Triple Disaster Pulverizes Japan

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On Friday, March 11, the world stood still … Or so it seemed to stunned observers. For a few minutes in Japan, what actually happened was far from that. At 2:46 pm local time, a 9.0 earthquake pummeled the northeast coast of Honshu, Japan's largest island. The temblor was so strong that it shifted Japan's main coastline by up to 13 feet to the east (*CNN* and USGS March 12).

The Geospatial Information Authority in Tsukuba, Japan reported that Oshika peninsula in Miyagi prefecture shifted 5.3 meters (17 feet) in an east-south-east direction toward the epicenter of the quake and its land sank 1.2 meters (4 feet) (*CNN* March 19, *Kyodo News/Japan Times* March 20). A geophysicist at Jet Propulsion Laboratory in Pasadena, California calculated that the earthquake may have knocked Earth off its axis by about 6.5 inches, causing our world to rotate faster and shortening the day — by about 1.8 microseconds or millionths of a second (*LA Times* March 13, *Space.com* March 11, *NPR* transcript March 18).

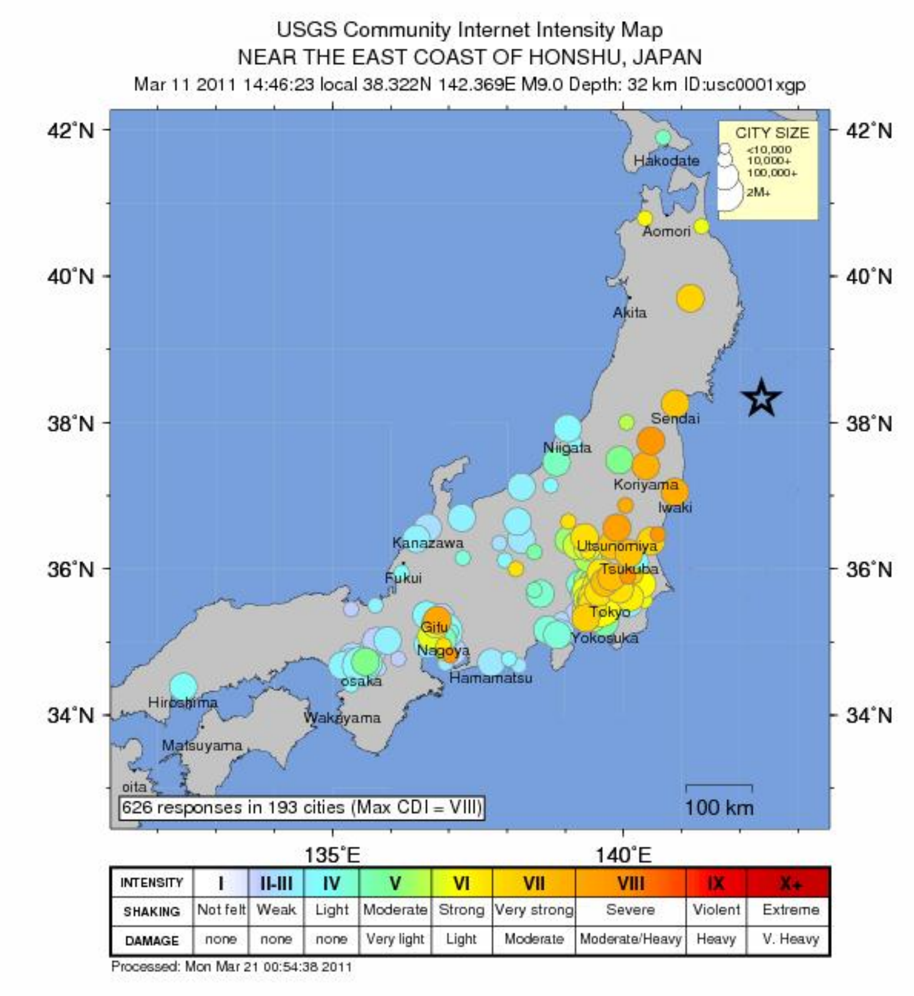
According to the U.S. Geological Survey (USGS), the epicenter was located 129 kilometers (80 miles) east of Sendai, Honshu; 177 kilometers (109 miles) east of Yamagata, Honshu; 177 kilometers (109 miles) east-north-east of Fukushima, Honshu; and 373 kilometers (231 miles) northeast of Tokyo. As tectonic plates slipped more than 18 meters, the Earth's crust ruptured a 400 kilometer (250 miles) by 150 kilometer (100 miles) area called "Tohoku," short for Tohoku-Chiho-Taiheiyo-Oki ("Pacific-offshore Tohoku Region") in Japanese. Tohoku is in the northern part of Honshu and comprises six of Honshu's northernmost prefectures. It is 250 kilometers north of Tokyo, with a population estimated at 9.7 million in 2008 (*Global Weekly Economic Monitor* March 11).

Records from USGS show that the Tohoku earthquake is the fourth largest in the world since 1900. It is the largest in Japan since modern instrumental recordings began 130 years ago. The March 11 earthquake was preceded by a series of large foreshocks over the previous two days, beginning on March 9 with a magnitude 7.2 event approximately 40 kilometers from the March 11 epicenter, and continuing with another three earthquakes of magnitude 6 or over on the same day.

The quake triggered more than 160 aftershocks in the first 24 hours — 141 measuring 5.0 in magnitude or higher. By March 18, as reported by *Kyodo News*, the Japan Meteorological Agency had registered 262 aftershocks of magnitude 5 or greater (one of magnitude 7.5, two of magnitude 7 or greater, 49 of magnitude 6 or greater). Over two weeks after the initial tremors, a 6.5 earthquake shook the northeastern coast on March 28 and prompted a brief tsunami alert. No damages or injuries were reported.

The 9.0 earthquake on March 11 set off a devastating tsunami that sent walls of water washing over towns and farmland along the coast. It traveled across the Pacific Ocean, triggering tsunami warnings and alerts for 50 countries and territories as far away as the western coasts of Canada, the US, and Chile (*CNN* March 12).

A 10-meter tsunami hit the port of Sendai in the Miyagi Prefecture, about 300 kilometers northeast of Tokyo. The quake and tsunami wiped entire towns off the map, causing fire, flooding, and landslides. In addition to destroying buildings, ports, roads, and local airports, and ravaging humans, cars, boats, and planes along its path, the assault knocked out power to the



INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+
SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy

Source: United States Geological Survey
http://earthquake.usgs.gov/earthquakes/world/japan/map.php
http://earthquake.usgs.gov/earthquakes/dyfi/events/us/c0001xgp/us/usc0001xgp_ciim.jpg

region, which is served by nuclear power plants operated and owned by Tokyo Electric Power Company (TEPCO), Tohoku Electric Power Company, and Japan Atomic Power Company (JAPCO). The reactors are designed to automatically shut down in the event of a quake, with diesel backup generators pumping water around the reactor cores to keep them cool. The generators at three of TEPCO's Fukushima-Daiichi reactors failed when the tsunami flooded the plant and the reactor cores began to heat up. Officials determined later that the tsumani reached a height of 14 meters at the plant. Some waves traveled 10 kilometers (6 miles) inland in Miyagi Prefecture.

The lack of cooling for the reactors quickly developed into the world's worst nuclear crisis since Chernobyl, in which radiation remains a primary concern.

The quake and the tsunami together made more than 360,000 people homeless and caused damages that could exceed JPY 25 trillion (USD 300 billion), making it the world's costliest natural disaster (*Reuters* March 23). In comparison, the 1995 Kobe earthquake cost $100 billion while Hurricane Katrina in 2005 caused $81 billion in damage. The Japanese yen spiked to a record high against the US dollar after the quake, prompting the first joint intervention by the Group of Seven (G7) rich nations in 11 years to stem the surge and help shield Japan's export-reliant economy (*Reuters* and *Associated Press* March 21). In the days that immediately followed the quake-tsunami, food, water, medicine, and fuel were in critically short supply, with freezing temperatures and snow hampering rescue and emergency repairs.

At press time, about 28,000 people are dead (12,009 confirmed) or missing (15,472) and over 163,710 people remain in temporary shelters; over 168,000 households in northern Japan are without electricity and at least 220,000 households in eight prefectures are without running water (*Reuters* April 3). TEPCO is still struggling to stabilize the plant three weeks after being struck, with new problems surfacing almost daily. Abnormal levels of radioactive iodine and cesium are detected in the air, tap water, and food supply (milk, vegetables, and one slaughtered cow) in the area since March 20; radioactive water has been found seeping into the Pacific Ocean from a newly-discovered 8-inch crack in a maintenance pit at the damaged nuclear site (*World Nuclear News* and *Reuters* April 2). Trace amounts of airborne radioactive particles have reached Russia, Europe, and the US at various times during the last two weeks. Negligible amounts of radioactive iodine were also present in milk samples in the states of California and Washington, probably a result of cattle feeding off grass irrigated by contaminated rainwater (*Associated Press* March 31).

As most aptly described by Australia-based fund manager Perpetual Investments, in a monthly market report and an update on the humanitarian and financial crisis, "The worst-case scenario doesn't bear mentioning and the best case scenario keeps getting worse."[1]

Energy Resources in Japan

Owing to limited natural energy resources, Japan is highly dependent on its 54 nuclear reactors that supply around 30% of electricity. Around 60% of power is generated by fossil fuel power stations that use imported liquefied natural gas (LNG), oil, and coal. Hydroelectricity contributes another 7.5% of total power supply.

As the largest utility provider in Japan and one of the world's biggest power companies, TEPCO serves 44.6 million customers (over a third of the population in Japan) in the Kanto region of the main island of Honshu, including Tokyo (*AFP* March 29).

Eleven reactors at four nuclear power plants in the Tohoku region were operating when the 9.0 earthquake and tsunami struck. All shut down automatically. These units were TEPCO's Fukushima Daiichi 1, 2, 3; Fukushima Daini 1, 2, 3, 4; Tohoku's Onagawa 1, 2, 3; and Japco's Tokai; which collectively accounted for net power of 9377 megawatt electricity (MW_e). Fukushima Daiichi units 4–6 were not operating at the time, but were affected (total 2587 MW_e). Onagawa 1 briefly suffered a fire in the turbine building, but the main problem initially centered on Fukushima Daiichi units 1–3. Unit 4 became a problem on day five (*World Nuclear Association* and *World Nuclear News March 28).*

Power, from grid or backup generators, was available to run the reactor heat removal (RHR) system cooling pumps at eight of the eleven units, and they achieved "cold shutdown" within about four days. The other three lost power at 3:42 pm, almost an hour after the quake, when the entire site lost the ability to maintain proper reactor cooling and water circulation functions (*World Nuclear Association* March 28).

Some reactors, including three at the stricken Fukushima Daiichi plant, the two units at Hokuriku's Shika plant, Chubu's Hamaoka 3, and Tohuku's Higashidori 1 were already offline for routine outages when the earthquake struck. Altogether, around 13,360 MW_e of Japan's installed nuclear capacity of just over 47,500 MW_e was out of action (*World Nuclear News* March 12).

World Nuclear News reported on March 14 that immediately after the earthquake, 12 of TEPCO's thermal power units and 22 hydroelectric plants also ceased operations. Later that day, about 2.4 million households in its service area were without power. By 3 pm on March 13, all the hydroelectric plants were back online, but nine thermal units totaling about 6750 MW_e of capacity remained out of service from the company's total thermal capacity of just over 38,000 MW_e. Around 260,000 households were still without power.

Upon realizing that all power-generating options have been compromised one way or another by the earthquake and tsunami, Japan's Ministry of Economy, Trade, and Industry (METI) announced on March 13 that it would take steps to suppress power demand from industry. TEPCO's capacity has been heavily diminished by the earthquakes. It estimated an electricity demand of around 37 GW_e against an available supply of 33 GW_e for March 15.

On March 14, Japanese utilities introduced rolling blackouts to allay energy shortages. Meanwhile, the country is relying more than ever on the continued operation of its other nuclear reactors. TEPCO and Tohoku Electric have been urgently procuring additional cargoes of LNG and fuel from other utilities and suppliers in Asia-Pacific to make up for the shortfalls (*ICIS News* March 18–25). The shortage and rolling blackouts are expected to last for months.

The destruction of manufacturing plants and transportation structure (roads, railways, etc.) and continued power shortages disrupt production across many industries, causing panic and speculation in the industrial and stock markets, and unleashing ripples down the supply chains. Japanese manufacturing activity slumped to a two-year low in March and posted the sharpest monthly fall on record (*Reuters* April 1). A report on the disaster's implications on the technology sector and industrial gas market will be available in *G&I*'s upcoming May/June issue of the print and digital magazine.

Special Report: Fukushima Reactor Design and Damage

The following is an excerpt from a paper, "Fukushima Accident 2011," that is researched and written by staff at London-based World Nuclear Association (WNA). It is reproduced here with permission from WNA and has been edited for clarification and to conform with G&I style. The paper is updated daily as information becomes available and the latest version can be viewed in full at http://www.world-nuclear.org/info/fukushima_accident_inf129.html.

Sources: TEPCO, NISA, IAEA, METI, JAIF

Organizational acronyms:
NISA = Nuclear and Industrial Safety Agency (Japan)
METI = Ministry of Trade, Economy and Industry (Japan)
IAEA = International Atomic Energy Agency
JAIF = Japan Atomic Industrial Forum (industry body)
ISRN = Institute for Radiological Protection and Nuclear Safety (France)

Site and earthquakes: background

The Daiichi (first) and Daini (second) Fukushima plants are located about 11 kilometers apart on the coast.

Japanese nuclear power plants are designed to withstand specified earthquake intensities evident in ground motion. If they register ground acceleration of a set level, systems will be activated to automatically bring the plant to an immediate safe shutdown. Peak ground acceleration (PGA) is measured in CGS units of Galileo (Gal), where 1 Gal = 1 cm s^{-2} and the gravitational constant g = 980 Gal. Geologists use the unit for measurements of local variation in the acceleration of gravity to study geologic structures underlying an area. In Fukoshima, the set level for safe nuclear shutdown was 135 Gal.

The design basis earthquake ground motion (DBGM) or PGA level Ss is defined as the largest earthquake that can reasonably be expected to occur at the site of a nuclear power plant, based on the known seismicity of the area and local active faults. A power reactor could continue to operate safely without release of radioactivity during an Ss level earthquake, though in practice they are set to trip at lower levels. In particular, reactor pressure vessel, control rods and drive system, and reactor containment should suffer no damage at all. If it did shut down, a reactor would be expected to restart soon after an Ss event. The revised seismic regulations released in May 2007 increased the Ss figure to be equivalent to 6.7 on the logarithmic Richter scale — a factor of 1.5 (up from 6.5). (*G&I Editor's note: See also WNA paper "Nuclear Power Plants and Earthquakes," updated April 2, 2011,* http://www.world-nuclear.org/info/inf18.html)

The maximum response acceleration against DBGM Ss for both Fukushima plants had been upgraded since 2006, and is now quoted at horizontal 438–489 Gal for Daiichi and 415–434 Gal for Daini. At this level they must retain their safety functions. In 2008, TEPCO upgraded its estimates of likely Ss level for Fukushima to 600 Gal, and other Japanese operators have adopted the same figure. The interim recorded data for both plants shows that 550 Gal (0.56 g) was the maximum for Daiichi, in the foundation of unit 2 (other figures 281–548 Gal), and 254 Gal was maximum for Daini. Units 2, 3, and 5 exceeded their maximum response acceleration design basis in the east-west direction by about 20%. The measurements were recorded over 130–150 seconds. All nuclear plants in Japan are built on rock (ground acceleration was around 2000 Gal a few kilometers north, on sediments).

The design basis tsunami height is 5.7 meters for Daiichi and 5.2 meters for Daini, though the plants were built higher than this above sea level. Tsunami heights were reported as 14 meters for both plants.

Reactors: background

The Fukushima Daiichi reactors are General Electric (GE) boiling water reactors (BWRs) of an early (1960s) design supplied by GE and Toshiba, with what is known as a Mark I containment. Reactors 1–3 came into commercial operation 1971–75. The reactor power is 460 MW_e for unit 1, 784 MW_e for units 2–5, and 1100 MW_e for unit 6. The fuel assemblies are about 4 meters long, and there are 400 such assemblies in unit 1, 548 in units 2–5, and 764 in unit 6. Each assembly has 60 fuel rods containing the uranium oxide fuel within zirconium alloy cladding. Unit 3 has a partial core of mixed-oxide (MOX) fuel (32 MOX assemblies, 516 LEU). They all operate normally at 286°C at the core outlet under a pressure of 6930 kPa and with about 400 kPa pressure in dry containment.

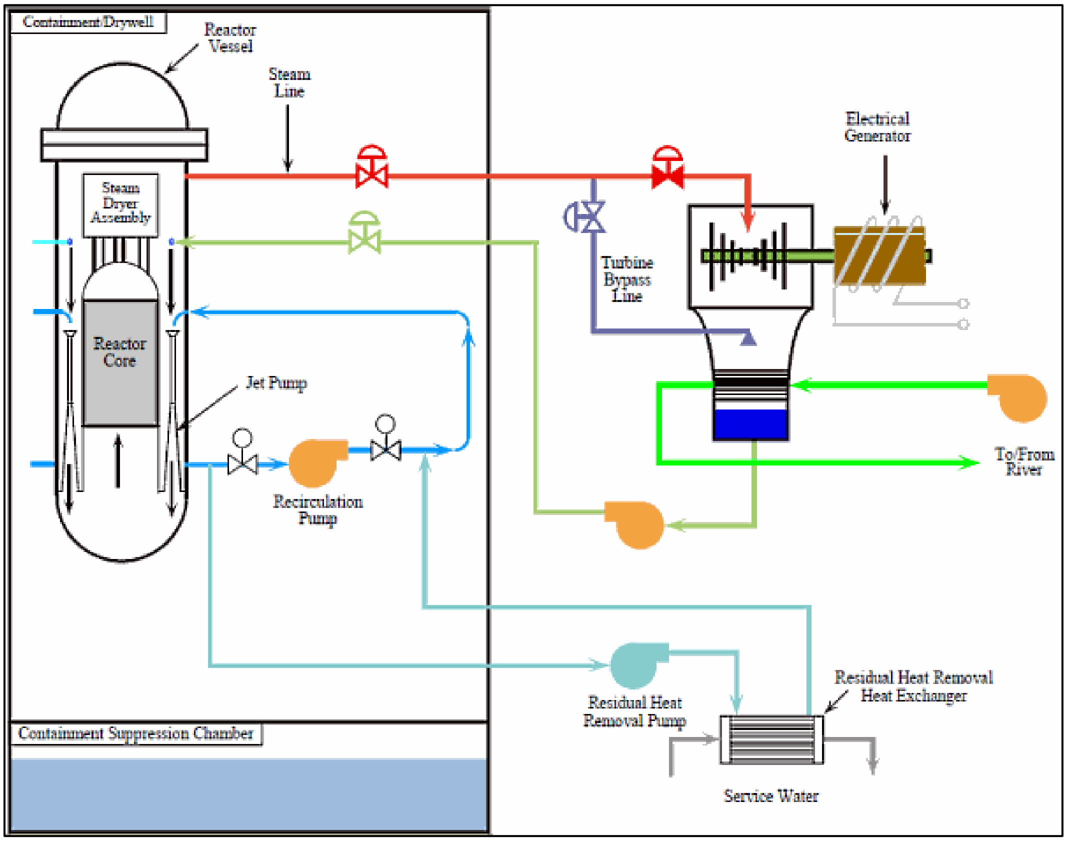
The BWR Mark I has a primary containment system comprising a free-standing bulb-shaped drywell of 30-millimeter steel backed by a reinforced concrete shell, and connected to a torus-shaped wetwell beneath it containing the suppression pool. The drywell, also known as the primary containment vessel (PCV), contains the reactor pressure vessel (RPV). For simplicity, we will use the term “dry containment” here. The water in the suppression pool acts as an energy-absorbing medium in the event of an accident. The wetwell is connected to the dry containment by a system of vents, which discharge under the suppression pool water in the event of high pressure in the dry containment. The function of the primary containment system is to contain the energy released during any loss-of-coolant accident (LOCA) of any size reactor coolant pipe, and to protect the reactor from external assaults. The Japanese version of the Mark I is slightly larger than the original GE version.

During normal operation, the dry containment atmosphere and the wetwell atmosphere are filled with inert nitrogen, and the wetwell water is at ambient temperature.

If LOCA occurs, steam flows from the dry containment (drywell) through a set of vent lines and pipes into the suppression pool, where the steam is condensed. Steam can also be released from the reactor vessel through the safety relief valves and associated piping directly into the suppression pool. Steam will be condensed in the wetwell, but hydrogen and noble gases are not condensable and will pressurize the system, as will steam if the wetwell water is boiling. In this case, emergency systems will activate to cool the wetwell, see below. Excess pressure from the wetwell can be vented into the secondary containment or reactor service floor of the building, or through the emission stack. If there has been fuel damage, vented gases will include noble gases (krypton and xenon), iodine, and cesium, the latter being scrubbed in some scenarios. Less volatile elements in any fission product release will plate out in the containment. (The later Mark II containments are similar to Mark I, but both are much smaller than the Mark III and those which became standard in pressurized water reactors [PWRs]).

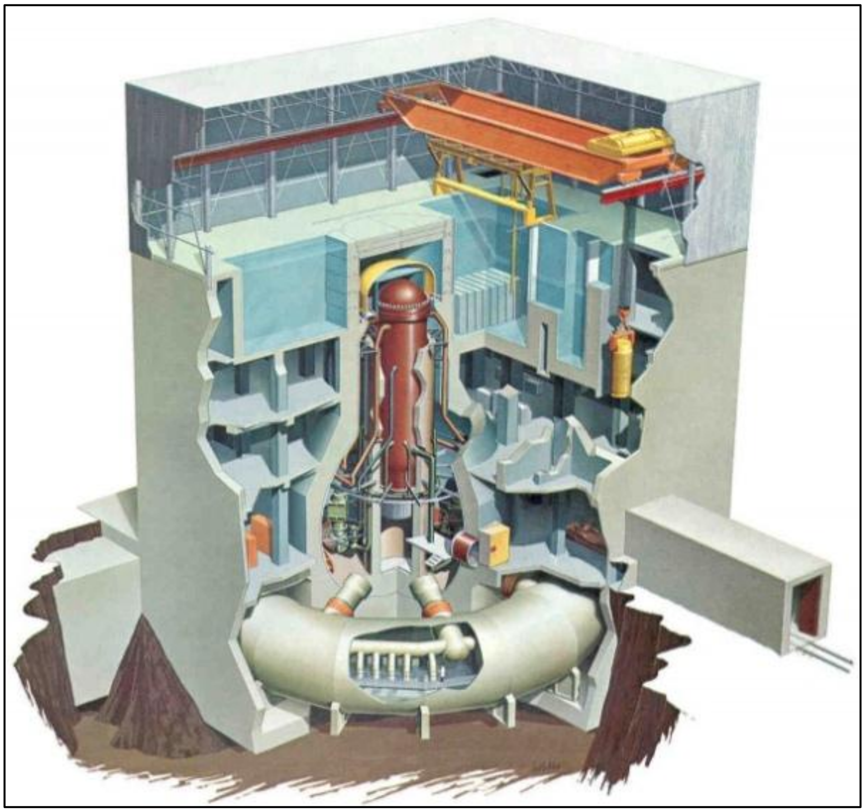
The secondary containment houses the emergency core cooling systems and the spent/used fuel pool. It is not designed to contain high pressure.

The primary cooling circuit of the BWR takes steam from above the core, in the reactor pressure vessel, to the turbine in an adjacent building. After driving the turbines, it is condensed and the water is returned to the pressure vessel. There are also two powerful jet-pump recirculation systems forcing water down around the reactor core and shroud. When the reactor is shut down, the steam in the main circuit is diverted via a bypass line directly to the condensers, and the heat is dumped there, to the sea. In both situations a steam-driven turbine drives the pumps, at least until the pressure drops to about 350 kPa (50 psi). In shutdown mode, the residual heat removal (RHR) system then operates in a secondary circuit (RHR is connected into the two jet-pump recirculation circuits), driven by electric pumps, and circulates water from the pressure vessel to RHR heat exchangers which dump the heat to the sea. There is also a reactor core isolation cooling (RCIC) system that can provide make-up water to the reactor. It is driven by a small steam turbine using steam from decay heat, injecting water from a condensate storage tank or the suppression pool. (The NISA account does not mention the RCIC, possibly treating it as part of the ECCS, though other accounts have RCIC systems playing a helpful role in all three units, and to 2 pm on March 14 in unit 2.)



There is an emergency core cooling system (ECCS) as further back-up for loss of coolant. It has high-pressure and low-pressure elements. The high-pressure coolant injection (HPCI) system has pumps powered by steam turbines that are designed to work over a wide pressure range. The HPCI draws water from the large torus suppression chamber beneath the reactor as well as a water storage tank. For use below about 700 kPa, there is also a low-pressure coolant injection (LPCI) mode through the RHR system but utilizing suppression pool water, and a core spray system, all electrically-driven. All ECCS sub-systems require some power to operate valves, etc., and the battery back-up to generators may serve this purpose.

Beyond these original systems, TEPCO in the 1990s installed provision for water injection via the fire extinguisher system through the RHR system (injecting via the jet-pump nozzles) as part of its severe accident management (SAM) countermeasures.



A frequently voiced concern during the first week of the accident was fuel meltdown. This would occur if the fuel itself reached 2400°C (or more, depending on make-up). At this point, the fuel rods slump within the assemblies. Conceivably, the "corium" (a mixture of molten cladding, fuel, and structural steel) begins to move to the bottom of the reactor vessel. If the hot fuel or cladding is exposed to cooling water en route, it may solidify and fracture, falling to the bottom of the reactor vessel. Given that the melting point of the steel reactor vessel is about 1500°C, there is an obvious possibility of the corium penetrating the steel if it remains hot enough. (In fact, in the 1979 US Three Mile Island accident, it did not, though about half the core melted and went 15 millimeters into the 225-millimeter thick pressure vessel steel. The pressure vessel glowed red-hot for an hour.) But the whole fuel melt scenario is much more probable with a sudden major loss of coolant when the reactor is at full power than in the Fukushima situation. Before this, cladding oxidation begins at about 1200°C and the cladding melts at about 1850°C.

Fukushima Daiichi 1–3 and 4

Reactors 1–3 were shut down in response to the earthquake, as designed, since the ground acceleration was about 500 Gal. The reactors then reverted to an auxiliary RHR cooling system, since the steam was no longer being conveyed to the turbines and condenser circuit. The RHR system is driven by electric pumps. Mains power was lost due to the quake, so the emergency diesel generators started up to drive this system and ran for 56 minutes, but then stopped when submerged by the tsunami. This put those reactors in a dire situation and led the authorities to order, and subsequently extend, an evacuation while engineers worked to restore power. About nine hours later mobile power supply units had reached the plant and were being connected. The capacity of these would be less than the main plant diesel system. Meanwhile units 1–3 had only battery power, insufficient to drive the main RHR cooling system. The batteries were apparently depleted in about eight hours anyway.

When the power failed about one hour after shutdown, the reactor cores would still be producing about 1.5% of their nominal thermal power, from fission product decay — about 22 megawatt thermal (MW_t) in unit 1 and 33 MW_t in units 2 and 3, according to calculations from well-established models. Without heat removal by circulation to an outside heat exchanger, this produced a lot of steam in the cores. The steam would be condensed in the suppression chamber under the reactor, within the containment, but their internal temperature and pressure rose quite rapidly. At 4:36 pm, water injection using the ECCS failed in units 1 and 2, less than an hour after power loss.

At 7:03 pm, the Japanese government declared a Nuclear Emergency, and at 8:50 pm the Fukushima Prefecture issued an evacuation order for people within 2 kilometers of the plant. At 9:23 pm the Prime Minister extended this to 3 kilometers, and at 5:44 am on March 12 he extended it to 10 kilometers. He visited the plant soon after. At 6:25 pm on Saturday, March 12, he extended the evacuation zone to 20 kilometers.

Over the first 12 hours, pressure inside the containment structures increased steadily. The structures were vented to the atmosphere repeatedly, starting with unit 1 early on Saturday, March 12, where pressure had reached 840 kPa, more than twice the design level. Inside, water levels had dropped, exposing fuel, and this was addressed by pumping seawater into the RPVs using external pumps brought to site, starting with unit 1 at 8:20 pm on March 12. This was apparently via the LPCI or firefighting system, connected into the RHR system. On March 25, water from a nearby dam started to be used instead of seawater. Boron was added to the injected water, to guard against any criticality.

Meanwhile, vented gases and vapor included hydrogen, produced by the exothermic interaction of the fuel's very hot zirconium cladding with steam and water. A hydrogen explosion occurred at 3:36 pm on March 12 after vented hydrogen mixed with air in the building above unit 1’s reactor containment, blowing off much of the roof and cladding on the top part of the building. At 11:55 am on Sunday, March 13, seawater injection to unit 1's primary containment started. On March 25, pressure inside unit 1 was down to 310 kPa.

In unit 2, as mentioned above, water injection using the ECCS failed at 4:36 pm on March 11. Pressure was vented at 11 am on March 13 and again on March 15, and meanwhile the blowout panel near the top of the building was opened. The reactor water level was found to be low in the afternoon of Monday, March 14, so seawater injection to the containment was prepared, and started on March 15. Then at 6:14 am on Tuesday, March 15, unit 2 apparently ruptured its pressure suppression chamber under the actual reactor, releasing some radioactivity and dropping the pressure inside. At 10:30 am, TEPCO was told to inject water into the pressure vessel and to vent the containment, and these activities continued. Containment damage is suspected. On April 1, TEPCO discovered a crack in the wall of a 2-meter deep cable pit that was leaking highly-contaminated water, apparently from the reactor itself. The company was preparing to plug it with concrete.

In unit 3, the containment was vented at 8:41 pm on Saturday, March 12. On Sunday, March 13, at 5:10 am, water injection using the ECCS failed in this unit also, and at 9:20 am the containment was vented again. At 11:55 am fresh water injection to the RPV commenced, soon being replaced by seawater through to March 25. On Monday, March 14, at 5:20 am venting was repeated, then at 11:01 am a hydrogen explosion in the building above unit 3 reactor containment blew off much of the roof and walls on the top part of the building. On Wednesday, March 16, at 8:37 am there was a major release of smoke and/or steam from the top of the building. Because of the possibility that the primary containment of Unit 3 was damaged, the operators were evacuated from the central control room of Unit 3 and 4 (a shared facility) at 10:45 am. They returned to the control room and restarted the operation for water injection at 11:30 am. Pressure then built up to 320 kPa in the containment but no further venting was required. Since at least March 16, pressure vessel damage has been suspected, and some leakage is apparently confirmed by radioactivity levels in the building. However, on March 25 the reactor pressure and drywell pressure remained stable, leading TEPCO to believe that "the reactor pressure vessel is not seriously damaged."

The heat from the fuel in the reactor cores was estimated by France's ISRN as 2.5 MW_t in unit 1 and 4.2 MW_t in units 2 and 3 after almost three weeks. This is enough to boil away 95 metric tons (1 metric ton = 1 tonne) and 160 metric tons of water per day respectively if all external circulation to heat sinks ceases, indicating the need for constant top up while the heat is not being dumped in the normal heat exchanger circuits. On March 30, water was injected into each reactor at a rate of 7–8 cubic meters per hour. These heat production levels will diminish only slowly from this point. The cores remained partly uncovered, and TEPCO said on March 15 that 70% of the fuel rods in unit 1 and one third in unit 2 were damaged. At one stage unit 2 core was dry for some hours, and a German source said that unit 1 core was without water for 27 hours, causing major fuel damage.

On Sunday, March 20, JAIF said that the containment vessel of unit 2 was thought to be damaged, and that of unit 3 could possibly be also, but unit 1 and 4 were intact. (Unit 4 has no fuel in it.).

The AC electricity supply from an external source was connected to all units by March 22, enabling more accurate monitoring of the plants and progress towards restoring the RHR cooling system of units 1–3. Power was restored to instrumentation in all units except unit 3 by March 25. TEPCO said that once the control rooms are operational, water levels can be checked as well as temperatures in the fuel storage pools, and normal cooling of those pools can be resumed. However, at least some pumps have been damaged by seawater and TEPCO says that radiation levels inside the plant are so high that normal access is still impossible. It is giving priority to removing contaminated water so as to allow better access.

Summary as of March 30: All three units have fuel damage and low water levels, units 2 and 3 have lost pressure and are suspected to have pressure vessel or containment damage (only unit 1 is still above atmospheric pressure). Cooling still needs to be provided from external sources, using fresh water and pump trucks. TEPCO has said that it is inevitable that the three reactors, with unit 4, will be written off and decommissioned.

Fuel ponds: background

Used fuel needs to be cooled and shielded. This is initially done by water, in ponds. After about three years under water, used fuel can be transferred to dry storage, with air ventilation simply by convection. Used fuel generates heat, so the water is circulated by electric pumps through external heat exchangers, so that the heat is dumped and a low temperature maintained.

There are fuel ponds near the top of all six reactor buildings at the plant, adjacent to the top of each reactor so that the fuel can be unloaded under water, when the top is off the reactor pressure vessel and it is flooded. The ponds hold some fresh fuel and some used fuel, pending its transfer to the central used/spent fuel storage on site. (There is some dry storage to extend the site's capacity.) From here it is periodically shipped for reprocessing, currently to Rokkasho for recycling.

At the time of the accident, unit 4's pond also held a full core load of 548 fuel assemblies while the reactor was undergoing maintenance, these having been removed from unit 4 at the end of November.

The temperature of these ponds is normally low, around 30°C when circulation is maintained with the fuel pool circulation and clean-up (FCP) system, but they are designed to be safe at about 85°C in the absence of pumped circulation (and presumably with low fuel load). They are about 12 meters deep, so the fuel is normally covered by 7 meters of water.

Unit 3 and 4 ponds are about 12 x 10 meters, with 1220 and 1590 assemblies capacity respectively (unit 1 is about 12 x 7 meters, 900 assemblies). Unit 4 pond has a total 1535 assemblies, giving it a heat load of about 3 MW_t, according to France's IRSN, which in that case could lead to 115 cubic meters of water boiling off per day, or about one tenth of its volume. Unit 3's pool contains 566 fuel assemblies. There is no MOX fuel in any of the ponds.

The central fuel storage on site has a pond about 12 x 29 meters, 11 meters deep, with capacity of 3828 cubic meters and 6840 fuel assemblies. Its building is about 55 x 73 meters. (There are 6375 assemblies in the undamaged central pool storage on site, with very low decay heat, and 408 in dry cask storage — utilized since 1995 for used fuel no longer needing much cooling.)

Fuel ponds: developing problems

A separate set of problems arose as the water in the fuel ponds, holding fresh and used fuel, in the upper part of the reactor structures was depleted. It is unclear why or how the low water levels came about, though elevated temperatures due to loss of cooling circulation would have been a major cause, especially in heavily-loaded unit 4. On March 13, TEPCO said it was consulting with NISA and METI regarding cooling of the ponds

In unit 4, at about 6 am on Tuesday, March 15, there was an explosion in the top part of the building, near the fuel pond, which destroyed the top of the building and damaged unit 3's superstructure further. Then there was a fire and soon after the radiation level near the building reached 400 milliSieverts per hour, apparently from this source. The fire was extinguished in three hours. Evidently the used fuel there got hot enough to form hydrogen. At 10 pm on March 15, TEPCO was told to implement injection of water to unit 4 pond. It appears that the water level dropped due to evaporation, if not boiling, caused by the high heat load from 1535 fuel assemblies once circulation ceased.

Since Tuesday, March 15, TEPCO had focused on replenishing the water in the ponds of units 3 and 4, through the gaps in the roof and cladding, using seawater. On March 19, unit 3 pond was reported to be stable, and on March 24, workers were able to replenish the pond using built-in plumbing for the FPC system. On March 25 the same was achieved for unit 4 and unit 2 ponds. These ponds, 12 x 10 meters, were not an easy target for ground-based fire pumps, but the arrival of a concrete pump with 58-meter boom on March 22 enabled more precise replenishment in units 1, 3, and 4 that had damaged walls. Unit 2 pond had been topped up internally. On March 19, the temperature of unit 4 pond had come back to 48°C. On March 25, water from a nearby dam started to be used instead of seawater.

On March 18, TEPCO made three 7.5-centimeter holes in each of the superstructure roofs of units 5 and 6 to allow ventilation of any hydrogen, though pond temperatures had reached only about 69°C. On March 19, the residual heat removal pumps for units 5 and 6 ponds were restarted as power was restored, and temperatures declined.

The central spent fuel pool holds about 60% of the used fuel on site, and is immediately west (inland) of unit 4. It lost circulation with the power outage, and temperature increased to 73°C by the time mains power and cooling were restored on March 24. The pool was filled on March 21.

Summary as of March 30: Spent fuel ponds in units 3 and 4 still need to be topped up repeatedly, with some use of internal plumbing for unit 3 and by concrete pump with boom for unit 4 (also unit 3 on March 27). TEPCO has said that it is inevitable that unit 4, with units 1–3, will be written off and decommissioned.

Radioactivity

Radioactive releases are measured by the amount of (radio)activity in the material, and quoted in Becquerels. Whether this is in the air or on the ground it may expose people to ionizing radiation, and the effect of this is measured in Sieverts, or more typically milliSieverts (mSv). Exposure to ionizing radiation can also be by direct radiation from the plants and fuels themselves, though not released to the environment. This is only a hazard for those on the plant site, and the level diminishes with distance from the radioactive source. It is the chief hazard for the plant workers, who wear film badges so that the dose can be monitored. A short-term dose of 1000 mSv is about the threshold of acute radiation syndrome (sickness).

The main radionuclide released from the many kinds of fission products in the fuel is volatile iodine-131, which has a half-life of 8 days. It has been in both venting to air and in water. Iodine-131 decays to inert and stable xenon-131.

Radioactive releases and hazards

After the hydrogen explosion in unit 1, some radioactive cesium and iodine were detected in the vicinity of the plant, indicating fuel damage. This had been released via the venting. Further I-131 and Cs-137 and Cs-134 were apparently released during the following two weeks, the cesium at low levels (about two orders of magnitude less than the iodine).

On March 16, Japan’s Nuclear Safety Commission recommended local authorities to instruct evacuees under 40 years of age leaving the 20-kilometer zone to ingest stable iodine as a precaution against ingestion (e.g., via milk) of radioactive iodine-131. The pills and syrup (for children) had been pre-positioned at evacuation centers. The order recommended taking a single dose, with an amount dependent on age.

On March 17, NISA raised the statutory intervention limit from 100 to 250 mSv per person after consultation with health experts, to allow work to be carried out on the Unit 4 reactor. By March 23, about seven workers had accumulated 100–150 mSv.

Gamma radiation on site close to the reactors decreased greatly when unit 3 fuel pond was replenished with water on March 19. On Sunday, March 20, levels were mostly below 3 milliSieverts per hour (mSv/hr) and on March 21 were nearly down to 2 mSv/hr about 500 meters north of unit 3.

IAEA reported on March 19 that airborne radiation levels had spiked three times since the earthquake, notably on March 15, but had stabilized since March 16 at levels significantly higher than the normal levels, but within the range that allows workers to continue on-site recovery measures. For instance, NISA reported 3.4 mSv/hr on the site boundary mid March 16, dropping to 0.65 mSv/hr 13 hours later at the same point. Late on March 24 it was about 0.2 mSv/hr at the front gate, having been ten times that a few days earlier. On March 30 it was below 0.2 mSv/hr at the front gate and below 0.1 mSv/hr at the west gate.

On March 24, three contractors laying cable in unit 3 received a dose of more than 170 mSv, two suffering beta radiation burns on their legs from contaminated water. The Fukushima Labor Bureau issued a stern rebuke to TEPCO. By April 1, 21 workers had received doses over 100 mSv.

Removing pools of contaminated water from the reactor and turbine buildings had become the main challenge of week 3, along with contaminated water in trenches carrying cabling and pipework. Run-off from the site into the sea is also carrying radionuclides well in excess of allowable levels. By the end of March all storages around the four units — basically the main condenser units and condensate tanks — were largely full of contaminated water pumped from the buildings. To cope with further water TEPCO plans to construct a 6000-metric-ton water tank as well as a 4000-metric-ton pond. These will work in conjunction with a 20-metric-ton-per-hour treatment facility to handle water from drainage canals around all six reactors at the plant. The tank and pond should be complete around the middle of April, with the treatment facility following about two weeks later.

As of March 29, no radiation casualties (acute radiation syndrome) and few other injuries had been reported, though higher than normal doses were being accumulated by several hundred workers on site. Fatal physical injuries of two TEPCO workers missing since the earthquake-tsunami were confirmed on April 3.

Government and IAEA monitoring of air and seawater is ongoing, with high but not health-threatening levels of iodine-131 being found. Environmental levels are decreasing. With an 8-day half-life, most I-131 will be gone within weeks. However a radiological hotspot was identified near Iitate village 30 kilometers northeast of the plant. See also the IAEA March 30 report.

Fukushima Daiichi 5 and 6

Units 5 and 6, in a separate building, also lost power on the 11th due to the tsunami. They were in “cold shutdown” at the time, but still requiring pumped cooling. An emergency diesel generator for Unit 6 was repaired on Saturday, March 19, allowing full restoration of cooling for units 5 and 6. While the power was off their core temperature had risen to over 100°C (128°C in unit 5) under pressure, and they had been cooled with normal water injection, presumably with the RCIC system. They were restored to cold shutdown by the RHR system on March 20, and mains power was restored on March 21–22. TEPCO said that local people would be consulted on whether the reactors might be restarted.

Fukushima Daini plant

Units 1–4 were shut down automatically due to the earthquake, but some interruption to cooling occurred due to the tsunami. The government ordered an evacuation within 10 kilometers (in practice this was within the Daiichi 20-kilometer zone).

In units 1, 2, and 4 cooling problems were still evident on Tuesday, March 15. Unit 3 was undamaged and continued to "cold shutdown" status on March 12, but the other units suffered flooding to pump rooms where the equipment transfers heat from the reactor heat removal circuit to the sea — the ultimate heat sink.

All units achieved "cold shutdown" by March 16, meaning the core temperature was less than 100°C at atmospheric pressure (101 kPa), but still requiring some water circulation. Radiation monitoring figures remained at low levels, little above background.

International Nuclear Event Scale assessment

Japan's Nuclear and Industrial Safety Agency eventually declared the Fukushima Daiichi 1–3 accident as Level 5 on the International Nuclear Events Scale (INES) of 1 to 7 — an accident with wider consequences, the same level as Three Mile Island in 1979. The Chernobyl accident in 1986 was rated Level 7.

The sequence of events relating to the fuel pond at unit 4 was rated INES Level 3 — a serious incident.

For Fukushima Daini, NISA declared INES Level 3 for units 1, 2,and 4 — a serious incident.

Accident liability

Beyond whatever insurance TEPCO might carry for its reactors is the question of third party liability for the accident. Japan is not party to any international liability convention but its laws generally conform to them, notably strict and exclusive liability for the operator. Two laws governing them are revised about every ten years: the Law on Compensation for Nuclear Damage and Law on Contract for Liability Insurance for Nuclear Damage. Plant operator liability is exclusive and absolute, and power plant operators must provide a financial security amount of JPY 120 billion (US$ 1.4 billion) — it was half that up to 2010. Beyond that, the government may provide coverage if damage results from "a grave natural disaster of an exceptional character," and in any case liability is unlimited.

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