so inclined, signatures of an abrupt phase transition.

When a quark–gluon plasma cools enough to congeal into hadrons, Lee points out, its entropy density decreases greatly as it loses the degrees of freedom of the unfettered quarks and gluons. "But the second law of thermodynamics won't let the overall entropy decrease," he reminded us. Therefore the hadronization of the cooling plasma must be accompanied by an expansion such that the product of the entropy density and the volume will have increased despite the loss of all those degrees of freedom. The diameter transverse to the beam axis might expand to 30 or 40 fermis.

How can one measure the size of the plasma? One borrows a trick from the astronomers. In the 1950s Robert Hanbury Brown (University of Manchester) and Richard Twiss (University of Sydney) developed a new interferometric method for measuring the angular diameters of stars. Photons, being bosons, tend to be positively correlated in phase space. The two-particle correlation function peaks when the momentum difference $\Delta\mathbf{p}$ between two photons goes to zero. Hanbury Brown and Twiss pointed out that the rate at which the correlation vanishes with increasing $\Delta\mathbf{p}$ is a measure of the source size. The smaller the source, the larger is the $\Delta\mathbf{p}$ at which one still sees correlation.

Pions, also being bosons, have the same clustering tendency. The idea of using pions to do Hanbury Brown–Twiss interferometry goes back to Gerson and Shulamith Goldhaber, Wonyong Lee and Abraham Pais at Berkeley in 1962. But only with the advent of RHIC will multiplicities be so large that one can make a statistically significant measurement of the source size in an individual event.

Pion interferometry of a quark-gluon plasma yields the expanded size at which the the pions start to freeze out. The transverse diameter of the plasma *before* this expansion is essentially given by the diameters of the incident nuclei. One can also imagine measuring the plasma size before expansion by doing the Fermi-statistics analog of pion interferometry with the much smaller population of leptons. But that is a questionable prospect not contemplated in the first round of detector proposals.

The enormous pion multiplicities will also make it possible to measure accurately the "temperature" of the central region in an individual event from the distribution of momentum components transverse to the beam axis. The higher the temperature, the greater the transverse momenta of the emerging hadrons. The multiplicity itself is a measure of entropy. Therefore one can look for an abrupt phase transition to the quark–gluon plasma by plotting the pion multiplicity of the central region against its temperature.

Some thermodynamic phase transitions are signaled by fluctuations on all scales. One can look for such wild fluctuations by dividing the central phase space into bins of different longitudinal momentum and comparing the multiplicities or energy densities of the different bins in an individual event.

Flavored and massless quarks

The quark–gluon plasma arising out of the excited vacuum should have a higher fraction of "nonvalence quarks" (antiquarks and strange quarks) than one sees in more mundane collisions between nuclei. The RHIC experimenters will therefore look for an increase in the relative yield of kaons and antihyperons with increasing temperature. Kaons are also expected to freeze out before pions. Therefore a smaller Hanbury Brown–Twiss source size from kaon interferometry would be regarded as evidence for the quark–gluon plasma.

QCD predicts that the onset of the quark–gluon plasma closely coincide with another phase transition: the restoration of "chiral symmetry," which, in effect, renders the quarks massless. A signal of the onset of this restored symmetry would be changes in the masses and widths of various common meson resonances such as the ρ and ϕ, which are seen as peaks in the invariant-mass distributions of lepton and kaon pairs emerging from the nuclear collisions.

Further up the invariant-mass spectrum of lepton pairs one comes to exotic-quark resonances like the famous J/ψ bound state of the charmed quark and its antiquark. Theorists expect that the production of such mesons will be noticeably suppressed by screening effects in a quark–gluon plasma. Some evidence of J/ψ suppression was already seen in the CERN heavy-ion runs. But this preview of coming attractions is no longer thought to have been a glimmering of the quark–gluon plasma. These CERN data seem to have a more mundane explanation.

"Perhaps more important than all these things the theorists are telling us to expect," says Ozaki, "is the search for the totally unexpected in this *terra incognita*."

—Bertram Schwarzschild

INTERNATIONAL TEAM EXAMINES HEALTH IN ZONES CONTAMINATED BY CHERNOBYL

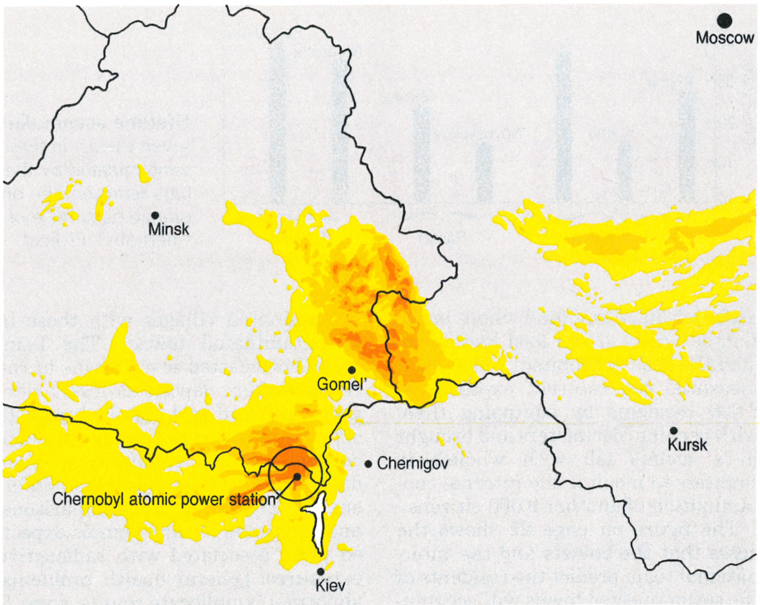
Glasnost notwithstanding, the Soviet Union has faced a credibility gap regarding its public pronouncements about the health effects from the explosion of a nuclear reactor at the Chernobyl atomic power station in 1986. While rumors have abounded in the affected republics of excess cancers or thyroid abnormalities, the central government has not found any clear evidence for maladies attributable to the accident. (See Physics Today, July 1990, page 62.) In October 1989, the Soviets asked the International Atomic Energy Agency to review government assessments of the radiological and health situation in the areas affected by the accident and to evaluate measures to protect the population. The resulting report, released at the end of May, largely validates the Soviet assessments to date. The study team did not find any significant health abnormalities that might be associated with radiological exposures except for high levels of stress and anxiety caused by concern over the radiation. Because of the limited scope of the study and the long latency period of cancers, the team could not determine whether there are any excess cancers in the populations examined. The report contains some recommendations for improvements in the ongoing assessments.

Limitations

The study launched in response to the Soviet request, called the International Chernobyl Project, eventually involved six agencies besides the IAEA and enlisted the help of 200 experts from 25 countries. The project sponsored 50 missions to the USSR between March 1990 and January 1991. Substantial though this effort was, it was not sufficient to evaluate comprehensively an accident of the scale of Chernobyl. Constrained by the limited time that the experts could devote to the job and faced with an affected area of over 25 000 km^2 containing a population of about 825 000, they could not begin to duplicate the voluminous assessments that the Soviets had undertaken in the five years since the accident. It could only review the Soviet methodology and data and make independent spot checks. Furthermore, because it was called in so long after the event, this team could not directly measure the dose from any of the short-lived radioisotopes from the fallout, such as iodine-131. (Even though ^{131}I has a halflife of only 8 days, many Soviet citizens near the reactor may have received a substantial radiation dose to the thyroid by inhaling ^{131}I or drinking it in contaminated milk.)

The study was also limited in scope: Responding to the inital Soviet request to assess the adequacy of measures to protect the population, the international study team confined its studies to people still living in contaminated zones. It did not examine those populations with potentially the largest exposures, in particular the more than 100 000 citizens who had been evacuated from the 30-km-radius zone around the reactor and the hundreds of thousands of workers who helped in the cleanup and who have been dubbed "the liquidators." The World Health Organization hopes to study the health of these liquidators.

The areas of the Soviet Union most severly affected by Chernobyl are shown in the map on page 21. Different colors represent the deposition densities of cesium-137 in the soil. That isotope, which has a halflife of 30 years, was released in significant amounts in the fallout. Deposition densities are measured in units of curies (ci) per square kilometer, where 1 ci is the activity of 1 gram of radium, or 3.7×10^{10} disintegrations per second. The international project concentrated on areas where the density was over 5 ci/km^2. (A portion of the population in areas with levels above 40 ci/km^2 have been evacuated.) The radiation dose to people in these regions depends a great deal on such factors as the amount of time spent outdoors and the quantity of locally grown food ingested. A very crude, and clearly unrealistic, gauge of the deposition levels is the fact that a person standing around the clock in a field contaminated with 5 ci/km^2 of ^{137}Cs (assumed to have penetrated 1 cm into the soil) would receive a whole-body external dose of about 0.2 rem in one year, twice the roughly 0.1 rem average yearly dose from background sources. (A rem is the quantity of radiation with the same biological effect as x rays delivering 100 ergs per gram of tissue.)



Densities of deposition of cesium-137 after the 1986 accident in a nuclear power plant at the Chernobyl power station sent radioactive fallout across the countryside. Regions shaded red have densities over 40 curies/km^2; dark orange regions, 15–40 ci/km^2; light orange regions, 5–15 ci/km^2; and yellow regions, 1–5 ci/km^2. Circle indicates evacuation zone around the reactor. In addition, many residents in the red zones were relocated.

Of the 825 000 people living in the affected areas, 45% are in the Byelorussian Soviet Socialist Republic, 31% are in the Ukrainian SSR, and the remaining 24% are in the Russian Soviet Federated Socialist Republic.

So far the International Chernobyl Project has widely distributed only the executive summary. The unedited full report has had limited distribution and will be published this fall.

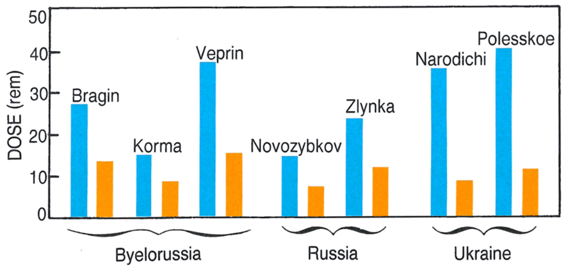
Study plan

The project was divided into five tasks: establishing an historical portrayal of events, assessing the radiological contamination of the environment, estimating the resulting doses to the population, determining any health effects from the radiation doses and evaluating the Soviet efforts to protect the population. The team that was assigned the first of these tasks compiled a brief history of events surrounding the accident.

The team assessing the environmental contamination reviewed data presented by the Soviets as well as Soviet practices for collecting and reporting them. The group independently took grab samples and made spot measurements of the radioactive contamination of soil, sediments, air, water, vegetation, milk and other food. They concentrated on ^{137}Cs, strontium and plutonium; any vestiges of ^{131}I have long since decayed away. (Strontium, with a halflife of 27 years, and plutonium, with a halflife of 24 000 years, are of health concern because of a combination of their toxicity and their relative abundance in the fallout.)

The map on page 21 is based on data produced by the Soviets in 1989, and the International Chernobyl Project found no spots where the radiation was appreciably higher than on the map. If anything, the contamination levels measured by the project tended to be lower than those published by the Soviets, especially for strontium. The concentrations of radionuclides in food and drinking water were below the maximum levels permitted by the guidelines for food moving in international trade.

The third International Chernobyl Project team reviewed how the Soviet scientists had arrived at their estimated doses, although there was not always sufficient information, especially on the ^{131}I exposure to the thyroid. Additionally, the project team independently reconstructed the doses for the villagers in seven towns where contamination levels



Lifetime accumulated doses predicted for residents of seven towns, in three Soviet Republics, in the regions contaminated by the Chernobyl accident. The blue bars represent the official Soviet estimates, and the orange bars those of the International Chernobyl Project.

exceeded 15 ci/km^2 (and where ingestion of locally grown food had consequently been prohibited). The team measured the external exposure of 8 000 residents by equipping them with personal dosimeters and brought in a mobile lab with whole-body counters to monitor the internal contamination of another 9 000 citizens.

The figure on page 22 shows the doses that the Soviets and the international team predict the residents of the seven selected towns will accumulate in the 70 years from 1986 to 2056. The considerable conservatism of the official Soviet estimates is evidenced by the fact that they are consistently higher than those of the international project team, by factors of as much as 2 or 3. The International Chernobyl Project estimates are all below the lifetime accumulation of 35 rem that the Soviets set as a criterion for evacuation.

Although the team could not assess the absorbed doses to the thyroid by ^{131}I, it did note that the Soviets had estimated rather high levels, especially in children. The reported doses to children ranged from 20 to 320 rad, and those for adults from 3 to 70 rads. (A rad is the radiation dose that delivers 100 ergs per gram of tissue.) The international group feels that these children should be carefully monitored, especially because thyroid cancers are treatable.

Health effects

The fourth team sought for any health effects attributable to the Chernobyl accident. (The quantitative link between radiation dose level and cancer incidence is discussed in the article by Arthur Upton on page 34.) In reviewing the Soviet data, the project team encountered deficiencies resulting from such factors as poorly maintained equipment and shortages of trained specialists in the local clinics. Another challenge was the very sparse information on the health of the involved populations prior to the 1986 accident. To properly identify any excess health problems in the contaminated areas, the project team had to compare the residents of the contaminated villages with those in uncontaminated towns. The team members selected seven towns in the regions where deposition levels were over 15 ci/km^2 and matched them to six control towns of similar sociological and economic composition. They divided their 1356 subjects into different age groups for the comparisons, and examined for any signals expected to be associated with radioactive exposures: general health problems; abnormal lymphocyte counts; anomalous thyroid hormones or blood lead levels; cataracts; chromosomal aberrations and somatic cell mutations; and so forth. In the areas where the team took measurements, it found no statistically significant differences in any of these indicators between the contaminated and control groups. Indeed for the doses estimated one would not anticipate any measurable health effects at this time. The study team adds, however, that the size of the population sampled was not large enough to exclude the possibility of an increase in the incidence of some tumor types.

Based on the reported estimates of absorbed thyroid doses in children they expect "there may be a statistically detectable increase in the incidence of thyroid tumors in the future," but the group concedes that "future increases over the natural incidence of cancers or hereditary effects would be difficult to discern, even with large and well-designed long-term epidemiological studies." It is still early for many maladies to have surfaced: The latency period for leukemias is about 2–5 years and those for other cancers are longer (10–30 years).

Marvin Goldman of the University of California at Davis, who headed a DOE team that in 1988 assessed the consequences of Chernobyl, is disappointed that the Soviets have not yet mounted a careful, focused epidemiological study like the one undertaken at Hiroshima and Nagasaki. Such a study, he feels, would have the best shot at detecting any excess cancers that might occur. Goldman's DOE team predicted that up to 17 000 excess cancer deaths in Europe and the Soviet Union might result from Chernobyl, with about half of those in the USSR. In the same population, one might normally expect about 600 million cancers.

While the residents do not show any physical symptoms that might be associated with their radiological exposures, they *have* been measurably perturbed by stress and anxiety over the accident. In both the contaminated and control towns, residents surveyed were psychologically affected by "the continuing and high levels of uncertainty" about the radiation doses they had received and their potential health effects.

The fifth study group addressed the measures that the Soviet Union had taken to protect its citizens and those it proposed to take in the future. The project was critical of relocation measures and food restrictions. The report states that "the protective measures taken or planned for the longer term, albeit well intentioned, generally exceed what would have been strictly necessary from a radiological protection viewpoint." It adds that "the social consequences, including costs, of banning the consumption of foodstuffs were in many cases disproportionate to the doses averted."

The international team felt that the Soviets had clung too tightly to the lifetime dose criterion (of 35 rem) rather than weighing the adverse effects of relocating against the dose thus avoided. In some cases the doses avoided by moving a person were on the same order of magnitude as the natural background radiation. But these considerations are not well understood by the population—72% of those in the contaminated zone want to relocate—and the central Soviet government is inclined to take measures to restore public confidence and to reduce anxiety. Thus the Soviets plan to implement a scheme adopted by the Supreme Soviet under which relocation will be obligatory for some people and optional for others, depending on their anticipated annual dose levels.

—Barbara Goss Levi ■