due to heat up by the ambient temperature rise, or when decompression was accompanied by the increase of the weight density of the reactor water, it will cause a false reading of approximately 1 m higher than the actual water level.

To put it more concretely, although the reactor water level reading at the time when the HPCI function stopped was approximately plus 7 m, the real reactor water level was, considering this error, approximately 6 m, or about the height of the top of the steam-water separator.

This misreading of the reactor water level gauge is described in (Appendix 2.6) which is at the end of this chapter. Please take a look if you are interested.

While the operating staff tried to reduce the water injection rate using a test line and the like, by around 3 a.m. of the following day the reactor pressure dropped to about 0.7 MPa, which is the lowest level that the pump can operate at. According to the TEPCO Report, the HPCI pump's speed dropped below the normal operating range. As a result of the lack of steam due to excessive cooling, the turbine for driving the pump was barely running.

Because of this sluggish running, the HPCI pump capability was essentially reduced to zero. Consequently, the reactor water level began to drop around 8 p.m. on March 12 and became minus 2 m (actual water level was minus 3 m) by the time

[1] A device for measuring the water level inside the reactor pressure vessel. It measures the pressure difference between the pressure vessel and the reference condensing water chamber.

the pump stopped at around 2:30 p.m. on March 13. Since the water level lowered 9 m in about 6 h, the lowering speed was 1.5 m/h. This information tells us a very important fact which will be described in the following subsection.

However, since the reactor pressure was lowered to around 1 MPa, it is safe for us to assume that both the reactor cooling water temperature and the fuel rod temperature were around 170–180 °C. Of course, both the fuel rods and the core were in a healthy state ((b) of Fig. 2.17).

2.6.2 Core Temperature Rise After HPCI Stoppage (② 2:42 a.m. on March 13–9:08 a.m. on March 13)

2.6.2.1 Reactor Pressure Drop

By this time, with no support from the outside available, the operating staff of the power plant seemed to have decided to solve the situation on their own. According to TEPCO report, they decided to make a last ditch effort by reducing the reactor pressure and injecting seawater using a fire engine. As the HPCI was gone, it was the only way to inject water.

In order to inject seawater using a fire engine, the reactor pressure needs to be lowered. This means that they needed to first lower the containment vessel pressure, which is located on the discharge side of the reactor. To inject as much water as possible to the reactor with such a low discharge pressure pump as a fire engine, it is necessary to lower the pressure injected as lower as possible. That is why not only the safety relief valve of the reactor but also the vent valve of the containment vessel has to be opened; that permitted the pressure from the reactor through to the containment vessel to be close to the atmospheric pressure.

It was explained that there are two vents, DW and SC, in the previous section. It was the SC vent which was used to make the gas in the containment vessel pass through the water in order to wash down radioactive substances.

Once they had decided to decrease reactor pressure and put it into practice, they hadn't felt any need to worry about the stop of the sluggishly operating HPCI. The site operating group went ahead with the task.

At 2:42 a.m. on March 13, the operating staff stopped the sluggishly operating pump.

The rest was to open the vent and go ahead with injecting water using the fire engine, but unfortunately it took some time to open the safety relief valve. Since they could not reduce the reactor pressure, they could not inject water. In the meanwhile, the reactor temperature and pressure started to rise again because of the decay heat.

At around 9:08 a.m. on March 13, the reactor pressure began to drop sharply as the safety relief valve was finally opened.

However it took as much as six and a half hours or so after the HPCI pump stopped before the pressure drop. Let us see what happened to the reactor in the meanwhile (Fig. 2.15). The reactor pressure rose again to 7.5 MPa and the reactor water level dropped to minus 3 m (in actuality minus 4 m). The core status changed substantially.

Incidentally, as we look at the water level data closely by interpolating the missing data with a straight line, we note that the lowering speed drops as the indication of water level gauge approaches minus 3 m from minus 2 m (in actuality minus 4 m from minus 3 m). Although it is only the data for a period of 1 h or so, it suggests that the water level does not change very much after the actual water level has reached the bottom of the core. This 1-h slowdown of the change in water level is very important.

This slowdown indicates that the heat removal from the core changed from heat conduction from the core to water to heat radiation to peripheral structures. As the core loses water, the decay heat is dissipated as radiation heat to the surrounding physical objects rather than heat used to evaporate water. Thus, the water evaporation rate decreased and the decrease in water level slowed down. By contrast, this caused the fuel rod temperature to rise. This radiation heat will be discussed in detail later in Sect. 2.7 of the chapter.

The slowdown in the decrease in water level means an increase of the fuel rod temperature.

In case of the foregoing Unit 2, the fuel rod temperature at the time when the reactor water level reached minus 4 m was estimated to be less than 1,000 °C at most (Sect. 2.5.2 of this chapter). The decay heat of Unit 2 was 0.4 %.

The condition of Unit 3 was not so much different either. Since it is estimated to be 2:30 a.m. on March 13 when the water level of Unit 3 dropped to minus 3 m, the decay heat of Unit 3 is estimated to be about 0.5 %, or slightly more than that of Unit 2. The core heat generation is about 10 MW and is capable of increasing the fuel rod temperature by about 1,000 °C/h.

Although it is a tough call to make, I say that the fuel rod temperature of Unit 3 had not reached a red-hot state, although it was slightly higher than that of Unit 2 and exceeded 1,000 °C at the time when the core lost water. The issue is, however, when did the water level lowering rate slowed down. I say that the less evaporation took place, the higher the fuel rod temperature rose, so that the center of the core must have reached a red-hot state. Please remember here the temperature rise of the fuel rods when they entered the sauna bath. The fuel rods had changed to the status [IV] of Fig. 1.5 ((c) of Fig. 2.17).

Leaving the discussion of the steps from here to the core melt to Sect. 2.6.3 of this chapter, let us review the steps from the stoppage of the HPCI pump to the pressure drop to see if there was any problem in the accident countermeasures. Let us take a few moments on this issue.

2.6.2.2 After Effects of the HPCI Pump Stoppage

Although the pressure reduction was finally achieved after a six-and-a-half hour struggle, this delay in reducing pressure was one of the factors that caused the core melt. More bluntly speaking, stopping the HPCI pump was the main cause of the failure. The core melt and the hydraulic explosion of Unit 3 would not have happened if the pump had not been stopped, but continued to operate sluggishly. I must explain here the reason why I believe so.

The evidence is Fig. 2.15. Please look at the reactor pressure data. Until 2:30 a.m. on March 13 when the HPCI pump stopped, the reactor pressure had been kept at 1 MPa or lower, which is very low. While this sluggish pump operation was in progress, there was no reactor pressure increase and the fuel rod temperature also remained low despite the fact that the core water level was decreasing because of evaporation. With only 0.5 % decay heat, the core could have been easily cooled by the breeze of steam and the fuel rod temperature must have been only up to 160–170 °C. What changed this state completely was the stopping of the HPCI pump.

As the HPCI was stopped, the reactor pressure started to rise instantaneously. It is because the steam that had been used for driving the HPCI lost somewhere to go to and the reactor became a sauna bath. The decay heat raised the fuel rod temperature while the steam that had no place to go started to raise the reactor pressure. This is the pressure increase shown in Fig. 2.15.

The heat generated by Unit 3 is estimated to have reached about 10 MW, assuming that the decay heat was slightly above 0.5 %, for a few hours prior to the pump stopping. This can evaporate approximately 25 tons of 7 MPa saturated water or 13 tons of seawater according to our calculations.

The next issue is the reactor water level lowering rate. The water level lowering rate during the period of 9 p.m. on March 12 through 3 a.m. of the following day was 9 m per 6 h. If this data is compared to the water level lowering rate of Unit 2, i.e., 10 m drop in 8 h (Fig. 2.8), we see that the two are relatively close. Considering the fact that the decay heat was approximately 0.5 % in Unit 3 and approximately 0.4 % in Unit 2, we can safely say that both are the same and are the results of the same cause.

The reason for the water level drop in Unit 2 was the reactor water's evaporation by decay heat. From this, we can safely assume that the reason for the water level drop in Unit 3 was the evaporation by decay heat, as in the case of Unit 2.

This has a very important meaning.

One is that it indicates that the HPCI pump was only running freely with no load, not pumping water at all, during the sluggish operation. If even a slightest amount of the cool water from the tank had been supplied, it would have affected the evaporation of the reactor water so that the water level lowering rate could have been different.

That means that the HPCI pump was not pumping water at this time, rather it was running idly, just like the idling of an automobile engine. It amounts to the fact that it was only serving the role of a conduit for transmitting the steam generated in the core by the decay heat to the SC via the turbine. In other words, it was serving as an outlet of the steam, or an outlet of the decay heat. When the operating staff stopped the HPCI pump, they closed this steam outlet themselves, thus taking away the means of removing the decay heat. As the reactor's water level lowering rate decreased, the reactor's temperature and pressure began to rise again.

If the HPCI pump continued this sluggish operation, the core would not have entered a sauna bath state, as it would have provided an outlet for the steam generated by the decay heat. The fuel rods were cooled by the breeze provided by the water evaporation, so that the fuel rod temperature would have never risen. This is the substance of the failure by the pump stoppage I raised earlier. The change in pressure and water level during the HPCI operation period are its proof.

In essence, stopping of the HPCI took away the outlet for the steam and caused the fuel rod temperature to rise.

I am not criticizing at all. I am simply suggesting that we should accept it as a fact. The fact that the sluggish operation of the HPCI pump was playing the role of a steam outlet would have been very difficult to think of at that time. I would not have thought of it, even if I was at site at that time.

As the outlet of the decay heat was closed, the reactor temperature and pressure naturally went up. That is the re-rising of the reactor pressure shown in Fig. 2.15.

Now, let us compare this to the reactor's condition in the TMI accident. Let's look at the reactor water level of Unit 3 shown in Fig. 2.15. Around 9 a.m. on March 13, just before the vent was opened, the status was such that the water level dropped to approximately minus 3 m (actual water level was minus 4 m), and the most of the fuel rods were exposed above the water surface – in other words, in a sauna bath state. In case of the TMI accident, the core was in a sauna bath state and the fuel rod temperature was rising after all of the reactor coolant pumps stopped and the block valve of the relief valve was closed. There was no current in the core after the HPCI pump was stopped in case of Unit 3 as well. In both cases, as time progressed the fuel rods went from being intact as shown in [I] to the red-hot state shown in [IV] of Fig. 1.5. Although there are some differences between the two in the water level, the stoppage of the HPCI created the red-hot condition of the fuel rods, similar to the TMI case.

If water comes in here, the core will collapse and melt. The lower half of the core was immersed in water in the case of the TMI accident, and contributed to the melting of the collapsed core. What did the injection of water into Unit 3, where the water level was below the core, bring about?

2.6.3 Start of Core Collapse (③ 9:08 a.m. – 0:20 p.m.)

At around 9:08 a.m. on March 13, the reactor pressure vessel's pressure began to drop sharply as the safety relief valve was finally opened. It must have caused decompression boiling of water that remained in the reactor pressure vessel and the bubbles generated must have caused the water level to rise temporarily from where it was below the core. The raised water suddenly cooled some of the red-hot fuel rods and then caused the rods to break up in pieces. Because of this breakup, the core collapse occurred in various places. As the extent of this collapse was a transient condition, we will not find it inside the core even if we are given a chance to look inside now, but I believe that the range of the core collapse was rather limited.

It does not make any difference to the final result. You are free to imagine though ((d) of Fig. 2.17).

Please pay attention to the change in the containment vessel pressure after the water injection was started (Fig. 2.16). The graph is rather complicated with peaks and valleys but the DW and SC data show matching tendencies so that we can trust the data.

The containment vessel pressure rose in one stroke up to about 0.6 MPa as the safety relief valve was opened, and dropped to about 0.3 MPa later as a result of the containment vessel venting (Fig. 2.16). On the other hand, it looks like the reactor pressure also dropped steeply (Fig. 2.15), and reached around 0.2–0.3 MPa in one stroke. However, since there is no way that the containment vessel pressure can be higher than the reactor vessel, I suppose both of them were around the same pressure of 0.5–0.6 MPa.

Immediately after the pressure releasing, or around 9:26 a.m. on March 13, the water injection using the fire engine started. With this water injection, I assume that some amount of reaction occurred between the collapsed fuel rods and water. My assumption, however, is based on these sharp changes of the reactor water level (Fig. 2.15) and the containment vessel pressure (Fig. 2.16) observed in the data after the water injection, and it is not a confirmed conclusion. This reaction was a localized one, not one that could develop into an overall core melt. This is because there was not enough water.

The amount of water injected into the core during this period between 9:25 a.m. on March 13 and the explosion on March 14 is not determined exactly. Since the water that a fire engine can pump is about 25–40 tons/h, the amount of water that should remain in the reactor must be approximately 10–25 tons at most after subtracting the evaporation of approximately 13 tons due to the decay heat from the above amount and also considering the fluid resistance of the hose and other piping connected. According to this calculation, the reactor water level is supposed to rise, but the water level shown in Fig. 2.15 is different. It shows only a constant value.

The water level shown by Fig. 2.15 goes up and down wildly for a period of about 3 h from 9:25 a.m. through 0:20 p.m. suggesting the occurrence of a zirconium-water reaction. After ups and downs, the water level finally settles down at minus 1 m. The increase of water volume from the time when the water level was minus 3 m can be calculated as about 12 tons. In other words, the increased amount of water per hour is approximately 4 tons, so that the calculation does not match unless approximately 8–23 tons of water evaporated per hour for some reason. This evaporation amount is too much even if the water evaporation due to the zirconium-water reaction is estimated at the maximum.

More problematic is the amount of water injected for a long period of time from 1:12 p.m. on March 13, when the water injection is restarted, until 11 a.m. on March 14, when the explosion occurred. If we assume that the pump was operating properly, it makes no sense at all that the water level stayed constant at 2 meters constant as shown in Fig. 2.15.

Since I could not solve this dilemma, I decided to explain the core condition disregarding the water amount calculated based on the fire pump capacity, and instead assumed the measured water level data is correct. If the pump was operating properly, the explosion of Unit 3 would not wait until 11 a.m. on March 14. However, this was proven to be a correct answer as explained below.

It was on December 13, 2013, when I was finishing up the final draft of this book, that TEPCO published a report of its investigation and examination of unidentified and unsolved matters. According to the report, there were several branch pipes connected to the fire engine pump so that the water injected into the core was not the same as the pump outlet capacity, but rather less than what was anticipated. In other words, a portion of the water from the pump was diverted elsewhere. This publication answered all the questions I had concerning the water injection using the fire engine. I learned that the water injection was done in accordance with the containment vessel pressure by automatically diverting the excess amount to the outside.

I also learned from the TECPCO report that the delivery capacity of the fire engine pump that they used was 75 tons/h. It was much larger than what I assumed in my analysis for writing this book, which was 25–40 tons/h. I decided that I would not rewrite the draft however. I decided so because the discrepancy is irrelevant to the explanation of the core situation if the case was as described above.

I suppose that the zircaloy-water reactions continued to occur intermittently between the water, which kept gradually rising as seawater was injected, and the agglomerates of debris for a few hours until 0:20 p.m.. I also believe that an egg-shell similar to the one observed in the TMI case was gradually being formed on the contact boundary between the water/steam and the molten core.

This core melt condition caused by water shortage, which was also described for Unit 2, occurred earlier in Unit 3, chronologically speaking. The zirconium-water reaction that occurred for a short period of time in TMI is not necessarily the same as what occurred in Units 2 and 3 under the water shortage conditions.

The random fluctuations of the containment vessel pressure data until around noon of that day seem to indicate the operators' intense efforts to combat the core reactions. According to the TEPCO report, they did everything they could manage to keep the vent valve open, including replacing the gas cylinder and temporarily installing an air compressor. They also manipulated the containment vessel spray, opening and closing it, in order to reduce the containment vessel pressure. All these manipulations were intended to lower the containment vessel pressure that is generated by the water evaporation due to the decay heat and the reaction heat. I have to remind you that there was no electric power at the site. They had to do all of these in the pitch dark. They did all they could do.

2.6.4 Sea Water Injection and Core Melt (④ Approximately 22 h from 0:20 p.m. on March 13 Through 11 a.m. on March 14)

At 0:20 p.m. on March 13, the water source was switched to seawater as the water supply from the fire-protection tank was running low. The water injection was interrupted during this switching period of about 1 h. The TEPCO report says that it was 1:12 p.m. when the seawater injection started.

What happened in the core during this 1 h period is unknown. I can only guess as no data is available but I suppose no substantial change occurred. I assume that the core water evaporated during this period because of the decay heat and the containment vessel pressure was rising slightly. During this period, the DW spray of the containment vessel was operating to lower the pressure.

During the period of about 22 h from 0:20 p.m. on March 13 through 11:00 a.m. on March 14 when the explosion occurred, the data of Unit 3 show no significant change except some fluctuations of the containment vessel pressure.

The reactor pressure (Fig. 2.15) maintained a constant value of approximately 0.4–0.5 MPa. The indicated reactor water level maintained an approximately flat value of minus 2 m (actual water level 3 m). This gives us the illusion that it is a stable condition. The containment vessel pressure change shown in Fig. 2.16 is simply going up and down in accordance with the aforementioned opening and closing of the vent. There was no significant change that needs to be described. It was like the calmness before a storm.

There was a precursor of the storm however. It is the fact that there were several sharp increases of the reactor water gauge reading starting around 7 a.m., just before the explosion (Fig. 2.15). The abrupt change of the reactor water gauge reading is the evidence that there was some kind of a significant change to the reactor. Please remember this precursory event.

The operation record on the TEPCO report simply mentions that there were vent opening/closing operations as shown in Fig. 2.16 and also that the water injection by the fire engine was interrupted at 1:10 a.m. on March 14, in order to replenish seawater to the injection pit, but the water injection was restarted at 3:20 a.m. However, it shows that the seawater injection was interrupted for 2 h. This is a key point. Please remember this as well.

It is difficult to provide a definitive description for this status for which the only data available to be used as the basis of analysis is the containment vessel pressure, but it is safe to say at least that there was an insufficient amount of seawater to cause a change to the core.

Although I am not sure if it is an appropriate example to tell you, I experienced a situation that reminds me of these long, drawn-out hours [of indecisive situation].

About 20 years ago, My student spilled an amount of high temperature liquid sodium on an iron tray during an experiment by mistake. Metallic sodium is a material that can be oxidized much more easily than zircaloy and causes a violent oxidation reaction and explosion if it is placed in water even in an environment of a normal temperature. Metallic sodium also forms an oxide protective film by catching moisture in the air and burns oozily as it gets slightly hotter.

The relatively large amount metallic sodium spilled on the iron tray continued to burn oozily for a long period of time. The surface of oxide film keeps inflating and bursting repeatedly, the film constantly moving as it inflates, and flickering red and blue small flames can be observed through the cracks. It looked just like a hot pool of mud I once saw in the Beppu Hot Spring Spa. The burning continued almost endlessly.

I am imagining that the state of the core that existed almost one full day from 1:12 p.m. on March 13 through 11 a.m. on March 14, was a minor zirconium-water reaction similar to the oozy burning (reaction) condition I once saw. There is no concrete evidence to claim it, but I don't know how else I can explain the state that continued for almost 20 h while causing no significant event.

I am not certain about the amount of water injected by the fire engine, but I imagine that it was slightly more than the amount of seawater evaporated, or 13 tons/h. If we assume a certain fraction of the amount of water is used for the oozy burning reaction between zirconium and water, we can see some matching stories here. The combination of the heat from the oozy burning and the decay heat was used for evaporating the water and raising the temperature of the mixed molten substance (core) little by little. Moreover, I suppose that the hydrogen gas thus generated and the water vapor together contributed to raising the containment vessel pressure and necessitated the operation of the vent.

That was the explanation of the indecisive condition that continued almost a full day ((e) of Fig. 2.17). The precursory phenomenon of the abrupt water level jump that occurred around 10 a.m. on March 14 was an indication of increasing water to reach more actively with the hotter core.

As we think of the existence of this oozy reaction, we can see clearly that the core collapse and melting were entirely different things. Come to think of it, while there were three major water level fluctuations (reactions) in the core melt of Unit 2 described in the previous section, we can understand the phenomenon better if we see that it was the oozy burning time, waiting for more water.

I would like to leave the verification of this finding related to the zirconium-water reaction under a water shortage condition for studies by future scholars (Appendix 2.7). I also hope that they use the result of the verification for the future safety of nuclear engineering.

At 1:10, a.m. on March 14, the water injection using the fire engine was interrupted for filling up the pit that had been used as the reservoir of the seawater to be injected. It was 3:20 a.m. when the water injection was restarted. The seawater injection was interrupted for as long as 2 h. This is the operation I asked you to remember above, but this was the beginning of the disaster.

During this 2 h period, the water that contributed to the oozy reaction with the core disappeared by evaporation (Fig. 2.15), and the mixed molten substance (core) that became like a sauna bath was probably close to the melting point because of the decay heat. The structural members surrounding the core must have partially melted down by the radiation heat similar to the case of Units 1 and 2. It is assumed that, most likely, a portion of them was melted and mixed with the debris to form a certain alloy. And, that must have included such items as boron carbide (B_4C), which is used for the control rods of BWR.

With the seawater injection restarted at 3:20 a.m., the mixed molten substance mixed with this high temperature alloy came to be gradually immersed into the seawater. The timing of the contact between the seawater and the mixed molten substance is estimated to be around 7 a.m. judging from the water level fluctuation found in Fig. 2.15. Although there is a time difference of about 4 h between 3:20

a.m. when the water injection started and this time (7:00 a.m.), it must be the time needed to replenish the amount of water that evaporated during the water injection stoppage. A chemical reaction starts when water contacts with the sufficiently hotter core. It probably must have generated hydrogen gas and formed the egg-shell as well. It was probably because of the hydrogen gas generation that the containment vessel pressure of about 0.5 MPa was maintained for 4 h from approximately 7 a.m. until the explosion (Fig. 2.16) although the vent was open.

The reactor water level jumped up abruptly to plus 2 m about 1 h prior to 11:01, a.m. (around 9–10 a.m. according to Fig. 2.15), when the hydrogen explosion occurred in the reactor building of Unit 3. This is the precursory phenomenon I asked you to remember.

A violent reaction most likely must have started at this time between the injected seawater and the mixed molten substance that was partially protected by the egg-shell. I believe that it was started when the seawater completed the invasion of the mixed molten substance which had been protected by the egg-shell, so that the skin was broken by the inner pressure increase of the egg-shell, or the seawater started to react violently with the zirconium mixed in the mixed molten substance across the egg-shell. I suppose that the sudden change of the water level gauge data indicates the water level inflated by bubbles when a large amount of hydrogen was developed by the reaction.

With this reaction, the core started to melt throughout the reactor. The reaction was a violent one, although it might have been intermittent so long as the speed of water injection could catch up the reaction.

Around 10 p.m. on March 14, the Unit 3 core melted. It goes without saying that a large amount of hydrogen gas was generated simultaneously ((f) of Fig. 2.17).

The progressive steps of the core melt and hydrogen generation were the same as described earlier. Although it probably did not have a big effect, it is possible that the salts in the seawater may have affected the reaction chemically. This needs to be studied in the future.

2.6.5 Explosion of Reactor Building (⑤ 11:01 a.m. on March 14)

Let us check here the change of the containment vessel pressure (Fig. 2.16) up to about 11 a.m. when the reactor building explosion occurred. Although the vent operation further complicates the matter, it is clear that the containment vessel pressure that had stayed flat around 0.5 MPa until 11 a.m., which is estimated to be the time of the reactor building explosion, dropped instantaneously to 0.3 MPa, and rose again sharply in the next instance. This sharp drop of the pressure is the time when the hydrogen explosion occurred.

This sharp pressure drop is a temporary drop caused by the release of hydrogen gas to the reactor vault as the top lid of the containment vessel that had been heated by the hydrogen gas was lifted up. The released hydrogen gas entered the reactor vault and pushed up the shield plug to go out to the fuel exchange floor. The mechanism of the containment vessel hydrogen gas escaping to the fuel exchange floor is the same as that of Unit 2 explained in Sect. 2.5 of this chapter.

In case of Unit 2, the hydrogen gas escaped into the atmosphere as the blowout panel of the fuel exchange room had already been dislodged. However, the panel was still in place in case of Unit 3. The reactor building still maintained a semi-sealed condition. The hydrogen gas which had nowhere else to go must have risen to and flowed along the ceiling, changed its direction, agitated the room air, circulated, and spread throughout the room. The hydrogen gas that mixed with air became diluted and thus became an explosive gas. Incidentally, the deflagration/detonation range of hydrogen in air in terms of its volumetric ratio is 4–75 % – in other words, very wide.

Hydrogen that has turned into an explosive gas can ignite instantly if it finds an ignition source. There is a wide variety of ignition sources, including sparks, electricity, and physical impact. However, since the power station was out of electricity then, an electrical ignition source is out of question. A physical impact was the ignition source in this case. It was an impact caused when the shield plug, which was lifted by the pressure as explained in case of Case 2, dropped.

The lifted shield plug cannot stay up in the air forever. When the gas pressure that supported the plug is gone, the plug drops due to gravity. When the heavy plug drops and hits the concrete floor, it must have generated a spark as a flint stone would. Maybe no spark was generated but the sound of impact must have been quite impressive. That is enough to ignite the gas. The time when the shield plug landed was 11:01 a.m., i.e., the time the explosion of the reactor building of Unit 3 occurred.

I am sure many of you wonder if such a heavy shield plug can be lifted up. Let me show you an example. There is an actual example where a much heavier plug was lifted.

Figure 2.18 is a sketch made at the Chernobyl accident site. A large circular disc can be seen sitting in a vertical position in the upper part of the hollowed-out core. This is the shield plug of the Chernobyl reactor, which is approximately 13 m in diameter and weighs 1,600 tons. It weighs almost three times that of the BWR shield plug, which weighs 600 tons.

The reason that it is vertically positioned is that the shield plug was lifted up by the hydrogen gas pressure when the explosion occurred in an obliquely upward direction relative to the original position of the plug. The shield plug made a three-quarter-turn before it landed just as if a judo player is attacked by a foot sweep just as he jumped up. You can tell that it was lifted fairly high from the fact that this large disc was rotated almost full turn.

The beard-like lines shown attached to the shield plug are the pressure tubes which contained fuel assemblies. The pressure tubes were built in such a manner as to extend through the core and to be attached to the shield plug. The hydrogen pressure that applied to the bottom of the shield plug was strong enough to tear off these pressure tubes to lift the shield plug up in the air. The investigators of the former

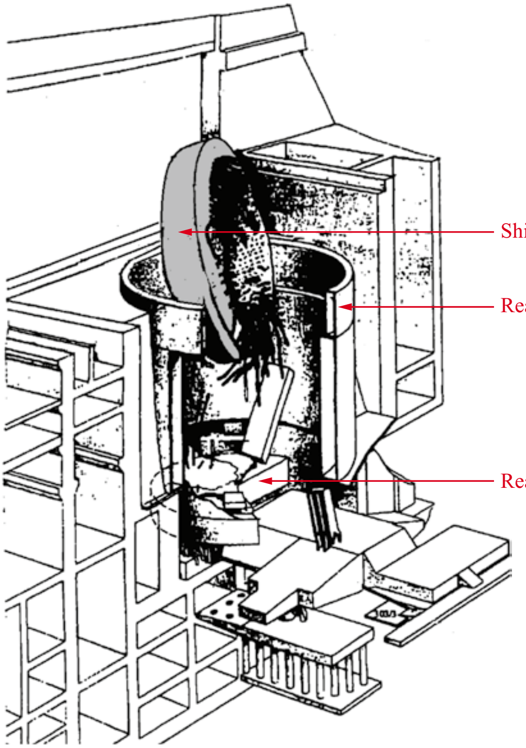


Fig. 2.18 Chernobyl reactor's appearance after the accident [1]

USSR estimated that the total pressure that applied to the bottom of the shield plug was approximately 1 MPa.

As this sketch from the Chernobyl accident indicates, the shield plug can lift up if the gas pressure applies to the bottom of the shield plug.

It is reported that the ignition source in the case of the Chernobyl accident was the zirconium oxide debris from the hot fuel cladding tube. As the tubes built through the core were torn off, the fragments of the red-hot fuel cladding tubes were scattered all around, mixing with the steam emitted from the tubes. One of those pieces ignited the hydrogen gas mixed with air and caused the explosion. The explosion was caused when the shield plug was high up in the air. It is different from the impact of the drop of the plug, as in the case of the Unit 3 explosion. Otherwise, the shield plug of the Chernobyl reactor could not have made the three-quarter-turn.

Lifting the shield plug of Unit 3 was pretty easy compared to lifting the shield plug of the Chernobyl plant. As we calculated it in case of Unit 2, it lifts up at least theoretically if a pressure of 0.05 MPa or so is applied.

Then why didn't an explosion occur in the case of Unit 2 due to the impact of the shield plug dropping, when the shield plug was lifted up in a similar manner? It is because the hydrogen gas did not become an explosive gas through mixing with air, as in the case of Unit 3. In the case of Unit 2, the hydrogen gas escaped from the reactor vault into the air as a plume. The hydrogen gas density of this plume is approximately 100 %. A plume that is as hot as 2,000 °C flows in clumps just like water in a brook, and neither agitates air nor mixes with it. Since it is a flow of non-ignitable 100 % hydrogen gas, it does not ignite even if there is an impact.

I must explain further the hydrogen gas of Unit 3. As it is clear from TEPCO's investigation, the cause of the Unit 4 explosion was the hydrogen gas from Unit 3. How was it possible that enough hydrogen gas to cause an explosion entered Unit 4?

Let me explain in the simplest manner avoiding details. Unit 3 and Unit 4 used the same stack (chimney) to discharge the exhaust from the standby gas treatment systems (SGTS), which are reactor air-conditioning facilities – The units shared the stack. The tail ends of SGTS are connected to the bottom of the stack and are open upward. It has been concluded that the hydrogen gas of Unit 3 flowed backward via the connecting part through the SGTS of Unit 4 and entered the reactor building of Unit 4.

Although I cannot go into detail here, I believe it suffices to say that this backward flow theory was proven by the fact that the contamination of the filter for removal of radioactive substances placed in the SGTS of Unit 4 was heavier on the stack side outlet and lighter on the building side. If the exhaust gas does not flow backward, no contamination from the outside to the inside can occur. In other words, it was like the smell from your neighbor's kitchen being detected in your apartment's kitchen.

So we know the entrance path of the hydrogen gas, but the more difficult question is how enough gas as to cause a hydrogen explosion could flow backward. In order to explain this possibility, we must think about the pressure difference and the flow time.

We can see that the pressure difference can be relatively high if we consider the fact that the hydrogen gas that entered the Unit 4 building was the gas that flowed into the bottom of the stack via the containment vessel vent. The pressure at the vent outlet is the pressure difference in comparison with the pressure inside the Unit 4 building, which was at atmospheric pressure. With sufficient time, hydrogen gas can flow into the Unit 4 building little by little.

The question is the time such flow took place. The first thing that comes into our mind is the pressure of the hydrogen gas generated by the violent zirconium-water reaction that lifted the shield plug. Although this pressure is very large, the reaction does not last long. Although it is possible that a portion of that gas flowed into Unit 4, it is not enough to cause the explosion.

The next thing that comes into our mind is the gas from the vent. The time period the vent was open after Unit 3 caused the core collapse and started to generate hydrogen was approximately 2 h from around 8 p.m. on March 13 and approximately 2 h from around 9 a.m. on March 14. A total of 4 h – that is one hint. Since the containment vessel pressure ranged from approximately 0.2 to 0.5 MPa, that was also sufficient.

Although earlier I spoke unkindly about the containment vessel pressure change during this time, saying that it does not provide us any hints as it only coincides with the vent opening/closing, I have to retract that. It contained an important hint for solving a quite significant event, i.e., the explosion of Unit 4.

The more probable cause was the hydrogen gas generated by the oozy zirconium-water reaction. This is a long running reaction. Although it is not accurate, there is a possibility that it could have run for 26 h from around 9 a.m. on March 13, when the vent was opened, until around 11 a.m. on March 14, when the explosion occurred. During this period of time, hydrogen could have moved little by little to Unit 4.

Those of you who have very watchful minds may wonder if the vent was open during the entire time the oozy reaction was ongoing. Actually, there is no need for it to be that way. Let us think, just for the sake of argument, that the valve is closed.

The decay heat is constantly generating steam. Since this steam is blown out to the containment vessel, the containment vessel pressure keeps rising constantly. So long as there is the decay heat, the pressure should be rising constantly. On the contrary however, we see that there was a time when the pressure stayed unchanged; for example, it stayed around 0.4 MPa for 3–4 h from 5 p.m. on March 13 (Fig. 2.16). That is the hint.

It is interesting to note that the containment vessel pressure rose sharply just before it went into a standstill at 0.4–0.5 MPa. This phenomenon can only be explained by assuming that a certain amount of gas leaked from the containment vessel. We can guess that the hydrogen gas generated by the oozy reaction probably leaked out from the containment vessel to the reactor building.

Then what was the opening that allowed this leakage? Although we cannot determine for sure, the places where the opening can occur is either a gap produced at the top lid of the containment vessel, the hatches through which people or things pass through, or the penetration areas where cables or pipes go through.

I have heard that someone talked about leakage found in an equipment entrance hatch in Unit 3 through which various items were transferred. The door to the equipment hatch of the containment vessel is sealed by dual gaskets. If the seals are broken by internal pressure, it could well develop into an opening. Incidentally, 0.4–0.5 MPa is about equal to the design pressure of the containment vessel. The door seal is one of the most likely suspects. Of the potential leakage points, I think that the equipment transport hatch was the dominant one among them.

I believe that the hydrogen that leaked into Unit 4 is the hydrogen generated by the oozy reaction. The reason can be found in the explosion condition of Unit 3. The explosion of Unit 3 occurred in the fuel exchange room (refer to Fig. 2.3), which was immediately followed by the explosion in the mezzanine, which ended up damaging the building seriously. TV pictures showed the blast reaching several hundred meters high into the sky. Unless a large amount of hydrogen gas was residing in the lower level of the reactor building, such a huge vertical explosion could not have happened.

Hydrogen tends to move up as it is light. There is no physical reason for hydrogen gas to climb down the narrow staircase to the lower level. The reason that there was such a large amount of hydrogen gas as to cause an explosion was that the leakage was occurring on the lower level. The equipment transport hatch is located on the first floor of the reactor building. If we assume that hydrogen was leaking out for a long time through it, the explosion of Unit 3 can be explained beautifully.

I thus imagine that the hydrogen gas that flowed into the reactor building flowed further into the lower part of the stack via the duct of the standby gas treatment system and flowed backward little by little over a long period of time into Unit 4.

It seems to me that both a strong flow while the vent was opened and the chronic flow while the vent was closed took place.

I realize that my explanation on the hydrogen gas flow into Unit 4 extended into the explanation of the state of the explosion in Unit 3. Let us get back to the explosion of Unit 3 to summarize it.

As the injection of cold water using the fire engine started at around 9 a.m. on March 13, the fuel rods were broken into pieces, thus starting the core collapse. At the same time, a small amount of zirconium-water (most likely steam vapor) reaction started. This oozy reaction continued for a long time without stopping. As a result of the steam generation due to the heating by the reaction as well as the decay heat, the containment vessel pressure kept rising. The operating staff operated the vent valve intermittently in order to release the containment vessel pressure.

At around 10 a.m. on March 14, a violent core melt occurred because of the zirconium-water reaction. The timing can be identified by the sharp increase in the reactor water level. This reaction caused a large amount of hydrogen gas to be released into the containment vessel. This hydrogen gas was very hot. The upper structure of the containment vessel was heated by the hot gas, which in turn caused a gap in the top lid because of the elongation of the fastening bolts, and caused the hydrogen gas to be leaked to the reactor vault. From this point on, the sequence of events is the same as in Unit 2. The hydrogen gas leaked to the reactor vault pushed up the shield plug and went into the fuel exchange room on the fifth floor of the reactor building.

Different from Unit 2, the fuel exchange room was held in an air-tight condition. The hydrogen that flowed into the fuel exchange room swirled around the room, became an explosive gas, ignited due to the impact of the shield plug dropping, and caused the explosion. Because of this explosion, the upper portion of the fuel exchange room of Unit 3 was blown off. Almost immediately afterwards, another explosion was caused by the hydrogen gas which had crept into the bottom of the building and the reactor building of Unit 3 was seriously demolished, with the blast reaching several hundreds meters into the sky.

That is the summary of the core melt and the reactor building explosion of Unit 3.

2.6.6 Section Conclusion

As I had to deal with a lot of data, this was quite a long explanation. I tried to explain things in a way that is easy for people to understand, but the phenomenon was quite complex. Let me try a general summary here.

Although Unit 3 lost all sources of AC power, some DC power survived so that the core was kept cool while the RCIC and HPCI were operating. Had power been restored at this stage, no core melting would have occurred in Unit 3.

However, as the power plant lost electricity and experienced a water shortage, they decided to try to cool the reactor by forcibly reducing the reactor pressure and injecting water with the help of the fire engine. During this process, the core became red-hot and collapsed when the core water temperature dropped at around 9 a.m. on March 13 due to the decompression boiling. Had this decompression operation been conducted without stopping the HPCI, Unit 3 could have been saved from the core collapse and hence the core melt.

After this core collapse in the morning of March 13, both the reactor water level and the reactor pressure were relatively stable as if to keep balance with the water injection amount. However, the containment vessel pressure alone kept rising. Things looked rather stable until 9 a.m. on March 14. During this period, the zirconium-water reaction was continuing sluggishly in proportion to the amount of water supply. This was the oozy reaction, the prelude to the core melt. Although the containment vessel pressure looked as if it was being tamed under the operating staff's vent valve control, in reality when the pressure reached 0.4–0.5 MPa a gap developed in the equipment transport hatch of the containment vessel, and hydrogen gas leaked out through it. This hydrogen gas infiltrated Unit 4 next door and became the cause of its explosion.

At around 10 a.m. on March 14, because of the water level that had been gradually rising for almost a full day, a violent zirconium-water reaction started in the Unit 3 core, causing the core to melt and generating a large amount of hydrogen gas. This hydrogen gas pushed up the top lid of the containment vessel, flowed into the fuel exchange room on the fifth floor of the reactor building, mixed with air to become an explosive gas, ignited due to the impact of the landing of the shield plug, and caused the explosion. It was 11:01 a.m. on March 14.

That is the summary of the core melt and the explosion of Unit 3.

The following is the summary of the important conclusions concerning the melting and explosion of Unit 3:

I. The cause of the core melt is, same as in Unit 2, the violent reaction between the mixed molten substance (mainly zircaloy) and water.
II. A large amount of hydrogen gas generated by the violent reaction lifted the top lid of the containment vessel and the shield plug, flowed into the reactor building, mixed with the air in the room, and caused the explosion in the reactor building of Unit 3.
III. The ignition source of the explosion is the impact that occurred when the lifted shield plug landed.
IV. The fire engine pump injected not that much water, and it did so slowly. As a result, the reaction between the mixed molten substance and water was not active, but rather occurred slowly. Even under such a condition, there is no evidence that the core melted down to flow out of the reactor pressure vessel. During this time, the hydrogen that leaked outside of the reactor building and/

or the hydrogen gas discharged through the vent flowed backward into the reactor building of Unit 4 via the exhaust facility to become the cause of the explosion of Unit 4.

V. It seems that a core melt would not have occurred in Unit 3 if HPCI was not stopped (hence maintaining the pressure at a lower level and allowing the water injection to be made easily), and the water injection was conducted accordingly.

2.7 Back to the Case of Unit 1

The reason I interrupted the description of Unit 1 earlier was that it was not clear to me what happened to the core melt condition at the time when the core lost water completely. That is why I decided to study the melting of Units 2 and 3 first and then make a deduction from those analyses. Let us review those cases here.

After losing the external power source, Unit 1 was switched to manual control cooling by means of IC, but the unit was hit by the tsunami immediately after the isolation valve was closed. The emergency power was made unusable because of the tsunami, thus leaving IC turned off. If they noticed that the IC had stopped soon enough and taken countermeasures, the history of the Fukushima accident could have been substantially different. It was an unfortunate missed opportunity.

In the meanwhile, the reactor that lost its means of cooling was using water evaporation for removing decay heat, as if a hungry octopus eats its own tentacles. The reactor's cooling was maintained by opening and closing the safety relief valve to release the generated steam. However, this octopus-tentacle-eating measure cannot last long. This has to end when all the water inside the reactor is lost.

With the evaporation, the reactor water level dropped with time. According to a calculation by TEPCO, the water level that was plus 5 m above the core in the beginning lowered to the top of the core (water level index: 0) about 3 h later (about 6 p.m.), and then to the lowest part of the core about 5 h later (about 8 p.m.). With some corrections, this calculation can be trusted. By midnight, the core lost water completely.

2.7.1 Radiation Heat in Reactor Pressure Vessel

When all the water in the core is lost, heat from the core will be released through heat radiation from the core, as opposed to heat transfer from the fuel rods to water. Just like the sun evaporates water, the heat radiation from the red-hot core evaporates the water below the core. However, since the radiated heat is not only absorbed by water, but also reflected, so not all of the heat gets transferred to water as in the case of thermal conduction. Moreover, the radiation heat irradiates everything in the vicinity, not just water. Thus, the reactor's heat dissipation changes the scheme entirely.

If we look at this from the standpoint of the fuel rods, the loss of water means that the heat removal totally depends on the radiation heat. Since the radiation heat emits in proportion to the fourth power of the absolute temperature, the heat source's own temperature needs to be raised in order to dissipate heat efficiently. Thus, the fuel rod temperature becomes much higher than when it was immersed in water.

Furthermore, as adjacent fuel rods radiate heat with each other, their exchange of heat is a net zero in the end, so that the entire set of fuel rods (core) becomes a one-temperature (although there may be slight deviations) group that radiates heat to the internal components.

More specifically, the temperature of the core (fuel rods) that has lost water rises sharply as it dissipates the decay heat by radiation heat. The temperatures of the internal components rise gradually as they receive said radiation heat, thus causing them to dissipate heat themselves, resulting in a chain-reaction, heat dissipation system. This heat dissipation system became stabilized after a fair bit of time passed from when the reactor pressure vessel completely lost water.

As the core loses its water and the heat dissipation system starts to change from a conduction system to a radiation system, the heat that is used for evaporation of water should be reduced by the amount that is used for heating the core and the internal components, so that the rate of water level drop slows down as well and the timing of the complete loss of water from the core will be delayed. I believe that this delay should be around 1–2 h.

According to the TEPCO's calculation, the reactor water level is estimated to have reached the very bottom of the reactor pressure vessel, i.e., minus 8 m, at around 11 p.m. on March 11, but I estimate rather that it was around midnight when the reactor pressure vessel lost its water completely.

That is the review of Sect. 2.4 of this chapter.

In case of the TMI accident, a lot of cooling water was injected when the core water level was only halfway down. Consequently, the core melt occurred immediately because of the zirconium-water reaction. In case of Unit 2, the core collapse and the core melt occurred as a result of the zirconium-water reaction when the cold seawater was injected after the reactor water level had dropped to as low as 1 m below the bottom of the core due to decompression boiling. The core melt of Unit 3 occurred after the core lost most of its water, the reactor pressure was reduced, and the oozy zirconium-water reaction had been occurring for about 24 h.

Common to all three reactors is the fact that the cause of the melting is the zirconium-water reaction, and that the core melt occurred when there was water in the reactor. However, as described before, the water level was halfway down the core in case of TMI, was near the very bottom of the core in case of Unit 3, and was 1 m below the core in case of Unit 2. This difference is very important in thinking about the heat dissipation of the core. In case of TMI, because there was water in the core, the main way in which the core was cooled was transferring heat to water, whereas there was no water left in the core of Unit 2, and so the core melt occurred while heat was being dissipated through heat radiation. The intermediate case was the core melt of Unit 3. In both Units 2 and 3, the core had lost its water and the heat was dissipated by heat radiation. In the case of Unit 2, this condition did not last long, and its core melted although the core essentially retained its shape. In case of Unit 3, oozy reactions continued for more than 24 h in the core, which was partially collapsed. However, in any of those cases, there was no difference in that the oxidation reaction occurred only when the high temperature fuel rods (core) met a large amount of cold water and the reaction heat caused the core to melt. The above discussion is the starting point of the analysis of Unit 1. In Unit 1, in which the reactor pressure vessel had lost its water completely, the heat radiation is the only means of removing the decay heat generated in the core. It is different from Units 2 and 3 in that sense.

Let us examine now what happens inside a core which has lost its water.

The decay heat was the heat generated as a result of radiation attenuation. There are three kinds of radiation, α, β and γ-rays. As α- and β-rays do not penetrate materials, heating occurs on the spot. However, γ-rays penetrate substances, so that heating occurs not only in the reactor but also in the pressure vessel walls and shielding concrete.

Since the fuel rods (core) are surrounded by water when the reactor is operating, γ-rays attenuate (generates heat) in the water and only a small portion of the γ-rays penetrates through to the reactor pressure vessel. Therefore, the α, β and γ-rays are treated together as a group as the source of the decay heat in the reactor. However, the situation is different in a core which has lost its water. Although a portion of the γ-rays is attenuated in the structural members surrounding the core, contributing to their heating, the majority of the γ-rays is attenuated (causes heat) in the reactor pressure vessel and the shielding concrete. Therefore, the heating by γ-rays, which amounts to one half of the total decay heat, needs to be considered separately from the heating of the core.

More precisely speaking, even after the water is gone, so long as the core maintains its shape much of the γ-rays attenuate in the process of penetrating through the surrounding fuel rods, and so the heating inside the core does not decrease so much. However, once the core loses its original shape, more γ-rays radiate outside so that the heating inside the core reduces. In the end, when the core loses its original shape and reduces to a lump of molten core, putting aside dissipation within the lump it is reasonable to think that virtually all of the γ-rays radiate outside. If that occurs, I believe as a ballpark estimate that about 70–80 % of the heating by γ-rays occur outside of the core.

If we look at this from the standpoint of the decay heat amount generated inside the core, since γ-rays account for half of that, and about 70–80 % of the γ-rays heating occurs outside of the core, the amount of generated heat is reduced by 35–40 %. This means that the decay heat that heats the core is reduced to two-thirds of the original amount.

In other words, an interesting phenomenon occurs when the core changes to the radiation-dominant phase, in that the decay heat that heats the core is reduced to two-thirds. Of course this change does not occur all at once, but rather occurs gradually caused by the combination of the lowering of the water level and the collapse of the core shape, and I will use the term "radiation heat phase," in this book to refer to the phase after the reactor water level has reached the core bottom as radiation will become the main mode of heat dissipation in that phase.

The core lost its cooling water at around 8 p.m. on March 11. Unit 1 moved into the phase of heat removal by radiation. Once it loses its means of cooling, the core temperature starts to rise rapidly and emits the radiation heat. Together with that, the temperatures of the internal components start to rise as well. What kind of effects did this change have on the reactor?

According to the TEPCO report, the reactor pressure, which used to be approximately 7 MPa at around 8 p.m. on March 11, dropped to 0.9 MPa by 2:45 a.m. on March 12. Those are the only two points in time when the reactor pressure data of Unit 1 were recorded. It is unfortunate that we don't know what happened in between, but it is at least certain that it is one change that the radiation heat phase caused.

The only Unit 1 data available to us is the containment vessel pressure shown in Fig. 2.19. And even this only shows the condition after midnight (around 1 a.m.). The reactor water level data is not reliable either. Given the lack of data, the rest of my descriptions include a substantial amount of speculations.

It can be presumed based on the case of Unit 2 that the original shape of the core was maintained until around 8 p.m. on March 11, or just before the core ran out of water, with the fuel rods cooled by the small amounts of steam that were flowing. It is confirmed that the reactor pressure was 6.9 MPa at this time because the operating staff read the instrument directly at site.

From this we can deduce that the core was intact until 8 p.m. on March 11.

The decay heat at the time when the core lost water (around 8 p.m.), by the way, was about less than 1 % of the rated power, as it was approximately 5.5 h after the

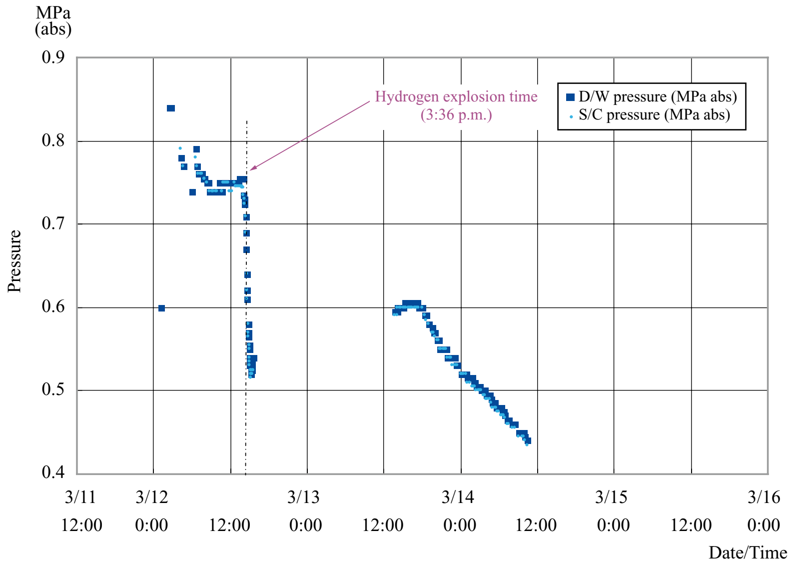


Fig. 2.19 Unit 1 containment vessel pressure change (measured data) (Source: from "TEPCO Nuclear Accident Investigation Report")

reactor stopped. Since the radiation heat is about two-thirds of that, that means approximately 0.7 %. As the rated thermal output of Unit 1 is approximately 1,500 MW, 0.7 % of that is approximately 10 MW. This amount of heat is capable of evaporating in 1 h approximately 25 tons of cooling water at the rated temperature and pressure, or approximately 13 tons of cold seawater. As the size of the core is approximately 3 m in diameter and approximately 4 m in height, the volume is about 30 m^3. For this small, water-less space, 10 MW of generated heat is an enormous size. These numerical values will be used later.

It was reported at 9:51 p.m. that the radiation level of the reactor building was increasing.

It was already 2 h since the water ran out in the core. This rise of radiation means both that radioactive substances had started to leak out from the fuel rods and also that such radioactive substances had leaked into the containment vessel. Both of these were things that we had not experienced before. These are probably the result of the reactor having entered the radiation heat phase. Let us carefully examine the status inside the core.

I suppose that the fuel rods in the core center, where the heat generation was most active, had started to deform. The fuel rods must have started to deform, bending and buckling, contacting and leaning with each other, and started to form a mixed molten substance consisting of uranium dioxide and zirconium, drawing into it the surrounding channel box as well.

I know that I have not yet mentioned the channel box. The channel box comprises rectangular outer plates that surround the fuel assembly of BWR, each consisting of a zircaloy plate having a width of approximately 14 cm on each side and a thickness of 2–3 mm (Fig. 2.20). As water and steam flow inside the channel box, when there is water in the core, the temperature of the channel box, which does not generate heat by itself, is low, so I have been treating this as something that is different from the fuel rods.

However, once the reactor is in the radiation heat phase, the temperature of the channel box which is made of thin plates becomes equal to the temperature of the fuel rods within a relatively short period of time.

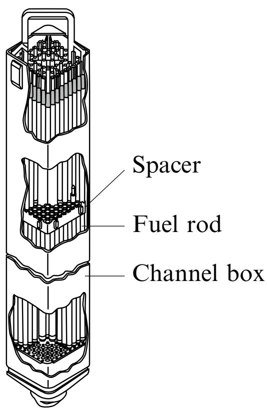


Fig. 2.20 Structure of fuel assembly (Source: from "Outline of BWR Power Plant" (Rev. 3) by NSRA)

Allow me to digress a little, but the amount of zircaloy used in the channel box is too large to ignore. Although it varies with the type of fuel rods, the proportion of the zircaloy in the core that is attributable to the channel box is 36 % where the channel box is 2 mm thick and 45 % where it is 3 mm thick.

As described later, the fuel rod temperature during the radiation heat phase is estimated to have reached around 2,000 °C by 4 a.m. of the following day. To our chagrin, this temperature is slightly in excess of the zircaloy melting point, so in the radiation heat phase the large amount of zircaloy in the channel box will be part of the core melt.

By this time, the entire surface of the channel box must have been covered by zirconium oxide film as a result of the reaction between zirconium and steam. In the meantime, however, the main part of the zircaloy sandwiched between the oxide films melts at around 1,800 °C and drops down by gravity. This process cannot be taken lightly. It seems that the temporal temperature change of the channel box significantly affects the core melt and the hydrogen explosion in the radiation heat phase.

The internal components in the vicinity of, and above the core are mostly made of a stainless steel alloy that has a low melting point (1,450 °C), so that they must have melted partially by the strong radiation heat from the core and flowed down on the mixed molten substance little by little. Thus, as the internal components in the vicinity of the core melt down, the radiation by the mixed molten core starts to heat the reactor pressure vessel directly.

On the other hand, the evaporation of water by the radiation heat must have been continued constantly and the water level presumably dropped gradually. However, the lower internal components of the core are thought not to have melted as they were kept relatively cool because their lower parts were still immersed in water.

That is the status of the reactor at around 10 p.m.

An hour later, at around 11 p.m., it was recorded that the radiation level was high in front of the double door in the reactor building. This is evidence that a substantial amount of radioactive materials leaked out into the containment vessel. According to the TEPCO calculation, the water in the reactor pressure vessel was completely depleted by this time.

It was confirmed that the DW pressure of the containment vessel reached 0.6 MPa at around 11:50 p.m. That means that an opening was formed in the reactor pressure vessel due to the heat, and the steam inside leaked out from the reactor.

Let's see if it is true by making a simple calculation. The time, 11:50 p.m., is about 4 h since 8 p.m. when the water level reached the very bottom of the core. If we assume that all of the radiation heat was used to evaporate water, it can be concluded that approximately 100 tons of water was evaporated within these 4 h since the evaporation amount is 25 tons/h according to the calculation we did a while ago. This evaporation amount is slightly more than the quantity of water retained below the core. I suppose that the reactor water was completely depleted by this time, i.e., midnight. The opening in the reactor pressure vessel was probably formed approximately this time.

That was the status of the reactor in the radiation heat phase, at around midnight on March 11.

2.7.2 Core Melt and Meltdown

What did the opening in the reactor look like?

I think the opening here is a gap that was formed when the top lid of the reactor pressure vessel was lifted up due to internal pressure when the fastening bolts used to keep it in place got elongated by thermal expansion on account of the top portion of the pressure vessel being directly or indirectly heated by the radiation heat. I surmise that steam leaked through that gap into the containment vessel. To put it simply, the reactor pressure vessel's top lid got loosened by thermal expansion and a gap was formed.

Some people imagine that the safety relief valve got hot and the valve closing force weakened. That is also a viable opinion.

There are various other theories, including a theory that says the flange coupling of the main steam piping that extends from the top of the reactor pressure vessel was damaged by high temperatures, a theory that the control rod-drive housing located at the bottom of the core or the neutron measuring piping was damaged by melting due to the drop of the molten core, etc. All of them are credible. I think you also should use your imagination freely. I believe that there is no question that an opening was form in the reactor pressure vessel by the time the new day started and the pressure vessel became connected to the containment vessel to allow the gas to leak to the latter.

The condition of the core must have been such that the mixed molten substance, which included molten upper components, had developed here and there during from 8 p.m. to midnight, and the entire core must have reached a very high temperature, although it had not completely collapsed. I have no choice but to think so since it had lost its coolant water. During this period, a portion of the nearly 100 tons of water that evaporated must have caused a oozy oxide reaction with the mixed molten substance and developed some hydrogen gas as well. Since this hydrogen gas is light and hot, it must have gathered around at the top portion of the reactor pressure vessel and heated its vicinity. Because of this core condition, the opening in question must be the loosening of the top lid of the reactor vessel.

This was the state of the core from between 8 p.m. on March 11 and 0 a.m. on the following day.

Let us now move the hands on the clock and think about the reactor's condition during the period from 12 a.m. through 4 a.m. on March 12. Since all the water in the reactor pressure vessel had already evaporated, the temperature of the mixed molten substance made from the core must have risen further, getting closer to its melting point. However, the core as a whole at this hour was probably on the core plate, although it had deformed substantially. My thought is based on the result of the PCM-1 test.

Because of the thermal effect of the radiation heat of the core and the molten upper core materials, probably the guide tubes of the control rod drive mechanism and the neutron measuring device were partially melted and holes developed at the bottom of the reactor pressure vessel. Although the top lid of the reactor pressure vessel still remained, its pressure keeping capability was completely lost.

The condition of the containment vessel was such that the temperature of the top portion of it had probably substantially increased from the superheated steam and hydrogen gas from the reactor. However, the containment vessel is such a huge structure so that the temperature rise occurred only in the top portion. It is difficult to believe that the entire structure was uniformly heated. Moreover, the radiation heat emanating from the reactor pressure vessel towards the containment vessel was shielded by the insulating material covering the reactor pressure vessel, so I think that it was not contributing much to the heating.

I believe that, in general, a serial radiation heating system was about to be formed consisting of the core which turned into the mixed molten substance, the reactor pressure vessel, the insulation material, and the containment vessel.

From 0 a.m. to 4 a.m. on March 12, when the water injection using the fire engine started, there was a span of 4 h. Yet, we have no data for that period. No decisive clue. The only thing we know is the physical fact that the decay heat dropped just a little bit.

There are many people who proclaim theories on how the mixed molten substance behave during this 4 h period, in particular that the substance partially or fully melted the bottom of the reactor pressure vessel and dropped in a liquefied state on the floor of the containment vessel. Those claims sound convincing. However, nobody seems to be able to tell us about the physical condition, e.g., how much material dropped, did it only drop once, or rather did it drop continuously, was it fluid, or was it in a squashy state just before melting, etc. It seems that they only claim that it melted and dropped somehow without any convincing reasoning, and I cannot blame them too much for that. It is because that there is no data on which to build presumptions.

2.7.3 Reverse Study from Hydrogen Explosion

I suppose that the proper thing to do in this kind of situation is to think backward. Let us try to think backward from the explosion, which is the final moment, leaving aside the phenomena between 0 a.m. to 4 a.m. on March 12 for the time being.

The explosion occurred in the reactor building of Unit 1, at 3:36 p.m. on March 12. The only thing that was damaged by this explosion was the fifth floor where the fuel exchange floor is located, exactly above the reactor. This is the unique feature of the explosion of Unit 1. The explosion in Unit 4 damaged not only the fifth floor but also the third and fourth floors, while even the 1st floor damage is observed in case of the explosion in Unit 3.

The explosion of Unit 1 affected only the 5th floor. This is the first clue of the backward analysis.

Figure 2.3 is the cross-sectional drawing of the reactor building. As we look at it closely, we see that the fuel exchange floor is directly above the containment vessel.

The fact that only the fuel exchange floor exploded means that the hydrogen gas existed only on the 5th floor. The only route that makes the hydrogen gas flow only to the 5th floor is the one that makes the hydrogen gas flow directly upward from the containment vessel.

The only hydrogen path available is, as I described in the explosion of Unit 2, for the hydrogen gas from the containment vessel to raise the reactor vault pressure, push up the shield plug, and flow into the fuel exchange floor. If the hydrogen gas had passed through other routes, the hydrogen gas left in those routes would have caused chain explosions. The flow of the hydrogen gas that lifted the shield plug, which I explained in connection with Unit 2, occurred in Unit 1.

Or rather, the fact that the explosion occurred only on the 5th floor in Unit 1 showed us how the hydrogen flowed from the containment vessel to the reactor vault and then to the fuel exchange floor. I have to admit that even my reasoning here was backward because the order in which I wrote this was backward.

In the case of Unit 1, there are many people who believe that the hydrogen gas first entered the stack from the vent as the vent was opened about 1 h prior to the explosion, and then backed up via the ventilation duct. This is wrong. In the case of Unit 4, the explosion was caused by the hydrogen back-flow from Unit 3, but it had a long time – as long as 26 h – to back-flow. In case of Unit 1, the time the vent was open before the explosion was only 1 h. It is unreasonable to claim that a sufficient amount of gas for causing an explosion can flow backward from the stack to the fifth floor in such a short time. Also, the explosion in case of Unit 1 occurred only on the 5th floor, different from Unit 4. There was no explosion on the lower floor where the ventilation duct is located.

That makes it necessary for a large amount of hydrogen gas to flow into the reactor vault in order to push up the shield plug before the explosion occurs. The containment vessel pressure was as much as 0.5 MPa even when the vent was open at around 2:30 p.m. on March 12, which is large enough relative to 0.05 MPa, the pressure required to lift the shield plug. The remaining mysteries are why and when the top lid of the containment vessel opened.

There is no question about the timing. It was immediately before 3:36 p.m., when the explosion occurred. I will explain why it opened later.

Without an ignition source, there can be no explosion. Since the power station is under a power outage, the only ignition source can be the vibration from an earthquake or the shock from something dropping. TEPCO confirmed that there was no earthquake at that time. The only possible ignition source is the shock generated by the drop of the shield plug, as in the case of Unit 3.

That means that the time that the explosion occurred, i.e., 3:36 p.m., is when the shield plug dropped. It means that the top lid of the containment vessel opened just before then, causing a large amount of hydrogen gas to enter the reactor vault to lift the shield plug. The top lid of the containment vessel must have opened widely just prior to that time. The only cause that could open the top lid of the containment vessel was the generation of hydrogen gas due to the oxidation reaction between the mixed molten substance and water.

However, for some unknown reason, the containment vessel pressure data (Fig. 2.19) that could have provided the evidence for such events is lost for a period starting around 1 h before the explosion. The route to prove facts based on backward analysis is also closed due to a lack of evidence. I can only proceed with my analysis from this point on by mixing in presumptions. Please keep that in your mind.

First, I will try to estimate the temperature under the radiation heat phase during the period of 4 h from 0 a.m. to 4 a.m. on March 12. The only thing that remains in the empty reactor pressure vessel now void of all water is the radiation heat. The strength of the radiation heat is a little less than 10 MW and the source of the heat is a cylindrical object of approximately 3 m in diameter and approximately 4 m in length, a mixed molten substance which used to be essentially the core, comprising uranium, zirconium, oxygen, stainless steel, etc. Although it is difficult to estimate, let us move forward with our calculation assuming that the core temperature at around 4 a.m. on March 12 was 2,000 °C, which is close to the melting point of the mixed molten substance based on the example of the TMI accident.

Thus the reactor which lost cooling water is generating 10 MW of radiation heat. As I mentioned previously, an equilibrium status of the radiation heat, or a serial radiation heating system consisting of the core, the reactor pressure vessel, and the containment vessel, was formed. Let us do some calculations about the temperature of this system.

The calculation, a very rough one I admit, is shown at the end of this chapter (Appendix 2.8). If the core temperature is assumed to be 2,000 °C, the equilibrium temperatures achieved by the radiation heat are approximately 550–600 °C as the reactor pressure vessel temperature and 120–130 °C as the containment vessel temperature. From this calculation result, we can be sure that the temperatures of the reactor pressure vessel and the containment vessel will not be unrealistically high even if the core temperature is as high as 2,000 °C.

If I may add, if there is a 10 % error in the assumption of the core temperature, the error in the radiation heat will be as much as 50 %. Using the fact that radiation heat is proportional to the 4th power of temperature as a hint, please confirm the above.

Then the next question is how long it would take to reach an equilibrium state of heat radiation. Let us check that time as well.

In terms of assumptions for our calculation, let us assume that the reactor pressure vessel, which weighs about 340 tons, has reached 550 °C, one half of the reactor internal components (the portion from the core up), which is estimated to weigh about 100 tons, melted by the radiation heat, and the rest of the internal components were heated to 550 °C – as they can dissipate heat because components such as the control rod drive mechanisms extend to the outside of the reactor pressure vessel (Appendix 2.9). Since the outside of the reactor pressure vessel is covered by a thin aluminum insulation material (melting point: approximately 650 °C), the heat radiation from the reactor pressure vessel to the outside is assumed to be zero in the calculation.

The above calculation indicates that a heat quantity of approximately 30 MWh will be needed to reach the equilibrium state. The core radiation heat at around

0 a.m. on March 12 was approximately 10 MW. Since the core radiation heat at around 4 a.m. on March 12 was 7 MW, the total radiation heat generated during these 4 h was slightly less than 40 MWh. If we compare both, the radiation heat appears slightly larger but in essence both are roughly equal considering heat dissipation, core temperature increase, etc.

This means that by 4 a.m. on March 12, when the water injection was started, the radiation heat equilibrium temperature system consisting of a core temperature of approximately 2,000 °C, a reactor pressure vessel temperature of 550–600 °C, and a containment vessel temperature of 120–130 °C was more or less established. The core temperature of 2,000 °C seems to have been appropriate judging from the calculation result. We can assume that the core has not yet started melting at this time.

2.7.4 Drop of Partially Molten Core and Its Internals

Once the temperature estimation is made, next is the estimation of the internal state of the core.

The melting point of the core fuel, i.e., uranium dioxide is 2,880 °C. That of stainless steel is approximately 1,500 °C. The two are vastly apart. The melting point of the mixed molten substance comprising uranium, zirconium and oxygen is approximately 2,000–2,200 °C. As you can see, the core toward the equilibrium temperature system comprised materials with widely varying melting points.

The matter would have been simpler if these materials were melting separately. Under the 2,000 °C core temperature state, stainless steel would have melted by the radiation heat and flowed down like water to the bottom of the reactor pressure vessel. The uranium dioxide would have remained as solid pellets. The mixed molten substance would have turned into a soft plastic object immediately before melting.

However, as the existence of the mixed molten substance consisting of uranium, zirconium and oxygen suggests, high temperature metals mix before melting and co-melt with each other, so that the result is quite unpredictable. Even stainless steel that can melt and flow down like water may react when it contacts a substance just before it melts and may produce an alloy we are not aware of. For a person like myself who has been brought up in a world of physics that can be dealt with using mathematical formulas, the reactions of high temperature metals joining and separating with each other seem, sorry to say, very mysterious and outlandish. To me they are very unpredictable.

Moreover, these mixed molten substances and other mysterious substances are sitting on a thick perforated stainless steel plate called the core plate. Since it is perforated, it allows fluid materials to pass through. It is presumed that molten stainless steel and such passed through the perforated holes and dropped to the bottom of the reactor pressure vessel and accumulated there. The molten stainless steel must have cooled at that bottom head of the reactor pressure vessel and solidified again. At the same time, the bottom head of the reactor pressure vessel must have been heated and softened because of the heat.

On the other hand, solids such as uranium dioxide and softened plastic components such as the mixed molten substance do not drop easily as they are supported by the thick core plate. Depending on their fates, those highly heated and plasticized substances may drop below as lumps, be mixed and melt to form alloys we have never seen, or survive as solids. One of the more probable scenarios is that a portion of the lower internal components is melted by heat and drops to the bottom of the reactor pressure vessel mixed with some of those indescribable formations. It is possible that the bottom of the reactor pressure vessel, which had lost its strength because of heating, broke down from the weight of those lumps dropping on it and then all of that dropped to the floor of the containment vessel floor.

Or rather, its drop could have been interrupted by obstacles such as the control rod device mechanism and the like, or melted the obstacles and piled on the bottom of the reactor pressure vessel. It seems to me that innumerable varieties of events could have occurred inside the reactor pressure vessel – the center of this mess, so-to-speak, during this period of time.

The pipes that go through the bottom of the reactor pressure vessel include the penetration part of the neutron measuring system as well as the penetration part of the control rod drive mechanism. Many people have pointed out the possibilities that various kinds of piping melted or broke down and that produced small cracks and holes at the bottom of the reactor pressure vessel.

I imagine that such conditions started around 4 a.m., or just before the water injection was started, although the precise timing may have been a bit different. As seawater is injected by the fire engine pump, an oxidation reaction starts between the highly heated mixed molten substance and the cool seawater. Since the oxidation reaction generates heat, the core melt accelerates automatically. The problem is whether the water injection was sufficient.

The water injection by the fire engine started at 4 a.m. on March 12. The TEPCO report notes that approximately 80 m^3 of water was injected by 2:53 p.m., just before the explosion of Unit 1. This amounts to 80 tons in about 11 h, or only 7 tons/h, but based on what follows let us assume a rate of 5 tons/h. Since it had been almost a half day since the reactor stopped by this time, the decay heat had reduced to about 0.7 % (approximately 0.7 MW in terms of the decay heat inside the core). Since this amount of heat can evaporate approximately 10 tons or more of cool seawater, the seawater injection by the fire engine of 5 tons/h does not even come close in matching the decay heat. That means the core temperature keeps rising. The mess in the reactor pressure vessel I described above must have been further intensified by this time.

It can be generally said of pumps that a higher discharge pressure results in a smaller amount of discharge. For 10 h from 4 a.m., when the water injection started, until 2 p.m., the containment vessel pressure was approximately 0.8 MPa, which was about equal to the pump discharge pressure. That is why the pump discharge was so small. However, as the SC vent was opened at around 2:30 p.m., the containment vessel pressure dropped sharply to about 0.5 MPa (Fig. 2.19). When the discharge pressure drops to 0.5 MPa, the pump discharge amount increases sharply. In order to further the discussion, let us assume approximately 30 tons of seawater, which is approximately one-third of the total 80 m^3 seawater injected, entered the reactor pressure vessel in such a state (Appendix 2.10). This means that the rate of water injection during the foregoing 10 h was 5 tons/h.

Incidentally, it is reported that the spray of seawater in Unit 1 was executed using the core spray which sprays the core with water from above, but the stainless steel piping on top of the reactor is considered to have been melted by that time, so that the water must have run down along the core's external wall surface. It is estimated that the majority of such a small amount of seawater, or 5 tons/h, was evaporated by the surrounding heat and some of the steam thus generated must have reacted with the high temperature mixed molten substance and the heat provided by said reaction must have further elevated the core temperature. I suspect that the dropping of the molten lumps mentioned before must have been quite active as well. All in all, however, the reaction itself was not that active because of the insufficient availability of water. We can consider this as a high-temperature version of the oozy reaction mentioned in the description of Unit 3.

If we are to analogize this semi-molten core status, it was like well-cooked and softened chestnuts embedded in the mushed sweet potato of a traditional Japanese sweet served on New Year's Day. The majority of the uranium dioxide pellets were soft but still solids. On the other hand, the mixed molten substance had become plastic, just like the main body of the Japanese sweet. This Japanese sweet in our analogy is protected by the thin incomplete egg-shell made as a result of the zirconium-water vapor reaction from the direct contact with water. I suppose that is how it was lying on top of the core plate. I wonder if this was when the bottom of the reactor pressure vessel fell through.

Although all kinds of conjectures are possible, my thinking is as follows: "At a certain point in time, a portion of the mixed molten substance, which had a certain amount of weight, fell through the bottom of the reactor pressure vessel and dropped on the floor of the containment vessel. The surface of what fell got cooled by the atmosphere of the cooler containment vessel floor and solidified. On the other hand, the remaining mixed molten substance left in the core reacted with steam vapor, widened the egg-shell, and remained on the remaining part of the perforated plate. I suppose, however, the heated and softened mixed molten substance still kept dropping in clumps from the cracks of the incompletely formed egg-shell, eventually forming a mound."

To reveal my secret about this discussion, it is at least partially based on the deduction from the Chernobyl core melt case. As it is described in Sect. 1.3.1, the fuel left after the core fire in the Chernobyl accident is considered to have melted the bottom of the concrete reactor vessel, dropped to another floor 2 m below, and produced a mound. Further melting and fluidization by the decay heat occurred inside of the mound, and the fluidized substances broke out the edge of the mound and flowed out like a flood three times.

I suppose a similar situation continued for 10 h. The mixed molten substance that dropped on the containment vessel floor must have been cooled by the cool atmosphere of the floor so that the outside walls must have solidified. However, the temperature in the inside must have risen further due to the continuing decay heat, and the mixed molten substance must have gradually melted. I am sure that the situation of the lower part of the containment vessel at that moment was quite confusing, with various ingredients partially and completely melted and mixed together.

2.7.5 Sea Water Injection and Explosion

At around 2:30 p.m. on March 12, the vent finally opened, and the pressure of the containment vessel dropped sharply. The water from the fire engine kept running. All the work-related people who worked all through the night must have gotten quite relieved. However, as soon as they were relieved, another monster appeared. It was an explosion that occurred at 3:36 p.m.

The explosion was caused by the large amount of hydrogen generated by the active reaction between cold water and the extremely hot mixed molten substance. The active reaction took place due to the increased injection of seawater. The rate of seawater injection which used to be 5 tons/h became 30 tons/h in a short time. The seawater, which had up to then evaporated, started to fall on the floor of the containment vessel floor as liquid water.

The seawater ran down along the core's external walls. Although there is no record to prove it, I assume that a large amount of hydrogen must have been produced by the reaction between water and the potpourri of molten alloys in the mound.

This assumption is basically correct but there is one thing that does not match the data. It is a time difference of about 1 h between the time the water injection amount was increased (a little past 2:30 p.m.) and the time of explosion (3:36 p.m.). The presumption that can solve this difference is the deduction from the Chernobyl accident, the mound on the floor. There is only one clue here: the fact that a large amount of water is needed at once in order to cause a violent reaction. Please remember the core melt in TMI as well as the Units 2 and 3 accidents.

The majority of the water that dropped on the containment vessel floor most likely must have dropped on the outside of the mound, and must have been unable to react immediately with the molten alloys as they were kept separate by the mound. The lower part of the reactor pressure vessel has many things, such as the control rod drive mechanism and neutron measuring cables, that must have been hanging down like drainpipes, so that the dropping water must have flown along them to the outside of the mound. They must have followed a route that was different from the straight-line route that the dropping semi-solid lumps followed.

The violent reaction started around 3:30 p.m., when the water level on the floor rose to exceed the height of the mound. The delay of about an hour from when the vent started must have been the time taken for the water level to rise. This is a situation similar to the Unit 3 reaction that happened three times. I wish I could write that's the case but I have no data to prove it.

The reaction between the high temperature mixed molten substance and a certain amount of seawater must have caused the containment vessel pressure to rise sharply (TEPCO's record is cut short). This pressure rise lifted the top lid of the containment vessel. The preheated fastening bolts of the top lid must have been elongated by thermal expansion and then further elongated by the lifting of the top lid. The pressure may have temporarily risen to more than 0.8 MPa.

Once we are convinced of the lifting of the top lid of the containment vessel, I suppose that there is no need to repeat the description of the process of the hydrogen entering the fuel exchange floor of the 5th floor of the reactor building, mixing with air to become an explosive gas, and igniting by the impact of the dropping of the shield plug.

So that is the presumption of the core melt and explosion in Unit 1.

The uniqueness of the explosion of Unit 1 is that it was limited to the 5th floor and the scale of the explosion was smaller than that of Unit 3.

The reason that the scale of the explosion was smaller was that the amount of hydrogen gas that contributed to the explosion was relatively smaller. This is believed to be caused by the fact that both the amounts of the mixed molten substance and water were smaller. Furthermore, a portion of the hydrogen gas that was generated on the containment vessel floor was discharged to the atmosphere through the vent as the vent of Unit 1 was open at the time of the explosion.

The water injection continued even after the explosion. There is no question that the reaction between the mixed molten substance left in the core after the explosion and steam continued. The reaction must have continued even after the core was flooded with water. However, the hydrogen gas thus generated after the explosion was diluted by a large amount of atmosphere, as there was nothing left to cover the containment vessel because of the explosion, and did not become an explosive gas.

In the case of Unit 3 explosion, immediately after destroying the 5th floor of the reactor building in horizontal directions, split the building vertically from around the 3rd floor. Its blast is said to have reached several hundred meters high into the sky. On the contrary, the explosion of Unit 1 occurred only on the 5th floor.

Actually, the fact that the explosion of Unit 1 occurred only on the 5th floor provided us the evidence for identifying the discharge route of the hydrogen gas. In other words, the route by which the hydrogen gas entered the reactor vault by pushing up the top lid of the containment vessel, lifting the shield plug by its pressure, and then going out onto the fuel exchange floor on the 5th floor was proven originally by the analysis of Unit 1. If the hydrogen gas went through a different route, the explosion of Unit 1 must have caused an explosion along the route, just like what happened in Units 3 and 4. The mysteries of the hydrogen gas flow routes and the causes of ignitions of the hydrogen gas explosions in Units 2 and 3 were solved with the hint provided by Unit 1 – although the explanation was provided in reverse order.

Although the explosive power was weak, the explosion of Unit 1 significantly affected the accident countermeasures of the other reactors. The overnight effort of directly providing electric power to Unit 2 was nullified by the damages caused by the explosion to the power source car and the connecting cable. Then, Unit 2 developed the core melt because the RCIC pump stopped 2 days later around 11 a.m. on March 14.

The explosion of Unit 1 did not cause any further damage to Unit 1, but it kicked off a major calamity to the entire Fukushima Daiichi Nuclear Power Plant.

2.7.6 Section Conclusion

The following is the summary of the important conclusions concerning the melting and explosion of Unit 1.

Unit 1 stopped as the earthquake occurred and was in the IC cooling state by manual operation, but unfortunately it was hit by a tsunami when its cooling was stopped so that it became impossible to restart it. It was further unfortunate that this information of cooling failure was not communicated to the supervising staff in a proper way, so that both the site manager and the consulting staff at TEPCO's head office misunderstood that Unit 1 was OK because the IC was working. As a result, they went into the accident without countermeasures. That was the biggest cause that invited the core melt and the explosion in Unit 1.

After the tsunami struck, the Unit 1 reactor had to keep cooling the decay heat without a drop of water supply. The only thing it could do was to evaporate the cooling water left in the reactor pressure vessel, akin to a hungry octopus eating its own tentacles. The water level of the reactor kept dropping with time, and it became empty by midnight on March 11. What happened in Unit 1 has never occurred in any other nuclear power plant. Even under such a reactor condition, the core has not been melted. This is a remarkable fact.

The only means of heat dissipation available once the reactor pressure vessel loses its water completely is to rely on heat radiation. The higher the temperature, the more heat is radiated. In order to be able to succeed in heat removal, the core temperature of the heat source needs to be very high.

It is only a rough estimate, but the core temperature of Unit 1 rose to 2,000 °C, and the reactor pressure vessel temperature rose to about 550–600 °C. In the meanwhile, a portion of the internal components of the core made of stainless steel must have melted, and the lower core support structure must have deformed as well. I suppose that various conduits that are passing through the bottom of the reactor pressure vessel head such as the guide tubes of the control rod drive mechanism and the neutron measuring system were melted as they met with the down flow of molten stainless steel, thus forming the openings for water leakage.

Around 4 a.m. on March 12, the water injection by the fire engine started. However, the amount of water injected was small because the pressure of the reactor pressure vessel was too high. Moreover, most of the injected water evaporated in the reactor pressure vessel. This steam and a portion of the high temperature core caused the oozy reaction and continued to generate heat and hydrogen gas for about 10 h.

The generated hydrogen gas accumulated on the top portion of the containment vessel, and heated the top lid of the containment vessel. Due to the temperature rise, the fastening bolts of the top lid thermally expanded and weakened the fastening force.

In the meantime, the heat from the oozy reaction in combination with the decay heat rose the temperature of the mixed molten substance and caused partial melting. A portion of the molten substance is assumed to drop to the bottom of the reactor pressure vessel together with the molten core plate. The bottom of the reactor pressure vessel which had been heated to a high temperature by the radiation heat and the conductive heat of the molten stainless steel became unable to withstand the weight of what had dropped, and dropped to the floor of the containment vessel together with the other molten droppings.

Once a hole is opened in the bottom of the pressure vessel, the already softened mixed molten substance (core fuel) is further heated by the oozy reaction heat, and drops little by little to the containment vessel floor to form a mound. Inside the mound, the mixed molten substance starts to melt by the decay heat. Such a condition continued inside the containment vessel for 10 h from around 4 a.m. on March 12, when the seawater injection started, until 2:30 p.m., when the vent opened.

As the vent opened and the containment vessel pressure stated to drop, the discharge quantity of the fire engine pump increased sharply. As the seawater that dropped to the bottom of the containment vessel accumulates so much as to cover the mixed molten substance, the reaction became active and generated a large amount of hydrogen gas all of a sudden, and the containment vessel pressure increased sharply. This gas pressure lifts up the top lid whose fastening force is weakened. The hydrogen gas that was stuck in the containment vessel escapes through the lifted top lid of the containment vessel into the reactor vault, lifts up the shield plug to flow onto the fuel exchange floor, and mixes with air to form an explosive gas. When the hydrogen flow weakens and the lifted shield plug drops, the impact of the drop ignites the explosive gas to cause an explosion.

That was the study of the core melt and explosion of Unit 1.

Let us list up the new findings and important items.

I. The state of complete loss of water from the reactor pressure vessel continued for at least 4 h. During that period, the core probably collapsed but never reached the state of complete melting. The heat dissipation by radiation continued in the empty reactor pressure vessel, a completely new accident condition that had never been experienced in the world.
II. The core temperature under the radiation heat dissipation process must have been around 2,000 °C, or close to the melting point of the uranium, zirconium and oxygen mixed molten substance, and a thermal equilibrium must have been maintained by the radiation heat. The empty reactor pressure vessel temperature is roughly estimated to have risen to 550–600 °C.
III. A portion of the collapsed core broke the bottom of the reactor pressure vessel and dropped to the floor of the containment vessel to accumulate during the water injection period that lasted about 10 h. Then, it reacted with the seawater whose injection rate had increased sharply as a result of the vent opening, and generated a huge amount of hydrogen gas. The damage by this hydrogen gas

explosion was limited to the 5th floor of the reactor building. This confirmed the entry route of hydrogen gas onto the 5th floor and also proved that the ignition source of the explosion was the impact caused by the drop of the shield plug which was lifted up by the hydrogen gas.

Column Were the Holes Developed in the Containment Vessel as Depicted in "China Syndrome"?

I have heard about a calculation which showed that the molten core of Unit 1 caused the bottom of the containment vessel to melt, leaving only several tens of centimeters before it stopped melting. People often ask me as well if any contaminated water is leaking through holes created by the heat of the molten core on the bottom of the containment vessel, as depicted in the movie "China Syndrome."

I learned about the calculation only through media reports and I have no specific information about it. However, based on my experience, I believe that the particular calculation result is overestimating the depth of the melting erosion. The depth of the melting erosion can be estimated with a certain amount of accuracy so long as we know the temperature, mass, contact area, and decay heat of the molten core, but it can be lead to a mistake if the floor is simply consisting only of concrete: a concrete structure normally has reinforcing steel bars embedded in it.

The heat conductivity of reinforcing steel bars is approximately 50 times larger than that of concrete. When the molten core reaches the depth where the reinforcing bars are arranged, the heat is transmitted to areas far beyond the contact area through the reinforcing bars. I wanted to do a calculation but I couldn't get the detailed specifications of the layout of the reinforcing bars for the containment vessel floor.

If it is an ordinary floor, reinforcing steel bars of approximately 1.2 cm in diameter are arranged in a grid-like pattern of a 20 cm pitch, and then covered by 5 cm of concrete.

Since there is no sense of doing a precision calculation, let me make a ballpark calculation. A 1.2 cm thick reinforcing steel bar with a heat conductivity 50 times larger than that of concrete is equivalent to 60 cm-wide concrete. When the molten core reaches the reinforcing steel bar level, the heat that has been heating a floor of only a 20 cm width will be equivalent to be heating a concrete slab of 20 cm + 60 cm = 80 cm width. This means that the thermal effect will be reduced to one-fourth.

The reinforcing steel bars run not only east and west, but also north and south, so that the heat transfer and thinning expands further. If we consider the heat dissipation from concrete itself, the effect expands further. As a result, the erosion of the floor concrete by the molten core stops at about the depth of the reinforcing steel bars. Actually, to reveal my secret concerning this discussion, I once asked the students of my laboratory to do a similar calculation, that remind me of the result at that time.

It seems that the molten core spread over the floor of the containment vessel only in the case of Unit 1. Moreover, the amount that was spread was only a portion of the core, not the whole core, even in the case of Unit 1. Combining these estimates, I believe that the melting of the containment vessel was quite limited and must have stopped at around the depth of the reinforcing steel bars.

2.8 Conclusion from Studies of Units 1–3

My explanation of the studies of the core melts and explosions of Units 1 through 3 has become a very lengthy one as you can see. For example, many of you may have forgotten what I said about the core melt conditions of Unit 2 already. That exemplifies how complicated the Fukushima accident is. Therefore, let me summarize here the key elements that are common to all melts and explosions.

The first and most important thing is that core melt occur due to heat generated by a reaction between zircaloy and water.

I have said so again and again and have proven this based in connection with the melts of Units 1–3. A reactor core does not melt because of decay heat. Also, it does not melt completely and flow down like a fluid would, as depicted in NHK TV's graphic image.

Let us recall that the decay heat at the time of core melting, which we discussed here, was only about 1 % of the rated output of the typical reactor at most. If we think about it from the other side, a reactor that is operating normally typically converts output of a 100 times that into electricity while cooling the core. The core is not so weak that it melts down by a decay heat of only 1 % or so. To prove it, we saw out that Unit 1, which did not receive even a drop of water, did not explode until over a day afterwards.

"Low-temperature burn" caused by a little bit of decay heat can be cured with proper care. The only thing that can cause an incurable serious burn like a core melt is an acute zirconium-water reaction that melted the TMI core in just 2 min. In order to cause such a reaction, two conditions must be satisfied: zircaloy must be at a high temperature and a there has to be plenty of water. Since a large amount of water was supplied in the case of the TMI accident, the core collapsed and melted all at once.

In case of the Fukushima accident, there wasn't enough water. The reactors had to wait for a long time before enough water accumulated to cause reactions so severe as to trigger core melts and explosions. It was only after plenty of water had accumulated that a severe zirconium-water reaction occurred, leading to a core melt and a hydrogen explosion.

The process by which water was supplied and accumulated varied among Units 1, 2 and 3. That is one reason that makes it difficult to describe the Fukushima accident. That said, in the big picture, I am sure you understand that the reason the core melts occurred was the same as in the TMI accident: a severe zirconium-water reaction. This is a fact that was reconfirmed for the first time in the Fukushima accident. It is tragic that the accident occurred, but the accident will make a great contribution to the safety measures of atomic power generation in the future.

Those of you who are responsible for the future of atomic power generation must not forget two things: that a severe zirconium-water reaction causes a core to melt, and that it generates a large amount of hydrogen. These two things cause nuclear calamities.

A thing that plays an important role in the process of this reaction is the outer skin (shell) of the melted core – most likely formed by the formation of zirconium oxide – that acts like an egg-shell or the bottom of the pan. This fact cannot be discussed without referring to the PCM test and the TMI accident. Without it, the clarification of the Fukushima accident was impossible. I think God has given us humans the diagram of the molten core of the TMI accident (Fig. 1.1) as a hint for understanding the Fukushima accident.

Although I believe that I have not made any big mistakes in my explanation of the core melt, I admit that there must be many minor places in which it is lacking. While I am ready to accept any criticism, I sincerely hope that those who wish to be scientific leaders in this field spend their energy in clarifying the real identity and performance of the egg-shell, because I believe the egg-shell holds the key to the safety measures of atomic energy.

Secondly, I wish to point out that sharp hydrogen generation and the pressure increase caused thereby are the key factors in hydrogen explosions.

Since the zirconium-water reaction occurs rapidly, it generates a large amount of hydrogen gas all of a sudden, which in turn causes a sharp pressure increase. In the TMI accident, the reactor pressure increased from 9 to 15 MPa within 2 min. In case of the Unit 2 and Unit 3 accidents, the containment vessel pressure increased approximately 1 MPa. Although there is no data for Unit 1, I am sure that a similar pressure increase occurred.

This pressure increase pushed up the top lid of the containment vessel whose fastening bolts had been slackened by thermal expansions, while the hydrogen gas that leaked out through the gap produced there filled up the reactor vault, which in turn pushed up the heavy shield plug, and leaked out onto the fuel exchange floor on the 5th floor (ref. to Fig. 2.21).

In case of Units 1 and 3, the hydrogen that flowed into the fuel exchange room became an explosive gas by mixing with air, ignited due to the impact of the shield plug dropping, and caused the explosion in the reactor building.

In case of Unit 2, since the blowout panel provided on the wall of the 5th floor had been dislodged, the leaked hydrogen gas flowed out to the outside of the building through the openings of the panel. The gas was very hot because it was from the molten core whose temperature was over 2,000 °C. I suppose the flow of the hot hydrogen gas flowed like a river stream by itself, never mixing with the room air, out to the atmosphere. Thus Unit 2 caused no explosion.

That is the summary of the hydrogen explosions of Units 1–3.

The third lesson we learned is that there is a chance that a large scale core melt can be avoided if we can inject water properly.

I mentioned in above that a “low-temperature burn” caused by a small amount of decay heat can be cured with proper care.

The fuel rods that are heated into high temperatures by the decay heat are cooled by the steam flow caused by decompression boiling if the reactor pressure is reduced forcibly. Please refresh your memory. In case of Units 2 and 3, the entire core was cooled to about 150–160 °C. If water was injected instantaneously at this very moment, the low temperature zircaloy does not react with water, so that even though the fuel rods could have broken up, the rods would not have melted. Thus no hydrogen explosion could have occurred.

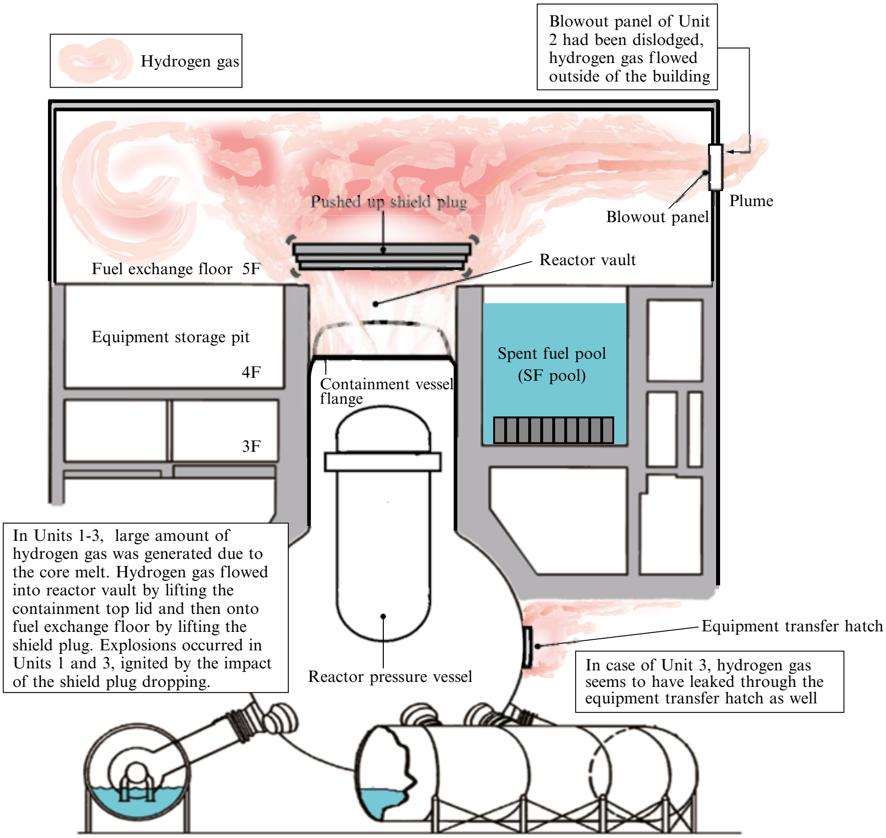


Fig. 2.21 Route of hydrogen gas leakage in case of Units 1–3 (Source: from TEPCO "Fukushima Nuclear Accident Investigation Report")

The countermeasures taken at Fukushima were correct up to the decompression boiling, but the water injection procedure was at least approximately 2 h late in all cases. That was their critical mistake. During these 2 h, the core temperature started to rise again due to the decay heat and the fuel rods became red-hot [IV]. And that's when the water was injected, so that the zirconium-water reaction occurred, leading to the core melt. It was an unfortunate missed opportunity. A delay in countermeasure turned a low-temperature burn into a high-temperature burn.

From another point of view, this means that even when the core water is depleted and fuel is at risk of melting, if decompression and water injection are done promptly and continuously, no core melt occurs even though a core collapse (breakdown of a fuel rod) may occur,. Such a measure will end in a small amount of radioactivity but no hydrogen explosion. If people who work in nuclear power generation remember this and calmly take proper measures with composure, calamities can be avoided.

Fourthly, it is important to estimate the current core status.

People seem to estimate the current status of a core differently.

I estimate that the molten fuels of Units 2 and 3 are all remaining in the reactor pressure vessels and no portion of them has leaked out to the containment vessels. As to Unit 1, a portion of the molten core has leaked out but most of it is still remaining in the reactor pressure vessel.

The reason I think that the molten cores of Units 2 and 3 are remaining in the reactor pressure vessels is that the reactor pressure vessels had some water left when the core melts occurred. Since this is the same condition as that of the TMI accident, I assume that the molten cores of Units 2 and 3 are remaining in the reactor pressure vessels same as in the case of the TMI accident. One of the reasons is that the reactor data after the cores had melted did not change much. I checked the data closely but I could not find any significant difference from those of the TMI.

The Unit 1 core is as described in Sect. 2.7. As described in Appendix 2.11, the γ-ray data at the bottom of the containment vessel measured by TEPCO in the year end of 2,012 showed that the values were larger in the areas closer to the core. This is the reason that I believe that most of the molten core still remains in the reactor pressure vessel.

Then what is the state of the core inside the cores inside the reactor pressure vessels? The TMI data gives us a clue to that question as well. I believe that, as shown in Fig. 2.13, a spherical molten part of about 40–50 cm in diameter is located in the center of an egg-shaped alloy casting of about 3–4 m in diameter and 2 m in height, and radioactive gas continues to emanate from it to this day. The gaseous substances leak out through the cracks formed on said casting, are cooled by the circulating cooling water injected from outside and thus solidify, and are deposited either on the bottom of the reactor pressure vessel or on the floor of the containment vessel.

I think it is safe to assume that said radioactive substances are very fine radioactive particulates. I suppose that some of them have formed water-soluble compounds after causing chemical reactions with water and other impurities. These are considered to have become the source of the contaminated water, as minute amounts of them move along with the movement of water from the openings of the containment vessel to the water sump provided on the underground of the turbine building.

However, we should not attempt to clean up this contamination all at once. Since an abrupt movement of water will take along with it the radioactive substances that have been settled, it could cause a very dangerous situation. It is better to leave it as is without giving it any agitation. It is not the same as environmental contamination issues relating to rain water and underground water.

Since the decay heat is down to less than 200 kW, the radioactive material leaking out of the cracks of the containment vessel is not that much. The temperature of the water remaining in the containment vessel was dropped to 30–40 °C according to a report made at the year end of 2012. Within a few years, there will be no need of cooling by water and the molten part in the middle of the egg will soon be solidified. Now we can safely say that no new incident due to heat can be expected from the radiation emission of the Fukushima accident. The state of the matter as of today has reached such a stage.

Column Possibility of the Molten Core Causing Recriticality

In case of the TMI accident, all the control rods were fully inserted into the core and they melted because the melting point of the control rods were relatively low, and they accumulated in the lower half of the thin outer skin (shell) that surrounded the molten core. Yet still no recriticality occurred in the TMI accident. This fact is evidence that the core never reached recriticality even though the control rods were unevenly concentrated in the molten core.

The core of the light water reactor consists of a large number of fuel rods, each of which is a circular zircaloy cladding tube having a length of approximately 4 m and a diameter of approximately 1 cm, containing numerous fuel pellets, and arranged in an array with a constant interval to form a fuel assembly.

Light water (water) flows around the fuel rods to remove the heat generated by the nuclear fission chain reaction as well as to moderate the neutrons that are generated by the nuclear fission chain reaction and move at high speeds. By the way, slow-moving neutrons tend to cause more nuclear fission reactions. Fast-moving neutrons generated in the fuel are moderated by light water outside the fuel and cause nuclear fissions when they return inside the fuel.

The spacing between the fuel rods is designed to cause the following cycle to occur as efficiently as possible: nuclear fission generate fast-moving neutrons → fast-moving neutrons move to light water → neutrons moderated in light water → moderated neutrons move to fuel → moderated neutrons cause nuclear fissions inside fuel → nuclear fission generate fast-moving neutrons. In other words, keeping an optimum distance between the fuel that generates neutrons and light water that moderates those neutrons makes it easier to cause a nuclear fission chain reaction. This is called the nonhomogenous effect.

When the fuel melts, the light water that moderates neutrons will be removed from the system because of the high temperature, and impurities that prevent nuclear fission reactions will be brought in. Furthermore, the core will become homogenous and lose the nonhomogenous effect that had been prepared with lots of effort to cause nuclear fissions efficiently. As a consequence, the probability of the molten core to reach recriticality becomes very small.

Although the cores and fuel rods of the BWRs in Fukushima are slightly different from those of the PWRs at TMI, their probability of reaching recriticality is as small as that of TMI. Of course, it goes without saying that TEPCO who is in charge of the control is responsible for making sure to provide criticality control for the molten cores by setting up an extreme condition (for example, assuming coagulation by some kind of chemical reaction, etc.) that does not allow any recriticality to occur under any circumstance, but recriticality is not realistic and is something we do not need to worry about.

Appendices

Appendix 2.1

The reactor water level is calculated by the remaining amount of water by subtracting the lost as steam from the reactor. This calculation is a simple one so that we should be able to avoid any error using a computer.

The steam that is generated when the fuel rods are immersed totally in water is all saturated steam. As the water level drops and the fuel rods start to stick out of the water surface, the saturated steam that rises above the water level is further heated to become superheated steam and the temperature rises. It is the same phenomenon as the air being heated when one makes a campfire. As the water level of the core drops, the length of the portion of the fuel rods in the water becomes shorter, so that the water evaporation amount reduces, and the degree of overheating of the steam increases proportionately. In other word, the heat used to be used for evaporation is now used for increasing the steam temperature. Therefore, the temperature of the upper portion of the core rises as well.

Let us now think about the condition where the water level lowers almost to the bottom ends of the fuel rods. Since the lengths of the portion of the rods that are immersed in water are so short, almost no steam is generated. On the contrary, the amount of superheated steam increases and the temperature of superheated steam becomes high and the fuel temperature in the upper portion of the core also rises. The computer does not make any mistake in the computation up to this point.

However, there are few points that are not well thought through in this computation. When the water of the core is lost and replaced by steam, the space occupied by steam increases and the γ-rays generated in the fuel rods disperse to the outside of the core, hence reducing the heating of the core. In addition, the amount of heat that is lost as radiant heat increases dramatically. It seems to me that these two considerations are not sufficiently modeled in the accident analysis computational code. Since the demonstration experiments have not covered that far, there is no proof for them.

Because of their physical nature, γ-rays pass more easily pass through the core which has lost water, enter the reactor pressure vessel and other structural members and generate heat.

Since roughly a half of the decay heat is the heat generated by γ-rays, the calculation done by assuming the decay heat is used for steam generation is overestimating the steam volume to be 20–30 %. I suppose you would agree with me that the more the water level drops, the more a correction is required for such an estimation, if you imagine a condition where the water level drops below the bottom of the core.

Next, the radiant heat. When the fuel rod temperature rises to well over 1,000 °C, we have to think about their radiant heat's effect on structural members of relatively low temperatures such as the reactor pressure vessel. Since the radiant heat is emitted in proportion to the fourth power of the temperature of an object that emits heat, the emission increases dramatically with the temperature. I assume that this radiation heat calculation is not modeled with sufficient accuracy either.

Considering all of these, I assume that, by the time the water level comes down to about the middle of the core, the amount of decay heat transmitted to water decreases dramatically, resulting in the drop of the amount of evaporation, so that the speed of water level drop in the reactor should slow down. However, there is no mention of such computation consideration in the report, and the water drop curve shown in the analysis is straight. Contrary to the evaluation of an imaginary safety analysis, such a correction is mandatory in an accident analysis that pursues the truth.

Appendix 2.2

Assuming the blowout pressure of the safety relief valve is approximately 7 MPa, the specific volume of 7 MPa saturated steam is 0.0274 m^3/kg, while the specific volume of saturated water is 0.00135 m^3, so that the volume ratio of steam vs. water becomes about 20.

As the lowering speed of reactor water (saturated water) level is 4.5 cm/min, the flow speed of the saturated steam is 90 cm/min, i.e., 1.5 cm/s.

Appendix 2.3

Why Did the RCIC Pump Stop?

The question will be answered when the RCIC pump is taken out and disassembled. However, I can guess why.

The reactor water level was maintained at the height of plus 6 m above the core for more than 2 days. This water level is about the same height as that of the steam-water separator. The RCIC pump that had lost the control capability due to the loss of DC power was still operating with the steam energy produced by the decay heat. However, as the water level of the reactor rises unnecessarily, the separation between steam and water deteriorates, and humidity starts to mix in the driving steam. When water mixes in steam, the water drops would pound on the turbine blades just like the sand blasting and damage the blades. If this condition continues, the impeller loses its balance and finally fails. The reason that the reactor pressure started to increase about 2 h before the pump finally stopped seems to be that the pump rotation became abnormal and did neither consume enough steam nor supply enough water.

In the modern technological world we live in, once the mechanical systems lose their control capabilities, they are doomed. As they are then forced to operate under conditions different from their designs, they will suffer malfunctions and damage. Incidentally, while the safety devices such as RCIC were designed based on the premise of 8 h of power loss, the RCIC pump of Unit 2 worked for 3 days. The safety devices worked more than they were designed for. I think this is a proof of excellence of Japanese technology in general, not just nuclear engineering.

Appendix 2.4

Evaporation Amount of Water by Decompression Boiling (Autonomous Boiling)

At 6:02 p.m. on March 14, the operating staff lowered the core pressure forcibly. The reactor pressure had dropped sharply from about 8 MPa to about 0.4–0.5 MPa. Due to this pressure drop, the water in the lower part of the reactor began violent autonomous boiling. Autonomous boiling is a boiling phenomenon that occurs when the saturation temperature drops with a pressure drop. Let me show you by a ballpark calculation how much water will be lost because of autonomous boiling.

The reactor pressure was about 8 MPa when the safety relief valve was opened. The heat quantity of 8 MPa of saturated water is approximately 1,320 J/kg. If it drops to 0.4 MPa, the heat quantity of the saturated water drops to about 630 kJ. The difference of 720 kJ of heat is to be used for autonomous evaporation. When 0.4 MPa water boils, the heat quantity of the steam is approximately 2,740 kJ. If X% of water is autonomously boiled, the equation is:

$$1{,}320 = 600(1 - \mathrm{X}) + 2{,}740\mathrm{X}$$

so that X = 720/2,140 = 0.3, i.e., it is 30 %. In other words, 30 % of the water remaining in the reactor will be lost by decompression boiling.

As I described in Chap. 1, a BWR pressure vessel is thick and long. There is about 100 tons of water beneath the core. Therefore, it means that 30 % of this, i.e., approximately 30 tons of water, was evaporated.

If I may add a little more, since the pressure is as low as 0.4 MPa, the steam volume increases to about 20 times. The speed with which the steam flows through the core is approximately 0.5 m/s, even if the pressure reduction time is 30 min. This steam flow speed is a sufficient speed to cool the fuel rods.

The core fuel that had been in the sauna bath condition was cooled sharply, although for a short period of time, by autonomous boiling. It requires the help of a computer to calculate accurately how much it is cooled, but I believe that the answer is close to the saturation temperature by the ballpark calculation.

Appendix 2.5

If we assume the hydrogen temperature is 2,000 °C at the core melt time, the weight of the hydrogen gas of 16,000 m^3 is:

$$16{,}000 / (22.3 / 2) \times 293 / 2{,}273 = 185 \text{ kg}$$

i.e., approximately 200 kg.

Appendix 2.6

Reactor Water Level Gauge Error After Decompression Boiling

Please look at Fig. 2.22. In "A. Normal operation" shown on the top left corner, we see that the reactor water level can be measured through the pressure difference if the water level inside the reference condensing water chamber is normal.

In "B. After decompression boiling," the reactor's water level is the same as A, but we can see that the pressure difference drops if the water level in the reference level gauge drops such as due to decompression boiling.

In "C. Decompression boiling + water level is below lower piping," the water level in the reference condensing water chamber is the same as in B, the measured water level is not affected by the actual water level change and always indicates a value higher than the actual water level if the reactor's water level drops below the lower side water level piping.

In addition to those above, if the decompression is significant, the weight density change of the reactor water cannot be neglected and should be incorporated.

Appendix 2.7

Zirconium-Water Reaction Where There Is Insufficient Water

Let me explain how I imagine zirconium-water reaction takes place when there is an insufficient amount of water – the so-called "oozy reaction."

The sodium-air reaction that gave me a hint was a reaction between liquid and gas. When the surface film was broken by the generated gas, showing flames, the outside air infiltrated into the inside of the film via the crack. The moisture content contained in the air reacted with sodium and produced hydrogen, which in turn became the gas to cause the next crack. This slow reaction continued again and again.

The oozy reaction is essentially a reaction between high temperature zirconium and water. When a red-hot fuel rod is broken into pieces when it meets with cold water, hot zirconium agglomerate (or liquid) comes into contact with water to generate an enormous amount of oxidation reaction heat locally, which in turn melts uranium dioxide in the vicinity or produces an alloy with zirconium, and causes the fuel pellets that were originally discrete pieces to weld together. During this process, the surface in contact with water must have formed a zirconium oxide coating, even though it might not be perfect.

I believe that this imperfect coating increased its size each time the reaction occurred, and eventually produced a shell like a cooking pot that protects its contents from coming into contact with water. This is the initial stage of the oozy reaction and I suspect that it was most likely formed on the core plate. Therefore I believe that the molten substance contains lower melting point stainless steel as well.

As a relatively large amount of heat was generated by this first reaction with water, the water level dropped by evaporation and I suppose that the pot contained

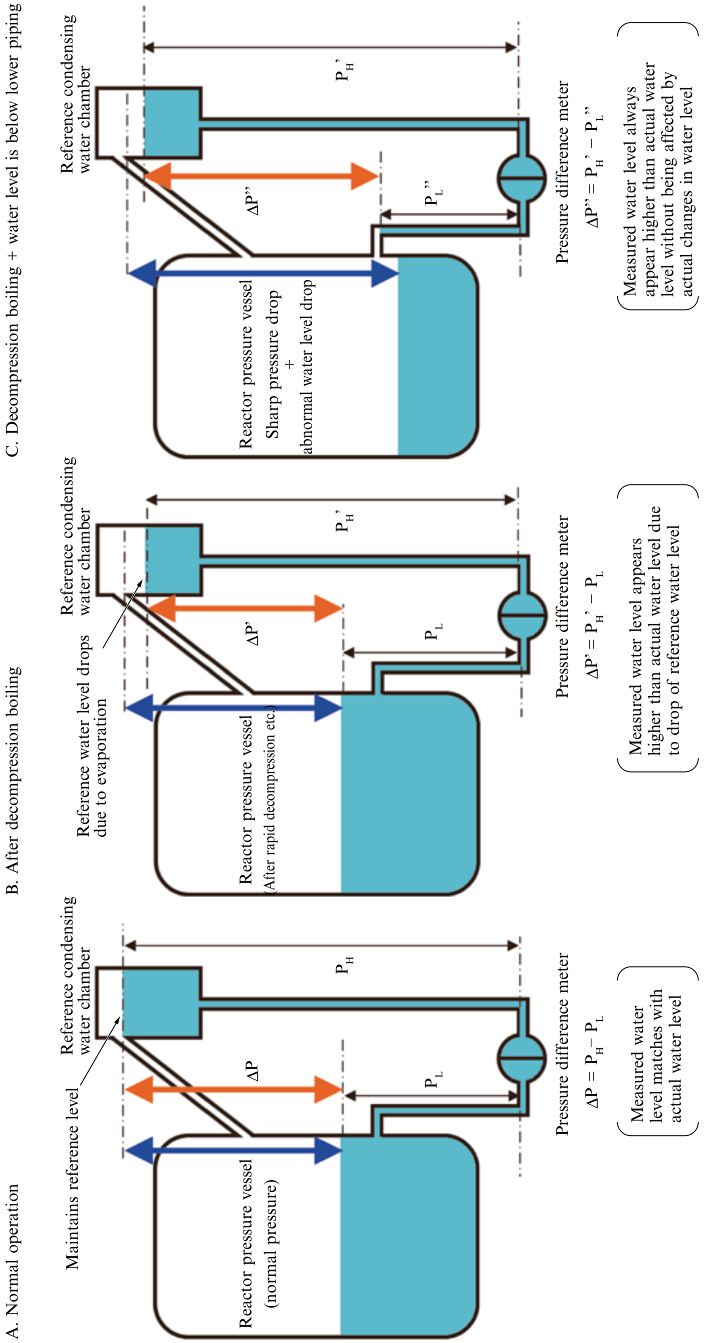


Fig. 2.22 Reactor water level gauge error after decompression boiling (explanatory diagram)

molten fuel rods and other things to a certain degree. The surface of the molten substance was covered by a thin oxide film and a small amount of reactions must have continued as the surrounding steam flowed in each time hydrogen gas was discharged. This is the oozy reaction. I believe that, during the oozy reaction period, the majority of the fuel rods must have stood upright on the pot made of the molten substance although they may be slightly bent or broken, and that the core as a whole had not collapsed.

The pot acts as a shield against heat. The fuel rods in the pot are heated by the decay heat and the heat of the oozy reaction and gradually melted from the lower part. As a result, the portion of the core exposed above the water was eventually swallowed by the rest as time passed.

On the other hand, the water level of the coolant water recovered over time, eventually exceeding the edge of the pot. The second reaction started in such a condition.

In addition to the fact that the temperature of the mixed molten substance itself had become higher, the water had increased so much as to go over the edge of the pot. As a result, the second reaction was huge, and melted the core.

That is what I believe happened in the oozy reaction.

Appendix 2.8

Temperature Calculation Related to Radiation Heat

An accurate calculation of radiation heat can be very complicated. However, its feature is that the heat exchange is conducted in proportion to the difference between the 4th power of the absolute temperatures of the heat-emitting and -receiving objects.

Let us assume the surface area of a mixed molten substance with a temperature of 2,000 °C (2,270°K) is 1 (half of the normal core surface, assuming that it is collapsed to a certain degree), the total surface area of the core shroud covering the core, upper part core plenum, and the top guide and core plate is 4, and the total surface of the reactor pressure vessel (approximately 20) and other internal components is 50. We will now make a rough calculation, disregarding the surface absorption rate and radiation shape factor, and assuming that the heat among the core, shroud and pressure vessel have reached an equilibrium state.

Paying attention to the fact that the radiation heat is proportional to the 4th power of the absolute temperature, and assuming the temperature of the shroud etc. is A°K, the equilibrium equation is as follows: since "$2{,}273^4 \times 1 = A^4 \times 4$," the equilibrium temperature is "A = 1,600 K (approx. 1,370 °C)."

The temperature B of the reactor pressure vessel is: since "$1{,}600^4 \times 4 = B^4 \times 50$," "B = 850 K (approx. 570 °C)."

Appendix 2.9

As the initial assumption for the calculation, we assume the temperatures of both the reactor pressure vessel and the core internal structural members are 250 °C.

Assuming that they are all made of steel, we assume the specific heat of 0.54 kJ/kg °C, the melting point of 1,500 °C, and the heat of solution of 272 kJ/kg.

The heat quantity required for the reactor pressure vessel (340 tons) and the lower half of the internal components (50 tons) to be heated to 550 °C is:

$$(340+50)\times10^3\times(550-250)\times0.54=6.3\times10^7\,\text{kJ}\,(17\,\text{MWh})$$

The heat quantity to melt the upper half of the core internal structural members is:

$$50\times10^3\times(1500-250)\times(0.54+272)=4.7\times10^7\,\text{kJ}\,(13\,\text{MWh})$$

It will require a heat quantity of approximately 30 MWh.

Appendix 2.10

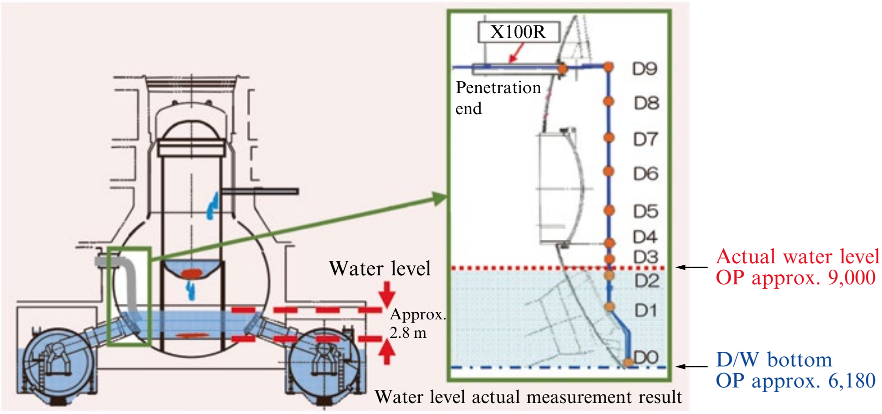
Asking the fire station about the typical shutoff pressure (pump pressure when the discharge quantity is zero) of a typical fire engine, I got the following answer:

"Although it varies with vehicle types, the typical pump vehicle's pump discharge pressure is approximately 0.85 MPa at most, and the nozzle pressure is 0.4 MPa. The discharge rate is 24–40 cubic meters per hour."

We do not know how the fire engine was connected at the time of the accident, but since the containment vessel pressure during the time period before the vent was opened was 0.8 MPa, it was close to the pump shutoff pressure. There is no question that the pump discharge rate was very small. When they opened the vent, the containment vessel pressure dropped to around 0.5 MPa so that the seawater injection rate increased substantially.

Since the flow resistance up to the nozzle varies with the length of hose connected to the pump, the discharge rate varies with it. Since the length of the hose cannot be assumed to have been as short as that when fighting fires, we guesstimate that it was 30 m^3/h. This makes the time until explosion to be around 1 h.

That means that the remaining 50 m^3 of seawater was pushed over a period of as long as 10 h, fighting the pressure of 0.8 MPa, which was close to the pump shutoff pressure (pump pressure when the discharge quantity is 0). The discharge quantity was 5 m^3/h in this case.



Measuring point	Height from D/W bottom	Radiation level data (Sv/h)
Penetration end	8,595	Approx. 11.1
D9	8,595	9.8
D8	Approx. 7,800	9.0
D7	Approx. 6,800	9.2
D6	Approx. 5,800	8.7
D5	Approx. 4,800	8.3
D4	Approx. 3,800	8.2
D3	Approx. 3,300	4.7
D2-water surface	Approx. 2,800	0.5
D1	—	—
D0	0	—

measured radiation level

Fig. 2.23 Unit 1 DW radiation and water level measurement data (Source: from reference materials of "TEPCO Intermediate-Long Term Countermeasure Meeting/Administration Meeting (Dec. 3, 2012)")

Appendix 2.11

Many people seem to believe that the molten core of Unit 1 flowed out of the reactor pressure vessel almost completely. However, I think the majority of it still remains in the reactor pressure vessel.

The reason can be found in Fig. 2.23, the result of the measurement made on December 3, 2012 by TEPCO as a preparation for the decommissioning measures. As the figure shows, the radiation level of the lower part of the containment vessel reduces to one-third as the measuring point lowers from D-9 (a point close to the bottom of the reactor pressure vessel) to D-3 (approximately 5 m below D-9), in other words, as the measuring point moves away from the bottom of the reactor pressure vessel.

The radiation is stronger at the bottom of the reactor pressure vessel than at the lower part of the containment vessel. This proves that the molten core still remains in the reactor pressure vessel.

However, we are not sure how much remains. Judging from the course of events, as well as from the temporal speed of the egg-shell formed by the mixed molten substance, I assume that about a half of it still remains inside. The above was written based on that assumption.

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