Fukushima Accident Summary(4)

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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 fuels in the core had been moved to the spent fuel pool in preparation for the maintenance within 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. The figure below shows decay heat curves by Shure adopted by America Nuclear Society (ANS) [1] and a slightly different curve by Atomic Energy Society of Japan (AESJ) [2]. With rated thermal power of 2,381MWth from 548 fuel bundles [3], the rated thermal power per fuel bundle is 4,345kWth. F4 was shut down on Nov. 30, 2010 for periodic maintenance [4], and the figure below 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. 0.6275kWhr of heat evaporates 1kg of water at 100 degrees Celsius, thus, 221tons of water evaporates 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.

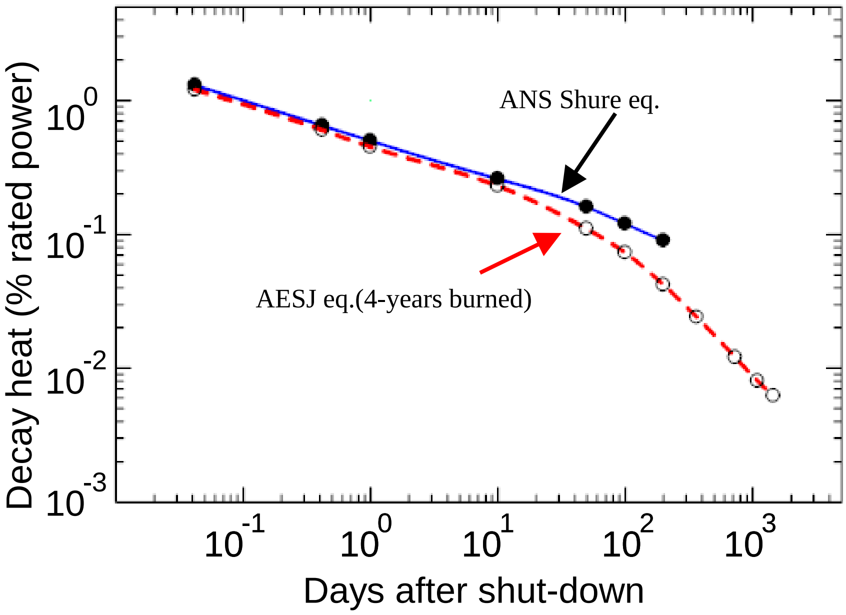

Figure Decay heat curve after shut-down

There are many risks associated with the spent fuel pool, but they are not well known in Japan. A US-NRC document[5] describes the number of hours allowed after loss of pool cooling. The next figure 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 has started, fuel is cooled only by air, but inefficient air-cooling will let a melt-down process start within 5-hours, as the 2nd figure 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.

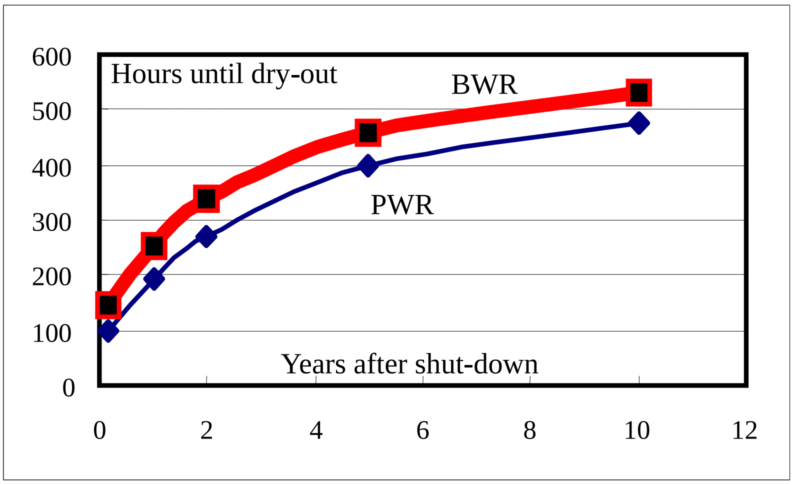

Figure　Hours until dry-out with different cooling time

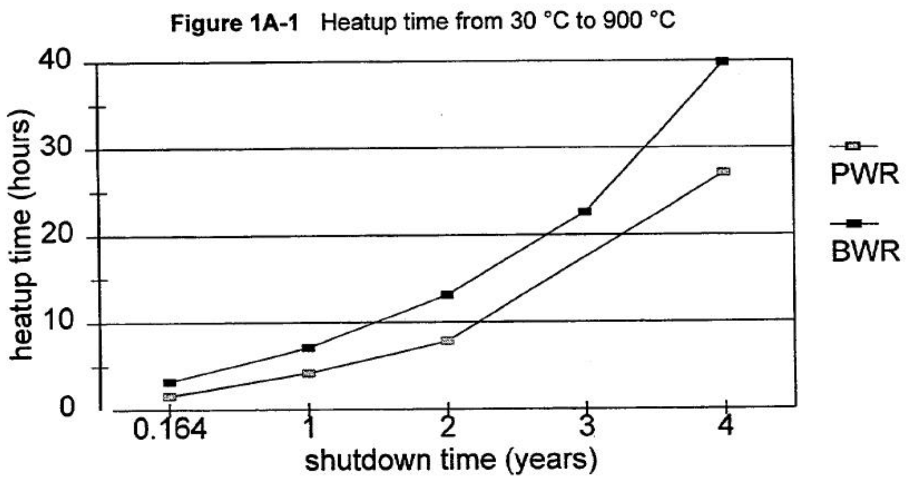

Figure　　Hours until 900deg,-C on air-cooled fuel

On March 15th 06:14, there was a hydrogen explosion at the top of reactor building of F4, and the first news said that there was a big hole at 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 20th photo below shows a square opening on the 4th floor.

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 may have caught on fire due to the high temperature in the spent fuel pool.

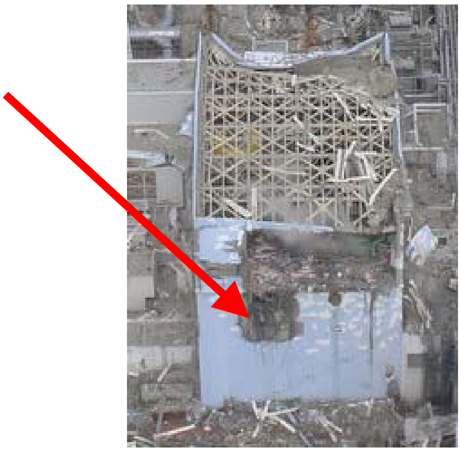

Figure　　Photo of F4 on March 20th.

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 March 24th photo of F4 shows the structure. This suggested 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.

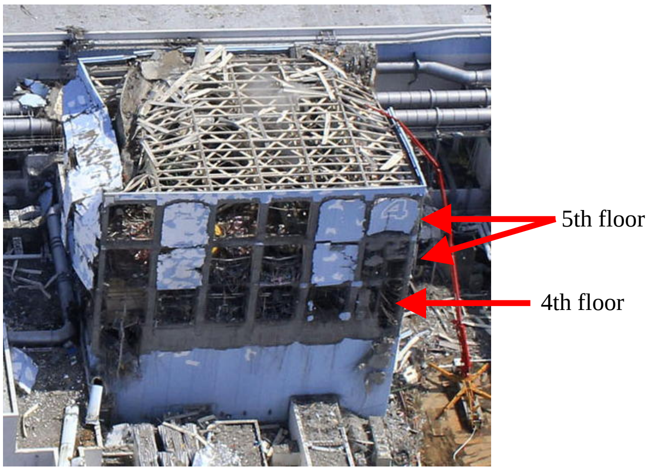

Figure. Photo of F4 on March 24th.

Since all fuel bundles in the core had been moved to the spent fuel pool, the pool gate was closed as the next figure shows. When the pool water level dropped and hydrogen explosion occurred, this pool gate might have been damaged to allow water from the DS pool (Dryer-Separator 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.

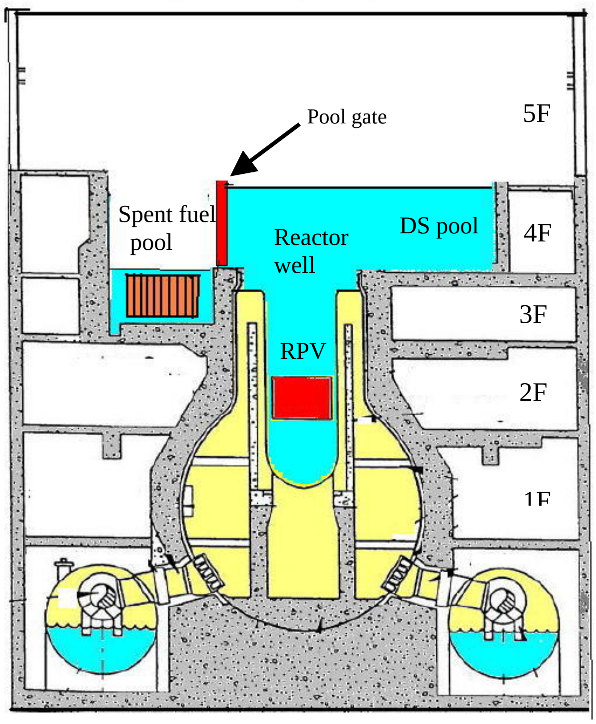

Figure. Water inventory of F4 before explosion

On April 29th, TEPCO showed a photo of the F4 spent fuel pool. It shows that the fuel racks, which separately hold each fuel bundle, were intact. But, we can not 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.

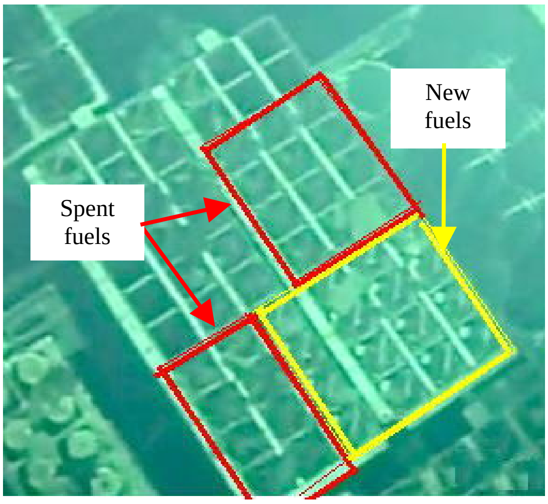

Figure. F4 spent fuel pool on April 29th

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 was almost 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 on 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(Diesel Generators) except one became unavailable.

Table. Location of DGs with each Fukushima plant : [6]

Reactor No.	Basement of turbine building	Other location
1	2	---
2	1	1 at spent fuel common pool (air cooled)
3	2	---
4	1	1 at spent fuel common pool (air cooled)
5	2	---
6	1	2 at basement of reactor building (1 is air-cooled)

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. This DG saved F5 and F6.

4. Conclusive summary

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

As a conclusive summary of the Fukushima accident on F1/2/3/4, the earthquake and tsunami caused a Station Black-Out and loss of sea-water cooling system. So, core cooling and spent fuel pool cooling functions were lost. There were some small contribution 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 process, and then hydrogen gas was generated. We do not know the actual status of fuel damage, but we presume that fuel pellets fell down in fragments and particles at high temperature, in an optimistic case. Anyway, they fell down to the bottom of the RPV and bottom of PCV.

Once fuel dry-out process had started, hydrogen explosion was inevitable. The risk of hydrogen explosion within a reactor building has not been recognized seriously in nuclear plants so far. 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 hydrogen explosion. So, there was no way to avoid the hydrogen explosion.

Radio-active isotopes measured so far are Iodine, Cesium, Tellurium and Strontium, all soluble to water, and they went out from the reactor to the environment by PCV-venting and hydrogen explosion. They have caused a wide area of contamination in the soils around 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 accident process, there might have been some delay but without any affect on the accident process. So, essentially there was 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. So, we believe that they did their best effort. Actually, if they had failed to inject water (either fresh water or sea water) for the first 3 weeks in any of 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 (International Nuclear Event Scale) and the same level with the Chernobyl accident. Although severe core damage occurred with 3 reactors in Fukushima, there were some differences from Chernobyl.

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 observations of symptom tell that there was 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 (or oxide) uranium, which is another requirement for steam explosion.

Acknowledgment

The authors appreciate members of the Association for the Study of Failure, especially for helping us understand the accident situation with a wide range of industrial knowledge.

References

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[2] “Decay Heat and its Recommended Value”, in Japanese, Atomic Energy Society of Japan, 1989

[3] “Fukushima Nuclear Power Station 1 Facility Data”, in Japanese (http://www.tepco.co.jp/nu/programs/viewf1-j.html)

[4] TEPCO Press Release, Nov. 29, 2010, “Periodic Maintenance of Nuclear Power Plant Fukushima Unit 4”, in Japanese (http://www.tepco.co.jp/cc/press/10112901-j.html)

[5] “Technical Study of Spent Fuel Pool Accident Risk at Decommissioning Nuclear Power Plants”, NRC, NUREG-1738, 2001

[6] Chubu Electric Power Co. Press Release, April 6,2011, “Countermeasures at Hamaoka Nuclear Power Plants for Tohoku Earthquake”, in Japanese (http://www.pref.shizuoka.jp/bousai/event/documents/siryou3-4.pdf)