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Fukushima Nuclear Disaster

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Summary

The huge earthquake and tsunami that struck Japan's Fukushima Daiichi nuclear power station on March 11, 2011, knocked out backup power systems that were needed to cool the reactors at the plant, causing three of them to undergo fuel melting, hydrogen explosions, and radioactive releases. Radioactive contamination from the Fukushima plant forced the evacuation of communities up to 25 miles away and affected up to 100,000 residents, although it did not cause any immediate deaths.

Tokyo Electric Power Company (TEPCO) operates the Fukushima nuclear power complex in the Futaba district of Fukushima prefecture in Northern Japan, consisting of six nuclear units at the Fukushima Daiichi station and four nuclear units at the Fukushima Daini station. All the units at the Fukushima complex are boiling water reactors, with reactors 1 to 5 at the Fukushima Daiichi site being the General Electric Mark I design, which is also used in the United States. The Fukushima Daiichi reactors entered commercial operation in the years from 1971 (reactor 1) to 1979 (reactor 6). The Fukushima Daini reactors shut down automatically after the earthquake and were able to maintain sufficient cooling.

When the earthquake struck, Fukushima Daiichi units 1, 2, and 3 were generating electricity and shut down automatically. The earthquake caused offsite power supplies to be lost, and backup diesel generators started up as designed to supply backup power. However, the subsequent tsunami flooded the electrical switchgear for the diesel generators, causing most AC power in units 1 to 4 to be lost. Because Unit 4 was undergoing a maintenance shutdown, all of its nuclear fuel had been removed and placed in the unit's spent fuel storage pool. One generator continued operating to cool units 5 and 6.

The loss of all AC power in units 1 to 3 prevented valves and pumps from operating that were needed to remove heat and pressure that was being generated by the radioactive decay of the nuclear fuel in the reactor cores. As the fuel rods in the reactor cores overheated, they reacted with steam to produce large amounts of hydrogen, which escaped into the unit 1, 3, and 4 reactor buildings and exploded (the hydrogen that exploded in Unit 4 is believed to have come from Unit 3). The explosions interfered with efforts by plant workers to restore cooling and helped spread radioactivity. Cooling was also lost in the reactors' spent fuel pools, although recent analysis has found that no significant overheating took place.

Radioactive material released into the atmosphere produced extremely high radiation dose rates near the plant and left large areas of land uninhabitable, especially to the northwest of the plant. Contaminated water from the plant was discharged into the sea, creating international controversy.

The United States and other countries, as well as the International Atomic Energy Agency, are providing assistance to Japan to deal with the nuclear disater. U.S. assistance has included transport of pumps, boron, fresh water, remote cameras, use of Global Hawk surveillance drones, evacuation support, medical support, and decontamination and radiation monitoring equipment.

Studies of the Fukushima disaster have identified design changes, response actions, and other safety improvements that could have reduced or eliminated the amount of radioactivity released from the plant. As a result, Fukushima has prompted a reexamination of nuclear plant safety requirements around the world, including in the United States.

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Introduction and Overview

The disaster that struck Japan's Fukushima Daiichi nuclear power station on March 11, 2011, caused the most extensive release of radioactivity since the Chernobyl accident in 1986 and was far worse than the 1979 Three Mile Island accident in the United States. Unlike at Chernobyl and Three Mile Island, the destruction at Fukushima was initiated by natural disasters—a huge earthquake and tsunami—rather than equipment failure and human error. The tsunami knocked out backup power systems that were needed to cool the reactors at the plant, causing several of them to undergo fuel melting, hydrogen explosions, and radioactive releases.

Studies of the Fukushima disaster have identified design changes, response actions, and other safety improvements that could have reduced or eliminated the amount of radioactivity released from the plant. As a result, Fukushima has prompted a reexamination of nuclear plant safety requirements around the world, including the United States.

Radioactive contamination from the Fukushima plant forced the evacuation of communities up to 25 miles away, affecting up to 100,000 residents, many of whom remain indefinitely barred from their homes. The evacuations are believed to have prevented radiation exposure among the population from exceeding Japanese regulatory limits in most cases. Near-term deaths and illnesses resulting from radiation are believed to be unlikely, although cancer and other long-term health effects remain possible. Workers at the plant site were exposed to far higher radiation levels, with at least two suffering radiation burns on their legs after wading in contaminated water. Two other workers drowned during the tsunami.

Recovery from the disaster has focused on restoring cooling systems at the three most severely damaged reactors at the six-unit plant and halting radioactive emissions into the air and water. That work has been hampered by continuing high levels of radiation in the plant and severe structural damage. The Japanese government announced December 16, 2011, that the damaged Fukushima reactors had achieved "cold shutdown," a milestone in which the reactor cooling water is below boiling temperature at atmospheric pressure. At cold shutdown, the diminished threat of further radioactive releases may allow some residents to begin returning to the least contaminated evacuation zones.[1]

Japan's environment minister announced December 19, 2011, that about $15 billion had been allocated for decontaminating the area around the Fukushima Daiichi plant, an unprecedented undertaking.[2] Complete decommissioning and dismantlement of the plant is expected to take 40 years, and the total cost of the disaster was recently estimated by a Japanese government committee to exceed $75 billion.[3]

The Institute of Nuclear Power Operations (INPO), a safety organization established by the U.S. nuclear power industry after the Three Mile Island accident, issued a detailed description of the Fukushima accident in November 2011. The INPO report provides timelines of the response actions taken at each unit of the Fukushima Daiichi plant and the sequences of events that led to major reactor core damage and radioactive releases. It is intended "to provide an accurate,

[1] Yuji Okada, Jacob Adelman, and Stuart Biggs, "Fukushima Dismantling to Start After Cold Shutdown," *Bloomberg*, December 16, 2011, http://www.bloomberg.com/news/2011-12-15/tepco-said-to-expect-approval-to-start-decommissioning-fukushima-station.html.

[2] Toko Sekiguchi, "Japan Allocates Money for Decontamination," *Wall Street Journal*, December 19, 2011.

[3] Shota Ushio, "Japan's Nuclear Power to Remain Competitive Through 2030: Panel," *Nucleonics Week*, December 22, 2011.

consolidated source of information" about the event. However, the report notes, "Because of the extensive damage at the site, some details of the event remain unknown or have not been confirmed."[4]

The purpose of this CRS report is to highlight the aspects of the Fukushima disaster that could bear on U.S. nuclear plant safety and nuclear energy policy in general. It provides a brief explanation of the Fukushima events, including new details provided by the INPO report, a general discussion of the consequences of the disaster, and a description of U.S. assistance provided to Japan. Other CRS reports provide additional information and analysis:

- CRS Report R41805, *Nuclear Power Plant Design and Seismic Safety Considerations*, by Anthony Andrews and Peter Folger.
- CRS Report R41728, *The Japanese Nuclear Incident: Technical Aspects*, by Jonathan Medalia (for information on nuclear plant radioactive releases and effects).
- CRS Report RL33558, *Nuclear Energy Policy*, by Mark Holt (for information on U.S. nuclear safety responses to Fukushima).
- CRS Report R41751, *Effects of Radiation from Fukushima Daiichi on the U.S. Marine Environment*, by Eugene H. Buck and Harold F. Upton.

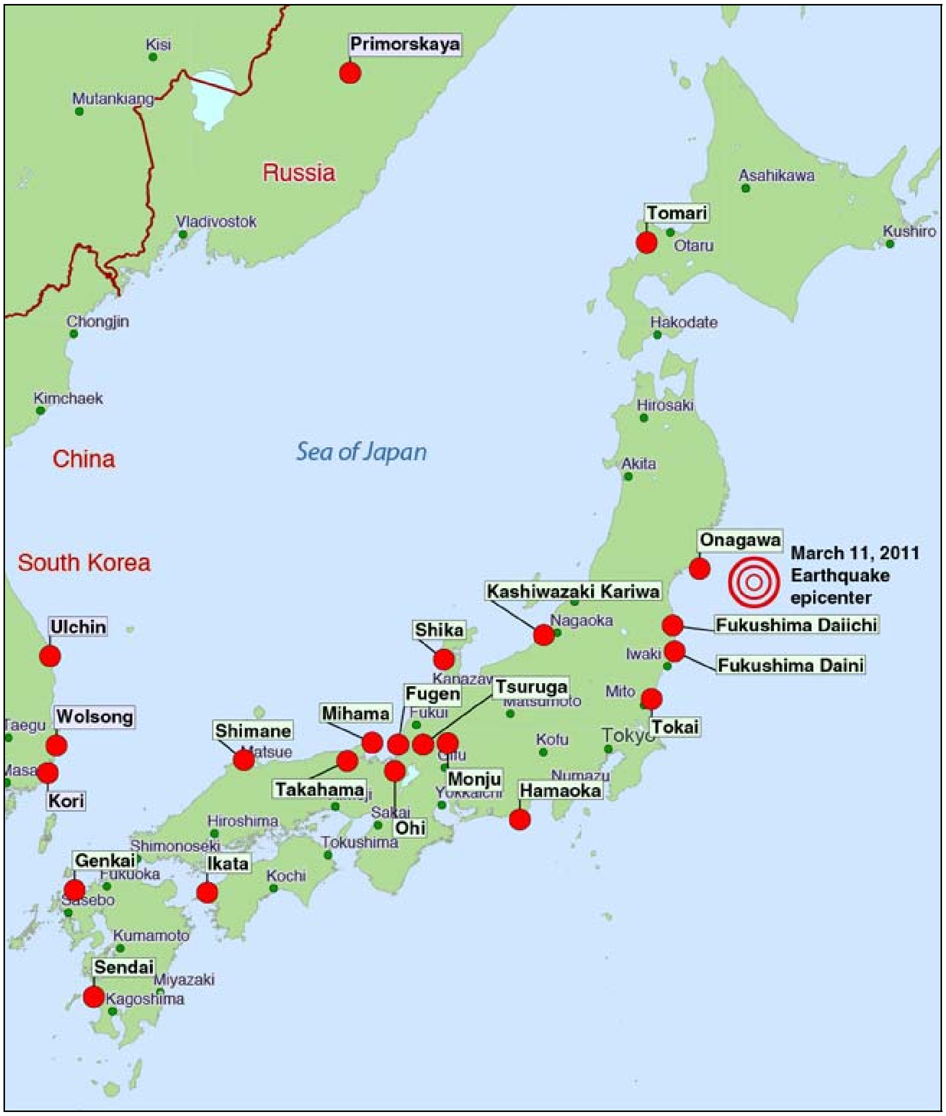
Summary of the Fukushima Daiichi Disaster

The earthquake on March 11, 2011, off the east coast of Honshu, Japan's largest island, reportedly caused an automatic shutdown of 11 of Japan's 55 operating nuclear power plants.[5] Most of the shutdowns proceeded without incident. However, the plants closest to the epicenter, Fukushima and Onagawa (see **Figure 1**), were damaged by the earthquake and resulting tsunami. The Fukushima Daiichi plant subsequently suffered hydrogen explosions and severe nuclear fuel damage, releasing significant amounts of radioactive material into the environment.

[4] Institute of Nuclear Power Operations, *Special Report on the Nuclear Accident at the Fukushima Daiichi Nuclear Power Station*, INPO 11-005, November 2011, available at http://www.nei.org/resourcesandstats/documentlibrary/safetyandsecurity/reports/special-report-on-the-nuclear-accident-at-the-fukushima-daiichi-nuclear-power-station.

[5] "Timeline: Japan Power Plant Crisis," *BBC News*, March 13, 2011, http://www.bbc.co.uk/news/science-environment-12722719.

Figure 1. Japan Earthquake Epicenter and Nuclear Plant Locations



Source: Nuclear Energy Institute, edited by CRS.

Notes: http://i1107.photobucket.com/albums/h384/reactor1/japan_map1.jpg.

Tokyo Electric Power Company (TEPCO) operates the Fukushima nuclear power complex in the Futaba district of Fukushima prefecture in Northern Japan, consisting of six nuclear units at the Fukushima Daiichi station and four nuclear units at the Fukushima Daini station. All the units at the Fukushima complex are boiling water reactors (BWRs),[6] with reactors 1 to 5 at the Fukushima Daiichi site being the General Electric Mark I design (see **Figure 2**).[7] The Fukushima

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[6] A common nuclear power reactor design in which water flows upward through the core, where it is heated by fission and allowed to boil in the reactor vessel. The resulting steam then drives turbines, which activate generators to produce electrical power. BWRs operate similarly to electrical plants using fossil fuel, except that the BWRs are powered by 370–800 nuclear fuel assemblies in the reactor core rather than burning coal or natural gas to create steam. U.S. Nuclear Regulatory Commission, "Boiling-Water Reactor (BWR)," http://www.nrc.gov/reading-rm/basic-ref/glossary/boiling-water-reactor-bwr.html.

[7] Nuclear Information and Resource Service, "Fact Sheet on Fukushima Nuclear Power Plant," http://www.nirs.org/ (continued...)

Daiichi reactors entered commercial operation in the years from 1971 (reactor 1) to 1979 (reactor 6).

Nuclear reactors produce power through the fission (splitting) of the nuclei of heavy isotopes, such as uranium-235 and plutonium-239, resulting from the absorption of neutrons. Each fission event generates additional neutrons that induce more fission events, creating a continuous nuclear chain reaction. The heavy nuclei split into lighter isotopes called fission products, many of which are highly radioactive, such as iodine-129, iodine-131, strontium-90, and cesium-137. To shut down the nuclear chain reaction, neutron-absorbing control rods[8] are inserted into the reactor core. However, even though the fission process has stopped, the fission products and other radioactive isotopes in the reactor core continue to generate significant heat through radioactive decay. Until the decay heat sufficiently diminishes, a source of electricity is needed to operate pumps and circulate water in the reactor. Under normal conditions, it would take a few days for a reactor core to cool down to a “cold shutdown” state.[9]

Reactors 1, 2, and 3 at Fukushima Daiichi were operating and automatically shut down when the quake struck, while reactors 4, 5, and 6 were already shut down for routine inspections. All four of the Fukushima Daini reactors were operating at the time of the earthquake and taken down after the quake. Although horizontal ground acceleration from the magnitude 9.0 earthquake exceeded the maximum designed level at two of the operating Fukushima Daiichi units (2 and 3), all the operating units maintained normal cooling immediately after the emergency shutdown.[10]

However, the earthquake triggered a tsunami that struck the Fukushima Daiichi station about 40 minutes later, devastating much of the area and overtopping the plant’s six-meter-high seawall. TEPCO estimated the tsunami’s height at Fukushima Daiichi to be 14 meters (46 feet).[11] The station was cut off from Japan’s national electricity grid, leaving the plant dependent on backup diesel generators for alternating current (AC) power.[12] The tsunami flooded most of the generators and electrical switchgear rooms, knocking out the backup AC power for cooling the nuclear reactors in units 1-5. An air-cooled diesel generator at Unit 6 survived the tsunami and provided backup power to cool unit 5 and 6, which therefore did not suffer fuel damage.[13]

Although backup batteries at the Fukushima Daiichi plant were designed to provide direct current (DC) power for eight hours, most of the DC power was lost when the tsunami flooded the plant’s DC power distribution systems. As a result, the shared control room for units 1 and 2 went completely dark, and the control room for units 3 and 4 had only emergency lighting available.[14]

(...continued)

reactorwatch/accidents/Fukushimafactsheet.pdf.

[8] A rod, plate, or tube containing a material such as hafnium, boron, etc., used to control the power of a nuclear reactor. By absorbing neutrons, a control rod prevents the neutrons from causing further fissions. U.S. Nuclear Regulatory Commission, “Control Rod,” http://www.nrc.gov/reading-rm/basic-ref/glossary/control-rod.html.

[9] U.S. Nuclear Regulatory Commission, “Cold Shutdown,” http://www.nrc.gov/reading-rm/basic-ref/glossary/cold-shutdown.html.

[10] Institute of Nuclear Power Operations, *op. cit*., p. 6.

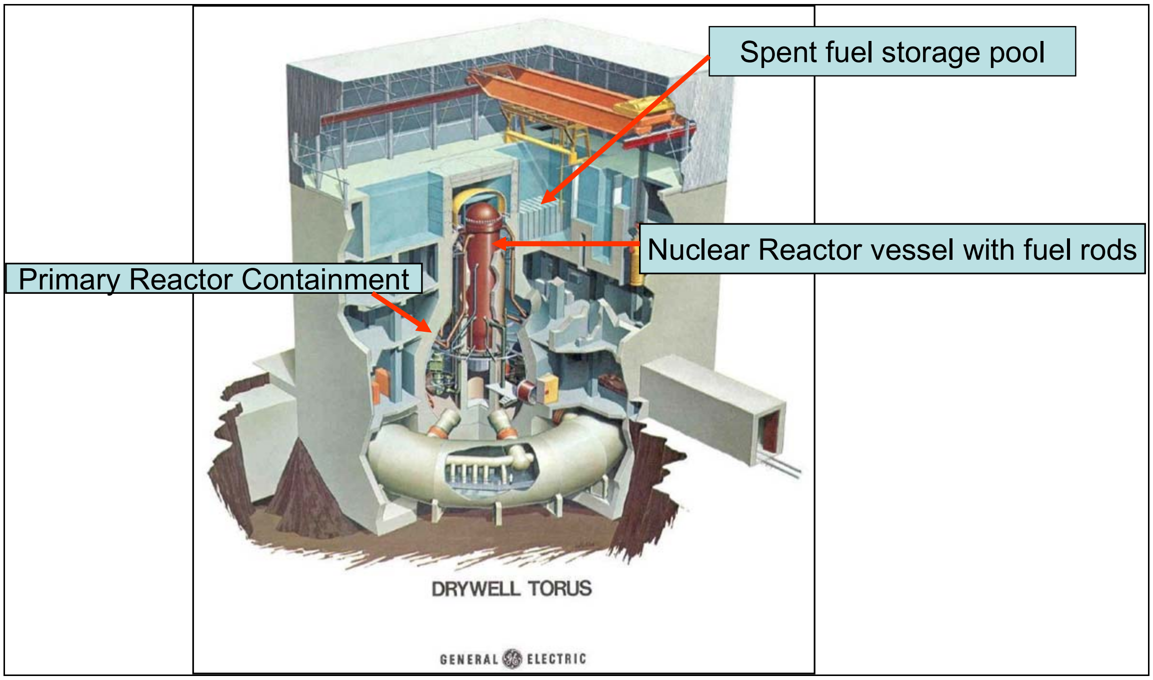
[11] “Fukushima Faced 14-Metre Tsunami,” *World Nuclear News*, March 23, 2011, http://www.world-nuclear-news.org/RS_Fukushima_faced_14-metre_tsunami_2303113.html.

[12] “Timeline: Japan Power Plant Crisis,” *BBC News*, March 13, 2011, http://www.bbc.co.uk/news/science-environment-12722719.

[13] Institute of Nuclear Power Operations, *op. cit*., p. 8.

[14] Ibid.

Figure 2. General Electric Mark I Boiling Water Reactor and Containment Building



Source: http://www.nrc.gov/, as modified by CRS

TEPCO immediately began to experience problems cooling the Fukushima Daiichi reactors. With alternating current no longer available to power the primary and secondary cooling systems, and batteries for backup cooling and control systems out of service, TEPCO began trying to cool the reactor cores with seawater.[15] Neutron-absorbing boron[16] was added to the seawater to prevent restart of the nuclear chain reaction. Despite those efforts, cooling water levels in the reactor cores remained low for many days, causing the reactors to overheat.

TEPCO estimated on December 2, 2011, that all of the nuclear fuel in Unit 1 had melted and that much of it had leaked from the reactor pressure vessel into the primary containment. Melting was considered likely for 57% of the fuel in Unit 2 and 63% of Unit 3. Because heat removal systems failed, pressure built up to high levels in the primary containments of units 1 through 3. The containments were vented to the atmosphere to relieve the pressure, allowing the escape of radioactivity leaking from the reactor cores.[17]

A chemical reaction between the fuel's zirconium cladding and high-temperature steam is believed to have generated large amounts of hydrogen in the containments of units 1 through 3. The hydrogen leaked from the containments or the venting systems into the reactor buildings and caused large explosions in units 1, 3, and 4. Japanese safety regulators estimated that each unit

[15] Yanmei Xie and Steven Dolley, "Damaged Reactor Design Has Weakness, But Not Cause for Crises, Say Experts," *Nucleonics Week*, March 17, 2011, p. 1.

[16] Boron is the main material that goes into control rods used to halt or slow fission reactions in nuclear reactors. *Japan Times Online*, "Seoul to Send Boron in Bid to Cool Reactors," March 16, 2011, http://search.japantimes.co.jp/cgi-bin/nn20110317a9.html.

[17] Shoto Ushio, "Tepco Report of Core Melting Renews Questions About Severe Accidents," *Nucleonics Week*, December 8, 2011, p. 1.

had produced 800-1,000 kilograms of hydrogen.[18] The hydrogen explosions caused tremendous damage and hindered TEPCO's efforts to restore plant cooling capability.

The loss of cooling also affected the plant's spent fuel pools (shown in **Figure 2**), which hold fuel rods that have been removed from the reactors after their ability to sustain a nuclear chain reaction has diminished. Although much of the radioactivity in the spent fuel has been decaying for many years, the large volumes of spent fuel in the pools represent a significant total heat load. If water in the spent fuel pools boils away or leaks out, the spent fuel rods may overheat and release radioactive material into the air. Because of concern that water in the Fukushima Daiichi spent fuel pools may have been splashed out or leaked during the earthquake and begun boiling away after cooling systems were lost, dramatic efforts were made to spray water into the pools or drop water from helicopters. Later analysis indicated that the pools did retain sufficient cooling water during the accident.[19] However, the explosions of reactor buildings 1, 3, and 4 exposed those pools to the atmosphere, and debris from the explosions may have fallen into the pools and damaged the stored fuel.

Substantial releases of radioactive material have occurred at the plant, most likely from leaking or venting from the primary containment structure that surrounds the reactor pressure vessel. Radioactive contamination exceeding regulatory limits was found in seawater around the plant, as well as contamination of agricultural products exceeding legal standards in surrounding prefectures.[20] Radioactive contamination in Tokyo drinking water on March 23 was measured at "more than twice the accepted level for infants."[21] As discussed later in this report, depositions of radioactive cesium "revealed high values comparable with the most contaminated areas of Chernobyl, even beyond the initial 20 km-radius evacuation zone around the Fukushima plant."[22]

Status of the Fukushima-Daiichi Reactors

All units of the plant were reconnected to off-site electrical power by March 23, and plant equipment was gradually reactivated. Diesel-generated backup power had been available at units 5 and 6 since March 19. Top priorities were restoring core cooling to units 1-3 and to the spent fuel pools in units 1-4 and eliminating discharges of highly contaminated water into the ocean.[23] All the reactors were declared to be in "cold shutdown" as of December 16, 2011.

Unit 1

Unit 1 was generating electricity when the earthquake occurred and shut down automatically, but the resulting tsunami halted emergency core cooling. Water levels in the reactor vessel dropped

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[18] World Nuclear Association, "Fukushima Accident 2011," December 22, 2011, citing the Japanese Nuclear and Industrial Safety Agency (NISA), http://world-nuclear.org/info/fukushima_accident_inf129.html.

[19] Institute of Nuclear Power Operations, *op. cit*., p. 12.

[20] Japan Atomic Industrial Forum, "Status of Nuclear Power Plants in Fukushima as of 22:00 March 24," March 24, 2011, http://www.jaif.or.jp/english/.

[21] U.S. Department of State, Bureau of Legislative Affairs, "Japan Earthquake Update 19," March 23, 2011.

[22] Institut de Radioprotection et de Surete Nucleaire, Assessment on the 66th Day of Projected External Doses for Populations Living in the North-West Fallout Zone of the Fukushima Nuclear Accident, Report DRPH/2011-10, May 27, 2011, http://www.irsn.fr/EN/news/Documents/IRSN-Fukushima-Report-DRPH-23052011.pdf.

[23] Ibid.; additional status information is from: Japan Nuclear Energy Safety Organization, "The State of Fukushima Dai-ich by the Impact of Tohoku Pacific Ocean Earthquake," March 23, 2011; Japanese Nuclear and Industrial Safety Agency, Seismic Damage Information (the 70th Release), April 3, 2011, http://www.nisa.meti.go.jp/english/files/en20110404-2-1.pdf.

below the top of the hot fuel, and steam began reacting with the zirconium fuel cladding to produce large amounts of hydrogen. After about 12 hours, pressure in the primary containment had increased to twice the designed level, radiation in the plant rose sharply, and preparations were made to vent the containment to the atmosphere. The population within 10 kilometers of the plant was evacuated, and venting began almost 24 hours into the emergency. About an hour after venting began on March 12, a large hydrogen explosion occurred in the upper area of the reactor building, causing widespread damage. The hydrogen may have leaked from the primary containment into the upper building structure during the overpressurization or from the vents.[24]

Plant workers began injecting seawater into the reactor pressure vessel on March 12 through a fire extinguisher line, and off-site power was restored on March 20. Freshwater injection into the reactor vessel began March 29.

TEPCO estimated on November 30, 2011, that all of the nuclear fuel in Unit 1 had melted and fallen to the bottom of the reactor pressure vessel (RPV) and that "a significant amount of the fuel fell out into the primary containment vessel (PCV) by destroying the RPV." At the same time, TEPCO estimated that molten fuel may have eaten into the concrete at the bottom of the primary containment to a depth of up to 70 centimeters, or about 28 inches.[25]

Unit 2

Unit 2 was generating electricity and automatically shut down during the earthquake. The tsunami flooded one backup diesel generator, but a second, air-cooled generator was on higher ground and continued to operate. However, the electrical switchroom for the operating generator was located below ground, suffered water damage, and subsequently failed. A portable generator was brought to Unit 2 and temporary power cables were hooked up, but just before power could be restored, the hydrogen explosion in Unit 1 propelled debris into the portable generator and cables and rendered them inoperable.

On March 15, while workers were attempting to vent the Unit 2 containment, they heard a loud noise near the torus (see **Figure 2**) followed by a reduction in containment pressure. The sound was later determined not to have been an explosion as initially suspected, but it may have been associated with a breach of the primary containment. Meanwhile, the rupture of a large, rectangular blowout panel in the outer wall of Unit 2 apparently allowed hydrogen to escape from the reactor building, preventing the explosions that occurred in the adjacent units.[26]

A steam-driven backup cooling system in Unit 2 continued to operate for about 70 hours after the tsunami, but all core cooling was subsequently lost for more than six hours, allowing the hot reactor core to become uncovered by water, possibly completely, and begin to melt. Seawater injection into the reactor vessel began March 14, after being delayed by a hydrogen explosion in Unit 3. Offsite power was restored on March 20, and freshwater injection into the reactor vessel began March 26.[27] TEPCO estimates that 57% of the fuel in Unit 2 melted during the period when cooling was lost, and some of the melted fuel may have dropped to the bottom of the reactor pressure vessel. However, as of November 30, TEPCO maintained that most of the melted

[24] Institute of Nuclear Power Operations, *op. cit*., p. 20.

[25] Tokyo Electric Power Company (TEPCO), "The Evaluation Status of Reactor Core Damage at Fukushima Daiichi Nuclear Power Station Units 1 to 3," November 30, 2011, pp. 6 and 21, http://www.tepco.co.jp/en/nu/fukushima-np/images/handouts_111130_04-e.pdf.

[26] Institute of Nuclear Power Operations, *op. cit*., p. 28.

[27] Institute of Nuclear Power Operations, *op. cit*., p. 27.

fuel had remained in the reactor vessel and had not fallen into the primary containment vessel as in Unit 1.[28]

Unit 3

Unit 3 was generating electricity and shut down automatically during the earthquake and then lost AC power during the tsunami. High-pressure injection of water into the reactor vessel was lost after about 36 hours, on March 13, and there was no cooling for nearly the next seven hours, when seawater injection began. During that seven-hour period, the reactor core became uncovered with water, resulting in severe fuel damage and the generation of large amounts of hydrogen. Damage to the reactor pressure vessel is considered likely.[29]

Pressure in the primary containment structure rose sharply on March 14, and after many hours, plant workers opened the necessary valves to vent the primary containment at about 8:30 a.m. A large hydrogen explosion occurred at about 11 a.m. that destroyed the secondary containment (the upper part of the reactor building), where hydrogen had apparently escaped from the primary containment or backflowed from the earlier venting. The explosion injured 11 workers and damaged portable generators, fire engines, hoses, and temporary power cables that had been brought in to restore cooling to the reactor. An undamaged fire engine was brought in and seawater injection resumed at about 4:30 p.m.[30]

Unit 3 had operated since September 2010 with plutonium-based fuel,[31] called mixed-oxide (MOX) fuel. The use of MOX fuel, which made up about 6% of the reactor core, heightened concerns after the accident about the potential release of plutonium. Although plutonium, a hazardous radioactive element, is also created during irradiation of conventional nuclear fuel, there is substantially more in MOX fuel than in conventional fuel. The Nuclear Energy Institute contends that the relatively small amount of MOX fuel in Unit 3 "did not have a significant impact on the offsite releases of radioactivity."[32]

Three workers received high doses of radiation from contaminated water while installing cables in the basement of the turbine building March 24. Injection of fresh water into the reactor vessel began March 25. TEPCO estimates that, as in Unit 2, much of the reactor core of Unit 3 melted but was retained in the reactor vessel.[33] The reactor's primary containment structure is not believed to be damaged, and damage has not been found to the spent fuel in the spent fuel pool.

Unit 4

Unit 4 was out of service for maintenance when the earthquake struck. All its nuclear fuel had been moved to the spent fuel pool, which eliminated the need for cooling the reactor core but greatly increased the spent fuel pool's heat load. A hydrogen explosion severely damaged the reactor building on March 15. Because there had been no fuel in the reactor core to generate the

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[28] TEPCO, *op. cit*., p. 7.

[29] Institute of Nuclear Power Operations, *op. cit.,* p. 10.

[30] Institute of Nuclear Power Operations, *op. cit*., p. 32; World Nuclear Association, *op. cit.*

[31] World Nuclear Association, "Nuclear Power in Japan," February 24, 2011, http://www.world-nuclear.org/info/inf79.html.

[32] Nuclear Energy Institute, "What Fuel Mix Was in Use at Fukushima and Was That a Factor in the Accident?," July 25, 2011, http://safetyfirst.nei.org/ask-an-expert/what-fuel-mix-was-in-use-at-fukushima-and-was-that-a-factor-in-the-accident-does-the-united-states-use-mox-fuel/.

[33] TEPCO, *op. cit*., p. 7.

hydrogen, suspicion initially focused on the spent fuel pool as the source. Early reports had indicated that most or all of the water in the Unit 4 spent fuel pool had been lost, potentially causing overheating that could lead to hydrogen generation. However, it was later determined that water in the pool had not dropped below the level of the spent fuel and that no significant overheating had occurred. Spraying of water into the spent fuel pool began on March 20.

Analysis by TEPCO now indicates that the hydrogen that exploded in Unit 4 came from Unit 3 during the venting that had begun the previous day. Units 3 and 4 share a single exhaust stack, and the loss of power had left Unit 4's exhaust gas valves in the open position. As a result, when the Unit 3 primary containment was vented, hydrogen and other gases were able to flow backward from the common exhaust stack into Unit 4 and eventually into the reactor building's air duct system. This scenario was supported by radiation samples from the Unit 4 exhaust gas filters that showed higher contamination levels in the filters closest to the common stack (and closest to Unit 3), the opposite of what would normally be expected.[34]

Units 5 and 6

Units 5 and 6, which are located separately from units 1-4, were not operating during the earthquake. Four of the five emergency diesel generators at units 5 and 6 were rendered inoperable by the tsunami, but one air-cooled diesel generator continued working. The working generator supplied continuous power to Unit 6 and later provided power to Unit 5 as well.[35] Cold shutdown of both units was declared on March 20. Holes were opened in the roofs of the reactor buildings to prevent hydrogen buildup. No other damage has been reported to the reactor buildings or spent fuel.

Fukushima Daini

The Fukushima Daini station is approximately 12 kilometers (7 miles) south of the Daiichi station, and further removed from the epicenter of the earthquake. The earthquake and tsunami apparently caused damage to the emergency core cooling systems at reactors 1, 2, and 4, while reactor 3 was apparently able to shut down without problems. The station reportedly retained offsite power to maintain its ability to circulate cooling water in the reactor. The makeup water and condensate systems were used as an emergency measure to maintain cooling water levels in reactors 1, 2, and 4. TEPCO has since made repairs to the cooling systems, and stable, cold shutdown conditions were reported at all Daini reactors on March 14, 2011.[36]

Radioactive Releases and Contamination

Radioactive material escaping from the damaged Fukushima-Daiichi reactor cores created high radiation levels throughout the plant and eventually caused widespread contamination. Large radioactive releases into the atmosphere resulted from the containment venting and hydrogen explosions. At the same time, large amounts of water being pumped or sprayed into the reactors became heavily contaminated and were discharged or leaked into the ocean.

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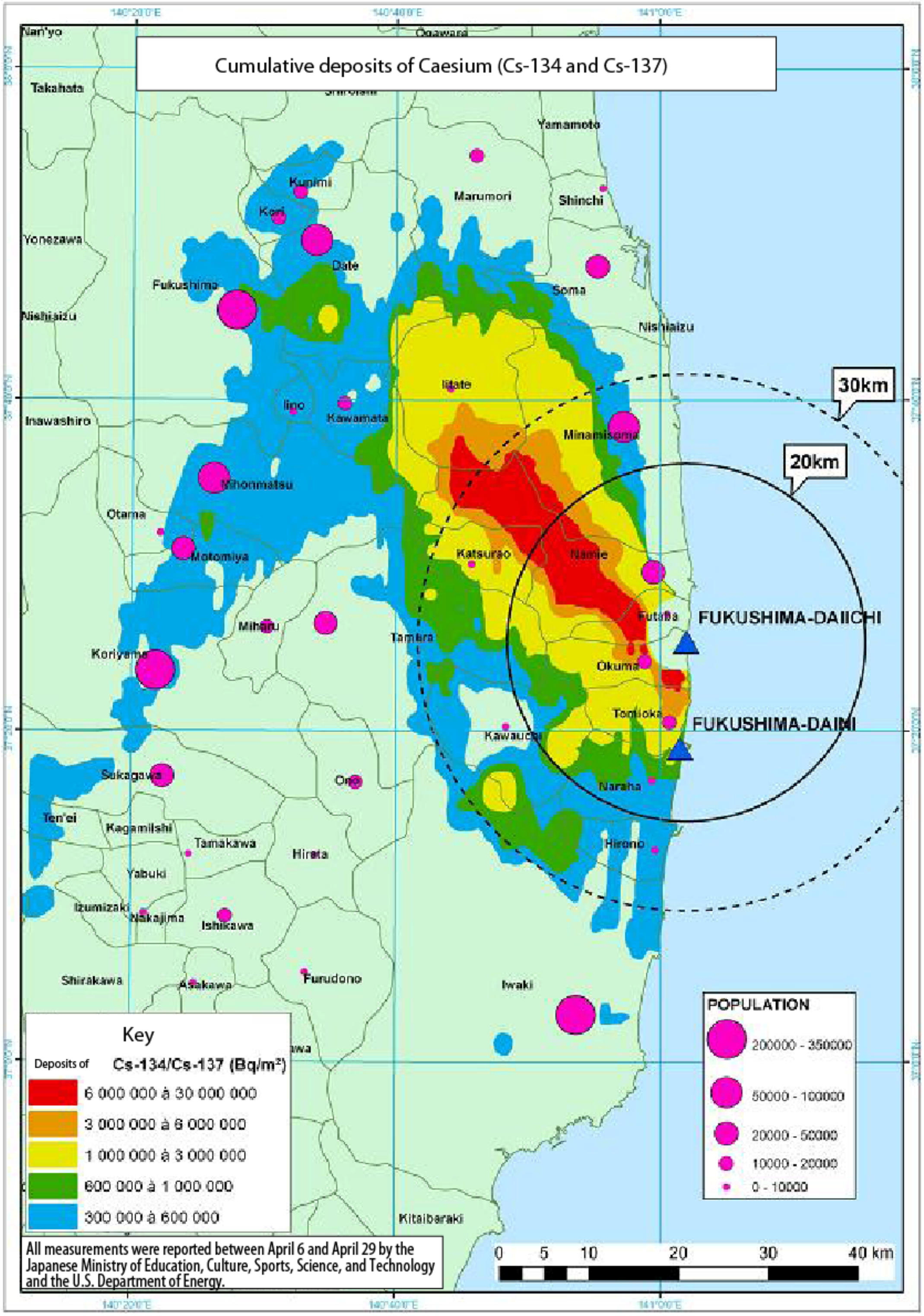
[34] Institute of Nuclear Power Operations, *op. cit*., p. 33.

[35] Institute of Nuclear Power Operations, *op. cit.,* p. 3.

[36] "All Fukushima Daini Units in Cold Shutdown," *World Nuclear News*, March 14, 2011, http://www.world-nuclear-news.org/IT-All_Fukushima_Daini_units_in_cold_shutdown-1503114.html.

Figure 3. Cesium Depositions Around Fukushima-Daiichi



Source: Institut de Radioprotection et de Surete Nucleaire (IRSN)

Note: 1 becquerel (Bq) = 27 picocuries (pCi)

A precautionary evacuation for a 3-kilometer radius around the plant was ordered on the day of the tsunami. Elevated dose rates were first detected at the plant site boundary on the next day, and the evacuation was expanded first to 10 kilometers and then to 20 kilometers. As the situation in the reactors deteriorated, dose rates at the site boundary rose rapidly, reaching 1,085 millirem/hour on March 16. Meanwhile, dose rates inside the plant were measured at up to 400 times higher, greatly complicating recovery efforts.[37] For comparison, a widely used international dose limit for members of the public is 100 millirem for an entire year.

Radioactive contamination of the ocean became an international concern after high concentrations of radioactivity were measured in the power plant's harbor on April 2. According to the INPO report, contaminated water had accumulated in the turbine building, flowed through a trench, and leaked into the harbor, totaling about 130,000 curies.[38] Controversy was raised by Japan's decision in early April 2011 to allow TEPCO to release more than 10,000 cubic meters of water with relatively low concentrations of radioactivity into the sea to make space to store more heavily contaminated water from the plant. Treatment facilities were since constructed at the site to remove radioactive material and other contaminants from the stored water, allowing it to be recycled for reactor cooling.[39]

Contamination of the land around the Fukushima plant was concentrated to the northwest, leaving large areas uninhabitable, as shown in **Figure 3**. Most of that contamination occurred when prevailing winds that had been carrying the plant's atmospheric releases over the Pacific Ocean shifted to the northwest during two days in mid-March and heavy rains washed the radioactive material from the air.[40] The depositions of radioactive cesium (the primary long-term land contaminant) are "comparable with the most contaminated areas of Chernobyl, even beyond the initial 20 km-radius evacuation zone around the Fukushima plant," according to the French Institut de Radioprotection et de Surete Nucleaire (IRSN). However, the amount of land around Fukushima with cesium deposits greater than 600,000 becquerels (16.2 microcuries) per square meter was estimated to be "only 8.5% of that of Chernobyl."[41]

About 84,000 residents within 20 kilometers (about 12.5 miles) from the plant were evacuated by April, and another 15,000 residents in the heavily contaminated area northwest of the 20-kilometer zone, up to 40 kilometers (25 miles) from the plant, were evacuated in mid-May. The Japanese government has announced plans to begin decontaminating the area, but how long the process will take is unknown. The long-term goal is to reduce annual radiation doses from the accident to the international standard of 100 millirem.[42]

[37] Institute of Nuclear Power Operations, *op. cit.,* p. 38.

[38] Institute of Nuclear Power Operations, *op. cit.,* p. 38. Curies and becquerels are units for measuring radioactive decay. One becquerel equals one radioactive decay event per second, while one curie equals 37 billion decay events per second. Rems and seiverts are the units for measuring the effect of radiation doses absorbed by the human body.

[39] World Nuclear Association, *op. cit.*

[40] Institute of Nuclear Power Operations, *op. cit*., p. 42; Nuclear Information and Resource Service, "Chronological Fact Sheet on 2011 Crisis at Fukushima Nuclear Power Plant," Update, December 7, 2011, http://www.nirs.org/reactorwatch/accidents/Fukushimafactsheet.pdf.

[41] Institut de Radioprotection et de Surete Nucleaire, *op. cit*., p. 4.

[42] World Nuclear Association, *op. cit.*

U.S. Assistance

The United States and other countries, as well as the International Atomic Energy Agency, are providing assistance to Japan to deal with the nuclear crisis. Japan requested assistance for the nuclear crisis from the United States a few days after the earthquake and tsunami. The United States provided advice and equipment, including transport of pumps, boron, fresh water, remote cameras, use of Global Hawk surveillance drones, evacuation support, medical support, and decontamination and radiation monitoring equipment. A U.S. Nuclear Regulatory Commission (NRC) advisory team traveled to Japan at the Japanese government's request, and NRC experts were resident at the U.S. embassy in Japan throughout the crisis. The National Nuclear Security Administration (NNSA) of the Department of Energy (DOE) sent "a team of 34 experts and more than 17,000 pounds of equipment in support of efforts to manage the crisis."[43] DOE also provided the Aerial Measuring System and radiation monitoring equipment, and provided analysis from the U.S. national laboratories. The U.S. Department of Defense provided high-pressure water pumps and fire trucks in the battle to cool the reactors and contain the damage.

The United States continues to work with Japan on environmental remediation efforts and the decommissioning of the Fukushima Daiichi plant. Deputy Secretary of Energy Daniel Poneman in a speech in Tokyo said that Japan has asked the Department of Energy to share its experience of environmental cleanup at nuclear sites such as Hanford and Savannah River.[44] The Department of Energy has participated in workshops and training for Japanese officials. For example, DOE's Office of Environmental Management conducted a workshop in Japan in October 2011 on the storage and disposal of radioactive waste.[45] This cooperation is expected to last many years into the future.

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[43] Remarks of Daniel Poneman, Deputy Secretary, Department of Energy, Tokyo American Center, December 15, 2011, http://energy.gov/articles/deputy-secretary-daniel-ponemans-remarks-tokyo-american-center-prepared-delivery.

[44] Ibid.

[45] http://www.em.doe.gov/pdfs/EM%20Program%20Update%2011-09-11.pdf.