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Post-Tsunami Situation at the Fukushima Daiichi Nuclear Power Plant in Japan: Facts, Analysis, and Some Potential Outcomes

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Takoma Park, Maryland, March 14, 2011 (completed at 11 pm, EDT, March 13, 2011, with notes at 6:30 am March 14 and later revisions): On March 11, 2011, the Fukushima Daiichi and the Fukushima Daini nuclear power plants (or Fukushima for short) experienced a severe earthquake, followed by a tsunami. This analysis relates to the Daiichi plant, which has experienced the more severe problems as of this writing so far as is known (9 p.m. March 13, 2011 Eastern Daylight Time, United States). Power from the grid was lost, and the reactors were successfully shut down as part of the emergency. But power to operate the site was still needed to remove the heat from the reactors. The Daiichi plant has six operating boiling water reactors. The oldest, Unit 1, which appears to have had a partial meltdown of the fuel, first went critical in 1970 (and was connected to the grid in 1971. Unit 3, which also appears to have had similar problems as Unit 1, whose fuel includes mixed plutonium oxide uranium oxide fuel ("MOX fuel") first went critical in 1976. Both reactors are of the Mark 1 Boiling Water Design. They do not have the sturdy secondary containment buildings of concrete that is several feet thick typical of later reactor designs. (March 14, 6:30 a.m. note: Unit 3 has also experienced an explosion and Unit 2 appears to have lost cooling. The problems described here would likely apply to Unit 3; Unit 2 may be headed to similar problems.)

A special feature of the Mark 1 design is that the used fuel, also called spent fuel, is stored within the reactor building in a swimming pool-like concrete structure near the top of the reactor vessel. When the reactor is refueled, the spent fuel is taken from the reactor by a large crane, transferred to the pool, and kept underwater for a few years. This spent fuel must be kept underwater to prevent severe releases of radioactivity, among other reasons. A meltdown or even a fire could occur if there is a loss of coolant from the spent fuel pool. The water in the spent fuel pool and the roof of the reactor building are the main barriers to release of radioactivity from the spent fuel pool.

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An explosion associated with Unit 1 occurred on March 12, at 3:36 p.m.[2] At first the authorities stated that this was in the turbine building next to the reactor building. However, it is the reactor building roof and part of the walls near the roof that were completely blown off leaving only a steel skeleton at the top of the building. This indicates an explosion inside the reactor building – probably a hydrogen explosion, since hydrogen is much lighter than air, it would accumulate near the top of the building. The explosion therefore seems to have occurred near the level where the spent fuel pool would be located in a Mark 1 reactor.

While Japanese authorities have stated that the reactor vessel is still intact, there has been no word regarding the status of the spent fuel pool structure, except indirectly (see below). Is it still intact? This is a critical question as to the range of potential consequences of the reactor accident.

Hydrogen is generated in a nuclear reactor if the fuel in the reactor loses its cover of cooling water. The tubes that contain the fuel pellets are made of a zirconium alloy. Zirconium reacts with steam to produce zirconium oxide and hydrogen gas. Moreover, the reaction is exothermic – that is, it releases a great deal of heat, and hence creates a positive feedback that aggravates the problem and raises the temperature. **The same phenomenon can occur in a spent fuel pool in case of a loss of cooling water.** In addition, there can be a fire. The mechanisms and consequences of such an accident are reasonably well known. A National Research Council of the National Academies study, published in 2006, is worth quoting at length:

> The ability to remove decay heat from the spent fuel also would be reduced as the water level drops, especially when it drops below the tops of the fuel assemblies. This would cause temperatures in the fuel assemblies to rise, accelerating the oxidation of the zirconium alloy (zircaloy) cladding that encases the uranium oxide pellets. This oxidation reaction can occur in the presence of both air and steam and is strongly exothermic—that is, the reaction releases large quantities of heat, which can further raise cladding temperatures. The steam reaction also generates large quantities of hydrogen….
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> These oxidation reactions [with a loss of coolant] can become locally self-sustaining … at high temperatures (i.e., about a factor of 10 higher than the boiling point of water) if a supply of oxygen and/or steam is available to sustain the reactions…. The result could be a runaway oxidation reaction—referred to in this report as a *zirconium cladding fire*—that proceeds as a burn front (e.g., as seen in a forest fire or a fireworks sparkler) along the axis of the fuel rod toward the source of oxidant (i.e., air or steam)….
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> As fuel rod temperatures increase, the gas pressure inside the fuel rod increases and eventually can cause the cladding to balloon out and rupture. At higher temperatures (around 1800°C [approximately 3300°F]), zirconium cladding reacts with the uranium oxide fuel to form a complex molten phase containing zirconium-uranium oxide. Beginning with the cladding rupture, these events would result in the release of radioactive fission gases and some of the fuel's radioactive material in the form of

[2] Tokyo Electric Power Company, Press Release, "Plant Status of Fukushima Daiichi Nuclear Power Station (as of 9pm [Japan time] March 13th)," on the web at http://www.tepco.co.jp/en/press/corp-com/release/11031310-e.html. These press releases are referred to below as TEPCO 2011, with the date and time of the press release and the URL provided.

> aerosols into the building that houses the spent fuel pool and possibly into the environment. If the heat from one burning assembly is not dissipated, the fire could spread to other spent fuel assemblies in the pool, producing a propagating zirconium cladding fire.
>
> The high-temperature reaction of zirconium and steam has been described quantitatively since at least the early 1960s....[3]

The extent of the release would depend on the severity of loss of coolant, how much spent fuel there is in the pool, and how recently some of it has been discharged. The mechanisms of the accident would be very different than Chernobyl,[4] where there was also a fire, and the mix of radionuclides would be very different. While the quantity of short-lived radionuclides, notably iodine-131, would be much smaller, the consequences for the long term could be more dire due to long-lived radionuclides such as cesium-137, strontium-90, iodine-129, and plutonium-239. These radionuclides are generally present in much larger quantities in spent fuel pools than in the reactor itself. In light of that, it is remarkable how little has been said by the Japanese authorities about this problem. From the tiny amount of information available, it appears that there is a problem of cooling of the spent fuel. According to a TEPCO press release, issued on March 13, at 9 pm, Japan time:

> We are currently coordinating with the relevant authorities and departments as to how to secure the cooling water to cool down the water in the spent nuclear fuel pool.[5]

This indicates that there is a spent fuel cooling problem. But there is no information on how serious it is and whether the pool has been damaged and is leaking. It is reasonable to surmise that pumping seawater into the reactor building from the outside would be directed more at the spent fuel pool than at the reactor. According to TEPCO, the injection of seawater into the reactor vessel of Unit 1 has been successfully done. This also appears to be the case for Unit 3, as of this writing.[6] Boric acid is being added to the seawater to prevent an accidental criticality, which could happen in the reactor or in the spent fuel pool. Venting of radioactive steam from the reactors will likely have to continue.

It is unclear at this stage whether there has been venting of radionuclides from the spent fuel pool in Unit 1. Venting from the reactor has been acknowledged by the authorities. Rather high levels of

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[3] National Research Council, *Safety and Security of Commercial Spent Fuel Storage: Public Report*. Washington, D.C.: National Academies Press, 2006, on the web at http://www.nap.edu/catalog.php?record_id=11263, pp.38-39. This report addressed the issue of terrorist attacks on spent fuel pools and the precautions that might be taken in light of the potential severity of the problem. See below.

[4] The Chernobyl reactor was a very different design – water-cooled and graphite moderated. The reactor itself exploded catastrophically due to a runaway accident in that case. That is not the case at present, where the reactor was shut down successfully almost immediately after the earthquake. At Chernobyl, the graphite caught fire and the fire lasted for ten days. In the case of the most severe spent fuel pool accident, it would be the zirconium that would catch fire, as described by the National Academies study quoted above.

[5] TEPCO Press Release, March 13, 9 pm. on the web at http://www.tepco.co.jp/en/press/corp-com/release/11031312-e.html

[6] TEPCO Press Release, March 13, 9 pm. on the web at http://www.tepco.co.jp/en/press/corp-com/release/11031312-e.html

radiation, over 1,200 microsieverts per hour[7] – which is more than 10,000 times natural background radiation at sea-level – have been reported outside the plant. At this level the *annual* allowable dose of the radiation to the public would be exceeded in less than an hour. Such levels indicate a partial meltdown in Unit 1 and possibly in Unit 3. However, while it seems to be widely assumed that the radioactivity has been emanating only from the reactor vessel (s), it is unclear whether some of it is also being released from the Unit 1 spent fuel pool, which may have been damaged by the explosion.

The consequences of severe spent fuel pool accidents at closed U.S. reactors were studied by the Brookhaven National Laboratory in a 1997 report prepared for the U.S. Nuclear Regulatory Commission. According to the results, the damages resulting from such accidents for U.S. Boiling Water Reactors could range from $700 million to $546 *billion*, which would be between roughly $900 million and $700 billion in today's dollars. The lower figures would apply if there were just one old spent fuel set present in the pool to a full pool in which the spent fuel has been re-racked to maximize storage. Other variables would be whether there was any freshly discharged spent fuel in the pool, which would greatly increase the radioactivity releases. The estimated latent cancer deaths over the years and decades following the accident was estimated at between 1,300 and 31,900 within 50 miles (about 80 kilometers) of the plant and between 1,900 and 138,000 within a radius of 500 miles (about 800 kilometers) from the plant.[8]

The spent fuel pools at the Daiichi reactors contain approximately these amounts: Unit 1, 50 metric tons; Unit 2, 81 metric tons; and Unit 3, 88 metric tons.[9] No mixed oxide (MOX) spent fuel is in the Unit 3 spent fuel pool. The typical U.S. reactor discharges 20 metric tons of spent fuel per year and stores that on site, in almost all cases, in wet or dry storage. The range of consequences in Japan would be somewhat different from those outlined in the Brookhaven report, since the consequences depend on population density within 50 and 500 miles of the plant, the re-racking policy, and several other variables. It should also be noted that Daiichi Unit 1 is about half the power rating of most U.S. reactors, so that the amount of radioactivity in the pool would be about half the typical amount, all other things being equal. But the Brookhaven study can be taken as a general indicator that the scale of the damage could be vast in the most severe case.

One hopes that the spent fuel pool in Unit 1 can be kept full of water and the various reactors can be kept cool enough to prevent much more serious consequences than have already occurred (there has been serious worker exposure and some public radiation exposure already, according to news reports[10]). But the accident makes clear that there is ample information and analysis that very grave consequences are possible from lighter water reactors – which are the designs used in Japan, the United States, and

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7 Hiroko Tabuchi and Matthew L. Wald, "Japanese Scramble to Avert Meltdowns as Nuclear Crisis Deepens After Quake," *New York Times*, March 12, 2011, at http://www.nytimes.com/2011/03/13/world/asia/13nuclear.html viewed at 8:15 p.m. Eastern Daylight Time, March 13, 2011

8 R.J. Travis, R.E. Davis, E.J. Grove, M.A. Azarm, *A Safety and Regulatory Assessment of Generic BWR and PWR Permanently Shutdown Nuclear Power Plants*, BNL-NUREG-52498 and NUREG/CR-6451, Brookhaven National Laboratory, 1997, link at http://www.osti.gov/bridge/product.biblio.jsp?osti_id=510336. Tables 4.1, 4.2.

9 Aileen Mioko Smith, speaking at the Friends of the Earth press briefing, "Explosion at Japanese Nuclear Facility," March 14, 2011, links on the web at http://www.foe.org/experts-comment-us-implications-japanese-reactor-crisis, to audio at http://www.foe.org/experts-comment-us-implications-japanese-reactor-crisis.

10 Hiroko Tabuchi and Matthew L. Wald, "Partial Meltdowns Presumed at Crippled Reactors," *New York Times*, March 13, 2011, http://www.nytimes.com/2011/03/14/world/asia/14nuclear.html (later called **"**Second Explosion at Reactor as Technicians Try to Contain Damage**"**), first viewed at 8:13 p.m. Eastern Daylight Time, March 13, 2011.

most of the rest of the world. Spent fuel pools have special vulnerabilities that are different in different specific designs, but all possess some risk of severe consequences in worst-case accidents or worst-case terrorist attacks (which were studied by the National Research Council in its 2006 report).

The United States should move as much spent fuel out of the pools as possible into hardened and secure dry storage. The tragedy in Japan is also a reminder that making plutonium and fission products just to boil water (which is what a nuclear reactor does) is not a prudent approach to electricity generation. While existing reactors will be needed to maintain the stability of electricity supply for some time (as is also evident from the earthquake-tsunami catastrophe in Japan), new reactor projects should be halted and existing reactors should be phased out along with coal and oil. It is possible to do so economically in the next few decades, while maintaining the reliability of the electricity system and greatly improving its security, as I have shown in my book *Carbon-Free and Nuclear Free: A Roadmap for U.S. Energy Policy* published in 2007, and in subsequent work that can be found on the IEER website, www.ieer.org. *Carbon-Free and Nuclear-Free* can be downloaded free at http://www.ieer.org/carbonfree/CarbonFreeNuclearFree.pdf.

Corrections made at 11:30 am EDT, March 16, 2011