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ANALYSIS

Anatomy of a Nuclear Crisis: A Chronology of Fukushima

The world's worst nuclear reactor mishap in 25 years was caused by a massive natural calamity but compounded by what appear to be surprising mistakes by Japanese engineers. The result has been a fast-moving disaster that has left officials careening from one emergency to the next.

BY DAVID BIELLO

On March 11, the ground beneath Japan swayed for as much as 5 minutes, a 9.0-magnitude earthquake that ultimately moved Japan some 2.4 meters (7.9 feet) closer to the United States. Thirty minutes later, a wall of water roughly 250 miles long slammed into the northeast coast of the island nation, smashing everything in its path. Among the victims were at least 7,000 dead and 10,000 missing — as well as one nuclear power plant: Fukushima-Daiichi and its six reactors.

In the ensuing days, the world has watched as Japanese engineers and plant workers have struggled to keep the fuel rods inside the crippled Fukushima plant from melting down, lurching from one crisis to the next as four of the complex's reactors have experienced explosions and releases of radioactive material. Amid the confusion, it was clear that some very basic mistakes — most noticeably placing backup diesel generators only slightly above sea level in a tsunami zone — had made the situation at Fukushima far worse.

Even now, 10 days after the crisis began, the situation at Fukushima is still not under control. The disaster is clearly worse than the 1979 partial meltdown at Three Mile Island in Pennsylvania, yet not as grave as the 1986 explosion at the Chernobyl nuclear plant, which spread radioactive material over large portions of Europe. A chronology of how the Fukushima crisis has unfolded demonstrates that even a country as advanced as Japan — and as practiced in dealing with natural disasters — was unprepared for an earthquake of this magnitude, the largest in Japan in 1,200 years.

March 11

When the earthquake struck at 2:46 p.m., the Fukushima-Daiichi nuclear power plant, along with at least three others, automatically shut down, sliding control rods — made of materials, like boron, that block neutrons — into the three reactor cores that had been up and running. That instantly stopped the fission of the enriched uranium fuel that allows a nuclear reactor to produce the steam that spins a turbine to make electricity.

But even with fission stopped, nuclear fuel rods must be kept cool, as byproducts of the nuclear reaction continue to break down and produce heat for years. The key to cooling the rods is simple: flow water past them. But because of the earthquake, no electricity could be delivered to the Fukushima-Daiichi nuclear power plant to run the cooling pumps. The back-up diesel generators that should have kicked in when power was lost did not survive the tsunami, which easily overtopped the seawall protecting the plant — leaving only batteries to run all the systems. At the same time, the tsunami flooded critical electrical equipment. After eight hours, the batteries went dead — meaning the nuclear power plant had no electricity, and no way to cool itself.

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In essence, the now-still water inside the reactors began to boil off, exposing the fuel rods and threatening a meltdown of the uranium fuel pellets inside.

By the evening of the first day, the Japanese government warned of cooling problems at the nuclear power plant and declared a "state of nuclear emergency," though stressing that no radiation leaks had been detected. Nevertheless, government officials advised people living within a few kilometers of the plant to leave. At the same time, portable diesel generators brought to the Fukushima-Daiichi plant restored power to some systems, although it is unclear why more generators weren't put into service to cool the reactors. By later that night, the Japanese government noted that radiation levels appeared to have risen in at least one of Fukushima's reactors.

March 12

In the early hours of Saturday, March 12, the nuclear power plant's owner and operator, Tokyo Electric Power Co. (TEPCO), reported rising pressure inside reactor No. 1, a sure sign that not enough water was reaching the core, allowing steam to build up. In fact, pressure readings reached 840 kiloPascals at Fukushima-Daiichi reactor No. 1 — more than double normal operating pressures. By dawn, pressure was also rising at another nearby nuclear power plant disconnected from the grid by the quake and tsunami — Fukushima Daini, with four reactors. But backup power there seems to have prevented further trouble.

That morning, TEPCO workers began venting radioactive steam at Fukushima-Daiichi reactor No. 1 to prevent pressure from getting any higher and bursting the thick steel vessel that holds the nuclear core. In essence, the operators moved radioactive gases from the inner containment area into the larger building that houses the reactor. At the same time, the government began evacuating some 20,000 people from the region within 10 kilometers of the stricken power plant.

AFP/Getty Images
On March 12, an explosion tore the roof off the building housing reactor No. 1 after workers vented high-pressure steam and hydrogen into the structure.

Without the ability to add more water due to pump failures, however, the fuel rods could not be cooled. Such nuclear fuel rods are encased in a hard zirconium cladding, which holds them together and allows the neutrons necessary for fission to pass through. But when the fuel rods are not cooled, that same cladding swells and cracks, allowing the release of radioactive particles produced by fission, such as cesium-137 or iodine-131. Worse, as temperatures rise as high as 1,200 degrees Celsius, the cladding strips oxygen from the surrounding steam — like high-speed, high-temperature rusting — leaving hydrogen gas behind.

When workers vented the high-pressure steam and hydrogen into the building housing reactor No. 1, it began to build up. At sufficient concentrations — roughly 4 percent or more — hydrogen is explosive if it finds oxygen or a spark. That is exactly what happened at reactor No. 1, where an explosion tore the roof off of the building housing the reactor. Four workers were injured.

But by nightfall, as pressure continued to swell, TEPCO workers began to pump seawater and boric acid into reactor No. 1 via lines put in place to put out fires. It was a desperate bid to cool the reactor and ensure that fission did not resume. The Japanese government began distributing iodine pills to nearby residents in an effort to ensure that any radioactive iodine released did not end up inside the thyroid glands of citizens.

March 13

By the morning of March 13, the Japanese government's evacuation efforts had expanded to include a full 20-kilometer radius around the plant, putting more than 100,000 people on the move. Radiation levels in Fukushima-Daiichi nuclear power plant had risen above safe limits. TEPCO expanded its seawater and boric acid pumping efforts to include reactors No. 2 and No. 3 — meaning cooling was now failing at all three nuclear reactors in operation at the time of the earthquake. The workers continued to vent radioactive steam.

March 14

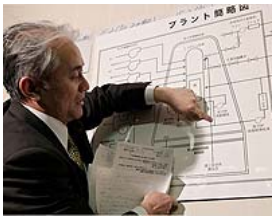
On Monday morning, March 14, another hydrogen explosion ripped reactor No. 3 at 11:01 a.m. local time, injuring seven workers and four soldiers. One of the soldiers may have ingested radioactive material and was transported to the National Institute of Radiological Sciences. The explosion tore open the building housing reactor No. 3 and caused its pressure readings to fluctuate, raising fears that its steel containment vessel might be cracked, according to NISA. Pressure readings quickly returned to normal, however, easing those fears, though water levels were as much as 2.3 meters below the top of the 3.7-meter-long fuel rods.

By nightfall, cooling had completely failed at reactor No. 2, potentially exposing the entire fuel rods in that reactor to the air and steam. To prevent another hydrogen buildup and explosion, TEPCO workers cut a hole in the side of the building housing Unit 2.

March 15

By Tuesday morning, March 15, another explosion was heard coming from the building housing reactor No. 2. Steam rose from the damaged building and radiation levels at the power plant increased four-fold. Worse, this explosion potentially damaged part of the core

containment system — a donut-shaped tube of water meant to both cool the reactor in an emergency and capture any radioactive particles. The so-called suppression pool might now have a leak, allowing radioactivity to escape — a problem the U.S. Atomic Energy Commission had identified in the design of this reactor as far back as 1972. Atmospheric pressure dropped from three times normal to normal in an instant after the explosion. And radiation levels spiked to 965.5 microSieverts per hour in the wake of the blast, suggesting some radioactive material might be escaping from the reactor.



AFP/Getty Images
A specialist from Tokyo Electric Power Co uses a diagram to explain the structure of the Fukushima-Daiichi plant on March 15.

That same morning, a fire broke out in the building that houses reactor No. 4, which contained spent fuel rods and had been shut down for maintenance even before the earthquake struck. Those rods, submerged in a concrete and steel tank filled with boric acid, need to continue to cool until they can be transferred for either reprocessing or storage in massive concrete and steel casks. The spent rods also began to heat up when cooling systems failed.

As a result of the danger posed by radioactive particles wafted into the air by the smoke, Prime Minister Naoto Kan, in a televised address, warned residents living within 30 kilometers of the failing nuclear power plant to remain indoors.

Another hydrogen explosion tore two holes, roughly eight meters across, in reactor No. 4's outer building. U.S. Nuclear Regulatory Commission Chairman Gregory Jaczko suggested in testimony to Congress on March 16 that the pool was actually dry — meaning the overheating fuel rods were exposed to the air.

By nightfall, radiation levels reached 400 milliSieverts an hour near reactor No. 3. As a result of those elevated radiation levels, TEPCO evacuated all non-essential personnel — some 750 workers — leaving a skeleton crew of 50 to continue desperate efforts to manually pump seawater and boric acid into the stricken reactors. Even those left behind had to evacuate the control room for reactor No. 4 because of increased radiation levels.

March 16

Wednesday, March 16, dawned with thick white steam billowing from the damaged building that housed reactor No. 3, suggesting that the spent fuel pool in that building was boiling off its cooling water as well. And yet another fire broke out in the building housing reactor No. 4.

Still, temperature and pressure began to come down at reactor No. 2, suggesting the workers' valiant efforts were having an effect there. By nightfall, continued pulses of radiation required the workers to pull back from such efforts — and a planned helicopter flight to drop seawater on the power plant had to be postponed.

Tests showed no radioactive cesium or iodine in local water supplies. The final two reactors — No. 5 and No. 6, the only reactors to show no signs of trouble — appeared to be staying cool. But radiation levels next to the reactors remained high, although radiation levels at the boundary of the stricken nuclear power plant were relatively low — roughly three times normal background radiation for a year.

> Flitting like ghosts through the stricken plant, workers struggled to bring cooling water to the boiling reactors.

The Japanese military began dropping seawater from two helicopters onto the exposed fuel pools at reactors No. 3 and No. 4. And water cannons vaulted cooling liquid into the spent fuel pools to good effect, according to TEPCO.

But pressure also began to rise again at reactor No. 3. And water levels remained too low in all three reactors operating at the time of the earthquake. The potential remained for a full meltdown — when all the fuel rods melt and flow to the bottom of the containment building, potentially causing a steam explosion that would release radioactive materials — to occur.

March 17-20

Over the past several days, Fukushima-Daiichi workers continued their heroic efforts, facing further explosions or invisible hydrogen fires and dangerous levels of radiation. Given an inability to either shield themselves or remain far from the sources of that radioactivity, the workers could only protect themselves by limiting the amount of time spent in highly radioactive areas. Flitting like ghosts through the

stricken nuclear power plant and breathing through special tanks and filters strapped to their backs, the skeleton crew of workers struggled to bring cooling water to the boiling reactors and the overheating pools of spent fuel.

Over the weekend, engineers continued to battle problems, such as a buildup of pressure in reactor No. 3. In addition, the Japanese government reported that milk, canola, spinach, and other agricultural products from regions near the plant contained elevated levels of radioactive elements, further heightening fears among the Japanese public. The government barred shipments of these products from the affected prefectures. Now, perhaps the best hope may be the completion of a new power line, which would bring much-needed electricity from power plants outside the area to restart the electric pumps to cool down the reactors. That progress has been slowed both by the damage from the earthquake and tsunami to the grid in general, but also by the high levels of radiation at the reactor buildings, where the line would need to be connected. Pumps and other safety systems may also have been damaged in the earthquake, tsunami, or subsequent meltdown prevention efforts. Those challenges were evident on Monday. Even after connecting a mile-long, high-voltage transmission line to reactor No. 2, engineers said they still had not succeeded in getting the reactor's electrical systems and water cooling pumps to work. The Japan Atomic Industrial Forum estimated that fuel rods remain exposed inside all three reactors in operation at the time of the earthquake.

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Japan's Once-Powerful Nuclear Industry is Under Siege

The disaster at the Fukushima-Daiichi nuclear power plant has highlighted the importance of nuclear energy to Japan and the power long wielded by the nuclear sector. But that influence now is sure to wane, to the relief of opponents who have fought for years to check nuclear's rapid growth, writes Caroline Fraser.
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Fukushima-Daiichi is unlikely to return to generating electricity via fission. Instead, it may become a memorial like Chernobyl, an entombed emblem of a terrible nuclear accident. And radioactive elements, like cesium-137, with a half-life of 30 years, will remain in the plant's environs for years to come, a reminder to the region's residents of the tsunami and its devastating blow to Fukushima.

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David Biello has been covering energy and the environment for nearly a decade, the last four years as an associate editor at *Scientific American*. He also hosts *60-Second Earth*, a *Scientific American* podcast covering environmental news. In previous articles for *Yale Environment 360*, Biello has written about geothermal technology and solar thermal technology and has explored the progress of carbon capture and storage technology.

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