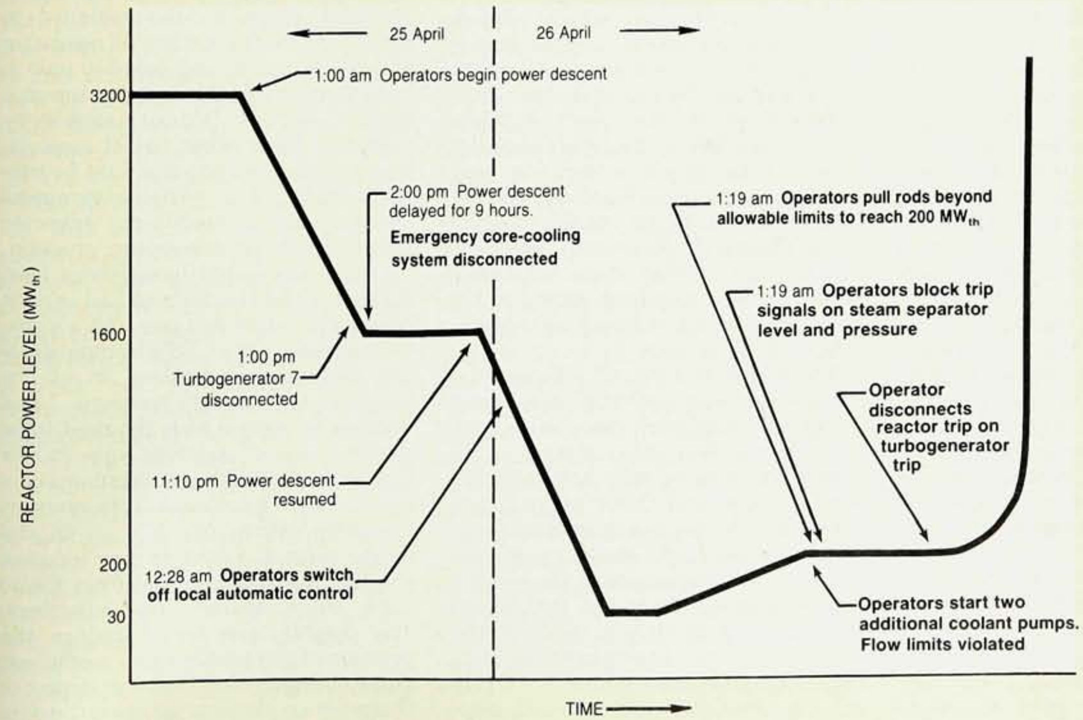
Soviets assess cause of Chernobyl accident

Some—but by no means all—of the Chernobyl story can now be told. Soviet scientists have assembled enough information from interviews, plant records and computer simulations to describe the chronology of events leading to a severe accident that destroyed a nuclear reactor at Chernobyl on 26 April and spread radiation over much of Europe. A Soviet delegation of 28 specialists headed by V. A. Legasov (Kurchatov Institute) presented a very frank report on the accident's causes and consequences to an experts' meeting sponsored by the International Atomic Energy Agency in Vienna on 25–29 August. Their report places heavy blame on the reactor staff for committing numerous violations of operating rules, one of which left the reactor operating at a power level where the consequences of further violations were greatly exacerbated.

The material presented at the meeting has since been summarized and evaluated by IAEA's International Nuclear Safety Advisory Group, a team of 14 reactor specialists from as many nations, headed by A. P. Vuorinen of Finland. The INSAG report stated that the information exchange at the meeting exceeded expectations. Overall, INSAG felt participants recognized the need for international cooperation on nuclear safety and radiological protection. (Herbert Kouts, a member of INSAG, discusses Chernobyl in his editorial on page 136.)

Sequence of operator errors. As had been rumored, the accident developed when the reactor staff was conducting a test at unit 4 of the Chernobyl nuclear power station (PHYSICS TODAY, July, page 17). The staff wanted to evaluate the turbogenerator's ability to power some electrical equipment even when the turbine is coasting down after its steam supply has been cut off. The equipment normally powered by the turbine in Chernobyl-type reactors includes some of the pumps from the fast-acting emergency core-cooling system. A previous test had indicated that the voltage from the generator fell off long before the mechanical energy of the turbine rotor was spent. The test of 25 April was to determine whether a special magnetic-field regulator for the generator could help capture that mechanical energy more effectively. In retrospect, the Soviet review team judged that the test plans specified safety regulations in only a cursory way, and they noted that the officer in charge was an electrical engineer, not a reactor specialist.

At 1:00 am on 25 April the staff began the test by reducing power to half its nominal peak value of 3200 thermal MW. (See the time line below.) At half power, they switched off one of two turbogenerators driven by the reactor. Soon after, they shut off the emergency core-cooling system in accordance with the test plan so that it would not interfere with the experiment. Operating procedures forbid disabling this system, and the Soviet



Time line portrays key events leading to the accident at the Chernobyl unit 4 power plant. The six actions identified by the Soviets as violations of operating procedures are indicated in boldface.

report identifies this as one of the six most dangerous violations of operating rules during the test.

After a nine-hour delay in further power reduction caused by a continued demand for power, the staff began to reduce power again, toward the 700–1000 MW_{th} at which the test was to be conducted. When the power level becomes this low, the computers regulating the reactor are supposed to receive their input from detectors located in the reflector region around the perimeter of the core rather than from those located within the core itself, because the core detectors are less sensitive at low power. As one operator made this switch, he neglected to enter a required instruction for the computer to hold the power at its current level. As a direct result of this second error, the power plunged to 30 MW_{th} before operators acted to reverse it.

Plant operators withdrew control rods to increase the power but could only bring the reactor back up to 200 MW_{th}. Further power increases were hampered by an excess of xenon-135, a fission-product daughter that absorbs neutrons and hence poisons the reaction. In steady-state operation, the xenon concentration is at equilibrium, but as the power level decreases, less xenon is removed by neutron absorption and subsequent decay, and its concentration temporarily increases. Just to boost the power back to 200 MW_{th} required a third violation of safety rules: the withdrawal of too many manual regulating rods. The regulations specify that the reactor core must always contain at least 30 such rods in effective positions to compensate for excess positive reactivity.

Dangerous operation. At this point the reactor was operating at a power far below the minimum of 700 MW_{th} specified by operating procedures. In this unstable region, the net power coefficient is positive; that is, any increase in power is likely to cause a further increase in power. The dominant term in the net power coefficient at low power is the void coefficient of reactivity: If the amount of void, or steam, increases, fewer neutrons are absorbed by water so that the flux, and hence the reactivity, increases.

Nevertheless, the staff proceeded with the test. They hooked an additional two pumps to the six then connected to the primary cooling loop to allow safe cooling after the trial rundown of the turbogenerator, which was powering four of the pumps. Although the test procedures called for this action, it increased the risk of pump cavitation, and the Soviets cite it as a fourth safety violation. The combination of excess flow rate and low power created difficult conditions, and the operators had to make many manual adjustments in an effort to keep the right steam pressure and water level in the steam drum. Because these parameters were fluctuating considerably and the operators wanted to avoid shutting down the reactor, they decided to disconnect the emergency protection signals relating to the steam pressure and water level. That action was safety violation number five.

About the same time—1:22 am, 26 April—a computer printout indicated that the available excess reactivity had fallen to just six to eight rods, a level requiring immediate shutdown. The operators nevertheless persisted with the test and made their last fatal error by blocking the trip signal on the turbogenerator. They did not want the reactor to shut down when they stopped the turbine, just in case they needed to conduct the test a second time. Such concern for completion of the test led to five of the six operator errors. Ed Purvis of DOE said that "although the Soviets characterize these as operator errors, they might more accurately be described as management errors in that operators appeared to be following instructions given them by those in charge."

When the test began at 1:23 am, the power began to rise slowly. The positive power coefficient accelerated this rise while the available excess reactivity was insufficient to control it. Operators pressed the "scram" button, which triggers the insertion of absorbing rods to stop the reaction.

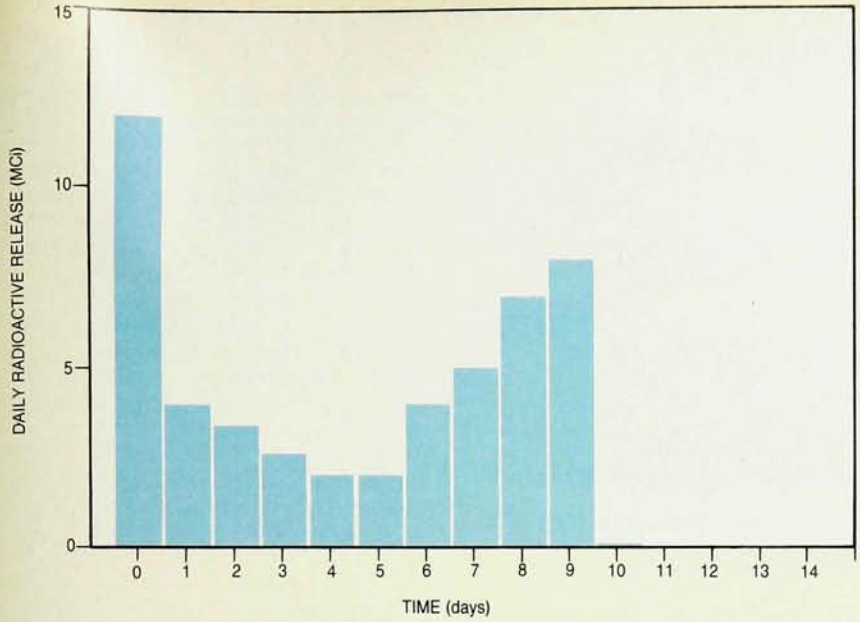
Soviet data indicate that the power started its precipitous rise at this point, and that some factor in addition to the increased void was now adding reactivity. A team of scientists from various DOE laboratories feels that the extra reactivity could have come from what they term a "positive scram." Below the absorbing material in each scram rod is a 5-m section of graphite, which moderates the reaction when the scram rods are withdrawn. As the many scram rods were inserted simultaneously, the graphite sections may have increased the reactivity in the bottom of the core just enough to make it go critical from prompt neutrons alone. The Soviets have calculated that the power may have soared to 100 times its nominal value of 3200 MW_{th} within four seconds.

The huge release of energy (the Soviets estimate over 300 cal/g) from this power excursion essentially fragmented the fuel into minute (millimeter diameter or less), hot particles. The fuel cladding failed and allowed these particles to contact the coolant in the channels. Rapid steam generation together with expansion of the volatile fission products from the fuel raised the pressure enough to destroy the cooling channels. Steam erupting from these channels caused the vault containing the reactor core to fail catastrophically, lifting and tilting the cover plate above the core and opening the enclosure to air. These events led to a worsening of reactor-power transients, and a second explosion was reportedly heard two to three seconds later. No one yet knows whether there was in fact a second explosion and, if so, what caused it. The Soviet report said that "witnesses observed these reactions in the form of a fireworks display of glowing particles and fragments escaping from the units."

Handling the aftermath. Flaming pieces of core and hot graphite landed on several of the roofs of the reactor housing, starting fires in 30 places (see the photo on page 20). The fires were out by 5 am on 26 April. For about ten more days, however, reactions within the graphite continued to produce dark smoke. Starting on 28 April, military helicopters dropped about 5000 tons of boron, dolomite, sand, clay and lead on the smoldering core to absorb and filter the aerosol particles. On 4–5 May the Soviets pumped nitrogen under pressure into the space beneath the reactor vault to cool the fuel. Radioactive releases were continuing all the while. By the end of June the Soviets had constructed a flat heat exchanger in a concrete slab under the reactor.

Work has begun on a structure to entomb the damaged reactor and separate it from the adjoining but undamaged unit 3. The structure will be ventilated by an open system with air filters. The goal is to reduce the radiation level below 5 millirads per hour at the roof and 1 mR/h at the walls. (Normal background levels are about 0.015 mR/h.) The government has removed contaminated soil and laid concrete around the plant site in an effort to reduce the radiation to rates acceptable for resumed operation of units 1 and 2, and possibly unit 3. Both units 1 and 2 had been restarted by the end of October, staffed by operators from other Soviet reactors, who will be rotated to this duty for two-week shifts. The Soviet government does not plan to modify the projected growth in its nuclear-power program.

Clearly the accident might have been averted if the reactor had had certain additional safety features. As a short-term measure, the USSR is implementing several modifications in all its graphite-moderated reactors. The number of control rods required to be partly inserted into the core will be increased to 70–80 and shutdown protection will be installed to prevent operation below 700 MW_{th}. In the longer term, the Soviets may increase the fuel enrichment level from 2% to 2.4% while adding more absorbers. The combination would reduce the problem of the positive void coefficient. Some observers feel that the impact of these design changes on overall safety



Daily release of radioactive nuclides after the Chernobyl accident shows first a drop and then rise. Not included are 45 and 5 MCi, respectively, of krypton and xenon, volatile gases presumed to have been released immediately.

is not clear, and worry that while these fixes might mitigate some of the circumstances that led to the accident, they could possibly aggravate others.

Radionuclide releases. The radioactive material in the Chernobyl core would have had an activity of 1000 megacuries if measured on 6 May. Because the accident exposed nearly all the fuel, the Soviets have estimated that virtually 100% of the noble-gas fission products xenon-133 and krypton-85 escaped from the reactor, amounting to 45 and 5 MCi, respectively. To estimate the releases of radionuclides other than noble gases the Soviets surveyed the ground contamination within their borders with aerial gamma photography. They concluded that the amount of radioactive fallout in the European territory of the USSR was between 30 and 50 MCi, or about 3.5% of the total activity accumulated within the reactor core. Of this, iodine-131 and cesium-137 accounted for about 7.3 and 1 MCi, corresponding to releases of 20% and 13%, respectively, of their core inventories. To put these numbers in perspective, the Three Mile Island accident released 15 Ci, millions of times less. The cesium from all atmospheric nuclear-weapons tests is estimated to be on the order of 30 MCi.

Both the composition and timing of the radionuclide release were considerably different from what reactor experts often expect from a catastrophic accident in a US light-water reactor. Postulated disaster scenarios frequently involve a core melt and rupture of the containment structure, so that the fission products are distilled from the molten core, releasing higher fractions of the more volatile isotopes. At Chernobyl, however, much of the early release consisted of fine fuel fragments explosively expelled from the reactor. Thus the radioisotopic composition in the total release corresponded roughly to that of the irradiated fuel, but was enriched in volatile isotopes of iodine, tellurium, cesium and inert gases. About 3–5% of the core inventory of relatively refractory elements such as strontium, plutonium and ruthenium escaped from the reactor—much more than would be expected in a light-water-reactor core melt. Surprisingly, although ruthenium is less volatile than strontium, it appeared in appreciable quantities in filter samples throughout Europe, while strontium did not.

Only about one-fourth of the total release of non-noble gases—about 12 MCi—left the reactor during the first day, according to Soviet data (see the figure above). The release rate declined in the next few days, only to rise again to about 8 MCi on 5 May and fall sharply the next day. The high release on 26 April was no doubt driven by the explosion and intense heat, and the decrease probably reflects the measures taken to extinguish the fire and filter the releases. The subsequent rise has not been fully explained, although many suspect that the blanket of boron and lead insulated the core and caused its temperature to rise, boiling off more radionuclides.

Long-term health effects. The Soviets have made a very preliminary estimate of the long-term health consequences of the accident, based on environmental monitoring supplemented by predictive modeling. They have directly measured the uptake of I^{131} in the thyroids of about 100 000 persons and the whole-body doses from Cs^{137} in about 10 000 people. The largest contribution to the collective long-term dose is expected to come from cesium, whose halflife is 30 years. People will be exposed over many years both to external radiation from cesium on the ground and to internal radiation from cesium ingested in food. The Soviets estimate that over the next 50 years the external radiation will expose the 75 million people in the western USSR to a collective dose of about 29 million person-rems. If one assumes a no-threshold linear dose–response relationship and takes the commonly used risk coefficient of roughly one cancer death for every 10 000 person-rems, this collective dose might result in about 3000 cancer deaths above the 9.5 million cancer deaths expected from other causes in the same population.

The 135 000 people evacuated from a zone 30 km in radius around the reactor had a collective dose from external radiation of 1.6 million person-rems. The average dose of 12 rems per person is surprisingly low for such close proximity to the accident. That may reflect the evacuation procedures, meteorological conditions and the special circumstances of the Chernobyl accident, which pumped material high into the atmosphere.

The Soviets had originally evaluated the dose commitment—that is, the dose expected from future exposure—from ingestion of cesium to be 210 million person-rems, a factor of ten higher than the external dose. In arriving at this estimate, the Soviets followed the procedures formulated by the United Nations Scientific Committee on the Effects of Atomic Radiation. However, other participants in the Vienna meeting felt this estimate was overly pessimistic. There is considerable uncertainty about how much cesium has fallen on different soil types, how cesium much will pass into the crops and how much contaminated food will be eaten. Analysis of atmospheric nuclear-weapons tests suggests[1] that the cesium dose from the food chain is somewhat less than that from external radiation. Marvin Goldman (University of California, Davis) told us that the Soviets recognized that their methodology would predict Cs^{137} body burdens, and hence dose levels, ten times higher than those they were measuring. Thus they lowered their estimate of the dose commitment from ingestion of cesium.

The Soviets' estimates of total radionuclide releases and of dose commitment apply to their own country only. To get a complete picture, one must match their numbers with those being assembled outside the USSR. Much work remains to be done before all the pieces are in place. The few simulations that have been done are as preliminary as the Soviet estimates.

Debris thrown up by force of the Chernobyl explosion litters roof of adjacent building. A large chunk at right, in front of a length of 6" pipe, appears to be half of a graphite block, with indentation left by cylindrical cooling channel. (Photo from Soviet tv, provided by Ed Purvis.)

Helen ApSimon and her colleagues at Imperial College, London, presented some initial findings to a World Health Organization conference last June in the Netherlands. They simulated the transport of 21 MCi of iodine and 1.5 MCi of cesium from the reactor across Europe, accounting for both winds and rainfall in the days after the accident. They estimate that the 500 million Europeans outside the USSR might have a collective dose from both ground-deposited and ingested cesium of 24 million person-rems.

Other simulations have been run by a collaboration in the Netherlands (the National Institute of Public Health and Environmental Hygiene and the Royal Netherlands Meteorological Institute) and by a team at Lawrence Livermore National Lab.[2] In these models the source terms have been adjusted to agree with surface-air concentrations measured at many places in eastern and western Europe as well as some points in the Middle East and Asia. Marvin Dickerson of the Livermore Lab says there is a need to work with the Soviets to arrive at a better estimate of the overall radionuclide release.

These simulations can only predict depositions averaged over very large regions. Chris Hohenemser (Clark University) points out, however, that Europeans have measured many "hot spots," such as places in southern Germany where rainfall produced dose levels up to 40 times those in places with no precipitation.

Studies under way. The implications of the Chernobyl accident are just beginning to unfold. Groups in many countries have already issued assessments of the radiological impact. Other institutions have assessments now in progress. UNSCEAR, with the cooperation of IAEA and the World Health Organization, will try to determine the overall radiological consequences. The US Department of Energy has established a task group under William Bair (Battelle Pacific Northwest Lab) in the Office of Health and Environmental Research. One of the group's four committees, under the leadership of Goldman, was scheduled to report at the end of October on its estimates of the radiological consequences. Another committee in the task group is assessing the opportunities presented by Chernobyl to validate existing models. A third committee is studying what the US might learn from the Soviet experience to improve emergency response preparedness.

Brian Sheron of the Nuclear Regulatory Commission told us that an interagency group in the US was preparing a factual report on the accident, from which each agency is to draw implications for its particular area of responsibility. Sheron is participating in a committee under the aegis of the Organization for Economic Cooperation and Development that is evaluating the implications of the accident for OECD member countries.

By the end of this year DOE was scheduled to receive six separate consultants' reports about the safety of the N-Reactor, a plutonium production reactor in Hanford, Washington. In late July, the National Research Council asked a panel of experts under Richard Meserve (Covington and Burling, Washington, DC) to report in nine months on the safety of plutonium production reactors and another nine months on US research reactors.

—Barbara Goss Levi

References

1. UN Scientific Committee on the Effects of Atomic Radiation, *Sources and Effects of Ionizing Radiation*, report to the General Assembly (1977).
2. P. Gudiksen, R. Lange, Nature, to be published.

Ozone hole attributed to solar maximum

In the 20 September issue of the *Journal of Geophysical Research*, Linwood Callis (NASA) and Murali Natarajan (SASC Technologies) suggest[1] that the recently hyperactive Sun, rather than manmade pollution, bears primary responsibility for the mysterious and troubling "ozone hole" that has for several years been appearing every October over the South Pole. They point out that 1979–80 witnessed one of the most intense solar maxima in centuries. This, they argue, would account for the striking increase in the level of "odd-nitrogen compounds"—various oxides of nitrogen—observed in the stratosphere between 1979 and 1984. Produced in an atmospheric layer above the stratosphere with the aid of sunlight and solar wind, these molecules can participate catalytically in the destruction of ozone.

Ozone resides primarily in the stratosphere. Callis and Natarajan suggest that these odd-nitrogen gases are drawn down into the Antarctic stratosphere during the winter by polar vortex winds. Once there, they begin attacking the ozone when the Sun reappears in September. The ozone hole thus created is eventually dissipated by the vortex in the polar summer.

The ozone holes have persisted beyond the solar-maximum year, Callis and Natarajan argue, because odd-nitrogen molecules survive in the stratosphere for about four years. If it is indeed this effect, rather than chlorofluorocarbon pollution, that is chiefly responsible for the polar ozone hole, this disturbing breach in our protection against the Sun's ultraviolet should be going away as the recent extraordinary solar maximum recedes into the past. And indeed, Callis told us, preliminary data indicate that the 1986 south-polar hole was significantly less pronounced than last year's, and that mid-latitude ozone levels are recovering from recent depletion.

A special issue of *Geophysical Research Letters*, scheduled for mailing at the end of November, contains 46 observational and theoretical papers dealing with the ozone hole.

—Bertram Schwarzschild

Reference

1. L. Callis, M. Natarajan, J. Geophys. Res. **91**, 10771 (1986).