Fukushima Accident Summary(1)

2011-June-26, Ritsuo Yoshioka

(Blue-colored note is Yoshioka's comment)

1) Earthquake and Tsunami

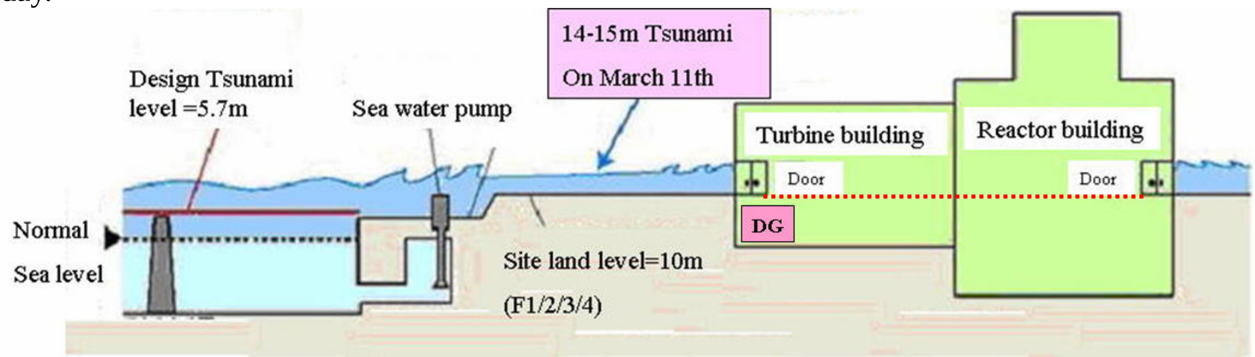
At 14:46 on March 11, the 2011 Tohoku Pacific Earthquake hit the ocean at about 80miles off the shore of northeastern Japan. Its magnitude was 9.0.

All the reactors of F1 (Fukushima-unit 1), F2, and F3 scrammed to fully insert all the control rods. Meanwhile, F4/5/6 were in their periodic inspection stages. The facilities to receive the external electric power for F1/2/3/4 were all destroyed by the earthquake because they were designed to withstand the lowest seismic level (current Japanese licensing criteria).

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 several days after the earthquake, and we might 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.

Then, a huge 14-15 meter Tsunami attacked several times between 15:27 and 15:41 on the same day.

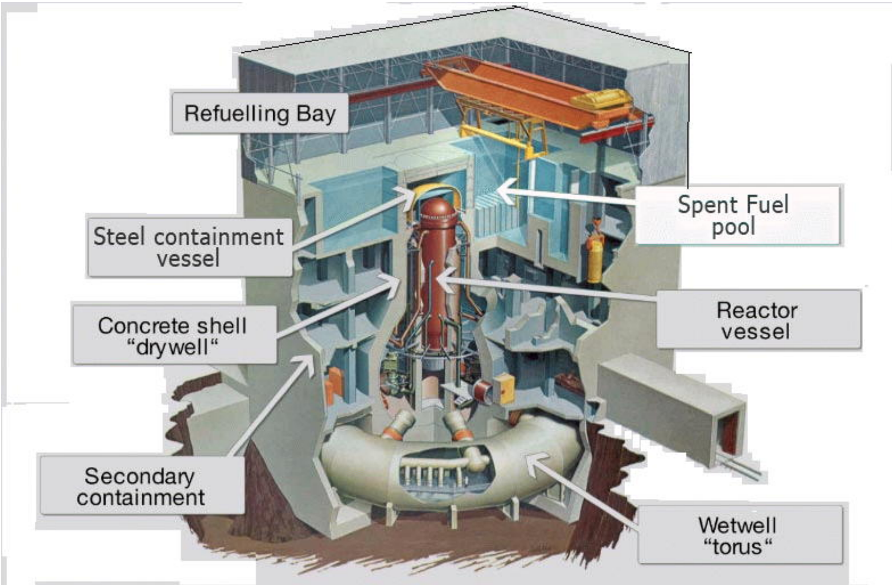


The tsunami flooded all but one DGs. That is, they were all installed in the basement of turbine buildings except the one survived, which was in the reactor building. The reactor buildings are believed to have withstood the tsunami. (The seismic design level of the turbine building against earthquakes is the lowest. Why the manufacturers installed the DGs in their basement is unclear. As a hindsight, they had to design correctly.)

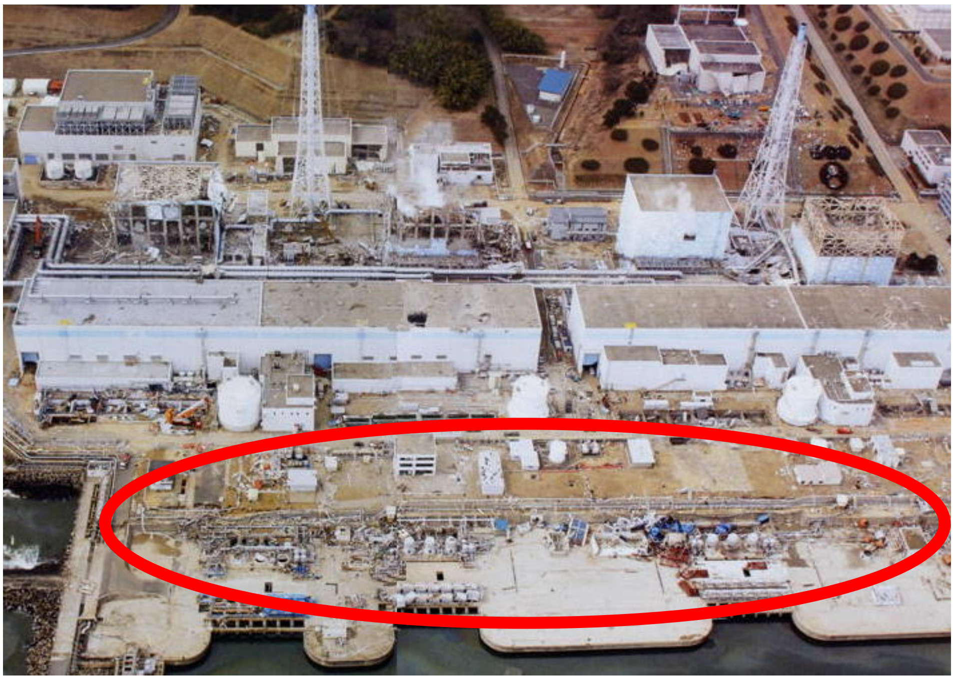
Among all DGs, 3 were air-cooled and one of the air-cooled ones was installed in the reactor building of F6. This was the only DG that survived the tsunami, and it saved F5/6.

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 F3/4, however, they were designed for cooling pumps control and not for their operation. Therefore, core cooling function was lost for F1/2/3, and fuel pool cooling function was also lost for F1/2/3/4.

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



The heat transferred to the water (about 2,000 to 3,000 tons) in the suppression chamber then would have to move on somewhere, and that destination normally would be the sea, the ultimate heat sink. Since the tsunami had destroyed most of the sea-water cooling systems, it was clear that the core cooling function would be lost sooner or later.

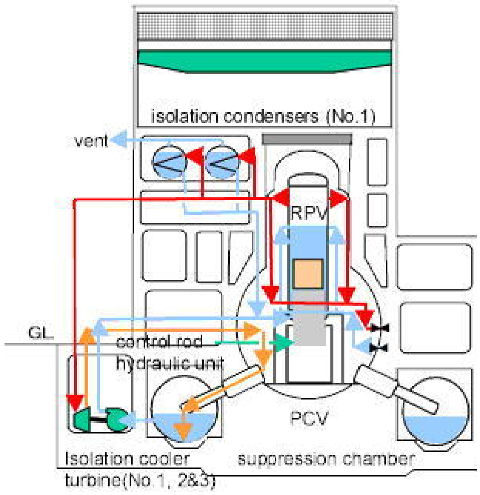


Fukushima 4/3/2/1 (sea-water cooling systems were destroyed)

2) Fukushima-1 Reactor

Melt-down process

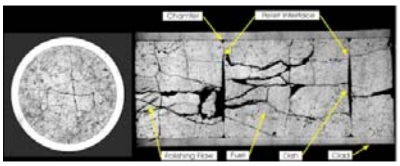
March 11th

14:52	Although all AC power was lost, the Isolation Condenser (IC) had started. IC does not require electricity for circulating cooling water. IC was installed on the 4th floor of the reactor building. How long the IC worked remains unknown. Its designed running time was 8 hours. The batteries in the basement of the turbine building were also hit by the tsunami. (But, I presume the IC repeated run-and-stop several times for several hours by TEPCO people.)	

Since the core cooling function was insufficient, the fuel temperature increased, and the fuel failure began.

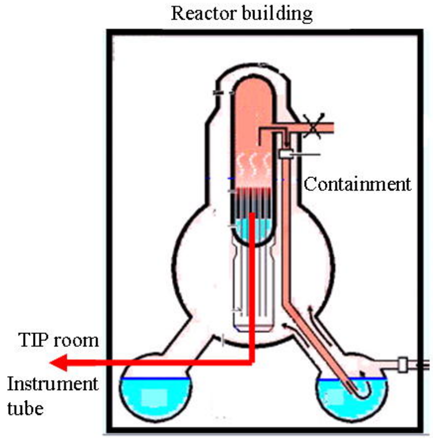
21:51	High radiation level (290mili-Sievelt/hour) was measured in the reactor building. So, the entry to it was prohibited. (The high radiation indicates cracking of fuel cladding tubes, and radioactive gas release from the fuel to outside of the containment. The leak path is not clear.)

March 12th

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 breaks at 0.55MPa. So, after this point in time, PCV venting was possible (See the description at 10:17).
01:48	Finally, the IC stopped, and water level decreased. (Core degradation (:core damage) 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). Fuel pellets, after being irradiated in the core, crack into fragments and particles (see the next photo).  Also, the following chemical reaction generated a large amount of hydrogen. $Zr + 2H_2O = ZrO_2 + 2H_2$
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 was broken, and its pressure dropped to the same with PCV.)

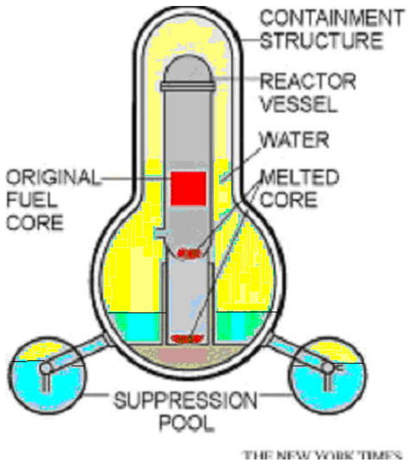
Broken place of RPV:

There was a fact that very high radiation was observed at TIP (Traversing In-core Prove)-room of F1. The instrument guide tube is a weakest point at the bottom of RPV, as is shown in the ORNL report: "Identification and Assessment of BWR In-vessel Severe Accident Mitigation Strategies."
(So, I 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.)



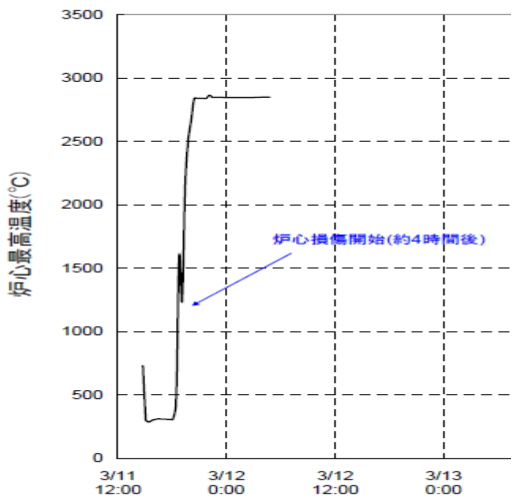
New York Times, in its April 4th issue, reported information from NRC. The article with the figure to the right described that fuel fell down to the bottom of RPV in the form of fragments and particles of fuel pellet.

Since the bottom of RPV was broken, fuel fell further down to the bottom of PCV.
(I consider that this is the current F1/2/3 situation.
Water level within PCV is my estimate.)



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 reached 2,800deg.-C during the night of March 11th, and all fuel 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. I 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.)

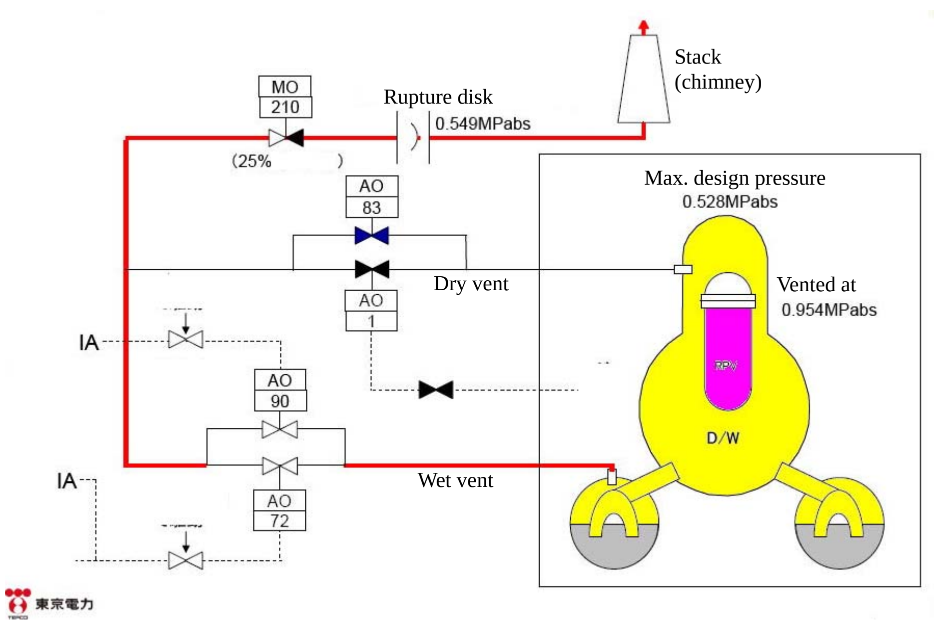


F1 max. fuel temperature

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 ~~1,390~~ 988deg.-C, and this was an evidence that fuel pellets reached above ~~1,390~~ 988deg.-C. The reason why the Government did not immediately open this information is not clear. (If this news had become open on March 12th, the following remedies might have been better, or at least we could have recognized the status of the reactors correctly.)

So, my conclusion is that Fukushima-1 is in “half melt-down” status, that is fuel pellets had 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 broken by hot fuel.

PCV venting

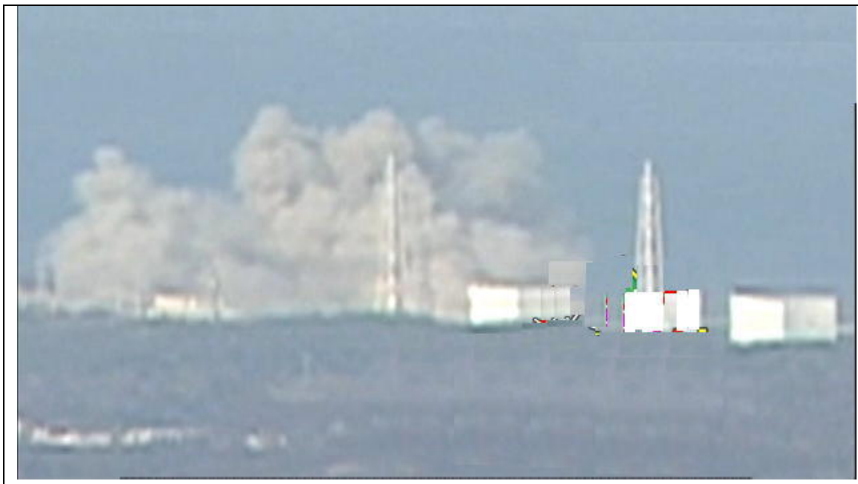
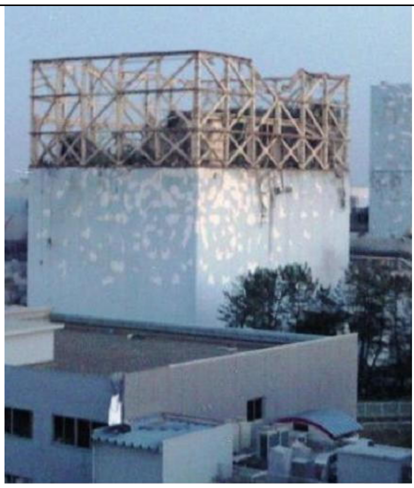
10:17	PCV venting was tried (wetwell vent) TEPCO had to open 2 valves to vent, one is MO(motor-operated), and the other is AO(air-operated), after the PCV pressure had reached the rupture disk breaking point. It took TEPCO long 9 hours to start venting because opening these 2 valves was very difficult due to loss of electricity and high-radiation. There are 2 routes for venting, but TEPCO basically applied the venting from wetwell (so-called wet-venting).  F1 vent route (Figure from TEPCO)
14:30	PCV venting succeeded. (Pressure decreased)
14:53	Fresh water injection stopped (Cause is not clear).

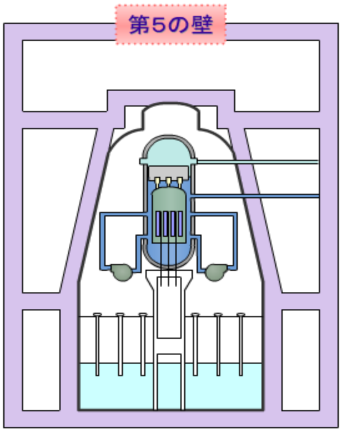
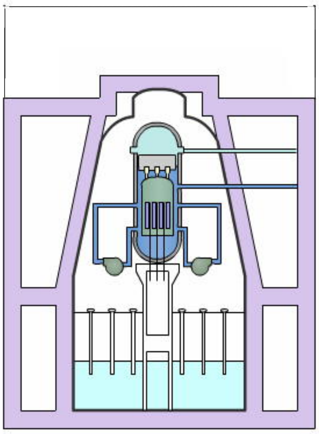
The purpose of PCV-venting is to release excessive pressure in PCV to maintain its integrity. But, if high-temperature fuel drop to the PCV bottom, its heat will break the PCV. So, PCV-venting is not a key issue when core cooling function is lost.
Meanwhile, PCV-venting releases radio-active material (Iodine, Cesium, Strontium and Tellurium etc. which without venting are contained within the PCV) to the atmosphere through a very tall chimney. The radioactivity results in a widely contaminated area. Actually, this is what happened in Fukushima.

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.

Hydrogen explosion

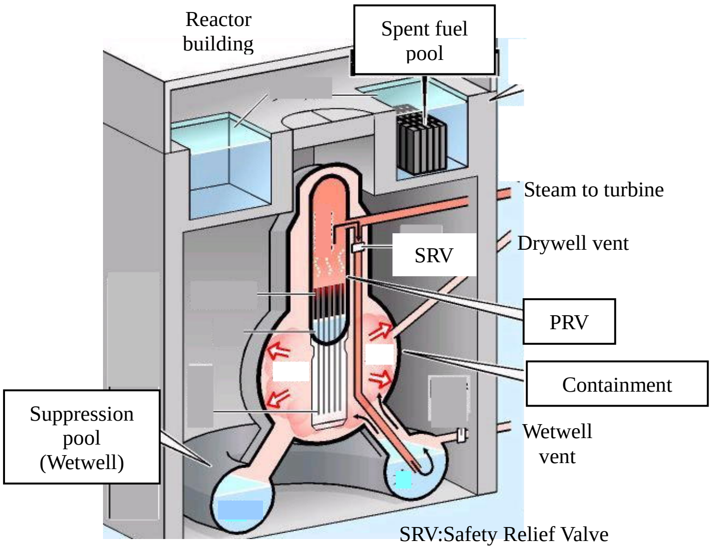
15:36	There was an explosion at the top of reactor building of Unit 1. Concrete panels on the sidewalls of the top floor and top-roof are intentionally made thin. They are designed to rupture in case of pressure buildup in the building after an accident. The rupture keeps integrity of the whole building. (I tried to find veteran GE designers to hear why they applied this design, but no luck here so far. If these walls were thick, an explosion with a larger energy could destroy the PCV.)

 Hydrogen explosion of F1	 Top floor was destroyed

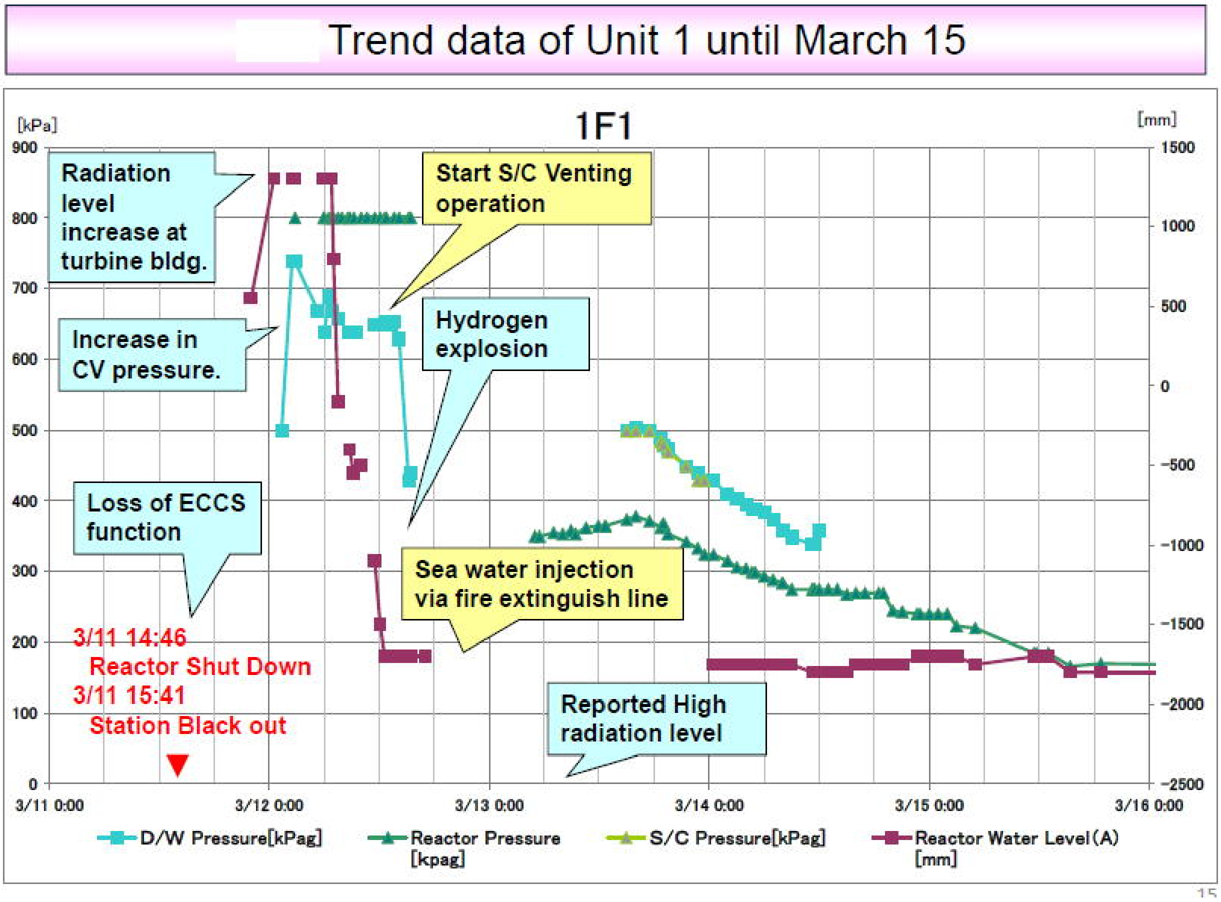
The 5th wall illustration is incorrect.	Actual sizing is as follows.
	

One of the mysteries is the route of hydrogen from the core to the top of 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 there. So, the hydrogen gas made its way to the upper wetwell and drywell. Venting of PCV is believed not to have contributed to this travel, because the vented steam and hydrogen gas went directly to the atmosphere through the chimney.

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. Overpressure might accelerate this phenomenon.
Another cause is the small size of hydrogen gas molecules. They can easily penetrate PCV walls.
(The hydrogen explosion gave a big impact to the public because it looked like an explosion of the reactor itself. Of course, it was not.)



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.



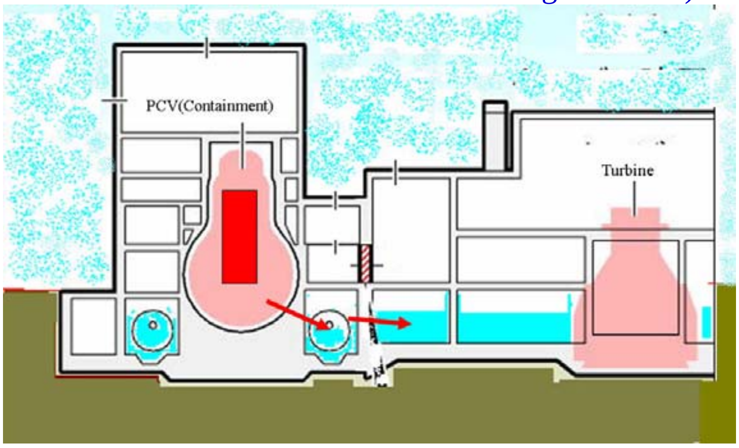
(from Governmental report to IAEA)

Since there was a hole 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. But, almost all water went out through holes in RPV and PCV, so TEPCO gave up the idea of filling up the PCV.

Radio-activity measurement was conducted with the water in the basements of the reactor and turbine buildings. The measurement detected Iodine-131, Cesium-134/137 and low level Strontium-89/90. Vaporizing temperature of Strontium is 1,382 deg.-C.
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 the reactor and turbine buildings would allow the water to reach the basement of the turbine building.

(Nuclear fuel material such as Uranium/Plutonium has not been found in the above water, but I guess since fuel fragments fell to the PCV and there is a break in the PCV, these materials could go out with water. TEPCO is now testing the circulation system for the contaminated water. If it fails, another disaster of sea contamination will strike soon. We need good luck.)



As for the spent fuel pool, the situation is not clear, because the roof panel fell down into the spent fuel pool, and we can not see fuels there. The pool is at least being cooled.