

## TECHNICAL REPORT: FUKUSHIMA ACCIDENT SUMMARY (AUG. 19, 2011)

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### ABSTRACT

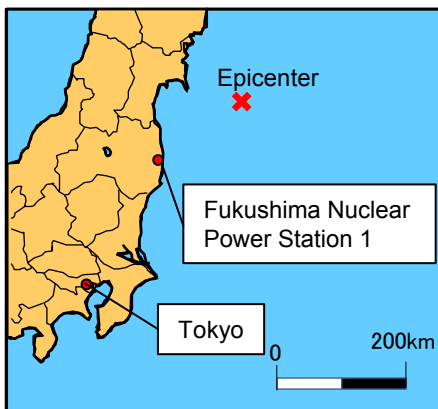
On March 11th, Tohoku Pacific Earthquake of magnitude 9.0 hit northeastern Japan. Approximately half an hour later, a series of Tsunami waves started attacking the coast taking down buildings, structures, automobiles, trees, and almost anything that they found in their ways. Over 15 thousand human lives were taken (as of August 8th) and the count is still rising.

The earthquake and tsunami caused unprecedented accidents in six units of Boiling Water Reactors (BWR) in Fukushima Nuclear Power Station 1, operated by The Tokyo Electric Power Company, Incorporated (TEPCO). This report, based on published information, summarizes the causes and processes of these accidents.

### 1. INTRODUCTION

The accidents at Fukushima Nuclear Power Station 1, now ranked at International Nuclear Event Scale (INES) Level-7, the worst, were triggered by natural phenomena, an earthquake followed by tsunami waves. Figure 1 shows the location of the power station and where the earthquake epicenter was.

The news, especially after the first hydrogen gas explosion on March 12, sent shockwaves throughout the world. USA, France and other countries offered aid in controlling the ongoing accident, whereas many foreign governments also advised their people to leave the area. As the accidents progressed, anti-nuclear movement roared over the world. The German government went as far as announcing they will cease nuclear power generation by 2022, whereas Russia and China seem to continue with their current plans [1].



**Figure 1 Location of Fukushima Station 1**

Whether to abandon the technology or to continue with it, it is absolutely necessary to find out how the accident events progressed and what caused them. While formal investigation will take months before it is finalized, mainly due to high radiation hindering investigation into the plant status, we can draw conclusions and unveil highly likely course of events from what are known so far.

The following Section 2 explains the disaster over the entire nuclear power station. In Section 3 we will take a close look into each of the 6 units of BWRs. We conclude our report in Section 4. Note that as the radiation level decreases in the future, we may find evidence that contradicts our current explanation.

### 2. EARTHQUAKE AND TSUNAMI

#### 2.1 Earthquake

At 14:46 on March 11, the 2011 Tohoku Pacific Earthquake hit the ocean at about 80 miles off the shore of northeastern Japan. Its magnitude was 9.0. All the reactors of Fukushima Nuclear Power Station 1 Unit-1, 2, and 3 (F1, F2, and F3) scrambled to fully insert all the control rods. Meanwhile, F4/5/6 were in their periodic maintenance stages.

The earthquake partially damaged or completely failed every equipment to receive external electric power for F1/2/3/4. The equipment were designed to the lowest seismic standards, which is the current Japanese licensing requirement. The earthquake also took down the steel tower for external power supply to F5/6. If this power line was alive, F1/2/3/4 reactors could have survived for several days after the earthquake, and we possibly would have found a solution to provide cooling within this period.

After shutdown, the emergency Diesel Generators (DG) started automatically. The basic design had 2 DGs for each reactor.

## 2.2 Tsunami

Then, a huge 14-15 meter tsunami attacked the coast at 15:27 followed by a series of tsunami waves until 15:41 on the same day. The tsunami flooded all but one DGs (Figure 2). All DGs were installed in the basement of turbine buildings except one in the reactor building that survived. The reactor buildings are believed to have withstood the tsunami. On the other hand, seismic design level of turbine buildings against earthquakes is the lowest. Why the manufacturers installed the DGs in the basement is unclear. As a hindsight, they had to design correctly. Among all DGs, 3 were air-cooled and one of the air-cooled ones was installed in the reactor building of F6. This was the only DG that survived the tsunami, and it saved F5/6.

At 15:41, all the other DGs were lost, and F1/2/3 had Station Black-Out (SBO, Loss of all AC power). Some of the batteries survived at F2/3/4, however, they were designed for controlling the cooling pumps and not their operation. The core cooling function, therefore, was basically lost for F1/2/3, and the fuel pool cooling function was also lost for F1/2/3/4.

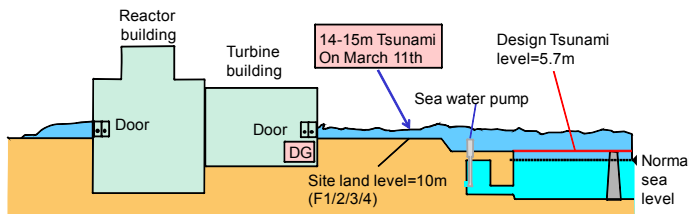


Figure 2 Elevation level of Fukushima facilities [2]

Another critical damage by the tsunami was its attack to the ocean-side facilities which were essential for providing the ultimate heat sink. If the plant had electric power available (either external power or DG), the decay heat from the nuclear fuel in the reactor would have been transferred to the water in the suppression chamber ("Wetwell torus" in the following figure).

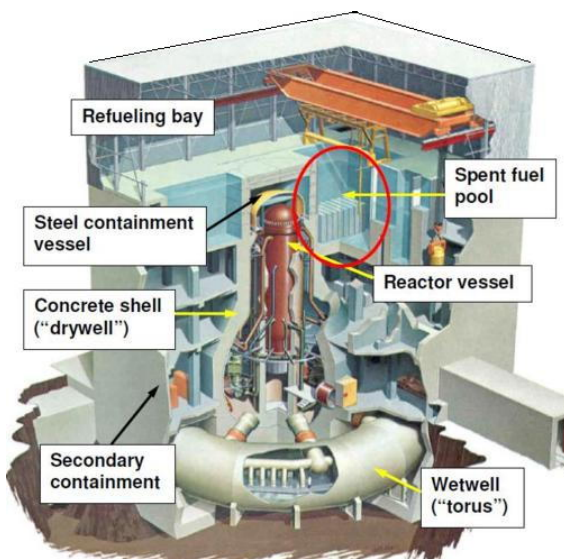


Figure 3 Mark-I containment building [3]

The heat transferred to the 2,000 to 3,000 tons of water in the suppression chamber would then have to keep moving on elsewhere, and its destination normally is the sea, the ultimate heat sink.

Since the tsunami had destroyed most of the sea-water cooling systems as Figure 4 shows, it was clear that the core cooling function would completely be lost sooner or later.



Figure 4 Sea-water cooling systems were destroyed [4]

## 3. EVENT SEQUENCE WITH REACTORS 1 THROUGH 4

This section looks at largely damaged units 1 through 4 and explain the sequence of events with them. Units 5 and 6 that escaped severe damage are briefly described at the end of this section.

### 3.1 Fukushima-1 Reactor

#### 3.1.1 F1 Melt-down process

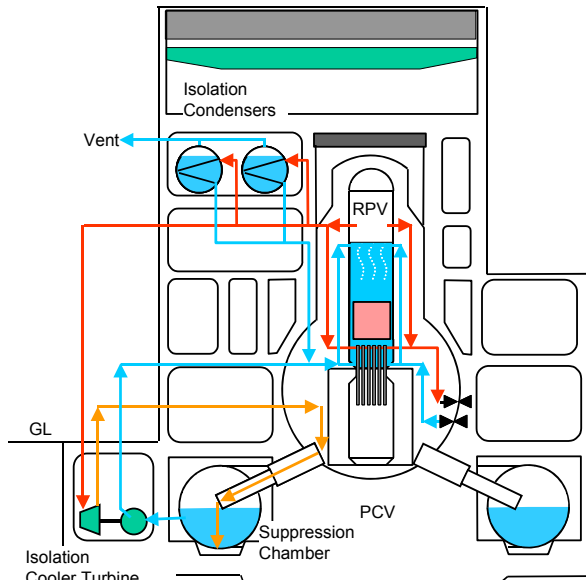
**March 11, 14:52:** Although all AC power were lost, the Isolation Condenser (IC) started. IC, installed on the 4th floor of the reactor building, does not require electricity for circulating cooling water (Figure 5). How long the IC worked remains unknown. Its designed running time was 8 hours, however, batteries in the basement of the turbine building for controlling IC were also hit by the tsunami, and our guess is that TEPCO operators repeatedly turned the IC on and off several times for several hours.

This core cooling function with intermittent operation of IC was insufficient, and the fuel temperature went up to start fuel failure.

**21:51:** High radiation level (290milli-Sievert/hour: mSv/h) was measured in the reactor building and workers were not allowed in the building. We presume that this high radiation was an indication of fuel cladding tube cracking and release of radioactive gas from the fuel to outside of the containment, however, the leak path is not clear.

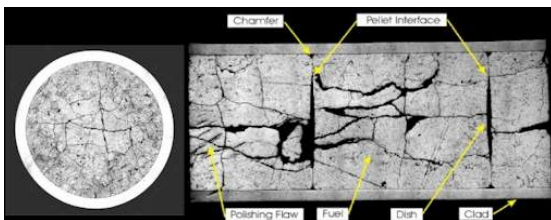
**March 12, 00:00:** TEPCO decided to apply Primary Containment Vessel (PCV) venting.

**01:00:** PCV pressure reached 0.6MPa (Mega-Pascal). The “Rupture disk” for PCV venting was designed to break at 0.55MPa. So, after this point in time, PCV venting was available (See the description in Section 3.1.2 at 10:17).



**Figure 5 IC system with F-1**

**01:48:** Finally, the IC stopped, and water level decreased. We presume that the core degradation (core damage) began at this point when fuel cladding temperature increased to 1,200deg.-C, and zirconium oxidation of cladding tubes began. Fuel cladding tubes collapsed, and high temperature fuel pellets fell to the bottom of the Reactor Pressure Vessel (RPV). Fuel pellets, after being irradiated in the core, crack into fragments and particles as Figure 6 shows.



**Figure 6 Sections of Used Fuel Pellet [5]**

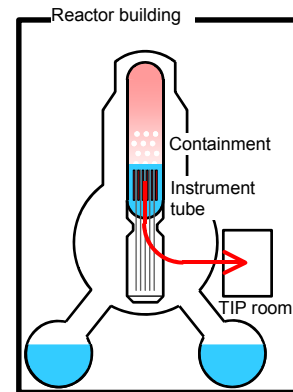
Also, the chemical reaction of  $(Zr + 2H_2O = ZrO_2 + 2H_2)$  generated a large amount of hydrogen gas.

**02:45:** RPV pressure decreased from 7.0MPa to 0.95MPa, on the other hand, PCV pressure increased to 0.95Mpa. This means that RPV broke, and its pressure dropped to the same with PCV.

#### *Where did the RPV Break?*

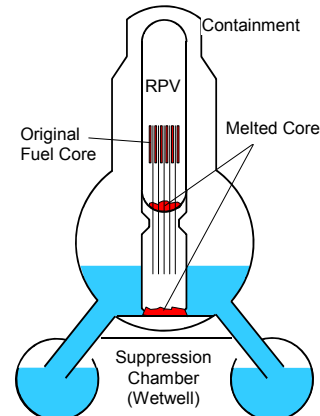
Very high radiation was observed in the TIP (Traversing In-core Probe) room of F1 (Figure 7). Oak Ridge National Laboratory (ORNL) reported that the instrument guide tube is the weakest point at the bottom of RPV [6]. So, we estimate that

several instrument guide tubes were broken, and some portions of fuel pellets fell down to the bottom of PCV through these holes. Small portions of fuel pellets reached the 1st floor of the reactor building. That is, PCV was also broken.



**Figure 7 Fuel melt-down path**

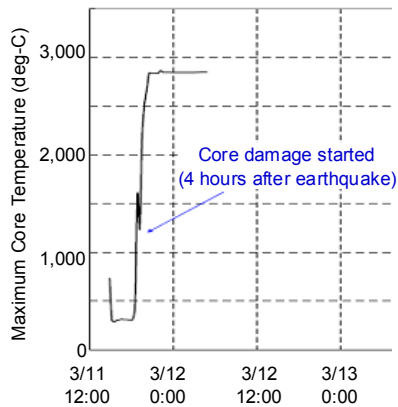
New York Times, in its April 6th issue [7], reported information from NRC. The article with the figure described that fuel fell down to the bottom of RPV in the form of fragments and particles of fuel pellet (Figure 8). Since the bottom of RPV was broken, fuel fell further down to the bottom of PCV. We believe that this is the current situation with F1/2/3. Water level within PCV in the figure is our estimate.



**Figure 8 Fuel melt-down status[7]**

**05:46:** Fire-engines injected fresh water. (14-hours without core cooling, if IC did not work.)

2 month later, TEPCO issued a report of calculation results. If IC did not work, 100% of the fuel pellets would have reached 2,800deg.-C during the night of March 11th, and all fuel would have dropped to the bottom of RPV. The melted core then broke the PCV. This is a real “Melt-down”. Meanwhile, TEPCO says that F1 shows some positive pressure values in RPV and PCV, and this means the hole is not big. This is a mystery, and no one has explained the phenomenon yet. We presume that there was some contribution of IC, as well as some cooling by the water at the bottom of RPV, and that is why there is no big hole at the bottom of RPV.



**Figure 9 F1 max. fuel temperature [8]**

**08:30:** 3 months later, Government released a very important piece of information. At 08:30 of March 12th, Te(Tellurium)-132 and its daughter Iodine-132 were observed 7km away from Fukushima reactors. Vaporizing temperature of Te is about 988deg.-C, and this was an evidence that the temperature of fuel pellets reached over 1,000deg.-C. The reason why the Government did not immediately open this information is not clear. If this news was open on March 12th, the following remedies might have been better, or at least we could have recognized the status of the reactors correctly.

### 3.1.2 F1 PCV Venting

**March 12, 10:17:** PCV venting was tried (wetwell vent)

TEPCO had to open 2 valves to vent after the PCV pressure reached the rupture disk set-point. One of the valves was motor-operated (MO), and the other air-operated (AO). It took TEPCO as long as 9 hours to start the venting due to difficulty in opening these 2 valves from loss of electricity and high-radiation in the area. There were 2 routes for venting, but TEPCO basically applied venting from the wetwell. This so called wet-venting traps most radio-active material in the wetwell water and largely reduces release of radio-activity.

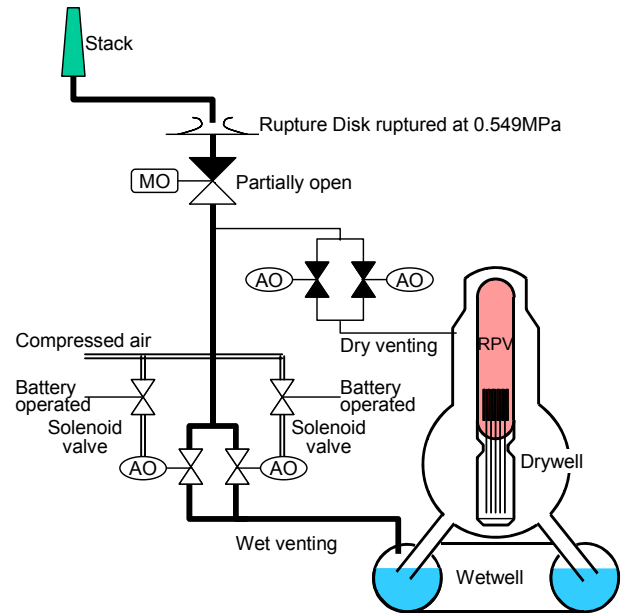
**14:30:** PCV venting succeeded. (Pressure decreased)

The purpose of PCV-venting is to release excessive pressure in PCV to maintain its integrity. If, however, high-temperature fuel drop to the PCV bottom, its heat will break the PCV. So, PCV-venting is not a key issue when core cooling function is lost.

Meanwhile, PCV-venting releases radio-active material (Iodine, Cesium, Strontium, Tellurium etc. which usually are enclosed within the PCV) to the atmosphere through a very tall chimney (stack). The radio-activity from such venting will result in a widely contaminated area. Actually, this is what happened in Fukushima prefecture.

In any case, the time-chart shows that PCV-venting became available after the fuel was already half-melted. So, PCV-venting could not have saved the PCV integrity.

**14:53:** Fresh water injection stopped. (Cause is not clear).



**Figure 10 F1 vent route [9]**

### 3.1.3 F1 Hydrogen Explosion

**March 12, 15:36:** There was an explosion at the top of F1 reactor building. Concrete panels on the sidewalls of the top floor and top-roof are intentionally made thin. They are designed to rupture in case of pressure buildup in the building after an accident. The rupture keeps integrity of the whole building. If these walls were thick, an explosion with a large energy could destroy both the building and PCV. We tried to find veteran GE designers to hear why they adopted this design, but no luck here so far.

We believe all the safety experts recognize that in case of a severe accident, a large amount of hydrogen gas is generated at the reactor core. Since PCV of BWR is filled with nitrogen gas, the possibility of hydrogen explosion might have been overlooked. For example, there is no description on hydrogen explosion within the reactor building in a famous severe accident report by US-NRC [10].

The hydrogen explosion gave a big impact to the public throughout the world because it looked like an explosion of the reactor itself. Of course, it was not.



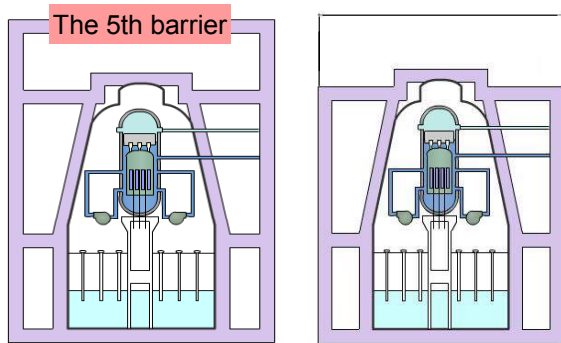
**Figure 11 Hydrogen explosion of F1 [4]**  
(The stacks are 120 meters tall)





**Figure 12 F1 Top floor was destroyed**  
(March 12th, released by TEPCO)

As we explained above, the walls and roof of the top floor were designed thin. The left-side illustration in Figure 13 was shown in a Government web site, where it said that the reactor building wall is 2 meter thick, and acts as the 5th barrier. This explanation was misleading and the page was deleted from the website after the accident. The illustration should have been like the one on the right side in Figure 13.



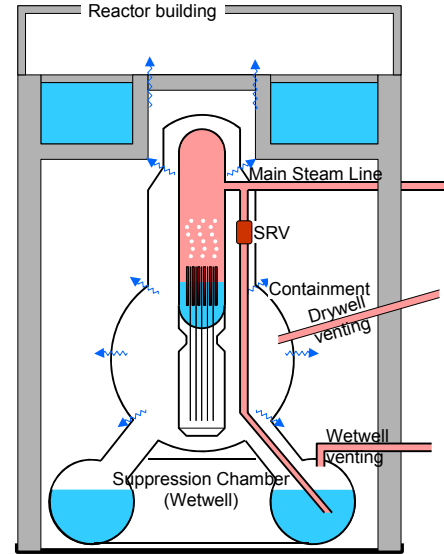
**Figure 13 Actual Thickness of the 5th Wall**

*Where did hydrogen escape from?*

One of the mysteries is the route of hydrogen from the core to the top of the reactor building. This has not been explained so far. At least, the hydrogen gas generated at the core moved from the RPV to the wetwell through the SRV(Safety-Relief Valve)s, but was not contained in the wetwell, because hydrogen is not soluble in water. So, the hydrogen gas made its way to the upper wetwell and drywell. We believe that venting of PCV was not a cause of hydrogen escape to the reactor building, because the vented steam and hydrogen gas went directly to the atmosphere through the stack.

One cause of the hydrogen escape is that the PCV is not tightly sealed, and there are always some small leaks at pipes or flanges (Figure 14). Overpressure might accelerate this phenomena.

Another cause is the small size of hydrogen gas molecules. They can easily penetrate PCV walls.



**Figure 14 Hydrogen escape route**

**19:06:** Sea water injection started. This means the reactor can no longer be used for power generation in the future, and Fukushima-1 was lost.

Since there were holes at the bottom of RPV, and somewhere in PCV as well, the injected water escaped to the basement floor of the reactor building.

In April, TEPCO tried to inject more to the PCV and fill it up with water. As was addressed by the New York Times on April 6th, filling water to PCV would cause a new threat of destruction of PCV by its weight [7]. Also, it is physically impossible to cool RPV from outside, because temperature difference is very small. A Japanese newspaper addressed this issue including comments by one of the authors, Yoshioka. But, in reality, almost all water went out through holes in RPV and PCV, and TEPCO gave up the idea of filling up the PCV with water.

Radio-activities in the water in the turbine and reactor building basements were measured. The measurements detected Iodine-131, Cesium-134/137 and low level Strontium-89/90. Vaporizing temperature of Strontium is 1,382 deg.-C. The results indicate that the fuel could have reached above 1,400deg-C. Strontium-89 decays from gaseous Krypton-89 (with half-life of 3min.), and Strontium-90 from Krypton-90 (with half-life of 0.5min.), thus uncertainty remains with how high the fuel temperature reached.

**Table 1 Radio-activity in water of F1 buildings**

Nuclides	Turbine bldg (4/13)	Reactor bldg (5/27)
Iodine-131	0.03	0.03
Cesium-134	0.12	2.50
Cesium-137	0.16	2.90
Barium-140	Not detected	Not detected
Strontium-89	57e-6	Not measured
Strontium-90	21e-6	Not measured

unit: million Bq (Becquerel)/cc

These results also suggest that water in the RPV went to the PCV, and then to the basement of the reactor building. Penetration holes between reactor building and turbine building would allow the water to reach the basement of the turbine building, as Figure 15 shows.

Nuclear fuel material such as Uranium or Plutonium has not been found in the above water, however, since fuel fragments fell to the damaged PCV with probable holes, they could go out with water. TEPCO is now operating the water circulation system to prevent sea contamination.

Figure 16 shows the event chart with pressure and water level of F1 for the first several days.

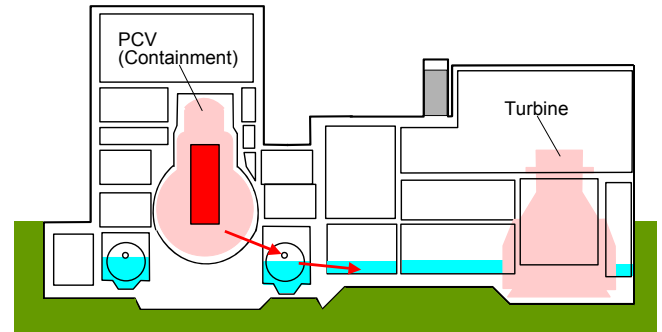


Figure 15 Water path

### 3.1.4 F1 Spent Fuel Pool

As for the spent fuel pool, the situation is not clear, because the roof panel fell down into it, and we can not get clean images of the fuel there. The pool is at least being cooled.

### 3.1.5 F1 Conclusion

We conclude that F1 is in “half melt-down” status, i.e., fuel pellets reached 1,400deg.-C or higher, but less than 2,800deg.-C. Hot fuel fell to the RPV bottom, broke holes there to fall further to the bottom of PCV. PCV is also damaged by hot fuel.

The situation with the spent fuel pool is not clear.

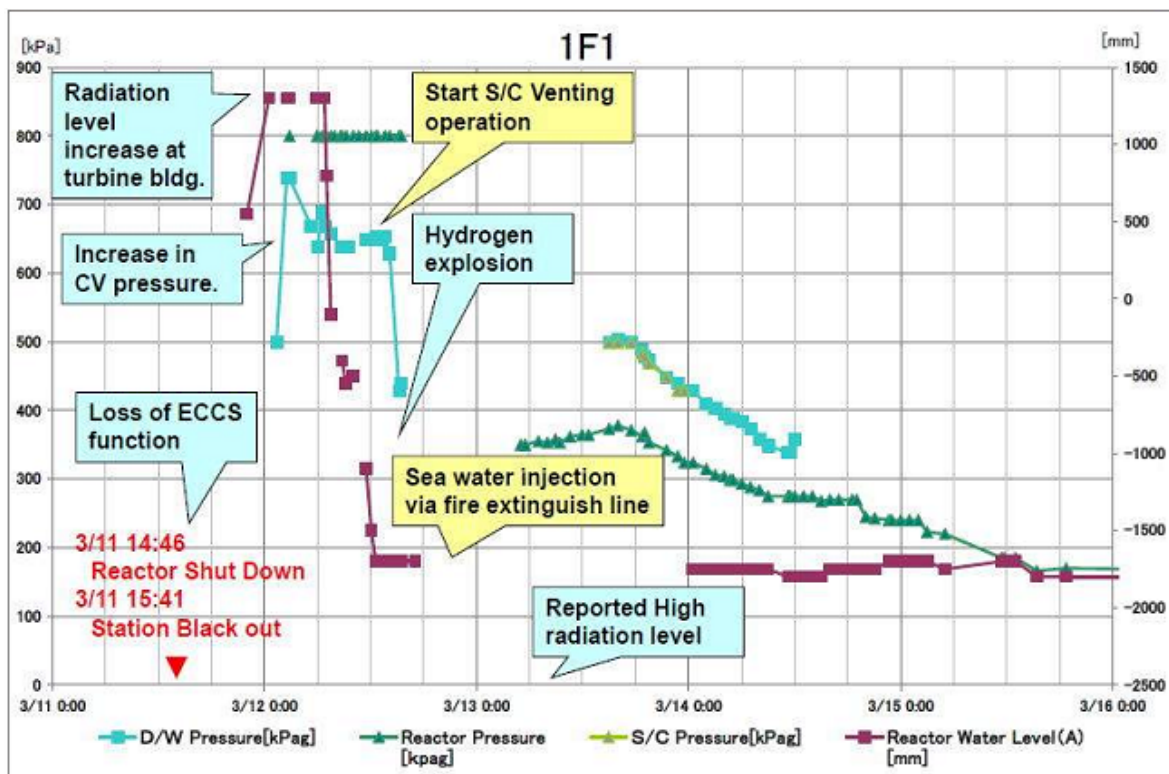


Figure 16 Trend Data of F1 up to March 15 [4]

## 3.2 Fukushima-2 Reactor

### 3.2.1 F2 Melt-down Process

**March 11, 14:50:** Immediately after the earthquake, Reactor Core Isolation Cooling System (RCIC) was manually started. RCIC is an emergency pump system driven by a steam-turbine with steam from the reactor, and RCIC feeds water to the reactor core either from the storage tank or the suppression chamber. Battery to control RCIC was alive after the tsunami.

This RCIC saved F2 during the initial SBO stage, but heat accumulation in the suppression chamber could not be removed because the tsunami had destroyed the sea-water cooling system.

**March 12, 04:20:** RCIC started to use water from the suppression chamber due to lower water level in the storage tank.

**March 13:** Situation remained the same.

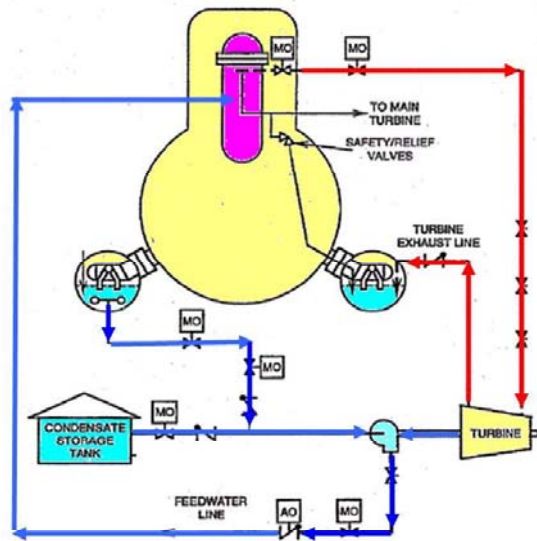


Figure 17 F2 RCIC [11]



Figure 18 Opened F2 Blow-out Panel  
(April, 11th, by TEPCO)

**March 14, 11:00:** Blow-out panel dropped. This panel is installed to release overpressure, in case it happens in the top floor area of the reactor building (Figure 18). This panel occasionally drops just by earthquakes or some shocks. So, the hydrogen explosion at the top floor of F3, which occurred at the identical time, may have caused it.

**13:25:** RCIC stopped. The cause is not clear. Batteries may have been used up, or maybe the suppression chamber temperature exceeded its limit.

As a result, we presume that the core started to degrade. Fuel cladding temperature rose to 1,200deg.-C, and zirconium oxidation started on the cladding tube. The tubes then collapsed and high temperature fuel pellets fell to the bottom of the RPV. Also, a large amount of hydrogen was generated.

**16:34:** SRVs opened. Reactor pressure decreased from 7Mpa to 0.5Mpa.

Sea water might have been injected at this point, but we could not find a clear statement about this injection.

**19:54:** Sea water injection was confirmed (7-hours of no core-cooling).

RPV pressure finally decreased to zero before March 16th. This means that RPV broke sometime between 14th and 16th, due to hot fuel at its bottom.

### 3.2.2 PCV Venting

Since PCV pressure was always lower than the break point (0.55Mpa) of the rupture disk, F2 never had PCV venting.

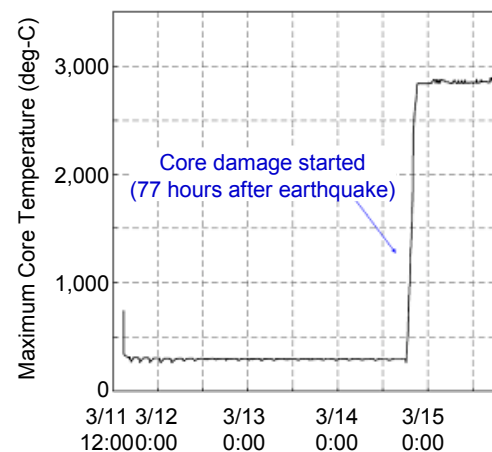


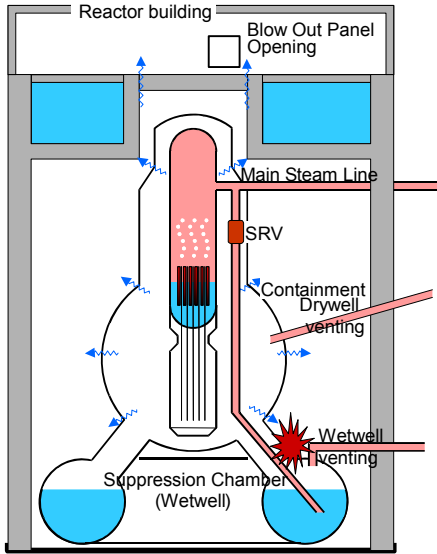
Figure 19 F2 max. fuel temperature [8]

2 months later, TEPCO issued a report of calculation results. After RCIC had stopped, about 50% of the fuel pellets reached 2,800deg.-C during the night of March 14th, and dropped to the bottom of RPV.

At this point in time, PCV might have kept its integrity, but the explosion in the following day broke the PCV.

### 3.2.3 F2 Hydrogen explosion

**March 15, 06:10:** There was a hydrogen explosion at the suppression chamber, and the PCV integrity was lost. This caused a large amount of radio-active water to leak into the turbine building (This is explained later).



**Figure 20 F2 hydrogen explosion**

One of the mysteries is the place of explosion. F1 had one at the top floor of the reactor building, but F2 had a blow-out panel ejection on March 14th. The panel prevented the same

explosion as F1, however, a different one happened at another place.

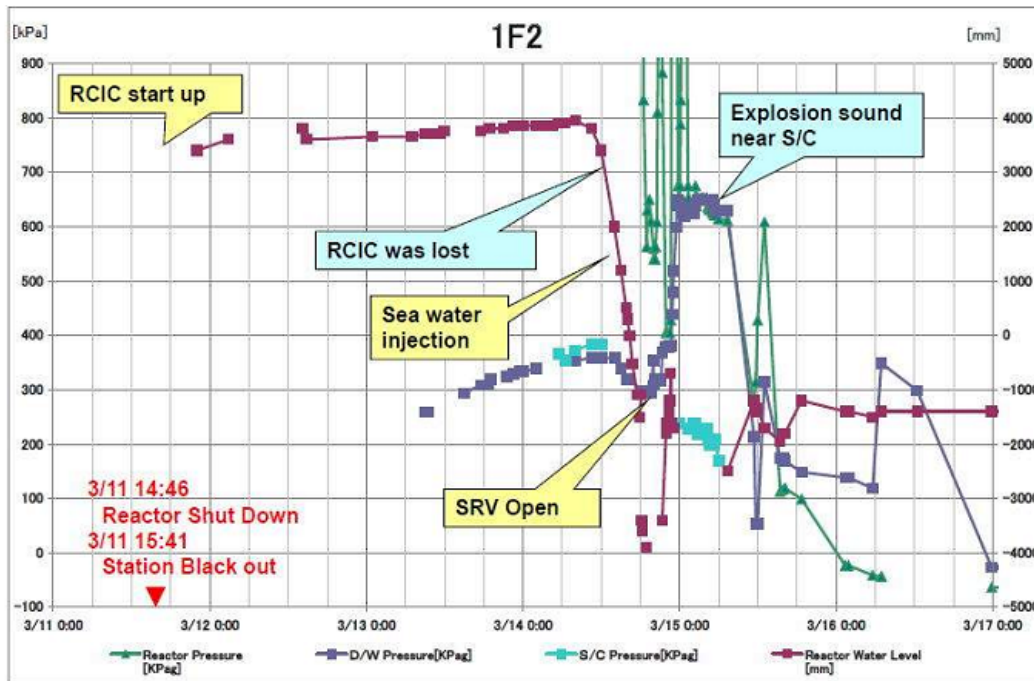
Since PCV of BWR is filled with inert gas, it is probable that hydrogen explosion occurred outside the suppression chamber. The place had the highest concentration of hydrogen from the reactor core. There are always some small leaks at pipes or flanges. Overpressure might have accelerated this phenomenon.

**April 13:** TEPCO, on April 13th, reported results of radio-activity measurement of water in F2 turbine building. Iodine vaporizes at 184deg.-C, Cesium at 671, Barium at 1,897, and Strontium at 1,382. Although Barium has a very high vaporizing temperature, it decays from Cesium and Xenon with a half-lifetime of about a minute. So, Strontium is probably the decisive element to determine the maximum fuel temperature.

**Table 2 Radio-activity in water of F2 turbine building**

Nuclides	million Bq/cc on April 13th
Iodine-131	2.00
Cesium-134	2.60
Cesium-137	2.80
Barium-140	0.24
Strontium-89	0.70
Strontium-90	0.14

Figure 21 shows the event chart with pressure and water level of F2 for the first several days.



**Figure 21 Trend Data of Unit 2 up to March 17 [4]**

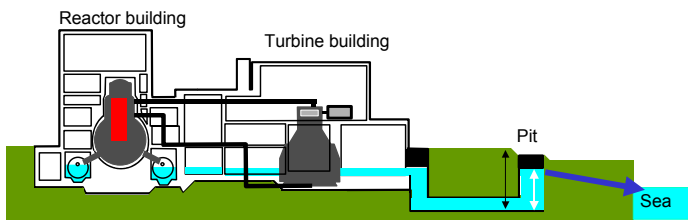


### 3.2.4 F2 Sea Contamination

**April 2:** Very high radiation (400mSv/h) was observed at a location 2-meters away from the “Pit” of F2. The pit is the exit of the turbine building water to the sea. When F2 was shut-down on March 11th, we estimated that there was radio-activity of  $4.2 \times 10^{18}$  Bq of Iodine-131 in the whole core. This Iodine went to the suppression chamber, and went out to the basement of the turbine building, because PCV was already broken. This high value means that water in the Pit had almost the same radiation level as the water in the core.

TEPCO also announced that Iodine-131 was measured at the sea in front of F2, and its value was as high as 5.40-million Bq/cc. Since the basements of the buildings were not watertight, some amount of leakage is likely. This means that sea contamination had begun. TEPCO is now installing barriers to the sea and the leakage is decreasing.

Nuclear fuel material such as Uranium or Plutonium has not been found in the above water, but we guess since RPV and PCV were broken, such material could go out with water. Also, underground of these buildings may already be contaminated.



**Figure 22** Water path to the “Pit”

### 3.2.5 F2 Spent fuel pool

Fortunately or not, the roof of F2 is intact, and we cannot see inside the building where the F2 spent fuel pool is. Spent fuel cooling function was lost since March 11th, but sea water was injected after March 20th.

On April 18th, TEPCO showed a radio-activity measurement of water taken from the spent fuel pool. I-131 was only 0.004-million Bq/cc, but Cesium-134 was 0.16-million Bq/cc, and Cesium-137 was 0.15-millions Bq/cc.

Since there was a large amount of Iodine-131 in the core, the above small amount of I-131 indicates that measured radio-activity must have come from the spent fuel, which might have been damaged earlier. The cause of this spent fuel failure, if it had occurred, is not clear. Since the decay-heat of spent fuel is small, dry-out of the spent fuel is unlikely.

### 3.2.6 F2 Conclusion

Our conclusion is that Fukushima-2 is in “half melt-down” status, that is fuel pellets had reached 1,400deg.-C or higher, but lower than 2,800deg.-C. Hot fuel fell to the RPV bottom, opened holes there to fall further to the bottom of PCV.

We presume that the hydrogen explosion broke the PCV. Of course, we cannot fully deny the possibility that hot fuel dropped to the PCV bottom to break it, a situation similar to F1.

As for the spent fuel pool, spent fuels have been damaged, although the cause is not clear.

## 3.3 Fukushima-3 Reactor

### 3.3.1 F3 Melt-down Process

**March 11, 15:05:** The F3 RCIC is the same with the one for F2 (Figure 17). This RCIC saved F3 during the initial SBO stage, but the heat accumulated in the suppression chamber could not be removed, because the tsunami had destroyed the sea-water cooling system.

**15:25:** RCIC was stopped by a high water-level signal. This suggests that RCIC had injected necessary water to the core.

**15:38:** Operator recorded Station Black-Out (All DGs stopped).

**16:03:** RCIC was re-started manually.

**March 12, 11:36:** RCIC was stopped. The cause is not clear.

**12:35:** HPCI (High Pressure Coolant Injection System) was automatically started by the low water-level signal. HPCI is one of the Emergency Core Cooling Systems (ECCS), and has almost an identical configuration with RCIC, shown in the above figure. Both are steam-turbine driven.

At the same time, pressure in RPV and PCV decreased suggesting that HPCI pipe broke at the time of the earthquake. 4 months later, however, TEPCO reported that maintenance crew entered the HPCI-room and found no leakage in HPCI, and the pressure drop was just a fluctuation in the flow.

**March 13, 02:42:** RPV pressure dropped and HPCI was stopped. Control system batteries were exhausted.

We presume that this stoppage triggered core degradation. Fuel cladding temperature rose to 1,200deg.-C, and zirconium oxidation of the cladding tube began. Fuel cladding tube collapsed, and high temperature fuel pellets fell to the bottom of the RPV. Also, a large amount of hydrogen was generated.

### 3.3.2 F3 PCV Venting

**March 13, 09:00:** PCV pressure reached 0.6MPa. Since the “Rupture disk” for PCV venting was designed to break at 0.55Mpa, PCV venting became possible at this time.

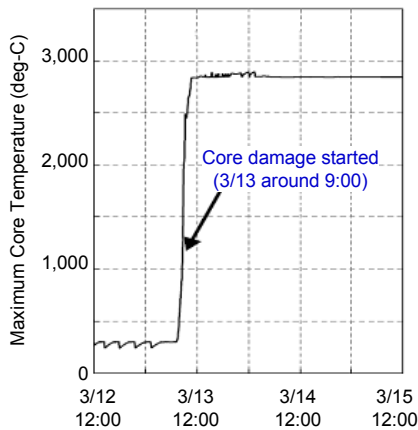
**09:10:** SRVs were opened, and PCV wet-venting started. Since PCV venting was done just after it became possible, there was no delay for venting on F3.

**10:00:** Fresh water was injected. (7 hours of no core cooling)

**12:00:** Sea water was injected.

**13:17:** High radiation level (300mSv/h) was measured on the 1st floor of the reactor building. This suggests that there was a severe fuel failure.

2 months later, TEPCO issued a report of calculation results. After HPCI had stopped, about 50% to 100% of the fuel pellets reached 2,800deg.-C in the morning of March 13th, and dropped to the bottom of RPV.



**Figure 23 F3 Max, fuel temperature [8]**

Up to March 19th, both RPV and PCV have kept their integrities, or at least, there were no big holes in RPV/PCV, because both pressure values were low but positive.

See Section 3.3.8 “Hot spots issue in Tokyo area by F3 pressure spike on March 20th” for a conclusion.

### 3.3.3 F3 Hydrogen explosion

**March 14, 06:10:** PCV pressure reached 0.5Mpa.

**11:01:** There was an explosion at the top of the F3 reactor building (Figure 24). Panels of concrete and steel on the sidewall and roof of the top floor are designed to rupture, in case of overpressure such as steam line breakage within the reactor building. So, they ruptured as designed (Figure 25), although hydrogen explosion had probably not been predicted before.



**Figure 24 Hydrogen explosion at F3 [4]**  
(Stacks are 120 meters tall)

Smoke reached 300-meters high, and the explosion was bigger than that with F1. Actually, F3 steel frameworks were destroyed, and this did not happen on F1. This cause might have been more hydrogen generation than F1, due to the larger fuel inventory at F3. When this explosion occurred, one of the authors, Yoshioka was in a TV studio, and was surprised by this news.

PCV venting was done 26-hours before the hydrogen explosion but it was not effective enough to remove the hydrogen gas before it exploded. The probable cause is wetwell venting that removes mostly steam, while hydrogen gas rises up in the drywell. Then, the hydrogen gas escaped from the drywell to the reactor building through seals or other penetrations. The paths were the same with those of F1 shown in Figure 14.



**Figure 25 Top (5th) floor and walls on 4th floor were destroyed (April 11th, by TEPCO)**

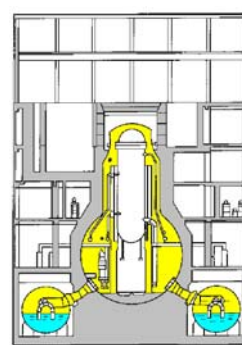
### 3.3.5 F3 MOX Fuel Risk

The F3 core contained 32 MOX (Mixed Oxide) fuel bundles which contained plutonium as initial fissile material. Of course,  $\text{UO}_2$  fuel generates plutonium when it is used in the core. For example, the total amount of plutonium was about 1ton in F3, and 0.5tons in F2. Total plutonium in the F4 spent fuel pool of about 2-tons was the largest among all cores and pools on the Fukushima-site. So, the risk with plutonium is not specific to F3.

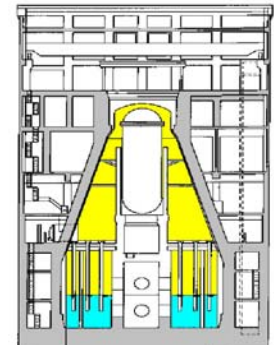
### 3.3.6 Influence of PCV Design

Mark-I PCV is said to have a relatively small volume compared to Mark-II (Figure 26). If we, however, compare PCV volume per reactor output, they are about the same (Figure 27). Even if Mark-I PCV is small, it was not a cause of the Fukushima accident. The cause was Station Black Out and loss of sea-water cooling system by the earthquake and the tsunami.

The main disaster at Fukushima was the release of large amount of radio-activity, caused mostly by venting with some contribution from the hydrogen explosions. If the PCV had a greater volume, it could have accommodated more steam for a while, but sooner or later, TEPCO would have had to start venting and release a large amount of radio-activity anyway. Also, hydrogen exploded outside of the PCV. We can thus say that even if Mark-I had a small volume as said elsewhere, it would have had little influence on the Fukushima disaster.

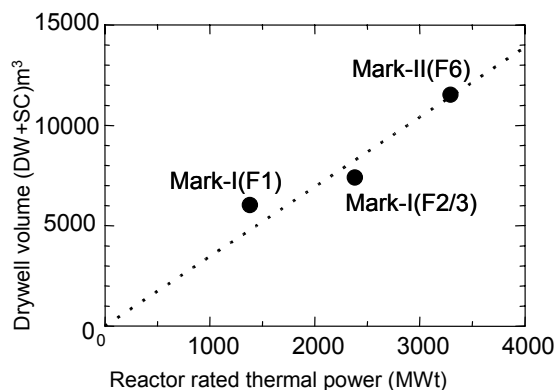


(a) Mark-I (F1/2/3/4/5)



(b) Mark-II PCV (F6)

**Figure 26 Mark-I and Mark-II PCV (F6) [12]**



**Figure 27 PCV Volume vs. Reactor Power**  
(calculated from data in [8] and [13])

### 3.3.7 F3 Radio-activity measurement of water

TEPCO, on April 14th, reported results of radio-activity measurement with the water in the F3 turbine building basement.

Numbers in the parentheses are ratios of F3 to F2. Strontium is a beta-emitter and its accurate measurement is difficult, so its values contain some error.

High level of radiation in the F3 reactor building (see Section 3.3.2, March 13th, 13:17) indicates that these radio-active isotopes came from the F3 core. Meanwhile, since these

ratios are roughly the same, these radio-active water might have come from the F2 turbine building.

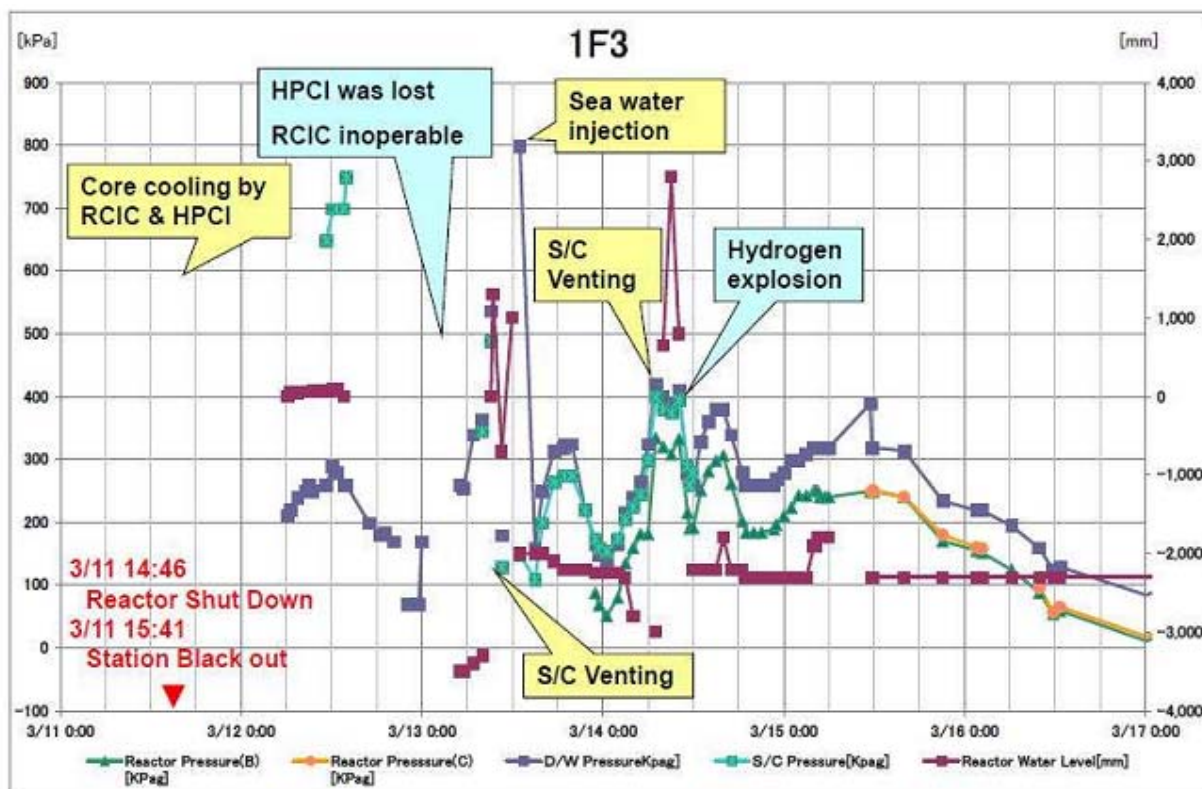
**Table 3 Radio-activity in water of F3 turbine building**

Nuclides	million Bq/cc on April 14th
Iodine-131	0.16 (8%)
Cesium-134	0.14 (5%)
Cesium-137	0.16 (6%)
Barium-140	0.015 (6%)
Strontium-89	0.086 (12%)
Strontium-90	0.015 (11%)

### 3.3.8 Hot spots issue in Tokyo by the F3 pressure spike on March 20th

Figure 28 and 29 show event charts with pressure and water levels of F3 for the first several days. Figure 30 shows detail trend of the RPV and drywell pressure in the red circle in Figure 29.

Both RPV and PCV are likely to have kept their integrities, or at least, there were no big holes in RPV/PCV until March 19th, because both pressure values were low but positive. On March 20th, however, we can see pressure spikes both in RPV and PCV, followed by decrease to zero pressure on March 21st. This increase and decrease in pressure suggest that a hole once closed and then opened.



**Figure 28 Trend Data of F3 up to March 17 [4]**



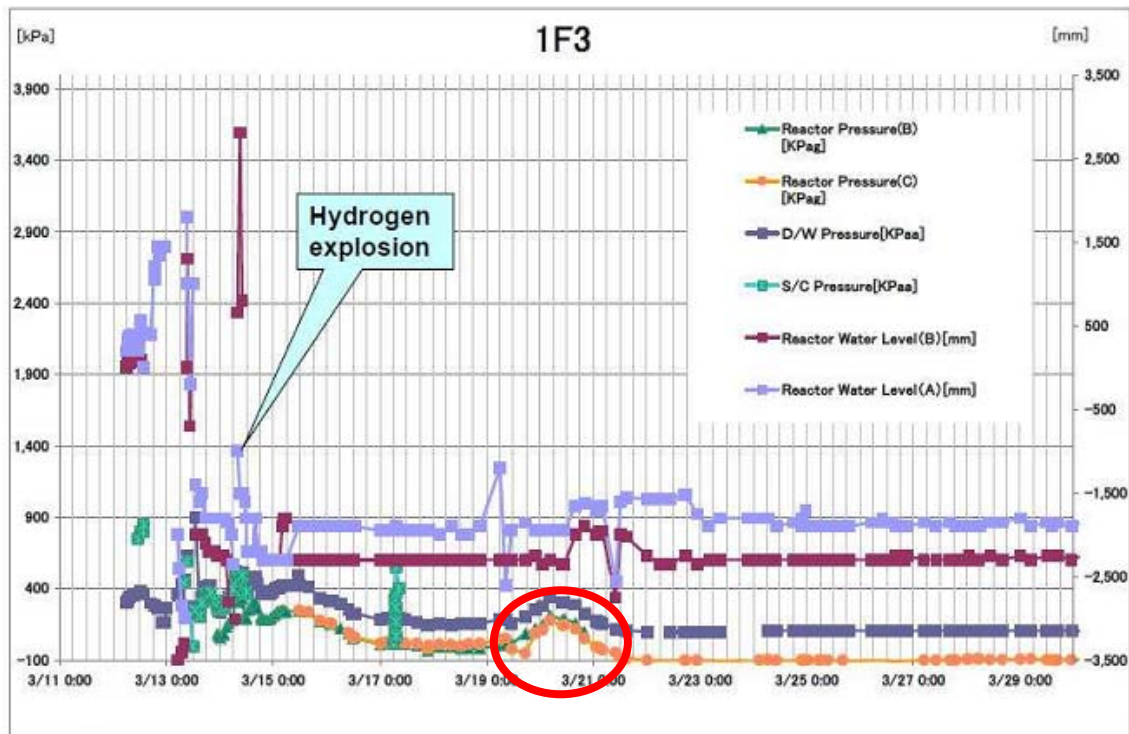


Figure 29 Trend Data of F3 up to March 30 [4]

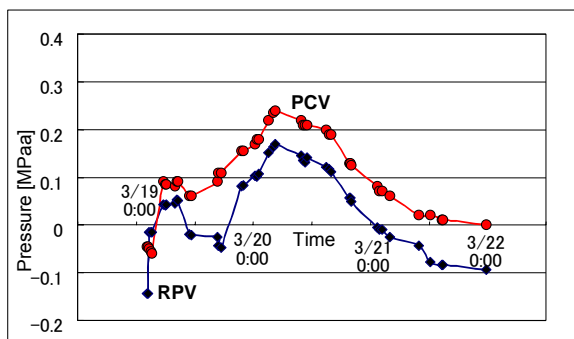


Figure 30 Pressure in RPV and PCV on F3

Meanwhile, a southbound wind blew and with some rain on March 20th in Tokyo. 3 months later, so-called “hot spots” were found in Tokyo, Chiba and Saitama prefectures all about 200km away from Fukushima plant. The radiation levels at the hot spots were 0.4-0.5 micro-Sv/h, that is about 4-5 times of natural radiation in the background. Although these values were not critical for human health at all, this unpredicted phenomena caused anxiety among citizens.

Figure 31 shows the radiation level change with different radio-active components in Chiba-city between March 15th to 31st. It shows that before March 20th and after the 21st had subtle differences. Neither TEPCO nor the Government so far has explained this phenomena, and the cause is unclear at this point.

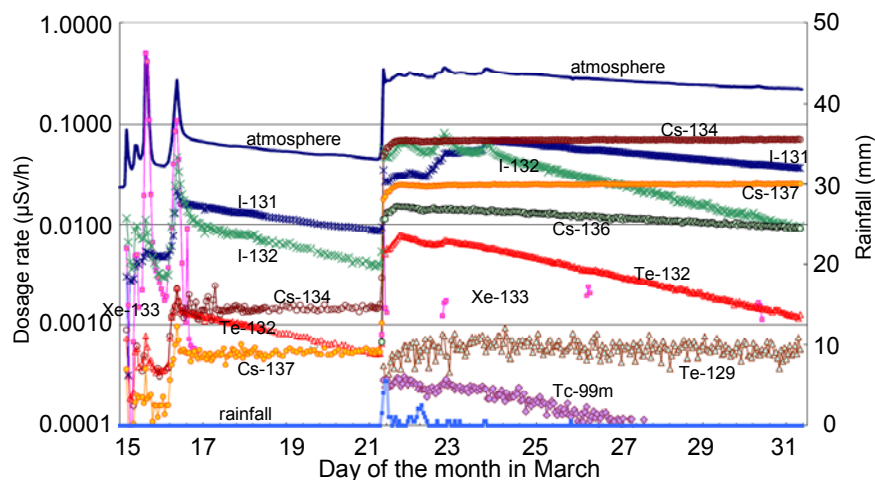


Figure 31 Radiation level in Chiba-city from March 15th to 31st. [14]



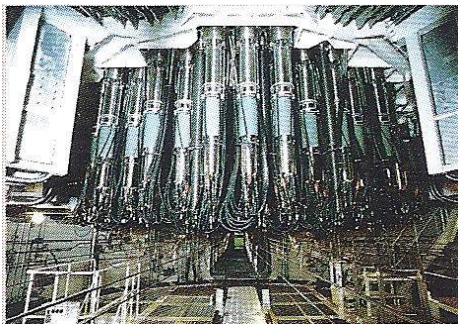
Our guess is that disintegrated fuel dropped and clogged up the small holes on March 20th to raise the pressure in RPV/PCV, then the holes grew larger on March 21st. Since these phenomena advanced slowly, we do not believe there was a re-criticality accident or any kind of explosion. The fact is that the PCV integrity was completely broken on March 21st.

On March 21st, black smoke rose from the spent fuel pool area of F3 from 16:00 to 18:00 (Figure 32). Also, radiation level at 1km west of F3 was 494-micro-Sv/h at 17:40, but increased to 1,932 at 18:30, and decreased to 442 at 20:30.



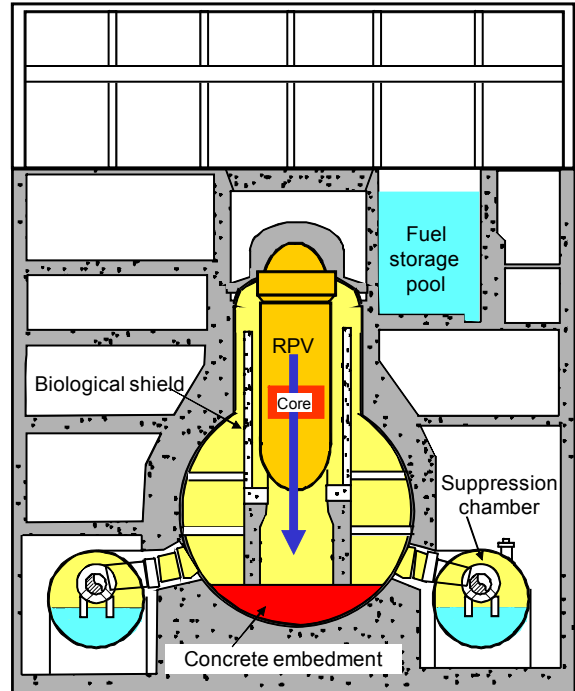
**Figure 32 F3 Smoke on March 21st (TEPCO)**

We presume that radio-active material went out at this time with the smoke. Black smoke is an indication of carbon from organic material such as cable insulators. There are many cables under the bottom of RPV for the control rod drive mechanisms and neutron detectors (Figure 33). As we explained in 3.1.1, hot fuel broke the instrument tubes and fell down to the RPV bottom. They probably burned the cables at this time.



**Figure 33 Bottom of ABWR RPV [15]**

The French national laboratory suggested that “core-concrete chemical reaction” was responsible for the black smoke. Of course, hot fuel fell down on the concrete floor of the PCV, as Figure 34 shows, however, a Japanese national laboratory says that Japanese plants do not use concrete with carbon, and this reaction will not occur. So, it is more probable that this black smoke was caused by fire of the cables when hot fuel fell on them.



**Figure 34 MARK-I PCV [16]**  
( PCV concrete floor is shown red)

### 3.3.9 Detection of plutonium [17]

On March 21st 13:30, the following plutonium isotopes were detected from soil at the Fukushima site. It is not clear if these plutonium came from the above F3 event or not, because there were no data before March 20th.

Pu-238:  $(5.4 \pm 0.62) \times 10^{-1}$  Bq/Kg-soil

Pu-239, Pu-240:  $(2.7 \pm 0.42) \times 10^{-1}$  Bq/Kg-soil

### 3.3.10 F3 Spent fuel pool

The hydrogen explosion on March 14th dropped concrete panels and steel re-bars in the spent fuel pool, and we cannot see if the fuel bundles are intact or not (Figure 35). The spent fuel lost its cooling function on March 11th, but sea water was injected after the 13th. Decay heat in F3 spent fuel pool is not large and we believe its cooling function has been maintained.



**Figure 35 F3 spent fuel pool (5/8 TEPCO)**

On May 8th, TEPCO reported radio-activity measurements in water from the F3 spent fuel pool. I-131 was 0.011-million Bq/cc (about 2-million Bq/cc on March 11th), Cesium-134 was 0.14-million Bq/cc, and Cesium-137 was 0.15-millions Bq/cc.

Since there were essentially no Iodine-131 in the spent fuel, this measured radio-activity must have come from the F3 core fuel that was damaged on March 13th. Of course, this does not guarantee that spent fuel in F3 are intact.

### 3.3.11 F3 Conclusion

We conclude that F3 is in “half melt-down” status, that is fuel pellets had reached 1,400deg.-C or higher, but lower than 2,800deg.-C. Hot fuel fell to the RPV bottom, opened holes there to fall further to the bottom of PCV.

We presume that a pressure spike on March 21st broke the PCV integrity. We, however, cannot fully deny the possibility that hot fuel dropped to the PCV bottom to break it, a situation similar to F1. As for spent fuel pool, the situation is not clear.

### 3.4 Fukushima-4 Reactor

When the earthquake and tsunami occurred on March 11th, Fukushima Unit 4 (F4) was in its periodic shut-down stage, and all fuel bundles in the core had been moved to the spent fuel pool in preparation for maintenance within the Reactor Pressure Vessel (RPV). At the time, the spent fuel pool had a total of 1,331 fuel bundles, of which 548 had high decay heat.

At 15:41 on March 11th, the earthquake and tsunami caused a Station Black-Out (SBO) and cooling pumps for the spent fuel pool stopped. The pool water temperature started to rise and the pool water began to evaporate.

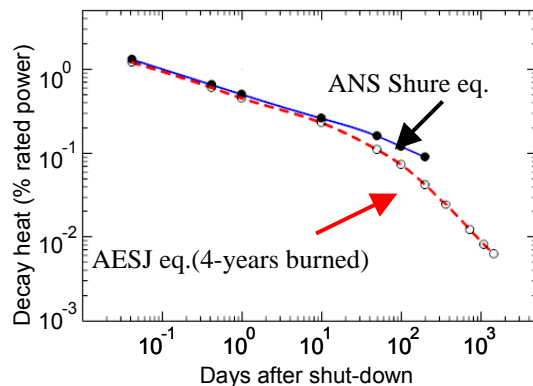


Figure 36 Decay heat after shutdown [18,19]

Figure 35 shows decay heat curves by Shure adopted by America Nuclear Society (ANS) [18] and a slightly different curve by Atomic Energy Society of Japan (AESJ) [19]. With rated thermal power of 2,381MWth from 548 fuel bundles [20], the rated thermal power per fuel bundle is 4,345kWth. F4 was shut down on Nov. 30, 2010 for periodic maintenance [21], and Figure 36 gives a conservative estimate of 0.1% decay heat at 101 days after shutdown at the time of the earthquake. Fuel bundles that had been sitting in the fuel pool had lower decay heat, however, without information of since when, we conservatively estimate the overall decay heat from the 1,331

fuel bundles to 5,783kW. On the other hand, 0.6275kWhr of heat evaporates 1kg of water at 100deg.-C, thus, 221tons of water evaporate from the fuel pool in 1 day, i.e., about 900tons of water during the 4 days from the 11th to the 15th. The F4 pool had only 1,300tons of water, and the decay heat might have caused dry-out of the spent fuel.

There are many risks associated with the spent fuel pool, but they are not well known in Japan. A US-NRC document [22] describes the number of hours allowed after loss of pool cooling. Figure 37 shows that a BWR spent fuel will start to dry-out in a week if it has been loaded with spent fuel from shut-down 2 months earlier. Once dry-out starts, fuel is cooled only by air, but inefficient air-cooling will let the melt-down process start within 5-hours, as Figure 38 shows.

Based on the former conservative analysis, we had to assume that the melt-down process was initiated in the F4 spent fuel pool on May 15th, and the fuel reached 1,200deg.-C to generate hydrogen gas. Of course, in the latter optimistic case, spent fuel might be intact.

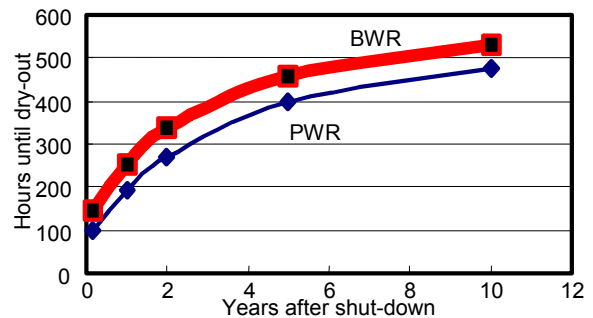


Figure 37 Hours to dry-out with different cooling time [22]

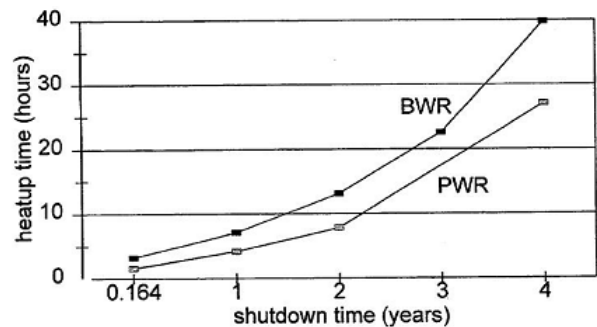


Figure 38 Hours for air-cooled fuel to reach 900degC [22]

On March 15th 06:14, there was a hydrogen explosion at the top of F4 reactor building, and the first news said that there was a big hole in the north-west wall. At 09:38, a fire broke out on the 4th floor of the reactor building.

A fire means that some organic material burned. The March 22nd photo below shows a square opening on the 4th floor (Figure 39). The layout drawing shows 2 MG(Motor-Generator) sets inside where the 4th floor broke. These MG sets control the reactor cooling pumps, and transfer torque using fluid oil. We presume that when the hydrogen exploded, leaked oil caught on fire due to the high temperature in the spent fuel pool.



**Figure 39 F4 Reactor building (3/22, TEPCO)**



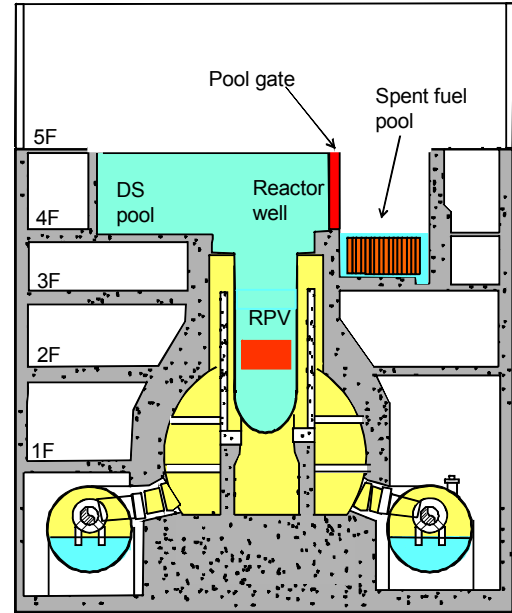
**Figure 40 F4 Reactor building (4/11, TEPCO)**

Sometime in the morning of March 15th, the explosion and fire tore down the walls of 4th and 5th floor and the roof, except the steel frame in a better shape than that of F3. The April 11th photo of F4 shows the structure (Figure 40). The explosion and fire suggest that the spent fuel reached 1,200deg.-C and hydrogen gas was generated as in the case of F1/F2/F3 cores.

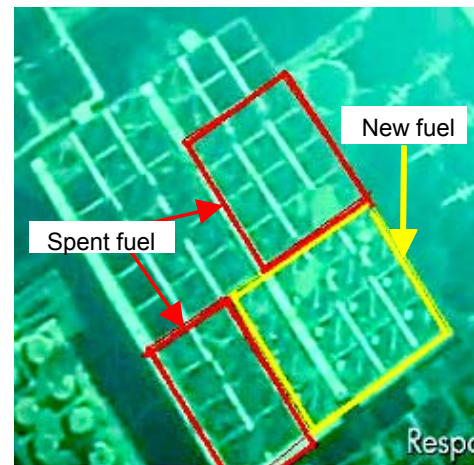
On March 16th 05:45, there was another fire on the 3rd floor of the reactor building.

Since all fuel bundles in the core had been moved to the spent fuel pool, the pool gate was closed as Figure 41 shows. When the pool water level dropped and hydrogen exploded, this pool gate was possibly damaged to allow water from the Dryer-Separator (DS) pool and reactor well to fall into the spent fuel pool. About 2,000tons of water could have been moved to the spent fuel pool, just enough to keep the spent fuel cooled for several more days.

On April 29th, TEPCO showed a photo of the F4 spent fuel pool (Figure 42). It shows that the fuel racks, which separately hold each fuel bundle, were intact. But, we cannot see the upper tie-plates and handles of the spent fuels (marked in red). On the other hand, we can see handles clearly for new fuels (marked in yellow). This photo alone cannot tell if the spent fuel bundles are intact or not, due to fragments of concrete panels atop the spent fuel.



**Figure 41 Water inventory of F4 before explosion [16]**  
(Water level assumed by the authors)



**Figure 42 F4 spent fuel pool (4/29, TEPCO)**

On April 14th, TEPCO reported radio-activity measurements of the F4 spent fuel pool water, and they were quite low. Iodine-131 was 220Bq/cc, Cesium-134 was 88Bq/cc and Cesium-137 was 93Bq/cc. If these measurements are correct, there have almost been no fuel failure with the F4 spent fuel.

On May 15th, TEPCO explained a possible route of hydrogen leakage from F3 to F4; when F3 underwent PCV-venting on March 13th, hydrogen might have invaded the F4 reactor building through the venting pipe which was common for both plants. The next day, however, TEPCO withdrew this idea because the valves were closed at the interface of the 2 plants.

It is difficult to determine what happened in F4 from the above contradicting observations, but it is likely that there was some kind of dry-out and failure with the fuel.



### 3.5 Fukushima-5&6 Reactors

When the earthquake and tsunami occurred on March 11th, F5 and F6 were in periodic shut-down stages, and both external power lines and all DGs except one became unavailable.

The spent fuel common pool was located 50-meters west of F4, but its ground level was the same with Fukushima plants. The common pool was also attacked by the tsunami, and DGs there were stopped. The actual cause has not been reported, but it is likely to be the tsunami.

Among all 13 DGs in Fukushima site, only one in F6 survived the tsunami, because it was in the reactor building and air-cooled (Table 4). This DG saved F5 and F6.

TEPCO has installed temporary sea-water cooling pumps since the original systems were damaged by the tsunami.

**Table 4 Location of DGs [23]**

Reactor #	DG Location
1	2: Turb. Bldg. basement
2	1: Turb. Bldg. basement 1: Spent fuel common pool (air cooled)
3	2: Turb. Bldg. basement
4	1: Turb. Bldg. basement 1: Spent fuel common pool (air cooled)
5	2: Turb. Bldg. basement
6	1: Turb. Bldg. basement 2: Rx Bldg. basement (1 is air-cooled)

### 4. CONCLUSION

Unfortunately, Fukushima accident is not over yet. If the final goal is de-commissioning of all nuclear reactors, it will take several decades. So, in this paper, we only described the process and direct causes of the Fukushima accident. We need to investigate the root-cause and background of the accident.

As a conclusive summary of the Fukushima accident with F1/2/3/4, the earthquake and tsunami caused Station Black-Outs and loss of sea-water cooling systems. So, core cooling and spent fuel pool cooling functions were lost. There were some small contribution to accident mitigation by the emergency cooling systems, but they were also lost when the batteries were used up. After that, fuel encountered dry-out and fuel damage processes, and then hydrogen gas was generated.

We cannot tell the extent of fuel damage, but we presume fuel pellets fell down in fragments and particles at high temperature. In this optimistic case, F1/2/3 cores and maybe fuel in the F4 spent fuel pool are in “half melt-down” status, i.e., fuel pellets reached 1,400deg.-C or higher, but not 2,800deg.-C. Hot fuel fell to the RPV bottom, broke holes there to fall further to the PCV bottom. Hot fuel also damaged the PCV.

Once fuel dry-out process started, hydrogen explosion was inevitable. The risk of hydrogen explosion within a reactor building had not been recognized seriously in nuclear plants before the Fukushima accident. The images of the explosions caused a big impact on the public. PCV-venting could have released mostly steam and some amount of hydrogen, but not enough to prevent these hydrogen explosions. Hydrogen explosion could not have been avoided.

Radio-active isotopes measured so far are Iodine, Cesium, Tellurium and Strontium, all soluble in water, and PCV-venting and hydrogen explosion sent them out from the reactor to the environment. They have caused a wide area of contamination in the soil around the Fukushima site. Since the most dominant isotope is Cesium after several months, and half-life of Cesium-137 is 30-years, it will take quite a long time for the environment to return to a state with reasonable contamination.

Almost all media in Japan suggested that there was a “delay” of venting to prevent hydrogen explosion or to mitigate the accident. But, as we explained in F2 and F3 accident processes, there was no delay of venting. As for F1, there might have been some delay but without any affect on consequences of the accidents. So, essentially there were no delay of venting with any plants.

In our study, we did not investigate the water injection activity by firemen. Once the fuel dry-out process had started, it was almost impossible to stop it because this process would reach its end within several hours. But, we believe their efforts have made a significant difference. Actually, if they had failed to inject water (either fresh water or sea water) for the first 3 weeks in any of the 4 plants, we would have faced a much severer disaster.

On April 12th, the Japanese government announced that radio-activity release by the Fukushima accident was about 1/10 of Chernobyl, and the accident level was at Level-7, the worst rank of INES and the same level with Chernobyl. Although severe core damage occurred with 3 reactors in Fukushima, there were some differences from Chernobyl as we list below:

- (1) There was no nuclear explosion, and no big fire as in Chernobyl. Although there were hydrogen explosions in F1/2/3/4 that looked severe, they were not nuclear explosions. Also, there were several fires, but they did not shoot nuclear materials into high sky like in the case of Chernobyl.
- (2) Most of the radio-activity released was Iodine and Cesium with the Fukushima accident, and most of them were transferred to and are still in the water of reactor/turbine building basement.
- (3) Evaluation and observation of symptoms tell us that there were no re-criticality accident with any plants, because the shape of fuel at the bottom of RPV is either a stack of fuel pellets or lump of melted fuel, not in shape to reach criticality.
- (4) There was no steam explosion at Fukushima. One reason is that there was no water pool under the RPV. We presume another reason is that fuel did not shape a large lump of metal uranium or uranium oxide, which is another condition for steam explosion.

### Acknowledgment

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