

A quick summary of the Japan nuclear power plant situation after the earthquake/tsunami last Friday

Arthur Motta, 3/12/11, revised 3/16/11

{Please note that the summary and discussion that follows is only based on reports from media, TEPCO, and on bulletins from agencies such as NEI, ANS, IAEA; we will make efforts to make this as accurate as we can, but considerable uncertainty exists; please send any corrections to atm2@psu.edu}

Update 3/28/2011

The situation is still fluid and requiring further work for stabilization, but has improved from last week. Some good news:

1. Power is being gradually restored to the nuclear power plants. If the cooling systems are functional this will allow the temperature in the spent fuel pools to be maintained without need for additional water injection.
2. Monitoring of radiation doses at the Fukushima-Daichi site boundary has shown only slightly elevated radiation levels. The radionuclides detected offsite so far have only been volatile nuclides, such as I and Cs.
3. Fresh water injection is now replacing the sea water injection into the reactors.

Not many detailed updates on the status of the spent fuel pools have been given, but water injection continues. Stabilization of the spent fuel pools is a really important job at this point.

The table of summary update reports from JAIF has now reported that hydrogen explosions did occur in the spent fuel pool of reactors 3-4, suggesting a substantial amount of reaction of the zirconium alloy fuel rods with the pool water. It is unclear to what temperature the fuel rods reached and what degree of fuel damage occurred.

The work at the plant will likely still last a good while. Reports of contaminated water and hot spots inside the plant are expected, given the amount of damage that the plant has sustained. The status of the reactor pressure vessels is still uncertain, and small leaks could exist, but still no evidence that large scale releases have occurred from the vessels. The containment of reactor 3 is now found to be undamaged. Containment pressure in the 3 reactors is now stable or decreasing.

Workers are trying to re-establish reactor functions, while working in dangerous conditions. One can imagine the dangers of working with electricity in these conditions. Reports of radiation levels 10 million times above normal contamination in the reactor water were later reported to be caused by a mistaken calculation.

During the week low level contamination of spinach and milk and the Tokyo water has been reported, but these are not high levels of radioactivity. Such findings could continue

over the next few weeks, and the dispersion of radioactivity will not necessarily be homogeneous.

Updates: 3/18/11 at 1 pm: Dose rate at reactor 3 at 2.5-5 REM/h. At the site boundary, 0.002 REM/h. Electrical cables being installed in units 3 and 4.

3/18/11 at 10:30: The reason it is difficult to fill the pool of number 4 with water is the extensive damage to the reactor building which does not leave a “clear shot” at the pool. This morning The Federation of Electric Power Companies of Japan (FEPC) has indicated that a flyover with helicopter showed water in the pool of unit 4.

Here is a quick summary of the sequence of events:

1. An earthquake of 9.0 hit Japan near Sendai: When the earthquake happened, the plants that were in operation at the time were immediately shut down (scrammed by insertion of control rods). In such a circumstance, the fission reaction stops, but the radioactive products continue to decay and release heat. This decay heat is on the order of 8% of the thermal power of the unit (decreasing exponentially with time, see below), so, for a 3000 MWth plant this would amount to about 240 MW. For Fukushima unit 1 (460 MWe), this is on the order of 1380 MWth, or about 100 MW.



2. Damage to diesel backup generators occurred: This amount of decay heat power requires forced convection of coolant for heat removal. Offsite power is assumed to be lost (as it was in this case) and diesel generators start which can provide enough power to run the pumps. The problem is that after about 1h the diesels stopped working, possibly because they were damaged in the quake, but principally because their fuel supply was damaged by the tsunami. Reports are that in addition to the above, the earthquake may have caused damage to the piping and causing small leaks in the reactor cooling circuit, but the status of this is unknown.

=> Note that for the Onegawa site and (mostly) for the Fukushima Daini site, the accident stopped here when the backup systems kept on working after the tsunami. Both are in cold shutdown, from what I understand. The following comments now refer to the **Fukushima-Daichi** plants, units 1-6. At Daichi, units 1-3 were in operation, unit 4 was on an outage, so its fuel was in the pool and 5 and 6 were in maintenance. For the

operating reactors (1-3) the main issue is then to cool the core. For unit 4 the main issue is the status of the fuel in the pool.

3. Loss of power caused cores to be uncovered: For the operating reactors at that point, if no circulation is re-established, the temperature of the coolant keeps increasing inside the pressure vessel, increasing the pressure and causing loss of coolant; but several hours should pass before the core is uncovered (during which time in a normal situation, one would expect backup sources of power to be available.) The situation is different in each of the individual reactors, but in at least a couple, part of the core appears to have been uncovered. This leads to an increase in temperature of the fuel cladding (Zr alloy) which reacts with water, and forms hydrogen. The decreased strength of the material at high temperature may also cause it to distort or balloon under internal pressure. The fuel rod containment of fission products is then lost, and fission gases, especially can be released. This release is not to the outside but to the primary coolant circuit.

4. Venting of gases causes hydrogen explosion: As the pressure went up further, the operators decided to vent gases to reduce pressure into the secondary containment (the reactor containment consists of a stainless steel dome and a concrete building). In units 1 and 3 the concentration of hydrogen in the containment reached an explosive mixture and the gas exploded, damaging the building but leaving the containment intact. The presence of hydrogen in the containment and the detection of Cs-137 in the plume outside the reactor are both strong indicators of cladding breach and fuel damage. The extent of the damage is not known. It could be a partial meltdown as in TMI or it could be a few failed rods that have cracked open. Although the destruction looks terrible, these explosions actually have little impact on the ability of the reactor to contain the fission products.

4a. Explosion in reactor 2: A subsequent event involving loud noises in the torus shaped suppression pool system occurred in reactor 2 Mon to Tue, which is suspected to have damaged the containment (barrier 3). The origin of this event may also be hydrogen accumulation. Recent NEI/TEPCO reports state that there may be no damage to the containment.

5. Borated Seawater Injection: TEPCO (Tokyo Power) has been injecting borated seawater into the cores of units 1, 2 and 3 to keep the fuel temperatures down. Boron is a neutron absorber and helps keep the reactor sub-critical. The fact that such a corrosive substance is being injected in the core appears to signal that TEPCO has given up on ever restarting these plants. Again, this is really an acceptable outcome, if radioactive release are thereby averted.

The Current situation (Thu 3/17/2011)

To understand this accident and its consequences, we have to think that the nuclear power plants in question were designed to withstand about a 7.0 to 8.0 magnitude earthquake, instead of a 9.0, to which this one has now been upgraded (the 3rd largest earthquake in the last century). In those extreme conditions, it is not expected that the plant will survive intact, but it *is* expected that its multiple safety features will stop widespread releases of radioactivity to the public. The design-basis earthquake is supposed to be withstood with the plant intact. The larger safe-shutdown earthquake assumes plant damage, but, as the name implies, safe shutdown. If this can be achieved in this case, the plants will have performed their public protection function. To understand whether this is being achieved, here is a quick review of defense in depth.

The Defense in Depth concept

What is being tested in this beyond design basis accident is the defense in depth concept. The defense in depth concept is based on placing multiple independent barriers between the radioactive elements and the public. In principle, in the case of an accident, any of these barriers can independently prevent release of radionuclides to the public, and conversely all would have to be breached for release to occur. In the case of the light water reactors such as the ones in Japan, the barriers are:

1. **The fuel itself:** The fission products and transuranic elements produced during the fission process (and which constitute the dangerous material to be kept away from the public) are mostly dispersed in solid solution within the uranium dioxide ceramic fuel pellets (Fig. 1 (a)). Thus, to disperse most of these fission products in solid solution it is actually necessary to melt the fuel. These fuel pellets are placed within rods (long skinny tubes) made of a zirconium alloy, Fig. 1 (b). The term “fuel damage” refers to damage to this first barrier and can range from a small mostly closed crack to fuel distortion ballooning, and ultimately melting. These fuel rods are made into fuel assemblies (Fig. 1 (c)) and tens of fuel assemblies constitute a reactor core (Fig. 1(d)).
2. **The pressure vessel** and associated cooling circuit. The pressure vessel contains the coolant water under pressure and provides the means to circulate the water through the core. It consists of a 7 inch thick ferritic steel wall, lined with stainless steel for corrosion protection (see Figure 2 indicated).
3. **The reactor containment** is an airtight steel structure which encloses the reactor pressure vessel and is sealed off from the outside atmosphere. The particular containment in the BWR reactor of the generation of the Japanese reactors in question has a smaller volume than the more common PWR (see indication on Figure 2).

Defense in depth also involves the use redundancy (multiple systems that can each do the job), diversity (several systems not subject to common cause failure), and generation of possible scenarios and examination of worst case scenarios and its consequences.

Current state of the barriers

In the Japanese reactors, some damage to the fuel (barrier 1) has been confirmed. Such damage also occurred in Three Mile Island, where about half of the core melted and ended up as rubble inside the pressure vessel. It is not clear how much damage has occurred to the fuel in the various Japanese reactors, however even for the very extensive damage sustained in TMI, the fuel was contained inside the second barrier (pressure vessel) and the only releases to the public came from the venting operations described below, and which were minor. The question of releases then lies on the integrity of these two barriers. There are now reports of “suspected damage” to the third barrier (the containment) in Unit 2 and 3 according to TEPCO. It is unclear whether the pressure vessels in question have sustained any damage. If these barriers can hold, there should be no major radiological consequences from the damage to the reactors. So far they appear to have held.

The most recent update (NEI website at the end of the article as of 11:35 am Thu Mar 17) says that the reactors 2 and 3 are stable and are being cooled by seawater.

The Spent Fuel Pools

Recent reports have indicated concern over the status of the spent fuel pools in these reactors. The spent fuel pool is the place where the spent fuel is stored after discharge from the reactor, providing both cooling (spent fuel still generates decay heat) and shielding from the radioactive decay particles. If the spent fuel pool can remain filled with water, then there is little concern. Conversely because these sit outside the containment, there is little protection against their release.

Depending on how “freshly out of reactor” the fuel is, the heat generation is higher or lower and again heat removal is needed, or in its absence the temperature will rise and the water could boil away. It is not clear at this point what the difficulty is in securing a water supply to these pools. The NRC chairman has stated (I could not find the basis for his statement) that the spent fuel in unit 4 is or was dry. This has been vigorously denied by the Japanese.

The most recent report (NEI website below as of 11:35 am Thu Mar 17) says that although the level is low, there is water in the pool, some was added by helicopters and some by water cannon. One of the pool walls has collapsed, but the steel liner is still present. There is apparently some difficulty in getting water into the #4 pool from afar due to structural damage of the building leaving no “straight shot” and it is difficult to approach because of high radiation fields.

Off site power has been reported to be on the verge of being restored; it is unclear how much this will help, although in the unlikely event the coolant circuits for the reactor and the spent fuel pool are still operational this would be a big step ahead. The more time passes, without further events, the situation should improve as more help becomes

available, and, importantly as the decay heat continues to decrease exponentially. **Figure 3** shows the decay heat curves after different reactor operation times. If the reactor is at steady state (upper curve in the **Figure 3**) one can estimate the decay heat reduction after shutdown. The decay heat now is likely more than a factor of 10 less than when the plant was shut down (on the order of 0.6% of the original thermal power, or about 15 MW for the previous example, and about 9MW for Fukushima-1) and will continue to decrease.

Fires and aftershocks

Several aftershocks have been recorded making the workers task more difficult. In large industrial complexes such as this, one would expect that the earthquake devastation could cause fires, which has indeed happened. A fire was reported near the spent fuel pool referred to above, which has since been extinguished and which has been attributed to an oil leak in a pump casing.

Dose Measurements

Radiation is invisible, but can be detected at extremely low levels, so small increases can be seen even as far away as Tokyo. A wide variation of measurements have been reported. Reported punctual measurements have been as high as 40 Rem/h between units 3 and 4 on Monday. This is a very high dose rate (for comparison, the NRC only allows 5 Rem/ year to nuclear workers). It is not clear what is the reliability of this measurement, the origin of the radiation, its chemical type and whether this was contamination or airborne. I have also not seen it confirmed so it should be used with caution. The majority of the other dose measurements at the plant boundary are lower, although still elevated compared to natural background. The workers at the plants may be getting higher doses than normal; the Japanese have increased their dose limit to 25 REM (from 10).

=>Note that only volatile elements such as Cs and I have been reported so far, which is good, as the presence of other elements would indicate more severe fuel damage.

Current reported exposures of 100 millirem are more or less equivalent to five x-rays, or about a third of the annual natural background in the US. One worker has reportedly received 10.6 REM, which is roughly twice the allowed dose for nuclear plant workers per year. One worker has however died from the hydrogen explosion.

Radiation dose units: 1 REM=0.01 Sievert (Sv) = 10 milliSievert = 10000 micro Sv;
1 Sv = 1 J/kg

The Toll of the accident so far

According to reports at least one worker was killed during one of the hydrogen explosions and 11 others injured in another explosion. There may have been other casualties of which I am not aware. The earthquake/tsunami event itself of course claimed many lives. A partial injury list is at

<http://www.tepco.co.jp/en/press/corp-com/release/11031803-e.html>

Overall Outlook:

Japan has suffered a very large combination of natural events reasonably well, although thousands of people are dead or unaccounted for. The nuclear power plants were stressed much beyond their design basis accident suffering extensive damage. The defense in depth so far has fulfilled their mission of protecting the public from radioactivity, although the plants may be scrapped and some radioactive releases have occurred.

1. The main concerns at this point are the status of the spent fuel pool in unit 4 and the cores in units 2 and 3.
2. For the units 2 and 3 indications are that the pressure vessels are holding, with the injection of sea water keeping the damaged fuel cooled.
3. The spent fuel pool has been reported to have water and an intact steel liner, with various attempts being made to supply more. In this case also time is an ally as the fresh fuel activity decays further. A disagreement exists between NRC and Japan on the level of water and damage to the spent fuel pool has not been resolved yet.
4. It is important to note that even a breach of the barriers does not automatically mean a dose to the public, as the radionuclides would have to be dispersed for that to occur.

At the moment (cross your fingers) the risk of significant radioactive release does not appear high as at least two barriers seem to be more or less intact. As a precaution, evacuations in a 12 mile radius have been ordered, and iodine tablets distributed (this is because saturating the thyroid with non-radioactive iodine is a good protection against retention of radioactive iodine which could be released if the situation were to worsen).

Further information can be found at:

ANS

<http://ansnuclearcafe.org/>

(this has the actual press releases from TEPCO and other sources)

Reactor Status Update: also examine the JAIF updates in table format at the same website. <http://www.jaif.or.jp/english/>

NEI website

<http://www.nei.org/newsandevents/information-on-the-japanese-earthquake-and-reactors-in-that-region/>

(constant updates from Nuclear Energy Institute)

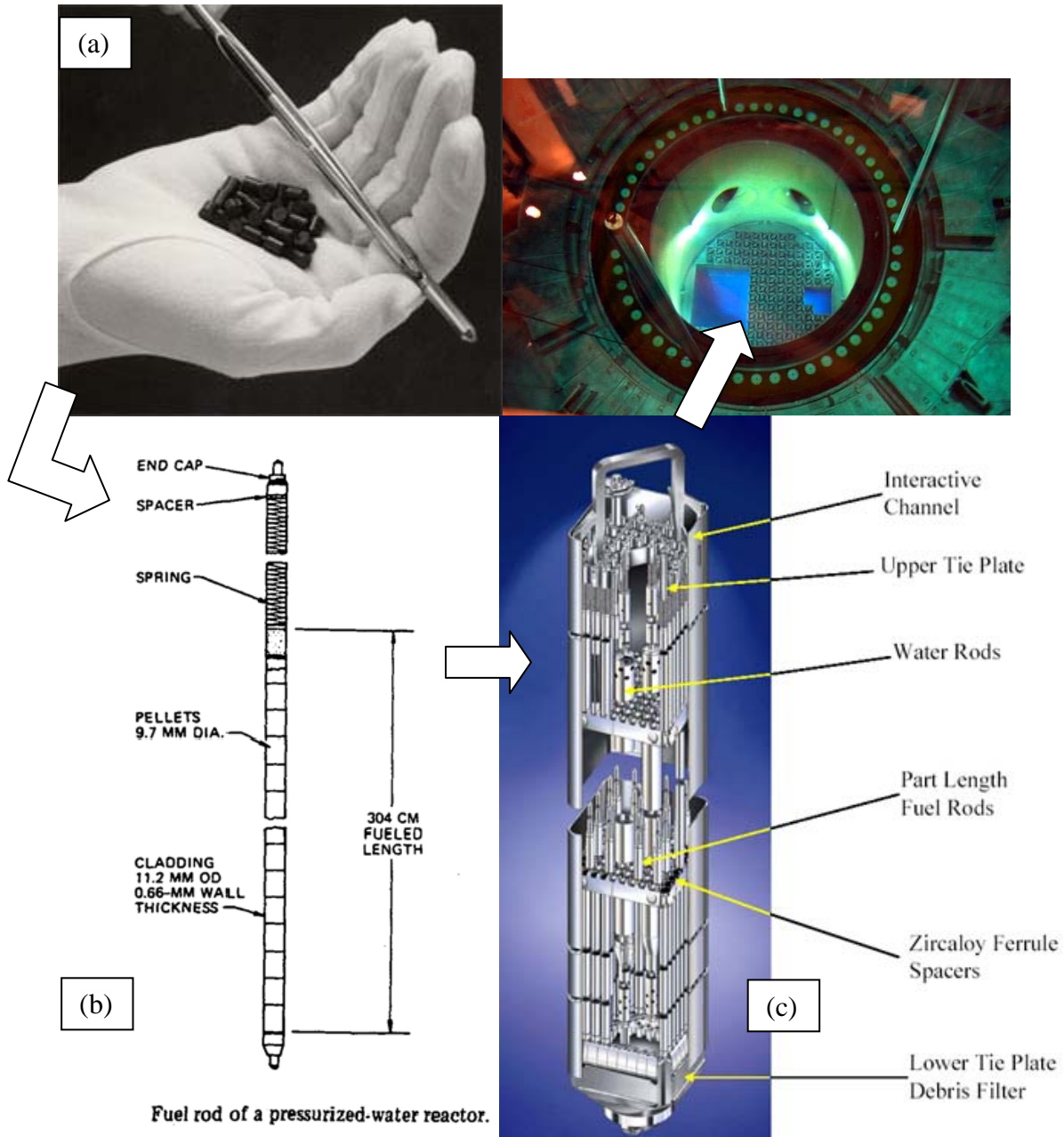


Figure 1: (a) The uranium dioxide (UO_2) ceramic nuclear fuel pellets are inserted into a Zr alloy cladding tube (b), constituting a *fuel rod*, several of which make a fuel assembly (c) and tens of which make a nuclear reactor core (d).

Boiling Water Reactor Design At Fukushima Daiichi

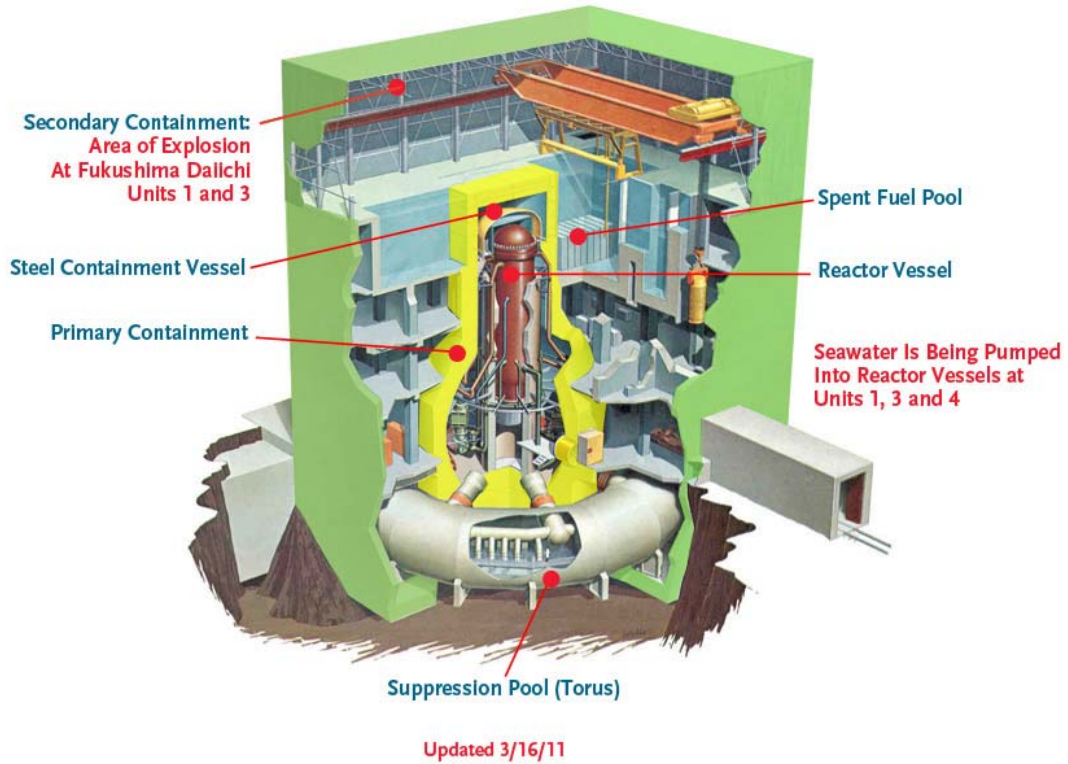


Figure 2: Boiling water reactor and associated containment.

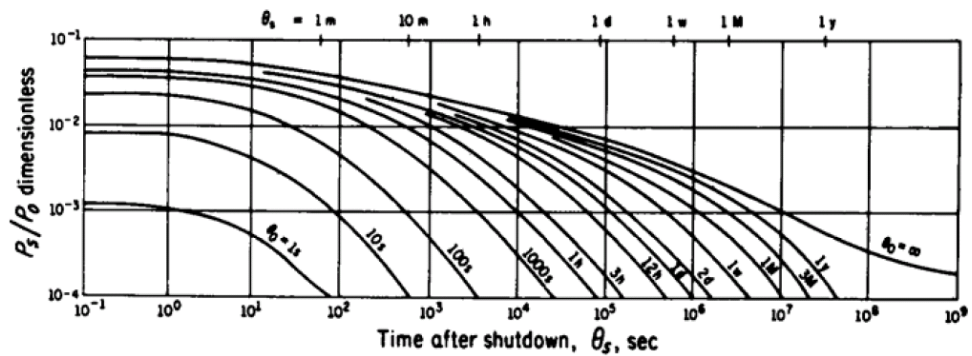


FIG. 4-10. Ratio of power after, to power before shutdown for various operation times before shutdown: s,sec; m,min; h,hour; d,day; w,week; M,month; y,year (Ref. 25).

Figure 3: Decay heat cooldown curves