Chernobyl: Errors and Design Flaws

An official Soviet investigation of the Chernobyl disaster places the blame on a chain of errors that turned potential weaknesses in the reactor design into deadly flaws

A botched experiment and a series of deliberate safety violations, and a reactor that was inherently difficult to operate and control combined to cause the world's worst nuclear accident. Those conclusions are contained in a voluminous official report on the explosion and fire that destroyed the unit IV reactor at the Chernobyl atomic power station in the Soviet Union on 26 April.

The report, prepared by a team of Soviet investigators and released at an international meeting in Vienna, Austria, on 25 August, has been welcomed by many Western experts as an extremely candid and detailed account of the accident and its aftermath. It indicates that an extraordinary sequence of human errors turned some weaknesses in the reactor design into deadly flaws.

It also provides the first public details of radioactive contamination in the region surrounding the devastated plant. According to Soviet estimates, some 50 million curies of radioactivity were spewed into the environment, and up to half of the ejected fission products may have been deposited within 30 kilometers of the plant. This is presenting the Soviets with a mammoth cleanup problem and raises the specter of lingering health effects as long-lived radionuclides—especially radioactive cesium—continue to enter the food chain over the coming decades.

This article, based on a copy of the report obtained by *Science* before the Vienna meeting, describes the causes of the accident. A subsequent article will examine the potential health implications of the disaster and report the discussion at the Vienna meeting, which is being held under the auspices of the International Atomic Energy Agency.

The report paints a horrifying picture of engineers running a risky experiment with many of the reactor's key safety systems turned off. It also describes how, in an effort to stabilize the plant before the experiment, the operators set the stage for a runaway reaction that released a burst of energy that tore open part of the plant and initiated a series of explosions and fires.

At the heart of what happened at Chernobyl is a design feature of the reactor that results in an increase in the fission reaction over certain ranges as the density of cooling water decreases. This feature, known as a positive void coefficient, can result in a power surge if cooling water is lost or excessive boiling takes place. In most reactor designs used in the West, loss of coolant has the opposite effect of shutting off the fission reaction and dampening the power output.

Under normal operating conditions, Soviet plants have safety systems that are supposed to guard against power bursts. But they can be difficult to control, and the Chernobyl reactor was operating under far from normal conditions when it exploded.

The events began at 1:00 am on 25 April, when operators began to reduce the power output of the reactor from its normal operating level of 3200 megawatts (thermal) in preparation for a planned shutdown. Engineers were intending to conduct an experiment while the reactor was running at low power, before the shutdown was completed, to test one of the plant's safety systems. "It could be called paradoxical," Valeri Legasov, a senior Soviet atomic energy official, said at a news conference on 21 August. "They were concerned precisely for the safety of the plant."

The most serious long-term health and environmental problem may come from radioactive cesium.

The experiment involved disconnecting the generators from the grid and determining how long one of them could continue to power some reactor systems from its own mechanical inertia. This residual energy may be required to run cooling pumps in an emergency. The report says similar tests had been conducted before at the plant.

By 1:05 pm on 25 April, the reactor output had dropped to 1600 MW and one generator was disconnected. The experiment was planned to take place on the second generator when the power went down to 700–1000 MW. At 2:00 pm, before starting the experiment, operators shut off the emergency cooling system. They did this to avoid any possibility of the system being activated during the tests, but the report notes that the action constituted a serious violation of safety regulations.

Over the next several hours, the operators had a tough time stabilizing the plant, and the planned test was repeatedly delayed. Part of the problem was that one automatic control system was disengaged, a move the report refers to as an "operator error." This caused the power to dip sharply, at one point falling below 30 MW.

Another problem appears to be a buildup of xenon in the reactor. A by-product of the decay of iodine-131, xenon acts as a poison, slowing down the nuclear chain reaction and causing the power output to drop. To compensate for this, operators withdrew many of the control rods.

This eventually succeeded in bringing the power up to about 200 MW by 1:00 am on 26 April, but it meant that the reactor was operating right at the margin, with very little reserve control that could be used to increase the power if necessary. Moreover, when the rods are completely withdrawn, a surge in the fission reaction would not be dampened, and it would take several seconds to drop the rods into the reactor to shut it down in an emergency.

When the power reached 200 MW, plant supervisors decided to proceed with the test. Two more pumps were connected to the reactor shortly after 1:00 am to provide enough pumps to support the experiment. However, because the reactor was running at lower power than originally planned, this resulted in too much cooling water flowing through the core, which in turn caused the steam pressure and the water level in the steam separators to drop. In order to prevent the reactor being shut down automatically when these parameters fell below a critical point, the operators blocked signals from pressure and water-level sensors, thereby disabling a key part of the emergency shutdown system.

The decrease in steam generation caused by the excess cooling water prompted the automatic control rods to be withdrawn completely. The report states that the operators appear to have withdrawn virtually all the manual rods as well in order to maintain the power level at 200 MW. This further reduced the operating margin and the capacity to respond quickly to an emergency. However, the reactor appeared to be stabilizing and at 1:23:04, the steam supply to the generator was shut off.

About a minute before the test began, the operator reduced the flow of feedwater to the plant, presumably to help maintain the steam pressure. Then, because four of the eight pumps supplying cooling water to the reactor were powered by the generator that was now running down, the amount of cooling water flowing through the reactor declined further. The operators were then faced with the opposite of the original problem: too little, rather than too much, cooling water.

The result was catastrophic. Boiling increased and, because of the positive void coefficient, the power started to climb sharply. At 1:23:40, the shift manager gave the command to hit the emergency button, which plunges the control rods into the reactor to shut off the nuclear reaction. However, because the rods were almost completely withdrawn, the response time was slow. Moreover, impacts were heard and some of the rods stopped before reaching the bottom. The operators then cut off the drive mechanism so that the rods fell by their own weight.

By this time, however, the situation was out of control. Intense steam generation was taking place around the fuel elements, which in turn cut down the ability to remove heat. The power output continued to surge, and the fuel started to disintegrate and fall into the cooling water. The result was a sharp increase in pressure, which ruptured the cooling channels and prompted a thermal explosion that "destroyed the reactor and part of the structural components of the building."

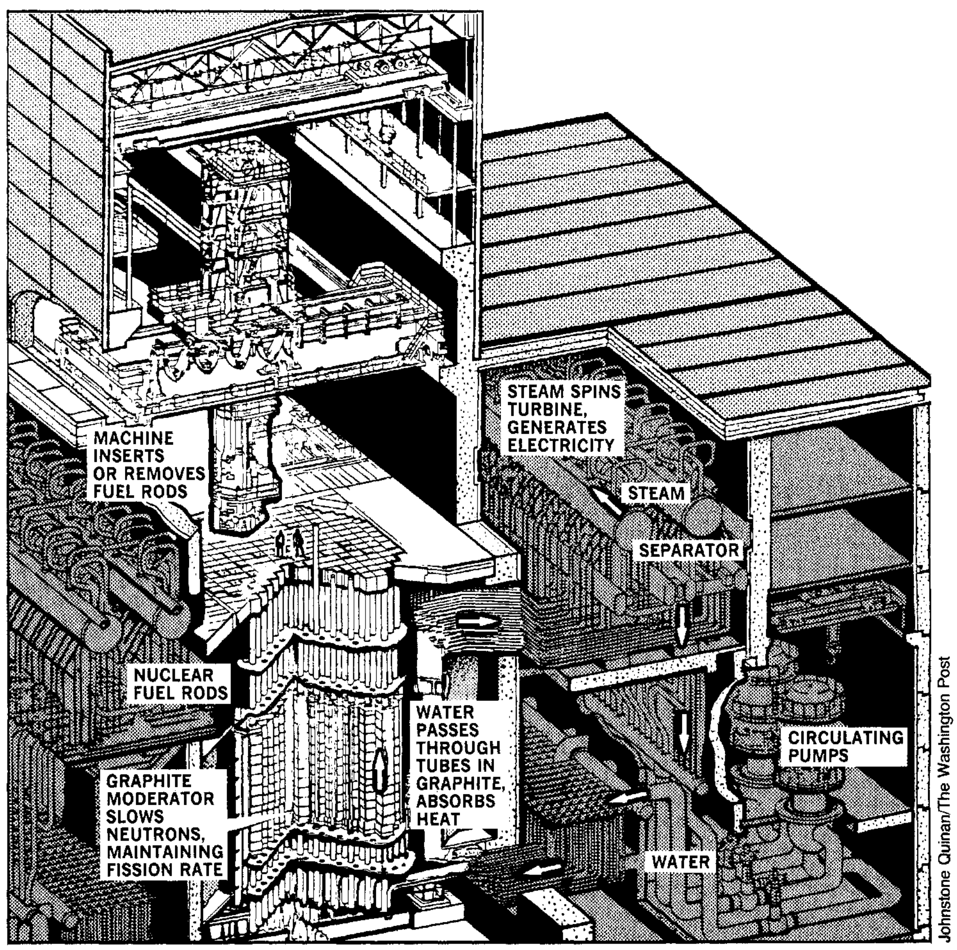
The initial blast that blew the reactor apart may have been caused by a steam explosion, a massive release of energy caused by sudden boiling of water, although this is not clear from the report itself. A second explosion may then have occurred as hydrogen and carbon monoxide, formed when superheated steam reacted with zirconium and with the reactor's graphite moderator, mixed with air in the reactor building. This would have occurred after the reactor compartment itself had been breached. The report notes that witnesses outside the plant heard two explosions, one after another, at 1:24 am.

The explosions sent showers of hot radioactive material around the reactor site, resulting in more than 30 fires. The most worrisome of these broke out on the roof of a turbine room next to the unit III reactor, which was still operating. It took 90 minutes for fire trucks to arrive from the nearby towns of Pripyat and Chernobyl, but by 5:00 am most of the fires were extinguished and the unit III reactor was shut down. The other two reactors at the site were shut down in the early hours of the following morning.

The devastated unit IV reactor would continue to pose a severe challenge for many days, however. According to the report, an attempt was made immediately after the accident to flood the reactor with water from emergency pumps in an effort to prevent the graphite moderator from catching fire. However, this proved unsuccessful, and it was not until 6 May that the graphite fire was brought under control and the temperature started to drop. This was achieved by dropping almost 5000 tons of boron, limestone, sand, clay, and lead into the reactor from military helicopters.

Between 26 April and 6 May, some 50 million curies of radioactivity were released into the environment in various fission products, according to calculations in the report. The largest single release occurred in the initial explosion, which sent a plume of debris at least 1200 meters into the air. This was followed by slowly decreasing discharges over the next 5 days. However, by 2 May, radioactive emissions began to rise sharply as decay heat in the remaining fuel drove up the temperature of the core and fission products were carried aloft in the gases produced by the burning graphite. Almost half the total release occurred between 2 and 5 May, according to the report, before dropping dramatically on 6 May.

Parts of the reactor complex itself became heavily contaminated not only from direct fallout from the accident but also from radionuclides that were carried through the ventilation system, which "continued to operate for some time after the accident," the report notes. Radiation levels within the reactor complex were extremely high, resulting in doses greater than 100 rads to several plant personnel and firefighters. Ac-



The reactor design. *A massive graphite moderator, weighing some 1700 tons, is pierced by pressure tubes containing fuel rods and circulating cooling water. Refueling can be carried out while the reactor is operating and the plant is relatively cheap to produce and operate. However, it requires a complex control system and, as the accident demonstrated, under extraordinary circumstances, the power output can surge uncontrollably.*

cording to the latest official figures, 31 people have died from burns and radiation sickness.

Outside the plant site, radiation levels began to increase sharply several hours after the accident. The report notes that immediately after the accident, winds carried radioactive debris past Pripyat, the nearest large town, but as the winds dropped, fallout increased. By 7:00 am on 27 April, radiation levels in the area of the town closest to the plant increased to 180–600 millirems per hour, up to 50,000 times the background level, and they continued to increase until about 5:00 pm, when they reached 720–1000 millirems per hour. At 2:00 pm evacuation of the town's 45,000 people was begun. Within a few days, a total of 135,000 people living within a 30-kilometer radius of the plant were evacuated.

The report is not sanguine about how soon people may be returned to their homes. It notes that radiation levels are likely to change as debris is blown around, and states that repopulation will not be considered until the entire 30-kilometer zone has been stabilized. This will require entombing the reactor itself in a concrete case, decontaminating the reactor site, and scraping up some heavily contaminated soils in the region. This could take as many as 4 years.

The report estimates that the Pripyat evacuees received 1.5–5.0 rads of gamma radiation and 10–20 rads of beta radiation to the skin, and perhaps a maximum of 30 rads to the thyroid gland resulting from ingestion of iodine-131. These doses may increase natural cancer morbidity among the evacuees by some 2%, the report estimates.

Outside the 30-kilometer zone, radiation exposure was of course much lower, but because millions of people were affected, the anticipated number of excess cancers could be very large. As a rough estimate, the report calculates that exposure to relatively short-lived radionuclides from the Chernobyl accident will increase cancer mortality by about 0.05% in western Russia. That would translate to some 5000 additional deaths over 70 years.

The most serious long-term threat to health and the environment may come from radioactive cesium, which has a half-life of 30 years. On the basis of "preliminary, purely speculative estimates," the report suggests that exposure to cesium-137 could increase the death rate from cancer in western Russia by a maximum of 0.4% over the next 70 years. That would result in almost 40,000 excess deaths.

These calculations are likely to be the subject of intense debate at the Vienna meeting. ■ COLIN NORMAN

Briefing:

Earthquake Research Center Siting Triggers California Tremors

A National Science Foundation decision to make the State University of New York (SUNY) at Buffalo the location for an earthquake engineering research center has caused a California backlash. Partisans of a rival proposal from the University of California at Berkeley are contemplating a challenge to the award.

Not only do the critics claim that Buffalo is far from the seismic action in the United States, but they charge that NSF departed from its stated criteria in awarding the center, and question the composition of the review panel that made the choice, pointing out that only one of seven members of the peer review panel is professionally identified with earthquake engineering.

The center will conduct research to improve basic knowledge about earthquake engineering practice and earthquake hazard mitigation. The center is to receive up to $25 million in NSF funds over 5 years. Other institutions associated with the Buffalo proposal are City College of New York, Columbia, Lamont-Doherty Geological Observatory, Cornell, Lehigh, Princeton, and Rensselaer Polytechnic Institute.

The SUNY Buffalo and Berkeley proposals were the only two seriously considered in the final stage of the competition. California Institute of Technology, Stanford, and the University of Southern California are parties to the Berkeley proposal. A requirement that federal funds be matched equally by state and private funds over the 5-year period was apparently a strong factor in narrowing the field.

Buffalo was guaranteed matching funds of $5 million for the first year by New York state's Urban Development Corporation. Funding support for the Berkeley proposal was provided by a combination of $3 million voted by the state legislature and more than $1 million earmarked by the universities involved. Although the first-year financing by the California group fell short of matching the maximum $5 million offered by NSF, sources in the foundation say that funding was only one of more than 15 requirements and not a decisive factor.

In announcing the award, NSF director Erich Bloch noted that the new center had been created through a foundation decision that a national center for earthquake engineering research was desirable. This sets the new center apart from a group of NSF engineering research centers whose research focus has been determined by choices among competing proposals.

The California reaction has included inquiries about the award to NSF from members of the California congressional delegation and discussions among researchers in the universities endorsing the Berkeley proposal about what course to take. There is sentiment among some of the Californians to press for a review and reversal of the award. The routes available include a request for a General Accounting Office investigation of the award or a review by a committee named by the NSF director.

At this point, Berkeley engineering professor Joseph Penzies, principal investigator for the Berkeley proposal, says the the only decision has been that he write to NSF requesting a detailed explanation of the choice and a clarification of what the critics see as major issues in the selection process.

The Californians would like to know if rumors are true that the foundation in selecting the winning proposal put heavy emphasis on the center's reaching out to researchers on a broad geographic basis. If so, the critics argue, the original NSF announcement did not place a premium on breadth. The Berkeley proposal would mainly involve researchers in California.

Buffalo dean of engineering George Lee said his impression is that NSF did not spell out the criteria restrictively, but welcomed imaginative proposals. He says Buffalo and the universities allied with it took a "consortium approach," aiming to create a center concerned with broad issues of earthquake engineering research and inviting all researchers capable of contributing to participate. Lee says that Buffalo will serve as administrative center for the enterprise, but research is expected to be distributed among the cooperating institutions. Of five faculty members designated as principal investigators, two are at Buffalo and one each at Columbia, Lamont-Doherty, and Cornell.

The makeup of the peer review panel is also at issue. The critics say that only one of the members of the panel has a background in earthquake engineering research and none were from the Far West. An NSF source says that the panel's composition reflects the effort to muster reviewers that were both highly qualified technically and had no conflict of interest on the center.

As for the matter of center's location, the NSF news release announcing the award noted that, "Although many people think of earthquakes as primarily a West Coast problem, they are, in fact, a national problem. Thirty-nine of the 50 states are subject to moderate to major earthquakes each year, making them a prime concern to planners." ■ JOHN WALSH