No.55

Fukushima Accident Summary(3)

2011-July-17, Ritsuo Yoshioka

(Text in blue are Yoshioka's comments)

1) Earthquake and Tsunami

(Please see Summary-1 report for detail.)

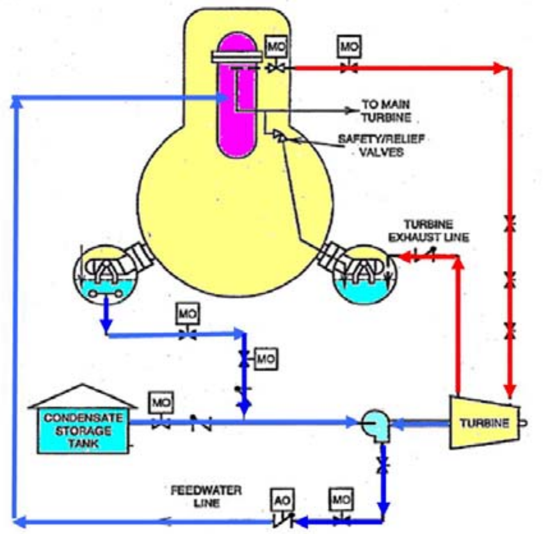
14:46 March 11th 2011	Tohoku Pacific Earthquake (magnitude 9.0) hit. All external electric power sources for F1/2/3/4/5/6 were lost. The emergency Diesel Generators (DG) started automatically.

15:41	A huge 14-15 meter tsunami attacked, and flooded all DGs except one in F6. So, F1/2/3 were forced into Station Black-Out (SBO), although some of the batteries survived at F3/4. The tsunami also destroyed most of the sea-water cooling systems. Core cooling function, thus, was lost for F1/2/3, and the fuel pool cooling function was lost for F1/2/3/4.

2) Fukushima-3 Reactor

Melt-down process

March 11th

15:05	Reactor Core Isolation Cooling System (RCIC) was manually started. RCIC is an emergency pump system driven by a steam-turbine that is turned by 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 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 the high water-level signal. (This suggests that RCIC had injected necessary water to the core.)	
15:38	Station Black-Out was recorded by the operator. (All DGs stopped.)	
16:03	RCIC was re-started manually.	

March 12th

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 ECCS (Emergency Core Cooling System), and has almost an identical configuration with RCIC, shown in the above figure. Both are driven by steam-turbine.
	At the same time, pressure in RPV and PCV decreased, and this suggests that HPCI pipe was broken at the time of earthquake, but this has not been investigated so far.

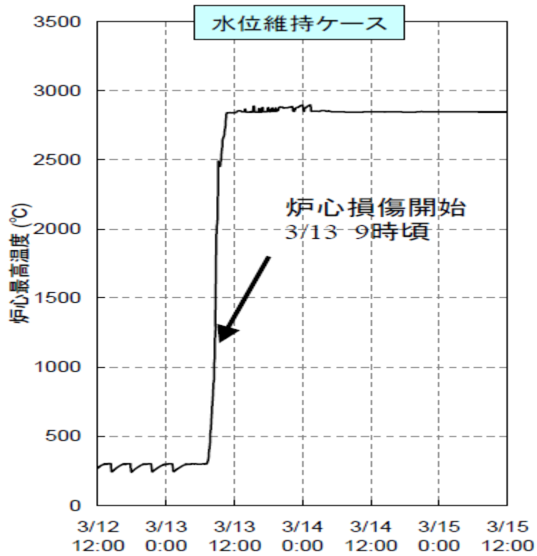
March 13th

02:42	HPCI was stopped, because RPV pressure became low. At the same time, battery for control systems was exhausted. (Core degradation began. Fuel cladding temperature increased 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 Reactor Pressure Vessel (RPV). Also, a large amount of hydrogen was generated.)

Primary Containment Vessel (PCV) venting

09:00 March 13th	PCV pressure reached 0.6MPa (Mega-Pascal). Since the "Rupture disk" for PCV venting breaks at 0.55Mpa, PCV venting became possible at this time.
09:10	SRV (Safety Relief Valve) was opened, and PCV wet-venting started. (PCV venting was done just after it became possible, and 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 (300mili-Sievert/hour) was measured at 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.
At this point in time, both RPV and PCV are likely to have kept their integrities, or at least, there was no big hole in RPV/PCV, because both pressure values were low but positive.
(See the column on Page-5 :"Hot spot issue at Tokyo area by F3 pressure spike on March 20th")



F3 max. fuel temperature

Hydrogen explosion

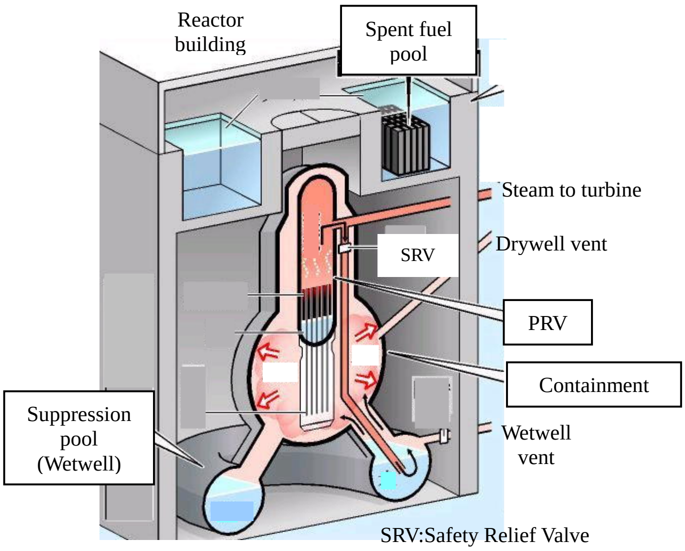
06:10 March 14th	PCV pressure reached 0.5Mpa.
11:01	There was an explosion at the top of the reactor building of Unit 3. Concrete/steel panels on the sidewall/roof of the top floor are designed to rupture, in case of over-pressure such as steam line breakage within the reactor building. (So, they ruptured as designed, although hydrogen explosion might not have been predicted before.)

Hydrogen explosion at F3

Top (5th) floor and walls at 4th floor were destroyed.

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

Although PCV venting was done 26-hours before the hydrogen explosion, it was not effective enough to remove the hydrogen gas to prevent its explosion.
This is probably because wetwell venting removes mostly steam, while hydrogen gas rises up inside the drywell. Then, the hydrogen gas escaped from the drywell to the reactor building through seals or other penetrations.

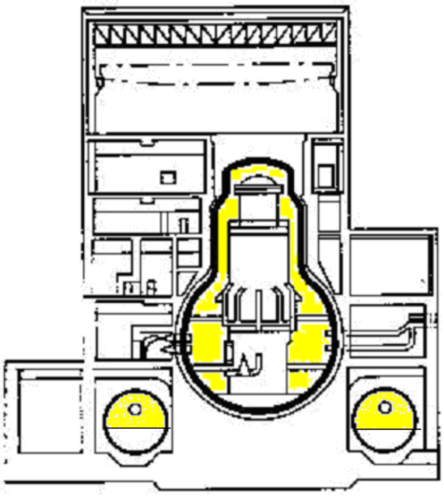


MOX fuel risk:
The F3 core contained 32 MOX(Mixed Oxide) fuel bundles which contained plutonium as initial fissile material. Of course, UO2 fuel generates plutonium when it is used in the core. For example, the total amount of plutonium was about 1-ton in F3, and 0.5-tons in F2. Total plutonium inventory in the F4 spent fuel pool of about 2-tons was the largest among all cores and pools in the Fukushima-site.
(So, plutonium risk is not specific to F3.)

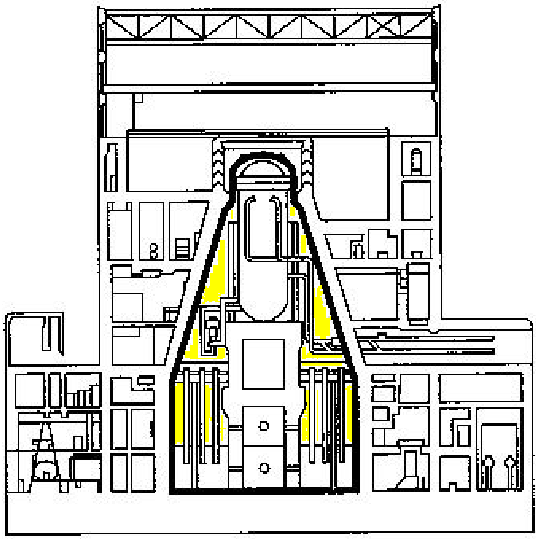
Influence of PCV design difference:

Mark-I PCV has a relatively small volume compared to Mark-II design. This difference, however, is 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 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. So, it is true that Mark-I is an old design, however, it had little influence on the Fukushima disaster.



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



Mark-II PCV (F6)

Radio-activity measurement of water (April 14th):

TEPCO, on April 14th, reported results of radio-activity measurement in the water from the basement of F3 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 half-lifetimes of about a minute. So, strontium is the decisive element to determine the maximum fuel temperature.

Nuclides	million Bq(Becquerel)/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%)

Numbers in the parentheses are ratios of F3 to F2 (see No.2 report). Strontium is a beta-emitter and its accurate measurement is difficult, so its values contain some errors.

High level of radiation in the F3 reactor building (see item 13:17 on March 13th) 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.

Hot spot issue in Tokyo area by the F3 pressure spike on March 20th:
As Figure 3-14 shows, both RPV and PCV are likely to have kept their integrities, or at least, there was no big hole 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 the pressure suggests that a hole once closed and then opened. Please see my comment below.)

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 hotspots were 0.4-0.5 micro-Sievert/hr, about 4-5 times natural radiation in the background. Although these values were not critical for human health at all, this unpredicted phenomena caused anxiety among citizens.

As the following figure shows, radio-active components were different before March 20th and after the 21st. TEPCO nor the Government so far has not explained this phenomena, and its cause is unclear at this point.
(My guess is that disintegrated fuel dropped and clogged up the small holes on March 20th to raise the pressure in RPV/PCV, and then the holes grew larger on March 21st. This, however, is just a speculation. Since this phenomena were slow, I do not believe there was a criticality accident or any kind of explosion.)
Anyway, as a fact, the PCV integrity was completely broken on March 21st.

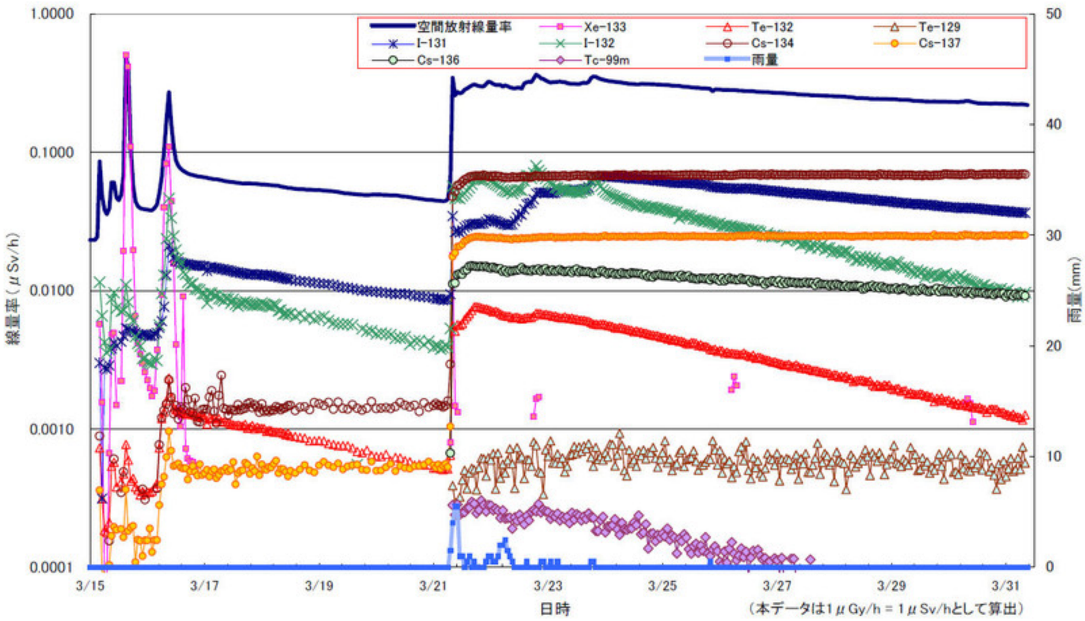


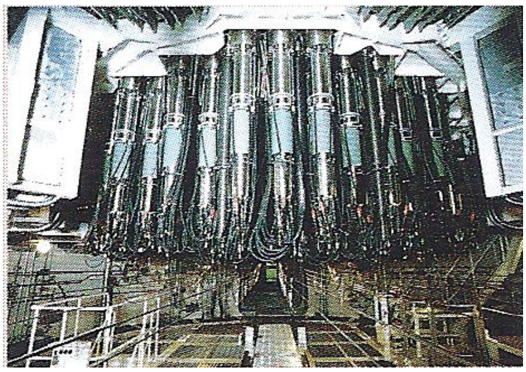
図1　日本分析センターにおける空間放射線量率の測定結果　2011/4/1 日本分析センター調べ
Radiation level in Chiba-city on March 15th to 31st.

On March 21st, black smoke rose from around the spent fuel pool of F3 from 16:00 until 18:00.

Also, radiation level at 1km west of F3 was 494-micro-Sievert/hr at 17:40, but increased to 1,932 at 18:30, and decreased to 442 at 20:30.

(I presume that radio-active material went out at this time with the smoke.)

Black smoke suggests carbon from organic material such as cable insulators. There are many cables under the bottom of RPV for the control rod drive mechanism and neutron detectors, as shown in the lower-left photo. As Report-1 explained, hot fuel broke the instrument tubes, and fell down to the bottom of RPV, and likely burned the cables.
The French national laboratory IRSN 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 shown in the lower-right figure, however, a Japanese national laboratory says that Japanese plants do not use concrete with carbon, and this reaction will not occur.
My intuition says that this black smoke was caused by fire of the cables when hot fuel fell on them.



Bottom of ABWR RPV

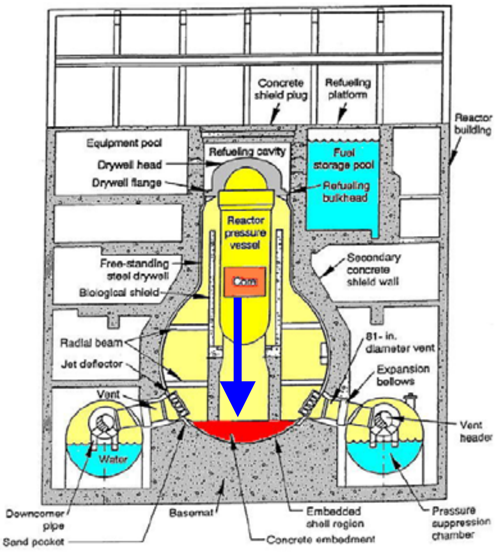
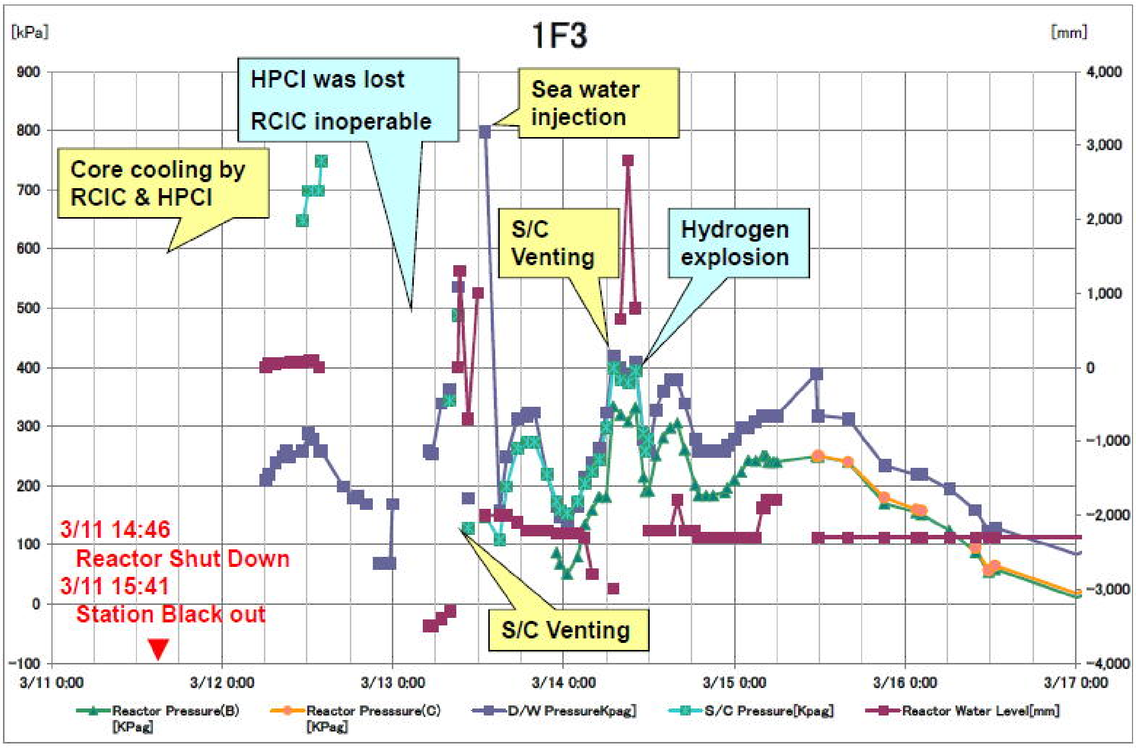


Figure 20. Mark I General Electric,GE BWR Containment.

(Red portion is the concrete floor of PCV.)

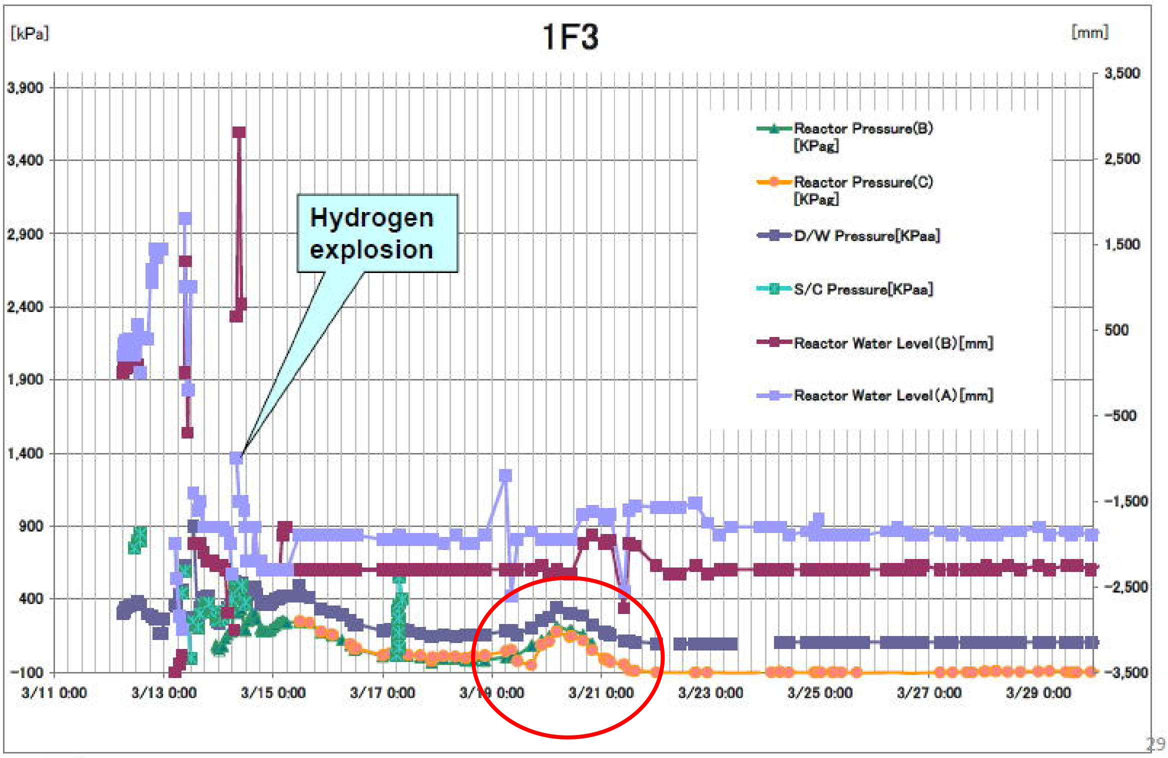
So, my conclusion is that Fukushima-3 is in “half melt-down” status, that is fuel pellets had reached 1,400deg.-C or higher, but lower than 2,800deg.-C. Hot fuel fell to the RPV bottom, opened holes there to fell further to the bottom of PCV.
I presume that the PCV integrity broke on March 21st by a pressure spike. I, however, cannot fully deny the possibility that hot fuel dropped to the PCV bottom to break it, a situation similar to F1.

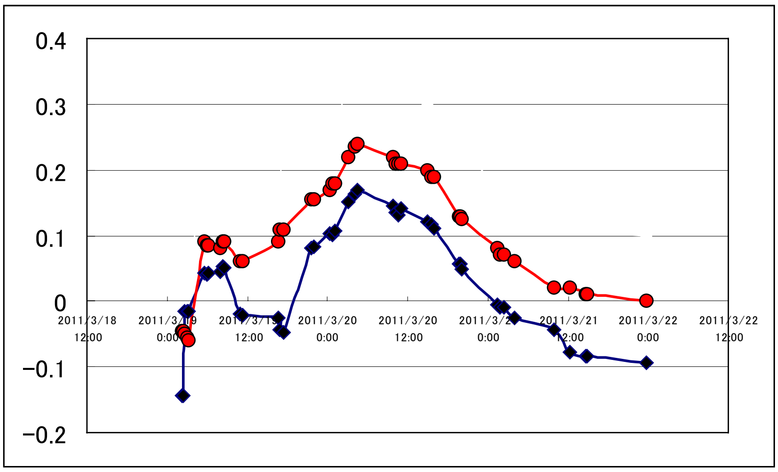
3-13. Trend data of Unit 3 until March 17



(from Governmental report to IAEA)

3-14. Trend data of Unit 3 until March 30





F3 RPV pressure (blue) and PCV pressure(red, gauge)

Detection of plutonium:

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 was no data before March 20th.

Pu-238 : (5.4±0.62)×10-1 Bq/Kg-soil

Pu-239,Pu-240 : (2.7±0.42)×10-1 Bq/Kg-soil

(data source: http://www.meti.go.jp/press/20110328011/20110328011-2.pdf)

Spent fuel pool

The hydrogen explosion on March 14th dropped concrete panels and iron framework in the spent fuel pool, and we cannot see if the fuel bundles are intact or not. Cooling function for the spent fuel was lost on March 11th, but sea water was injected after March 13th. Decay heat in F3 spent fuel pool is not large and I believe cooling function was maintained.

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 was 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 F3 spent fuel are intact.)