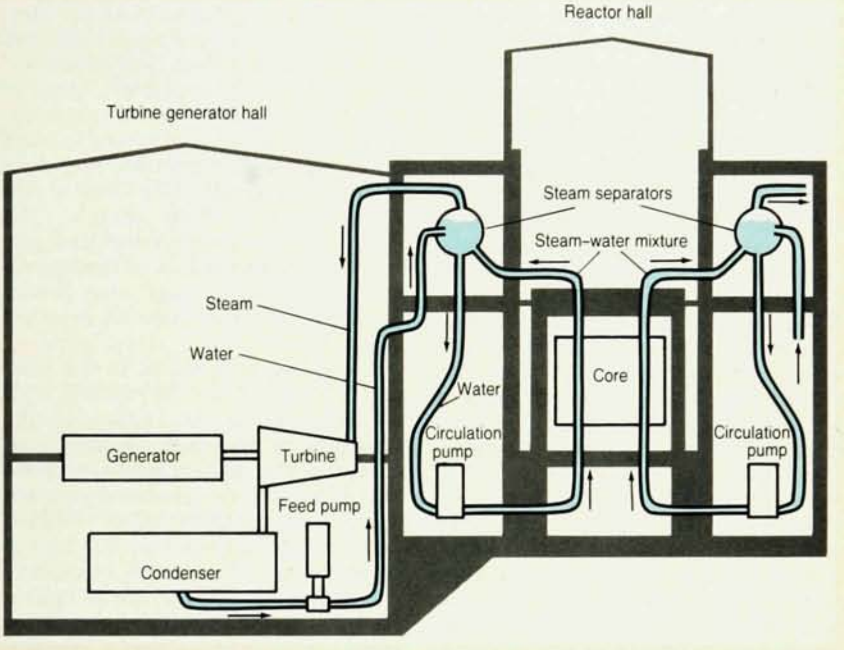
Cause and impact of Chernobyl accident still hazy

At the Soviet Union's Chernobyl nuclear power plant, the plume of smoke is gone, but a cloud of uncertainty still obscures the cause of the severe accident there. That accident, which began early on Saturday, 26 April, caused an intense fire that lasted many days, melted unknown quantities of reactor fuel and released into the environment a large fraction of the reactor's inventory of volatile radioactive fission products (including perhaps a million times more iodine-131 than came from Three Mile Island). On 11 May Soviet officials reported that they had stabilized the reactor and had successfully prevented the core from melting through the bottom of the containment building. Although the crisis is past, formidable tasks lie ahead. These chores include entombing the severely damaged core; isolating or decontaminating an area more than 30 km in radius around the plant, from which about 100 000 people have been evacuated; monitoring radiation levels over far more extensive areas; and determining the cause of the accident to prevent repetitions elsewhere.



Reactor at Smolensk in the USSR is apparently very similar to unit 4 at Chernobyl. In this simplified diagram the thick lines indicate walls of concrete and steel. Not shown are two suppression pools beneath the reactor floor, which quench any excess steam.

Design of the reactor. The damaged reactor, operating since 1983, was the most recent of four nuclear power plants at Chernobyl, about 100 km northwest of Kiev. All four completed units there, plus two under construction, are graphite-moderated, water-cooled plants, each designed to produce about 3200 MW of thermal power and 1000 MW of electric power. The Soviets have built approximately 14 nuclear power plants of a similar design—called RBMK-1000. These reactors are direct descendants of the reactor type first built in both the US and the Soviet Union to produce plutonium for weapons. While US companies building commercial power plants have opted largely for reactors moderated by light water—either pressurized-water reactors or boiling-water reactors—the Soviets have chosen a modified version of the graphite-moderated design to provide more than half of their electricity. The remaining fraction is provided by PWRs.

In an RBMK-1000 reactor, pellets of the fuel—uranium dioxide slightly enriched in U-235—are encased in zirconium–niobium cladding to form a fuel pin. Eighteen such fuel pins are clustered into one fuel assembly, and two of these assemblies are placed end to end in the middle of a concentric, 88-mm-diameter zirconium–niobium pressure tube, or fuel channel, through which water flows to cool the assembly. The fuel channels—about 1700 in all—are embedded vertically in columns of graphite blocks 250 mm on a side. The entire graphite structure contains about 2000 tons of this moderator, shaped into a cylinder 7 m high and 11.8 m in diameter.

The figure above illustrates the general layout of the RBMK-1000 reactor. Although this diagram is based on information about the graphite-moderated reactor at Smolensk, it is presumed to be quite similar to unit 4, the damaged reactor at Chernobyl. Both the Smolensk unit and units 3 and 4 at Chernobyl have confinement and steam-suppression features that differ significantly from those of earlier RBMK-1000 designs. Water at 270 °C is circulated through the individual pressure tubes by six circulating pumps, which feed the water into a manifold and then upward into the many individual channels. Steam produced within the assemblies is extracted from the top of each pressure tube and collected in a header leading to one of the four steam drums.

For controlling the reaction rate, the RBMK-1000 has about 200 boron carbide rods. These rods are cooled by a separate water system, with water entering at the tops of the channels. The rods are electrically driven, at a

0031-9228 / 86 / 0700 17- 07 / $01.00

rate slower than that for most US power reactors, and it is not known whether there are provisions to insert them in case of a power outage. The reactor has two independent emergency cooling systems, one for rapid, emergency cooling and the other for long-term cooling. Two RBMK-1000 units share three emergency diesel generators.

The channel structure of the reactor enables it to be refueled while still operating at full power. Thus these reactors are potentially more available for power generation than are reactors that must be shut down for refueling. (The ability to remove fuel whenever desired also enables these reactors to be used for production of weapons-grade plutonium—that is, plutonium with a larger ratio of the isotope Pu-239 to heavier isotopes than in commercial reactor fuels—although there is no indication that the Soviets have operated the Chernobyl units for this purpose.) Refueling is done by a large machine that is positioned by a huge crane above the top of the reactor core. Despite the elaborate control systems for performing this operation, the risk of accident is higher when refueling is done on line than when it is done, as in light-water reactors, with the reactor shut down, depressurized and cooled to a rate of heat generation less than 1% of its value during power generation.

The RBMK-1000 design is prone to power excursions because it has a positive reactivity coefficient. That means that an increase in the power level of the core tends to make the core more reactive: The higher power levels give rise to larger steam fractions (voids) in the water–steam mixture. With less neutron-absorbing water between the fuel and the graphite moderator, the neutron density increases, as does the power level. This tendency must be countered by a computerized control system, which in the RBMK-1000 plant is very complex. By contrast, reactors moderated by light water have negative reactivity coefficients because the water becomes a less effective moderator at higher temperatures owing to its reduced density. As the RMBK-1000 reactors reach equilibrium after five to seven years of operation, their reactivity coefficient becomes less positive.

How did the accident happen? No one really knows, and it may be a long time before even the Soviets solve the complex puzzle, many of the clues having been destroyed by the explosion and fire. One Soviet statement implied that the incident was an unexpected sequence of unlikely events. Nevertheless reactor experts around the globe are combining the information gleaned from sparse Soviet statements with technical descriptions of the graphite-moderated reactor design, anxious to learn whether the accident has taught any lessons relevant to other reactor designs.

On 14 May, Soviet leader Mikhail Gorbachev gave the following account of the events at Chernobyl: "As specialists report, the reactor's capacity suddenly increased during a scheduled shutdown of the fourth unit. The considerable emission of steam and subsequent reaction resulted in the formation of hydrogen, its explosion, damage to the reactor and the associated radioactive release."

Before the accident, the reactor had been operating at only about 7% full power. Statements made informally by Soviet scientists to American counterparts suggest that the Soviets may have been conducting some "experiments" or "tests" with the reactor; some of these scientists have further commented that the accident involved human error. The reactor was said somehow to have gone from 7% to 50% of full power in less than a minute. The coolant may have overheated and produced steam as a result of this reactivity excursion, a large pipe break, blockage of coolant channels or other causes.

The hydrogen produced in the reactor is most likely to have resulted from the oxidation by hot steam of the zirconium of the fuel cladding and channel walls. At temperatures above roughly 1000 °C this reaction proceeds rapidly and exothermically. RBMK-1000 reactors contain over 100 tons of zirconium in their cores (compared with less than 20 tons for a typical PWR) so they can potentially generate large quantities of hydrogen. In addition, both hydrogen and combustible carbon monoxide are produced by the slower, endothermic reaction of hot graphite with any steam that may escape from the cooling channels. Graphite will burn in steam once it has been ignited, stripping oxygen from the water moderator.

It is easier to postulate how the hydrogen might have been generated than it is to understand how it exploded, comments Walter Kato of Brookhaven Lab. The reactor core is in a steel shell filled with inert helium and nitrogen gases. There normally would not be enough oxygen present to burn the hydrogen. (Hydrogen may burn in air when its concentration is above approximately 4% by volume.) Perhaps damage to the cooling system led to the overpressurization and destruction of this reactor shell, allowing air to enter or hydrogen to escape.

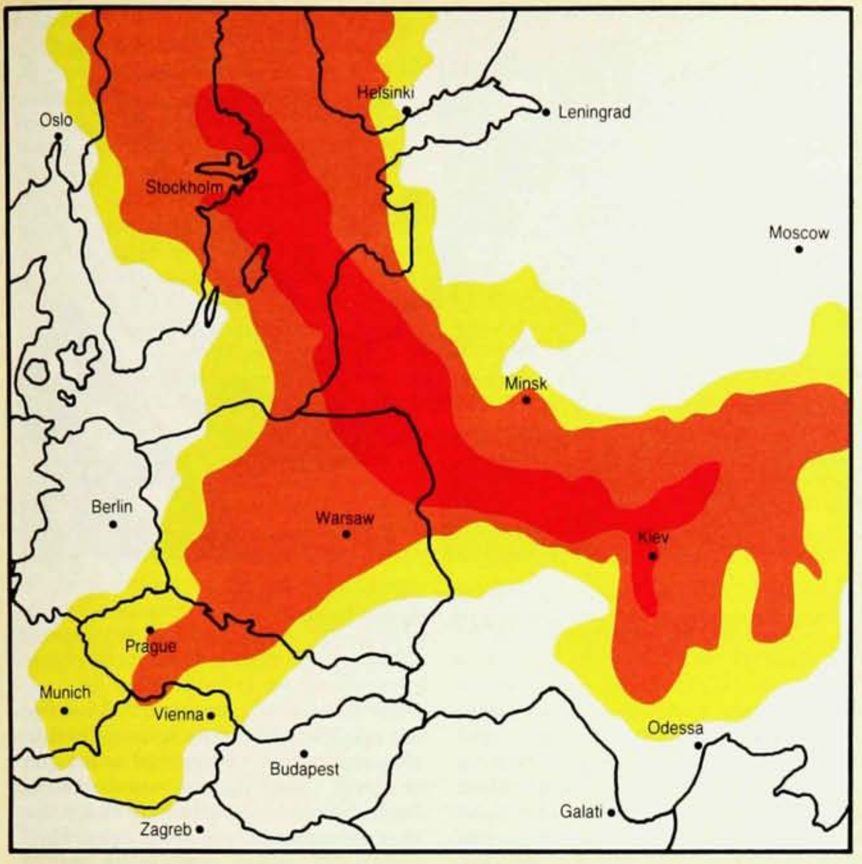
The resulting hydrogen–air mixture probably exploded, causing further damage to the reactor and surroundings. The path was then open for the escape of any volatile fission products that might have seeped out of the fuel pins damaged by the decay heat and by the steam–metal reaction. The combination of events appears to have ignited the graphite, which burns only at very high temperatures. (Even under ideal controlled conditions with an ample supply of oxygen or air available, graphite must be above 700 °C to burn.) As the graphite fire smoldered, the Soviets attempted to smother it by dropping sand, boron and lead onto it from helicopters.

Still, after ten days, "the heart [of the reactor] was a white-hot core, a scorched, active zone that was somehow 'hanging,' " according to statements made by Evgeny Velikhov (vice-president of the USSR Academy of Sciences) to the Soviet paper *Pravda*. Velikhov said that the Soviets worried that the core might cause a steam explosion if it dropped into the water-filled suppression pools located under the reactor cavity. The Soviets decided to pump out those pools and then to drill holes (at an unspecified location) to create a "cooling zone" that would draw heat away from the core.

The strategy seems to have worked. The Soviets reported on 11 May that the situation was under control. They are planning now to encase the reactor in concrete with a water cooling system to carry off heat from the radioactive decay of the more refractory fission products, which remain in the molten core. The Soviets have stated that they have sprayed large areas around the reactor, presumably with some type of plastic, to prevent the radioisotopes deposited on the ground from being washed into nearby streams.

Confinement or containment? Considerable debate now centers on the strength and tightness of the structure that surrounds the reactor core at Chernobyl: Was it designed to withstand the pressures that might be anticipated in worst-case conditions? The reactor shielding and support structure consists of two enclosures of steel and concrete (see the figure on page 17). The Soviet literature suggests that the enclosure surrounding the core might withstand pressures of 27 psi and that the structure around the cooling system might take pressures of up to 57 psi, comparable to typical design pressures for many American reactors. Beneath the reactor building are two pressure-suppression pools containing water, which are designed to condense excess steam if the pressure in the reactor vault rises by 3 psi. These pools are designed to quench steam, but they offer no protection against excess hydrogen.

Brian Sheron of the Nuclear Regulatory Commission cautions that the pressure ratings may not be determined according to the same codes as



Simulation of integrated dose of I^{131} from Chernobyl accident to adult thyroid glands accumulated from 26 April to 1 May, based on calculations done at Lawrence Livermore National Laboratory. Areas in which doses predicted by the simulation are above 1 rem (that is, the radiation dose medically equivalent to 1 roentgen of gamma rays) are shown in red; orange indicates doses between 0.1 and 1 rem; and yellow indicates doses between 0.01 and 0.1 rem.

the US uses for containment structures, and that we don't have enough information to permit an independent evaluation. Several features of the Chernobyl confinement structure would certainly complicate the task of making it pressure tight: The reactor cavity is rectangular rather than domed, as is typical of large containments around PWRs, and its top must be penetrated by thousands of fuel tubes and pipes to enable the core to be refueled continuously from above. The volume of the reactor cavity is tens of thousands of cubic feet, one hundred times smaller than most PWR containment buildings, so pressures can build up faster and to higher values. Richard Wilson (Harvard), who directed the APS study group on radionuclide releases from severe accidents at nuclear power plants[1] (PHYSICS TODAY, May 1985, page 67), feels that the structure around the Chernobyl core cannot be called a containment building if by that term one means the type of structure surrounding US commercial power reactors.

The APS study group headed by Wilson found that containment buildings in the US might be able to withstand pressures up to $2\frac{1}{2}$ times their design pressure before failing. However, the panel recommended more study of reactors that rely on pressure suppression or ice condensers for reduction of steam pressure.

In addition to hardware differences between Soviet and Western reactors, some have noted qualitative differences in the approach to safety. Wilson feels that the Soviets have been followers rather than leaders on reactor safety. Edwin Zebroski of the Electric Power Research Institute told us that there is very little evidence that the Soviets analyze low-probability (but high-consequence) events; thus they cannot use results of such analyses to redesign components or reevaluate operation or maintenance procedures.

Could it happen elsewhere? The spotlight is focusing on reactors with design features similar to those of the RBMK-1000. One of the reactors receiving the most attention is the N-Reactor at the Hanford Reservation near Richland, Washington, which, like the Chernobyl reactor, is moderated by graphite and cooled by water. It is one of five plutonium-production reactors operated by the Department of Energy. None of them is licensed by NRC and none has a containment building. Even before the Soviet accident, all five were scheduled for DOE technical safety appraisals this year. In the wake of Chernobyl, Secretary of Energy John Herrington has accelerated the appraisal schedules. The review of the four heavy-water-moderated reactors at Savannah River, South Carolina, will begin in September rather than in December. The review of the N-Reactor began 19 May.

The similarity of the N-Reactor to the Chernobyl plant, and hence the sensitive nature of its review, has prompted Herrington to establish a special safety-review panel of outside experts to evaluate the facility. The panel is headed by Louis H. Roddis, a consulting engineer who was formerly president of Consolidated Edison Company in New York. Other panel members are Miles Leverett (formerly of General Electric), Harold Lewis (University of California at Santa Barbara), Thomas Pigford (University of California at Berkeley), Gerald Tape (special assistant to and past president of Associated Universities, Inc) and Eugene P. Wilkinson (formerly of the Institute for Nuclear Power Operations). A separate committee of the US National Academy of Sciences and Academy of Engineering will evaluate the five plutonium-production reactors and six large US research reactors.

The N-Reactor, which has a thermal power of 4000 MW, has been operating since December 1963 to produce plutonium for the US weapons program, and since 1966 also to produce electricity, which is sold to a commercial grid. Although it has the same channel structure as an RBMK-1000, it has some notably different features: It has been designed to have a negative reactivity coefficient. Its fuel is 1% enriched, metallic uranium clad with zirconium alloy, and the reactor contains about twice as much fuel (350 tons) as the Chernobyl plant. The fuel melts at a much lower temperature than the oxide fuel, and operates at a maximum center-line temperature of about 475 °C, compared with more than 1800 °C for uranium oxide. The horizontal fuel channels allow water to be fed from either end of the channel.

The Hanford facility also features, in addition to the primary cooling loop for the fuel, an independently powered system that circulates water through the graphite blocks. If all direct cooling of the fuel fails, the graphite cooling system provides an indirect means of removing heat. The reactor operators feel that a graphite fire is prevented by temperature control and limitation of available oxygen.

A 1980 safety analysis examined[2] the consequences of a loss-of-coolant accident in which the graphite cooling system continues to function. The analysis predicted that about one-third of the core would melt. The hydrogen produced from the steam–cladding reaction would, at its maximum amount, have an average volumetric concentration of 1.2%. This concentration would not be a concern, the study stated, as long as the hydrogen was reasonably well mixed—as their simulations predict it would be.

The reactor has a large confinement system designed to handle a major pipe-break accident in which the initial pulse of steam is separated in time from the release of fission products. Large vents would permit the escape of steam from the building, and then would close so that the fission products would be either washed out by fog sprays or removed by filters in the stacks. Hanford does not, however, have a pressure-tight containment building. Steve Sholly of MHB Technical Associates, a consulting firm in San Jose, told us it would be helpful to see a quantitative analysis of the risk of a hydrogen explosion in the N-Reactor.

Another category of graphite reactor is the high-temperature, gas-cooled reactor. The US and Germany each have an operating HTGR, and both countries have programs to design reactors of this type made of small modules (about 350 MW_t). Testifying before the Subcommittee on Energy Research and Development of the House Science and Technology Committee on 14 May, Richard Dean of GA Technologies stressed that the occurrence of an accident at the Chernobyl plant does not mean that all graphite reactors are unsafe. On the contrary, many feel that the passive safety features of HTGRs provide a high degree of protection. They are fueled with ceramic-coated particle fuel imbedded in the graphite structure, and they are cooled with helium gas. Safety features include the high heat capacity of the graphite, high temperature stability of the core and the inert nature of the coolant, which cannot react chemically with the fuel, the moderator or other reactor components. These features should buy a lot of time for correction of any malfunction. However, HTGR designs do not include a pressure-tight containment structure.

The Windscale accident. The first reports of radioactive releases from the Soviet graphite-moderated reactor prompted the inevitable comparisons to the 1957 releases from an accident in Great Britain's graphite-moderated, air-cooled Windscale reactor. That reactor was fueled with metallic uranium and was being used solely to produce plutonium for the British nuclear-weapons program. The graphite moderator at the Windscale plant had to be annealed periodically to remove in a controlled manner the so-called Wigner energy that builds up as the neutrons displace the carbon atoms from their normal lattice positions. Wigner energy is not a problem for the RMBK-1000 reactors or for plants like the N-Reactor that operate at graphite temperatures greater than 300 °C, because the moderator is constantly annealed.

Chernobyl nuclear power plant a few days after the accident. The arrow indicates the damaged unit. (Photo from Tass, courtesy Sovfoto.)

During the annealing at Windscale, the operators misinterpreted some of the thermocouple readings and failed to realize that some of the channels had overheated. Inappropriate application of a second nuclear heating led to the rupture of the uranium fuel cans and a uranium fire, which may have caused some of the graphite to burn as well. The fire eventually spread to about 150 fuel channels and lasted four days before it was extinguished with water. Radioactive gases were released through the stack, which filtered out about half of the I^{131} and Cs^{137}, releasing very roughly 10 000–20 000 and 1000 curies, respectively, of these nuclides. The doses to nearby residents were too low for health effects to be statistically established.

Releases of radioactive nuclides. At the time of the Chernobyl accident the winds were blowing northwest, and the Finns first noticed the contamination on the evening of 27 April. The Swedes traced the fallout to a source in the Soviet Union, and have continued to monitor the radiation levels in their country. L. Devell and his colleagues from the Studsvik Energy Research Station in Sweden, using particle filters to sample the radioactive emissions from Chernobyl, measured[3] 16 different nuclides, including some refractory elements. They examined some particularly "hot" particles and deduced from their size and spherical shape that they were particles of nearly pure Ru^{103} and Ru^{106}, which must have melted. Ruthenium has a melting temperature of 2500 °C, so these results suggest that some parts of the Chernobyl reactor became that hot.

Although most European countries have measured the radiation doses within their borders since the Chernobyl accident, it will take some time for a consistent picture of the radiation contamination to emerge from these data. The numbers represent different quantities—such as dose rate of I^{131} in air or time-integrated deposition of Cs^{137} on the ground—measured by various techniques at different times. Agencies such as the World Health Organization and the US Department of Energy are collecting these numbers so they can be sorted and merged into a coherent database. Fragmentary information about air activity, ground deposits and I^{131} levels in milk in various parts of Europe was collected[4] by Chris Hohenemser (Clark University), together with Manfried Deicher, Anneliese Ernst, Hans Hofsäss, Gerhard Lindner and Ekkehard Recknagel (all from the University of Constance, FRG). They found that the air activity during the passage of the cloud from Chernobyl reached 10^5 times background levels in Poland. Ground-level deposits at locations with heavy rainfall were as high as 30–40 times background levels as far as 1500 km from Chernobyl, but near normal in places that had no precipitation. From measurements of the relative abundances of radioisotopes in the fallout, Hohenemser and his colleagues estimate that at most 25% of the volatile fission products in the reactor were released. A task force set up by the Department of Energy will examine the potential health impact of the Chernobyl accident.

Until data are available in usable form, some scientists have been running atmospheric-transport models to simulate the possible magnitude and extent of contamination from the reactor accident. Joseph Knox and his colleagues at Livermore, and, independently, Helen ApSimon and J. Wilson of Imperial College, London, have undertaken such simulations, using actual wind patterns for the days after the accident. Their efforts are very preliminary because there are few or no data describing the nature of the releases. The simulations must make assumptions about the probable inventory of radioactive fission products in the reactor, the fraction of the volatile fission products that may have escaped, the height to which they were carried by the heat and fire, the time over which that release occurred and the rate at which the radioisotopes are deposited on the ground. Thus the results could well be in error by an order of magnitude or more.

The Livermore simulation corresponds to a hypothetical total release of 40% of the core inventory of volatile radionuclides in the first day after the accident and an additional 10% spread out over the subsequent five days. It was assumed that the reactor had been operating at full power until just before the accident, in which case the core may have contained 80 megacuries of I^{131} and 6 MCi of Cs^{137}, among other fission products. The simulation does not include the effects of terrain or rainfall. The figure on page 19 shows contours predicted by the Livermore program for the time-integrated dose to the adult thyroid that a person would have received by the fifth day after the accident from inhaling the I^{131}. The dose values obtained from the model are high compared with measurements near Stockholm and in Poland, but agree with data taken off the coast of Sweden and in Italy, Knox says. The Imperial College simulation, which does include rainfall, assumes the accident released 21 MCi of I^{131} and 1.4 MCi of Cs^{137}.

The simulations of contamination from the Chernobyl plant have concentrated on I^{131} and Cs^{137} because they pose considerable health concern and are released in appreciable quantities. Iodine-131 is a beta emitter and has a halflife of only eight days, but it is taken up quickly into the thyroid once it is inhaled or ingested. Cesium-137 is a gamma emitter with a halflife of 30 years, so it can contaminate the ground for long periods.

Frank von Hippel (Princeton University) and Tom Cochran (Natural Resources Defense Council) have made[5] some very preliminary estimates of what the long-term health consequences of the Chernobyl accident would be if the doses were distributed as these simulations predict. They used the Imperial College maps to deduce the numbers of people possibly exposed to given levels of radiation. They then applied the so-called linear hypothesis—which assumes that the health effects of low doses of radiation can be extrapolated linearly from those seen at higher doses—and found that among the roughly 100 million exposed people in the western USSR and Eastern Europe there might be thousands to tens of thousands of tumor cases from I^{131} and cancers from Cs^{137}. About half of the Cs^{137} cancers, but only a few percent of the thyroid tumors, might be fatal. These fatality predictions result only from summing very small incremental cancer risks to individuals over very large numbers of people. Over the lifetimes of the exposed population, one might expect about 20 million cancer deaths from other causes. Von Hippel and Cochran caution that these are very uncertain, first-order estimates, which rest on the model simulations, assume a uniform population density and rely on a linear model of the dose–effect relationship.

Since the Chernobyl accident, many have spoken of the need for international communication and cooperation in matters of nuclear safety. In his speech of 14 May, Gorbachev stated his readiness to cooperate in such efforts, within the framework of the International Atomic Energy Agency. IAEA has scheduled a meeting of experts in Vienna for 25–29 August. At that time the Soviets have promised to give a post-accident briefing. The IAEA board of governors will meet 22–23 September, and a special session at the ministerial level will follow on 24–26 September. An IAEA spokesman told us they expect to strengthen an existing agreement on cooperation in matters of nuclear safety and expand it to cover all aspects from design to decommissioning. —Barbara Goss Levi

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Panel reaffirms high-field magnet choice for Supercollider

The Superconducting Super Collider, if it is built before the end of the century, will certainly be the largest scientific instrument in the world. But whether its circumference should be 100 miles, or a mere 50 miles, has been a bone of some contention. The design energy is not at issue: SSC is to be an ultra-high-energy proton–proton storage-ring collider with countercirculating beams of 20-TeV protons providing p–p collisions at 40 TeV in the center of mass. The radius of the gargantuan storage ring required to keep these protons going round in circles varies inversely as the strength of the superconducting bending magnets one chooses to make up the ring.

Last September the issue appeared to have been settled once and for all by the magnet-selection advisory panel headed by Frank Sciulli (Columbia). The Sciulli panel and its industrial consultants unanimously recommended the selection of the high-field "$\cos\theta$" magnet design developed by a Brookhaven–Fermilab–Berkeley collaboration (PHYSICS TODAY, December, page 59). With a field intensity of 6.6 tesla, these bending magnets would require an SSC circumference of 52 miles. A 3-tesla "superferric" magnet design, developed and championed by the Texas Accelerator Center, had emerged as the chief rival of the $\cos\theta$ design at the Sciulli-panel meetings. This presumably less expensive low-field magnet would require an SSC circumference of 100 miles, but its proponents argued that the additional civil-engineering cost of the longer tunnel would be more than offset by the savings in magnet fabrication. The Sciulli panel was not convinced that a superferric SSC would in fact be significantly cheaper. They opted for the high-field $\cos\theta$ magnets, which they felt were at a significantly more advanced state of development.

The calm that followed the selection of the high-field magnets was disturbed in April by a letter to DOE from Russ Huson and Peter McIntyre, the leaders of the Texas low-field-magnet effort, requesting that the SSC magnet-selec-