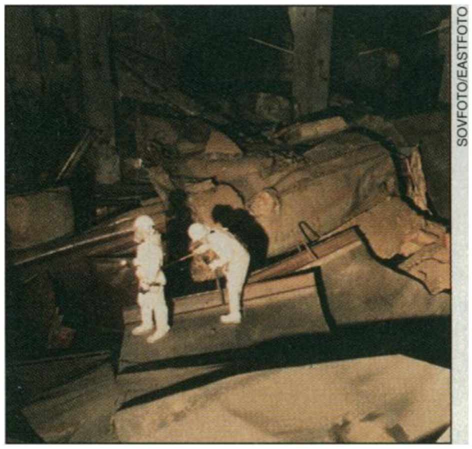
The Explosions That Shook the World

Researchers know what led up to the explosion of the Chernobyl reactor on 26 April 1986, and they are getting an idea of its legacy of health effects. But they are still debating where some of the fuel went

CHERNOBYL, UKRAINE—In the 10 years since the world's worst nuclear accident turned this obscure town's name into a household word, armies of scientists have been trying to figure out exactly what happened inside reactor number 4 of the Chernobyl nuclear power plant on 26 April 1986—and what is likely to happen to the health of the surrounding population as a result. Researchers are confident they know what triggered the accident, and preliminary results from some of the medical studies are trickling in: Aside from a sharp increase in the incidence of childhood thyroid cancer, much of the medical news so far is reassuring (see page 357). But for a small band of 200 scientists based in a former kindergarten here, an urgent question remains unanswered: What happened to the 190 tons of uranium oxide fuel that originally resided in the destroyed reactor?

Estimates of the amounts released into the atmosphere and the tally so far of the fuel in the rubble beneath the reactor leave between 10 and 50 tons unaccounted for. Three different scenarios have emerged to explain this discrepancy: Some or all of the missing fuel may have been ejected in the initial explosion, or it may have been spewed out in the subsequent fire, or it may be as yet undiscovered beneath the reactor. Each of these alternatives is based on different views of what occurred in the early stages of the accident—a period of this much-studied event that remains a topic of considerable scientific debate.

Figuring out how the accident progressed and where the missing fuel ended up is largely the job of the 200 researchers in this ghost town who belong to the Ukrainian National Academy of Sciences' (UNAS's) Intersectorial Scientific and Technical Center (ISTC). Because most of the reactor's monitoring equipment was lost in the two explosions that destroyed reactor 4, these nuclear detectives are trying to piece events together by rooting around inside the sarcophagus—the hastily built concrete shelter covering the wreckage. And this dangerous work is of more than theoretical interest.



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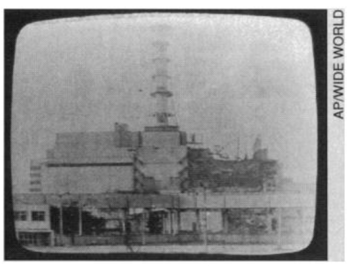
Deadly rubble. Workers in the sarcophagus trying to determine what happened to the core.

Exactly what happened bears closely on the total amount of radionuclides released into the environment. Also, finding the missing fuel "is an extremely important question for us—the nuclear safety of the [reactor] depends on it," says Edward Pazukhin, who heads ISTC's department of nuclear and radiation safety. The reason: A growing pool of water in the bowels of the reactor building could theoretically cause a portion of the remaining fuel to go critical, says ISTC deputy director Vladimir Shcherbin. But because researchers do not know how much fuel is in the warren of rooms beneath the reactor, they do not know how likely such a reaction is, says Pazukhin.



AP/WIDE WORLD

Adding to this anxiety is growing concern over the state of the sarcophagus itself. It is full of holes, and an engineering report released last year concluded that it would collapse in an earthquake measuring 6 or more on the Richter scale—an event estimated to strike the Chernobyl region on average once a century—releasing clouds of radioactive dust. Says nuclear safety expert David Schwarzbach of Princeton University, "It's ironic that as we approach the 10th anniversary of the Chernobyl accident, it is at Chernobyl that we have the greatest risk of a major accident."

Explosive theories

Piecing together the events that preceded the explosion has proved to be relatively easy, thanks to records that have survived from the control room. During a low-power safety test, operators removed the control rods and decreased the flow of cooling water around the nuclear fuel cells. However, they decreased the flow so much that there was insufficient coolant to absorb the energy being generated by the fuel. After a series of fruitless steps to stabilize the reactor, operators tried to slow the nuclear reaction by pressing a "scram" button that inserted control rods. But the tips of the control rods were made of carbon, which for a split second boosted the chain reaction in the fuel because carbon slows down, or "moderates," neutrons emitted by fission to a speed where they can trigger more fission reactions. The power increase heated the water further, leading to an uncontrollable power surge.

Observers outside the plant heard a muffled explosion, followed by a louder explosion several seconds later accompanied by a bright flash and the destruction of reactor 4. Scientists have long debated the nature of the two explosions and the resulting release of radionuclides into the atmosphere. Based largely on work at ISTC, two recent reports propose different interpretations of the explosions and their aftermath. The reports have, however, provoked a bitter dispute that has divided ISTC researchers.

The first report was issued last April by

1986

26 April 01.23 hr — During an electrical power test, reactor becomes unstable and experiences a huge power surge. Two explosions destroy the reactor and its building.

Firefighters extinguish burning buildings and turn to graphite moderator core.

27 April — 49,360 residents of the town of Pripyat evacuated.

30 April — Iodine supplements are distributed in some settlements in Belarus.

1 May — Melting core begins to heat up and radioactive releases rise.

4 May — Core cools again, and releases drop off sharply.

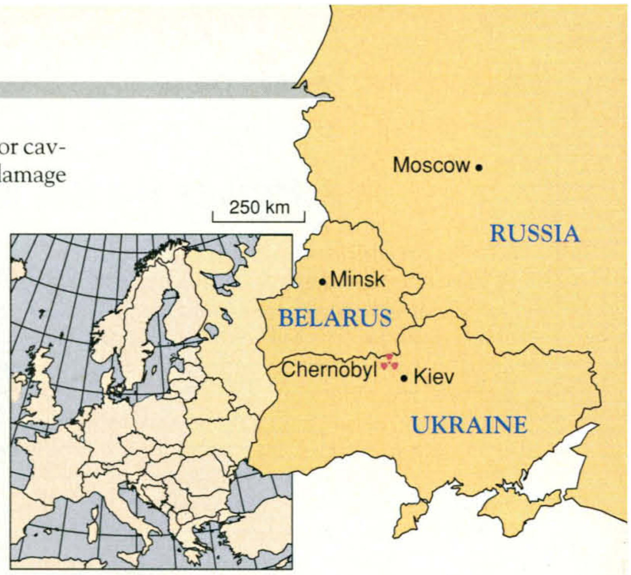
nuclear physicist Edward Purvis, a consultant based in Damascus, Maryland, who headed the U.S. Department of Energy's task force on Chernobyl in the late 1980s. Purvis visited Chernobyl again in January 1994 on behalf of several companies keen to do business there, and during his visit, Purvis says, Viktor Baryakhtar, vice president for natural sciences of the UNAS, asked him to prepare a report based on ISTC's work.

After analyzing photographs of the damaged reactor chamber, computer simulations, and physical data gathered by ISTC and other researchers, Purvis concluded that the first explosion was caused by rapid heating of the coolant water coupled with a breakneck rise in the reactor's power level, events that caused the fuel to break apart. According to Purvis's report, "the fuel fragmented because it had gotten too hot, too quick, much as an egg explodes in a microwave oven."

Most researchers agree with Purvis up to that point. They differ, however, on what happened next. The most widely accepted view, put forward by Alexander Sich, a nuclear engineer who spent 18 months living and working in Chernobyl in the early 1990s, is that this initial explosion in the reactor core lifted the reactor lid up to 10 meters into the air, carrying with it "a small portion of the core still connected by pressure tubes."

Purvis offers a more radical theory: He argues that the fragmenting fuel sent a shock wave rippling through the cooling water, splitting joints at the reactor's base and converting the water to steam. The steam exploded through the fissures in the joints and catapulted the entire core assembly—the fuel, the graphite moderator rods, and the reactor vessel lid—some 14 meters into the air, causing any remaining cooling water to flood out of the reactor core.

Near the apex of its flight, Purvis continues, the nuclear fuel in the core assembly exploded, throwing pieces of fuel rods and graphite onto the roofs of nearby buildings, setting them alight and dispersing radionuclides into the air. Purvis supports this scenario with ISTC photographs of the inside of the reactor hall after the explosion, which depict an undamaged wall only a couple of centimeters thick that had shielded personnel from the blast. "If the explosion that destroyed the building had occurred in the reactor cavity it would have done considerable damage to this wall," Purvis says.



Several researchers have challenged this scenario, however. "I doubt there was a nuclear reaction in midair," Harvard University physicist Richard Wilson told *Science*. And Sich, who now works on nuclear safety issues for the European Bank for Reconstruction and Development in London, offered a critique of Purvis's theory in last November's *Nuclear Engineering International*. Calling the theory "questionable on a number of counts," he criticized Purvis's focus on the failure of the lower joints to the exclusion of the upper joints. He also contends the scenario is flawed because "most of the melted core has been located in the lower regions of the reactor building, precluding a nuclear explosion above the nominal position of the core."

If Purvis is correct, much of the missing fuel would have been ejected in the initial explosion and deposited in the surrounding countryside. Ironically, although Sich disagrees with Purvis's explosion theory, he too thinks that is where a lot of the material ended up. In the first few days after the accident, Soviet helicopters dumped more than 5000 tons of materials—including sand, boron, lead, and dolomite—into the destroyed reactor building in an effort to cool what they thought was the smoldering fuel. Soviet experts assumed that this buried the fuel, and hence a total of 50 million curies of radionuclides escaped the reactor.

But Sich's analysis of data gathered in the sarcophagus suggests that the helicopter crews, through no fault of their own, mostly missed the burning fuel, which continued to spew debris into the environment, in the end releasing 150 million curies. "Sich is right," says Wilson. "I think the uranium core is in bits and pieces all over the dump sites in the [exclusion] zone."

Probing the depths

However, Pazukhin, a radiochemist, believes that most of the missing fuel is still underneath the reactor. He bases this on evidence gathered by some two dozen ISTC physicists and engineers, dubbed "stalkers," during forays into the bowels of the sarcophagus. These scientists "are a rare breed," says former ISTC director Vladimir Tokarevsky. "A lot of information was gathered only by these stalkers," says Tokarevsky, who adds that their work "was very dangerous, and practically illegal" because of the "fantastically high" doses they received.

Soon after the accident, stalkers had determined that reactor fuel existed in three states: ejected fragments of the core, such as pieces of fuel rods; uranium- and plutonium-laced dust known as "hot particles"; and solidified lava, a mixture of uranium oxide and graphite from the reactor core and melted concrete and zirconium from the reactor housing.

From analyses of the lava's composition, Pazukhin estimated that the maximum temperature of the explosion was about 2255 degrees Celsius and that the lavas must have been held at a temperature greater than 1660 degrees for at least 4 days. He believes that when the reactor exploded, chunks of concrete from the walls collapsed into the reactor chamber. The fuel rods heated to the point that their zirconium cladding melted, exposing the uranium oxide fuel. About 4 hours later, melting concrete, zirconium, and uranium oxide began to mix with about 145 tons of the mineral serpentine which was packed around the reactor as heat insulation. Within half an hour the serpentine heated to more than 500 degrees Celsius and began to decompose, releasing 19 tons of superheated water as vapor. The melted materials cooked for another 60 hours, forming a lava that flowed into several damaged rooms beneath the reactor chamber.

Shcherbin thinks that much of the missing fuel will be found in one of those rooms, number 307/2, which is blocked by debris. Scientists have drilled 144 holes in the west wall through which they have inserted

5 May — Relocation of 135,000 people from the exclusion zone completed.

6–31 May — 35,700 people evacuated from areas of Ukraine outside exclusion zone.

SOVFOTO/EASTFOTO

9 May — Graphite fire extinguished, and work begins on reinforced concrete shield underneath reactor 4.

14 May — Radioactive releases stop. A total of 31 people died as a result of the explosion or from radiation sickness.

Power Needs Keep Flawed Reactors Running

KIEV—Reactor 4 at Chernobyl was one of 28 RBMK-type light-water-cooled, graphite-moderated reactors then in use in the Soviet Union. When researchers figured out the devastating chain of events that led to the explosion, engineers made hundreds of safety modifications to the other reactors—from increasing the number of graphite control rods inserted during normal operation, to installing systems that would quickly inject energy-absorbing materials into the core in an emergency. Chernobyl alone spent $400 million of mostly Western financial aid on improving its two operating RBMKs.

For Western experts, however, the 15 RBMKs on line are still a worry. "There's no question that RBMKs are intrinsically unsafe and cannot be brought up to an adequate level of safety," a scientist on a U.S. National Security Council panel on Chernobyl told *Science*. The RBMK's flaws have cast a pall over the entire industry. "Chernobyl became a symbol of weakness of the world's nuclear industry," says Viktor Baryakhtar, vice president for natural sciences of the Ukrainian National Academy of Sciences.

The international community is continuing to apply pressure on Ukraine to close Chernobyl. Ukrainian government officials have repeatedly pledged to do so, but the country needs the power, so closure hinges on receiving more Western aid. With this in mind, the European Commission, the G7 group of industrial powers, and Ukraine last December signed a memorandum of understanding promising $2.3 billion in Western funds to help pay for closing all the Chernobyl reactors by 2000. The funds would pay for construction of a gas steam power plant to replace the lost energy output, as well as a nuclear energy safety and research center just outside Chernobyl's exclusion zone.

But until such funds appear, says Chernobyl power plant director general Sergei Parashin, two RBMK reactors will be kept on line, and a third RBMK may even be reactivated. Parashin boasts that safety and efficiency ratings put Chernobyl at the head of Ukraine's five nuclear power stations last year. But few others are leaping to Chernobyl's defense. Says nuclear safety expert David Schwarzbach of Princeton University, "The RBMK reactors should be shut down at the earliest possible time."

–R.S.

probes that have measured heavy doses of gamma rays and high neutron flux. "We have found at least some of the missing fuel," Shcherbin told *Science*.

Locating the missing fuel is crucial to defining the hazard posed by water inside the sarcophagus. Water can act as a moderator, slowing down neutrons emitted by fission reactions so they can trigger more fission reactions in a chain reaction. The big question is whether enough water from rain, condensation, drilling solutions, and dust suppressants might accumulate in the sarcophagus to allow an uncontrolled chain reaction in the remaining fuel, possibly triggering an explosion. "In principle, it is quite possible to have a self-sustained fission reaction" if there is enough water and enough uranium in certain lava configurations, says Shcherbin.

A worrisome sign of this possibility occurred in June 1990, when for 2 weeks after a period of heavy rain a detector registered a 60-fold increase in neutron flux in reactor 4's room 304/3. "People were alarmed," says Shcherbin—so alarmed that Victor Popov, a nuclear physicist with the Complex Expedition, which maintained a lab inside the sarcophagus until 1992, dashed into room 304/3 and dumped a solution of gallium nitrite to absorb neutrons. The neutron flux readings then fell away, says Shcherbin.

Since then, ISTC scientists, along with technicians from the Chernobyl nuclear power plant, which maintains the sarcophagus, have been trying to plug the estimated 1000 square meters of gaps in the sarcophagus walls. However, up to 3000 cubic meters of water may still be trapped inside. "Without the water, the fuel-containing masses would be absolutely safe," says Tokarevsky. Purvis says the solution is obvious: "Get rid of the damn water." Chernobyl officials say they are considering such a measure, but first must find a suitable place to store it.

In the meantime, ISTC scientists spray a kilogram of gallium solution into various sarcophagus rooms every 2 weeks. They are also designing a gallium-based foam to spray in accessible rooms with a lot of lava. "The situation makes me nervous," admits Pazukhin. "There's no guarantee that this gallium mixture will penetrate all the rooms and floors equally."

A lingering threat

In spite of these unanswered questions, ISTC's efforts to study all aspects of the accident are threatened by political turmoil at the center. To reduce its $3 million budget, ISTC management on 1 February fired some 500 staff members, including 200 scientists, and demoted Tokarevsky. The new director, physicist Aleksander Klyuchnikov, declined to be interviewed for this article, but in an address to staff in February, says Shcherbin, Klyuchnikov announced that 90% of ISTC's work would be directly connected with physical studies of reactor 4. Radioecological, medical, and other studies are now being curtailed, Shcherbin says.

Personnel changes are not the only threat to science. Conditions inside the sarcophagus are deteriorating. "Very high humidity has destroyed many of the devices inside," says Tokarevsky. The humidity has also forced the Chernobyl plant to turn off electricity to the interior. "We have no possibility to do any kind of research without a real power supply," Tokarevsky says. With working conditions worsening and money getting tight, the ISTC's search for the missing fuel is beginning to look ever more desperate. The question for many is how long they can continue working in such a difficult environment—and other scientists are not exactly queuing up to replace them. Asks physicist Edward Denisenko, who maintains ISTC's archives, "If people from the West and Russia don't want to work here, who will? God? The devil?"

–Richard Stone

SOVFOTO/EASTFOTO

May/June: Hundreds of thousands of people tested for radioactive iodine in their thyroid glands.

3–10 June: 6017 people evacuated from areas of Belarus outside exclusion zone.

August: Construction of sarcophagus begins.

September: Relocation of affected population completed.

October: Chernobyl reactor 1 resumes operation.

November: Construction of sarcophagus completed. Reactor 2 resumes operation.