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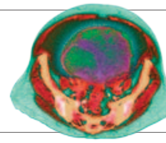

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TOKYO ELECTRIC POWER CO./PRESS ASSOCIATION IMAGES

Smoke rising from a reactor at the Fukushima Daiichi nuclear plant meant workers had to be evacuated.

JAPAN

The meltdown that wasn't

How a handful of operators at a crippled reactor averted a greater catastrophe at the Fukushima plant.

BY GEOFF BRUMFIEL

The magnitude-9.0 earthquake rocked Fukushima Daiichi nuclear power station at 2:46 p.m. on 11 March, but the real emergency began an hour later. A wall of water swept across the site, washing away power lines and the fuel tanks for the emergency backup generators designed to take over if grid power failed. Inside the control room of the unit 1 reactor, the lights went out and the 1970s-vintage analogue gauges drifted to zero.

It will probably be years before anyone knows exactly what happened inside the three reactors at Fukushima Daiichi that seem to have partially melted down in the wake of the tsunami. But from press reports, public statements and interviews with experts, it is possible to work out the most likely scenario. And already it is clear that decisions made in the initial 24 hours by the handful of operators in the control room probably averted a much greater nuclear catastrophe than the one that now faces Japan.

In the moments after the power was lost, the operators "would have literally been blind", says Margaret Harding, a nuclear engineer in Wilmington, North Carolina. Harding worked for two decades with General Electric, which designed Fukushima's boiling-water reactors, and she witnessed a similar outage in 1984 during a safety test at a boiling-water reactor in Switzerland. "Basically the emergency lights came on and all the panels went black," Harding says.

During the Swiss test, the power returned in 5 minutes. At Fukushima, batteries ran a handful of emergency lights in the control room and a few instruments tracking the reactor's vital signs, such as the pressure inside the core.

The core was next door. Inside a large, cube-shaped building, enclosed in a heavy concrete containment vessel, sat a thick, steel capsule filled with around 50 tonnes of uranium. Until an hour previously, that fuel had been pumping out 460 megawatts of power, but the reactor had automatically shut down immediately after the earthquake. Boron–carbon control rods driven between the long columns of fuel had soaked up neutrons and halted the nuclear reactions.

MODEL RESPONSE

That didn't mean the reactor was cold. Radioactive by-products of the fission reactions still generated heat — some 7 megawatts of it, preliminary computer models by the National Nuclear Laboratory in Sellafield, UK, suggest. The fuel still needed to be actively cooled.

Without power, operators could use steam from the reactor's pressure vessel, plus minimal amounts of battery power, to drive a pump that would keep the cooling water circulating. What they probably didn't know was that the cooling system had sprung a leak. The leak caused water levels inside the core to drop, allowing the fuel to heat up, which generated more steam and raised the pressure inside the steel vessel. The emergency cooling system was unable to cope, according to a press release from the Tokyo Electric Power Company (TEPCO), the plant's ▶

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For full coverage of the earthquake and nuclear crisis, see: go.nature.com/ulsz2n

AN UNFOLDING CRISIS

At the Fukushima Daiichi power station, the plant hit hardest by the earthquake and tsunami, unit 1 was the first of four operating reactors to reach a point of crisis.

FRI 11 MARCH

14:46 The M9.0 earthquake struck; reactors were shut down.

15:42 Mains power was lost.

15:45 Oil tanks were washed away by tsunami.

16:36 Emergency core cooling system failed in **unit 1** and **unit 2**.

19:03 A nuclear emergency was declared at Fukushima Daiichi.

20:50 Residents living within 2 km of Fukushima Daiichi were told to evacuate.

SAT 12 MARCH

4:00 Pressure in the containment at **unit 1** reaches 840 kPa, twice the design value.

5:44 Evacuation was expanded to a 10-km radius of Fukushima Daiichi.

14:30 Steam was vented from **unit 1**.

14:49 Radioactive caesium was detected around **unit 1**.

15:36 Hydrogen explosion took place at **unit 1**.

20:20 Sea water was injected into the reactor at **unit 1**.

SUN 13 MARCH

13:12 Sea water was injected into the reactor at **unit 3**.

MON 14 MARCH

4:08 Spent fuel pool at **unit 4** overheated.

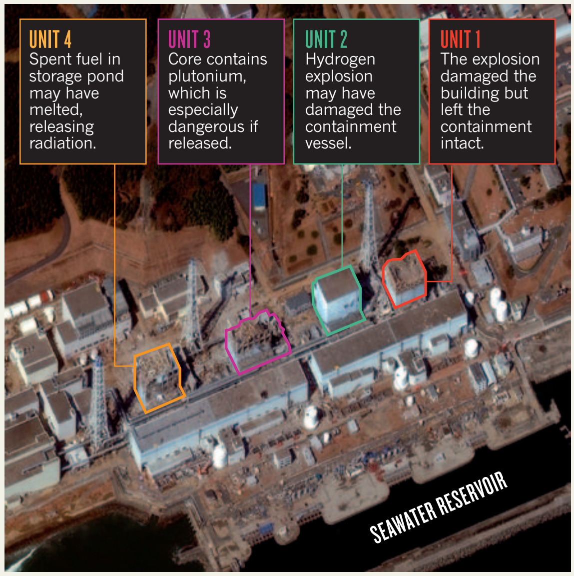
11:01 **Unit 3** exploded.

16:34 Sea water was injected into the reactor at **unit 2**.

TUE 15 MARCH

6:10 **Unit 2** exploded.

9:38 Fire broke out at the reactor building of **unit 4**.



DIGITALGLOBE/REUTERS

A satellite view of the Fukushima Daiichi plant shows heavy damage from explosions or fire at three of the four affected reactors.

operator. At 7:03 p.m. a state of nuclear emergency was declared. Less than 2 hours later, evacuations began within a 2-kilometre radius of the plant.

By 4:00 a.m. the pressure inside the thick steel vessel of unit 1 had reached 840 kilopascals (kPa), more than twice the operating limit, according to the Nuclear and Industrial Safety Agency, the Japanese nuclear regulator. Radiation levels at the front gate of the site had begun to rise above background, although they were still far from dangerous. At 5:44 a.m. the evacuation cordon was expanded to 10 kilometres.

At some point, the falling water levels must have left the fuel exposed. In a reactor such as unit 1, the uranium pellets are enclosed in long, skinny pipes made of zirconium alloy, chosen because it does not inhibit the neutrons needed to drive the fission reactions. As temperatures rose above 1,000 °C, the steam in the pressure vessel began to oxidize the zirconium, probably releasing hydrogen gas. Meanwhile, fuel pellets, liberated from their shell, began to fall to the bottom of the reactor. The meltdown had begun.

This was the crucial moment. If the operators at unit 1 could not stem the meltdown, the fuel would gather at the bottom of the vessel. The uranium pellets, now in close proximity, could begin exchanging neutrons and resume their heat-producing nuclear reactions. Slowly, the pile could build towards a 'critical mass' that would restart the nuclear process normally used to generate electricity.

TURNING POINT

Nobody can be sure about this sequence of events because there has never been a full meltdown in a boiling-water reactor. Harding says that she thinks it's unlikely that the nuclear processes would have reignited. Even if they did, the worst case, in her opinion, is that the fuel would have burned through the steel pressure vessel and splattered onto the 'base mat', a thick concrete slab that would have spread out the fuel, extinguishing any fission reactions.

But even that might have been catastrophic. The volatile hydrogen gas generated by the zirconium was safe inside the steel pressure vessel, but it was liable to explode if exposed to air in the outer containment vessel. If the blast were big enough, it might have breached the outer vessel's thick, concrete walls.

This scenario is highly unlikely, but had it happened, the workers struggling to save the plant would almost certainly have received a lethal dose of radiation, says Malcolm Sperrin, a medical physicist at the Royal Berkshire Hospital in Reading, UK. Citizens near the plant could have been at higher risk for cancer later in life, he says. And the contamination would have made emergency operations much more difficult at the other reactors, which were also in trouble. The situation could easily have spiralled out of control.

"The fire trucks were brilliant. I'm not sure I would have thought of that."

Just metres away was a vast reservoir of sea water. It could stop the reactor's meltdown, but operators had no way to pump it into the core. Emergency generators could not be hooked into the system, for reasons that are still unclear.

At some point, somebody on the site realized that fire engines were essentially giant portable pumps with their own power supplies. "The fire trucks were brilliant," Harding says, "I'm not sure I would have thought of that." Engines were rushed to the plant and hooked into the lifeless emergency cooling system. Yet there was still a problem: the pressure in the core was too high for the engines' pumps to force in the sea water.

Around 2:30 on Saturday afternoon, operators began to vent pressure from the containment vessel. An hour later something sparked the gas that had built up inside the outer building during venting. The entire top of unit 1 was blown away, and four workers were injured, although the sturdy concrete containment vessel below seems to have survived the blast.

CHAIN REACTION

The explosion, broadcast around the world, was the first of a series of setbacks at the reactor complex. In the ensuing days, reactors 3 and 2 followed a similar path to unit 1 (see 'An unfolding crisis'); each was rocked by a massive hydrogen explosion. In units 3 and 4, the pools for storing used fuel lost their cooling water and it is believed that the rods began to melt, emitting more explosive hydrogen along with powerful radiation.

At the time of writing, radioactive material from Fukushima Daiichi continues to blow across Japan at levels high enough to cause concern for Sperrin — although he says that they are not immediately dangerous. In the coming weeks and months, the government, TEPCO and safety authorities are likely to face heavy criticism. People will ask what went wrong.

Still, at unit 1 the immediate crisis has passed. With the pressure down, fire engines began to flood the reactor with sea water at 8:20 p.m. on 12 March, allowing the fuel to slowly cool to a safe temperature. The response at unit 1 also provided a model for stabilizing the other two reactors. And day by day, the radioactive decay in the reactor cores is ebbing. It could be days or weeks before the reactors are truly safe, but for now things remain stable.

As for the operators at unit 1, says Harding, "I think they really did respond pretty well." ■