Estimating long-term health effects

by Frank von Hippel and Thomas B. Cochran

THE ACCIDENT that occurred at Unit 4 of the Chernobyl Nuclear Power Station last April resulted in a near-worst-case release of fission products. But it is important to remember that comparable consequences from industrial accidents are not unique to nuclear power plants—nor is the Soviet Union the only country in which massive releases of highly toxic materials have occurred. For example, the accident at Union Carbide's chemical plant in Bhopal, India, is reported to have killed over 2,000 people and injured more than 100,000 others. The principal difference is that most of the health effects of the Chernobyl episode will be statistically undetectable because they will be spread anonymously through a population of hundreds of millions and over a period of decades.

About 300 people—mostly fire fighters and others on site during the Chernobyl accident—are reported to have received radiation doses large enough to be hospitalized. Twenty-six of these have died.[1] Long-term health consequences can be expected to be relatively invisible but much larger, due to the lower radiation doses from the fission products that spread over much of Europe. The associated individual risks are very small for all but those populations within a few tens of kilometers of the accident. However, these small risks, added up over hundreds of millions of individuals, could total thousands to tens of thousands of cancer deaths and generally less fatal thyroid tumors. These potential long-term health effects have been for years the principal concern of those arguing for design improvements in the containments around U.S. nuclear reactors.[2] Two fission products in particular, iodine 131 and cesium 137, which are key determinants of the scale of these longer-term consequences, are the focus of this article. We start by briefly discussing their effects and how public health authorities sought to reduce exposures to them.

ABOUT 3 PERCENT of all fissions produce an atom of iodine 131, having an eight-day half-life. That is, after eight days, half of them will have undergone radioactive decay and, after 80 days—or 10 half-lives—only one in 1,000 will remain. Most of the radiation doses due to iodine 131 were therefore incurred during the first few weeks after the Chernobyl accident.

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Another consequence of iodine 131's short half-life is that the amount of the isotope in a reactor core at any time depends primarily upon the reactor's average power level during the previous few weeks. If Chernobyl Unit 4 had been operating at its full power of 3.2 million kilowatts heat output for several weeks (something about which there continues to be considerable uncertainty), the core would have contained about 80 million curies of iodine 131 in relatively volatile chemical combinations.[3] The initial overheating and the subsequent destruction of the reactor containment and burning of the core would have released a large fraction of this iodine 131 into the atmosphere.

Iodine 131 is of special concern as an internal hazard because it concentrates in the thyroid which would, as a result, be irradiated much more intensely than the rest of the body. The adult thyroid inhalation radiation doses from a Chernobyl-scale release could be over 100 rads out to a distance of 100 miles (160 kilometers) downwind from the accident.[4] The doses to the smaller thyroids of children would be higher still. A 100-rad dose to the thyroid would be associated with an extra 1–6 percent chance of developing thyroid tumors during the next 30 years.[5] The hazard from radioactive iodines to children's thyroids has been of special concern to public health authorities since the 1954 U.S. nuclear test "Bravo" blanketed Rongelap, an inhabited South Pacific atoll, with radioactive fallout. Before the Rongelap natives were evacuated, they drank water contaminated with radioactive iodines. Nineteen children under age 10 received an estimated average thyroid dose of about 1,000 rads.

All but one of these 19 suffered serious thyroid problems by age 21. Fifteen developed thyroid tumors, which were treated surgically followed by a lifetime prescription for medication with thyroxine hormone to prevent recurrence. Two other children lost their thyroid function entirely—something that was only discovered when they failed to grow normally. Two out of three of the children who were *in utero* at the time their mothers were exposed to radioactive iodines also developed thyroid tumors in their 20s.[6]

Because of the Polish government's concern about the possibility of such consequences from Chernobyl, when the public health authorities there became aware of the high concentrations of iodine 131 in the air coming into Poland from the Soviet Union, they made the dramatic decision to give a thyroid protection chemical to all Polish children under age 17. The medication, a compound containing normal nonradioactive iodine, acts by raising the level of iodide in the bloodstream to the point that the thyroid cannot take more in. Then, radioactive iodine that is absorbed into the body bypasses the thyroid and is excreted in the urine. Since the thyroid-blocking medication does not reduce the radia-

A Soviet technician checks toddler Katya Litvinova, in her mother's arms, during a radiation inspection of residents of Kopylovo village near Kiev. (*AP/Wide World Photo*)

tion dose from radioactive iodines ingested or inhaled more than a few hours earlier, distribution by the Polish authorities was probably not rapid enough to greatly reduce thyroid doses of iodine 131 due to inhalation, but it may have reduced doses due to contamination of food.

Seven years earlier, the U.S. Food and Drug Administration, similarly concerned about the possible large release of iodine 131 from the damaged Three Mile Island reactor, ordered 260,000 one-ounce bottles of saturated potassium iodide solution, the first of which were delivered to Harrisburg four days after the emergency began. As in Poland, this would probably have been too late if there had been a large release of iodine 131. However, despite this experience and the Food and Drug Administration's endorsement of the safety and effectiveness of the technique to prevent projected thyroid doses above 25 rads,[7] opposition by the staff of the Nuclear Regulatory Commission has largely stymied efforts to set up arrangements to make potassium iodide rapidly available to the public in case of need.[8]

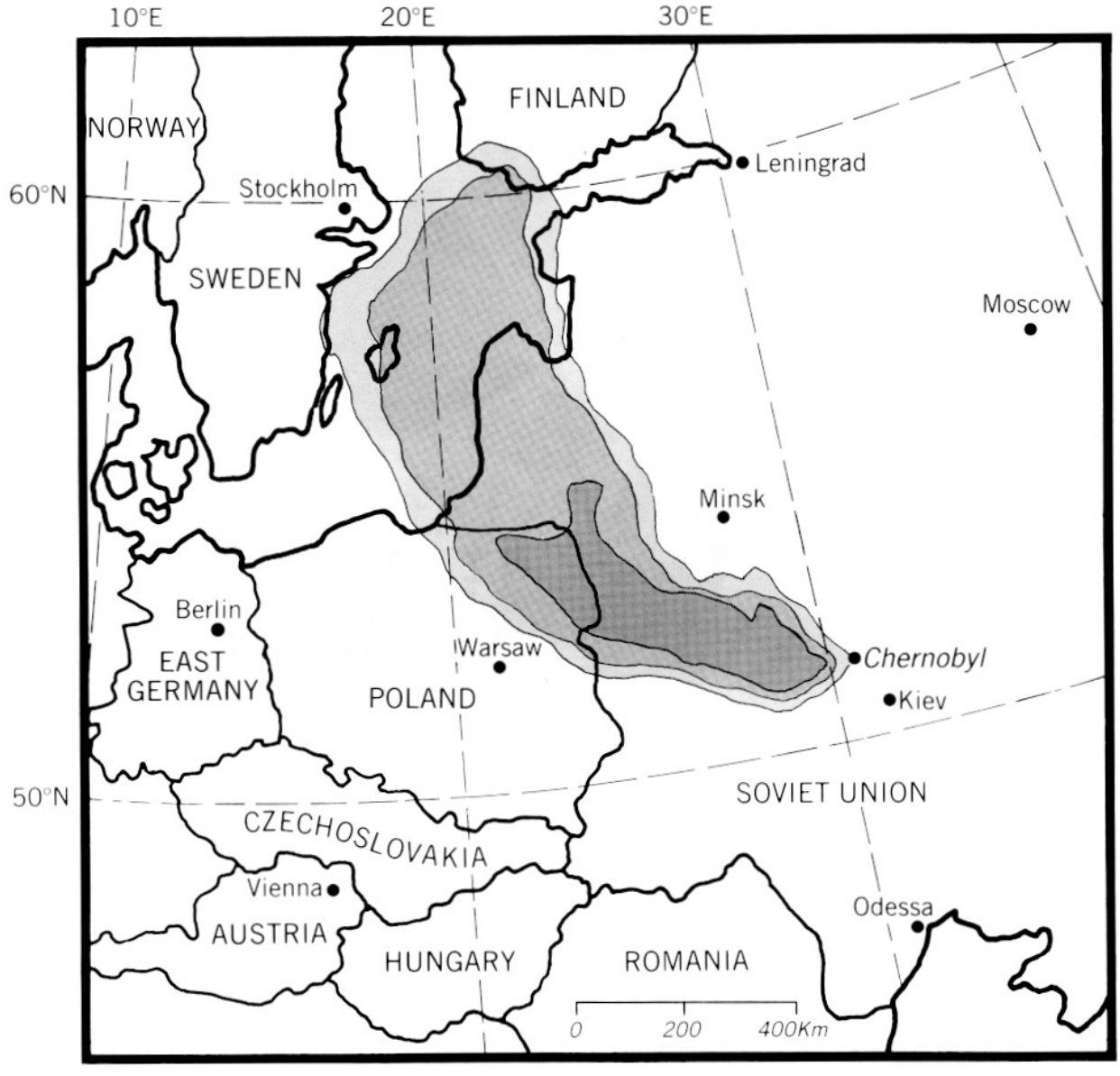
Many European governments acted to protect their populations from food contaminated by iodine 131 and other fission products from the Chernobyl accident by monitoring levels of contamination and by forbidding the distribution of foods contaminated above a certain level. Perhaps the greatest concern was milk contamination, because cows feeding on pasture would ingest relatively large amounts of iodine 131 and pass on much of it in their milk. Public health authorities therefore ordered that milk cows be confined to barns and fed relatively uncontaminated stored feed. Milk found to be contaminated above permissible levels was diverted to the making of cheese and other products that could be stored until the iodine 131 had decayed to safe levels.

Despite all the countermeasures, it is likely that there will be tens of thousands of cases of thyroid tumors as a result of the iodine 131 released from Chernobyl. Only about one quarter of these thyroid tumor cases will involve malignancies, and thyroid malignancies have a fatality rate of only about 10 percent—that is, only a few percent of the total number of tumor cases will be fatal.

ABOUT 5 PERCENT of all fissions in a nuclear reactor result in the production of a cesium 137 atom. Cesium 137, like iodine 131, would have been in relatively volatile chemical form and would therefore also have been released in large quantities by the explosion and fire. Cesium 137 atoms have a 30-year half-life, and they are therefore much less intensely radioactive than iodine 131, but they represent a much longer-lived hazard. The radiation level above land contaminated by it will remain elevated for decades.

Contamination by cesium 137 will therefore probably be the primary determinant of which areas around the Cher-

Figure 1. **The spread of radiation: April 27**

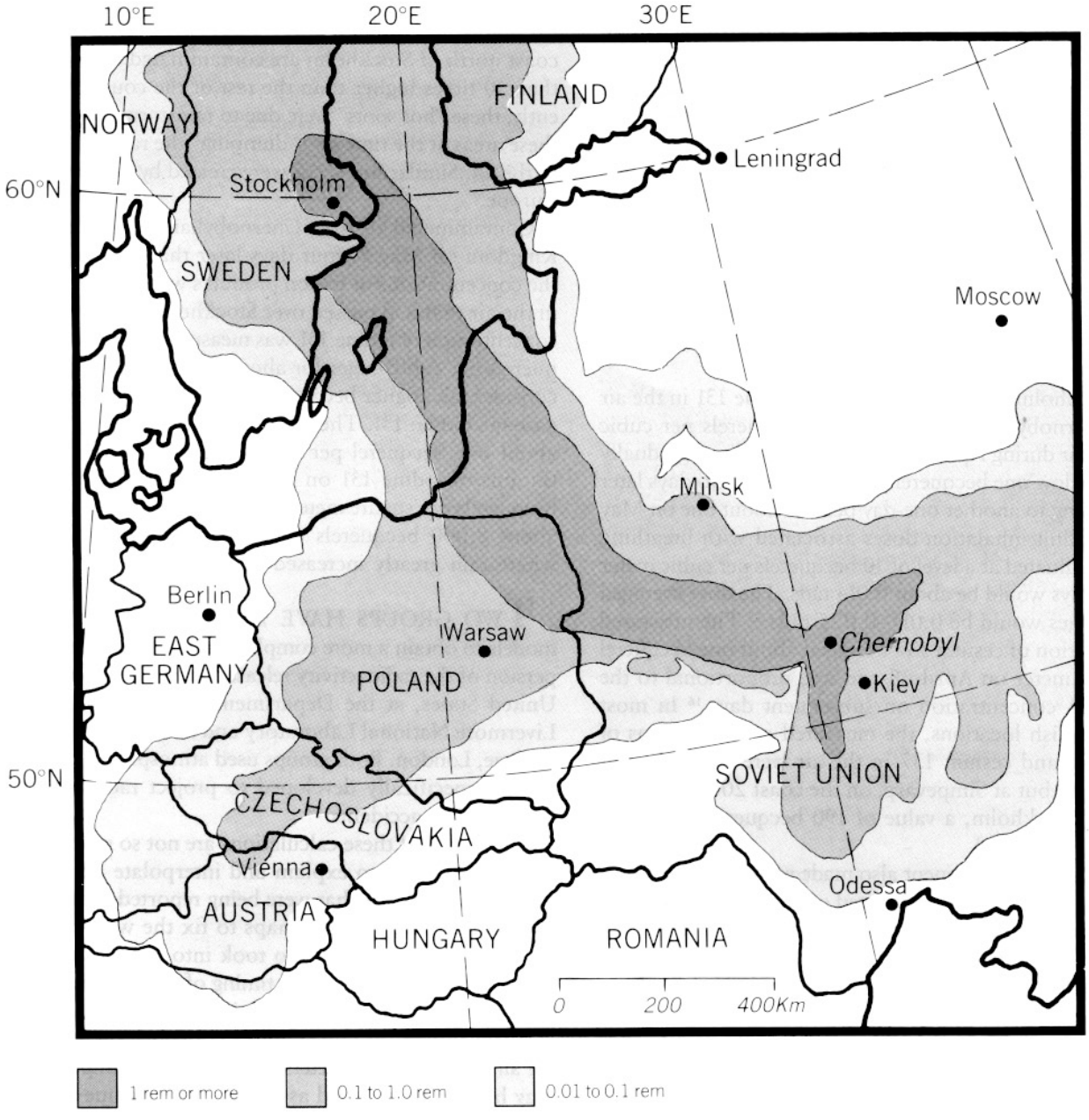


The maps, based on Lawrence Livermore National Laboratory data, show the spread of thyroid inhalation doses after the April 26 accident at the Chernobyl reactor.

nobyl reactor will have to remain evacuated for years or be decontaminated at great cost before they are suitable again for long-term human habitation. Cesium 137 contamination will also slightly increase the cancer rate in areas where the contamination level is deemed too low to warrant such drastic actions. The hazard will be both from external radiation and from food grown in contaminated areas.

The accumulation of cesium 137 in Unit 4 would have depended upon the length of time the average fuel bundle had been in the reactor before the accident. Because of its long lifetime, cesium 137 builds up steadily until the fuel is replaced. The mixture of isotopes released by the Chernobyl accident indicates that the average lifetime of the fuel in the reactor had been about the equivalent of 400 full-power days—or about two years.[9] This means that it is unlikely that the reactor might have been in use as a "dual-purpose" reactor, like the U.S. Department of Energy's very similar N-reactor at Hanford, Washington, which produces plutonium for nuclear weapons as well as electricity. Because it is easiest to make nuclear weapons using plutonium 239 with a low concentration of plutonium 240, which builds up as a result of neutron capture on plutonium 239, the production of weapon-grade uranium would involve fuel staying in the reactor about one-tenth as long as appears to

Figure 2. **The spread of radiation: April 29**



have been the case at Chernobyl Unit 4 before the accident.

After 400 days of full-power operation the Chernobyl reactor would contain about three million curies of cesium 137. If spread uniformly over an area of 30,000 square kilometers (12,000 square miles), one-tenth of this amount could contaminate the land to a level of 10 curies per square kilometer. This would increase the average indoor radiation level for decades by about 0.075 rads per year, approximately doubling the background radiation level from cosmic rays and naturally occurring radioactive isotopes.*[10] The contamination level was probably considerably higher in the 30-kilometer-radius zone around the Chernobyl reactor that was evacuated initially—an area of about 3,000 square kilometers (1,200 square miles). Children have apparently been evacuated from a still larger area.[11] The extra radiation dose over a lifetime in an area contaminated with 10 curies of cesium 137 per square kilometer—about 2.5 rads—would result in an extra lifetime cancer risk of 0.1–0.4 percent with the extra risk of death by cancer about half as large.[12] Risks further downwind would be much less. We assume that the

*This allows for a two-thirds reduction of the radiation level during the first few years due to leaching of the cesium 137 into the soil—as observed for the cesium 137 from atmospheric nuclear tests—and a further 70 percent reduction of the average dose (a combined reduction of 90 percent) due to the shielding provided by buildings.

doses will be increased by roughly 50 percent as a result of cesium 137 contamination of food.[13]

ALTHOUGH THE LEVEL of radioactive contamination downwind from Chernobyl inside the Soviet Union would be much greater than outside, at the time of this writing little information had been reported on radiation exposures to the Soviet population. Most of the direct evidence as to the scale of the release is based on radiation levels reported from other countries in Europe. Even there, however, there are great uncertainties. For example, one Swedish group found that the standard procedure of filtering air to measure its concentration of radioactivity was yielding values for iodine 131 concentrations that were only 20–25 percent of the actual values. Apparently, most of the iodine 131 was not being trapped on the filters because it was in vapor form.[14]

In Stockholm, the concentration of iodine 131 in the air from Chernobyl averaged about 10 becquerels per cubic meter of air during April 28 and 29, then declined gradually and fell below one becquerel per cubic meter two days later before rising to another one-day peak of about one on May 8.* The adult inhalation doses associated with breathing air contaminated at a level of 10 becquerels per cubic meter for two days would be about 0.014 rads. The dose averaged over all ages would be 0.015–0.025 rads.[15] The measured concentration of cesium 137 averaged about one becquerel per cubic meter on April 28 and was proportional to the iodine 131 concentration on subsequent days.[16] In most other Swedish locations, the measured concentrations of iodine 131 and cesium 137 in the air were lower than at Stockholm, but at Simpevarp, on the coast 200 kilometers south of Stockholm, a value of 190 becquerels per cubic meter was reported.

The Swedish government also made many measurements of the level of iodine 131 deposited on large grass fields and recommended that cows not be allowed into pastures contaminated to levels above about 10,000 becquerels per square meter. Near Stockholm, the contamination level was found to be slightly lower than this, but on Gotland, a large island in the Baltic halfway between Sweden and Latvia, levels of 40,000 becquerels per square meter were measured. Studies by a U.N. scientific committee and by the U.S. Food and Drug Administration have estimated respectively that cows pastured on land with a peak iodine 131 contamination of 10,000 becquerels per square meter would produce milk contaminated at peak levels of 200 and 1,100 becquerels per liter with resulting adult thyroid doses of 0.03 and 0.22 rads respectively. Taking into account the higher thyroid doses received by infants and children would raise the U.N. and Food and Drug Administration contamination-dose factors for iodine 131 contamination to 0.08 and 0.35 rads per 10,000 becquerels per square meter respectively (using in both cases the U.N. numbers for the milk consumption of children and their thyroid dose per unit of iodine 131 intake).[17]

The most detailed maps that we have seen of cesium 137 contamination come from Sweden and show a very large variability in contamination levels. Two areas along the coast north of Stockholm are contaminated to levels more than 10 times higher than the rest of the country. Apparently, these "hot spots" were due to rainstorms passing over these areas at the time and "dumping" the radioactivity out of the air. Similar hot spots were created by rainfall all over Europe.

Contaminated air from Chernobyl arrived in the United Kingdom on May 2, four days later than in Sweden, but the concentrations of fission products were similar to those in the air that had passed over Stockholm. The average air concentration of iodine 131 was measured at about two becquerels per cubic meter for about a day, but was probably considerably higher because of the presence of undetected gaseous iodine 131. The concentration of cesium 137 was about one becquerel per cubic meter. Measured concentrations of iodine 131 on grass were typically about 500 becquerels per square meter in the south of the country and about 8,000 becquerels per square meter in the north, where rain greatly increased deposition levels.[18]

TWO GROUPS HAVE attempted to use computer models to obtain a more complete understanding of the dispersion of the radioactivity released from Chernobyl: in the United States, at the Department of Energy's Lawrence Livermore National Laboratory and in Europe at Imperial College, London. Both groups used atmospheric dispersion models specifically developed to project radiation doses from reactor accidents.[19]

The results of these calculations are not so much predictions as attempts to explain and interpolate between the early measurements that were being reported. Both groups used barometric pressure maps to fix the winds, and the Imperial College group also took into account the effect of rainfall. The amounts and timing of the releases of radioactivity, its initial height distribution, and the rates at which airborne iodine 131 and cesium 137 deposit on the ground are all adjustable parameters. Some of the assumptions used may have to be changed as harder data become available, but the maps produced by the first round of calculations are illuminating.

Figure 1, for example, shows the Livermore map of thyroid inhalation doses due to exposures during the weekend of the accident, April 26 and 27. The contours shown are for doses of 0.01, 0.1 and 1.0 rads. The shape of the contours reflects the fact that the Livermore group assumed that most of the release occurred during Saturday, April 26, when the low-level air passing over Chernobyl was on a trajectory that carried it across Belorussia and the Soviet Baltic republics toward Sweden. Figure 2 shows the results of two more days of exposure (through April 29). Due to a shift of the low-altitude winds, a lobe of elevated iodine 131 levels had developed over Poland.

*Radioactivity is measured in terms of disintegrations per unit of time. One becquerel is one disintegration per second. One curie is the rate of disintegrations in one gram of radium: 37 billion per second.

The Imperial College projections are in qualitative agreement with the Livermore maps of Eastern Europe but extend over Western Europe as well and are reported by the lead author to be in "reasonable agreement with the measurements in Central Europe as far as we can tell with the large scatter in the data." Because of the greater coverage of the Imperial College maps and their inclusion of deposition by rain, we have used them for making our consequence estimates. The Imperial College group estimates a release of 10–15 million curies of iodine 131 and 1–2 million curies of cesium 137 to the atmosphere from the accident—mostly on the weekend of April 26 and 27 but tailing off through the following Monday and Tuesday. The deposition, which was calculated through 9:00 a.m. May 8, accounts for 70 percent of the releases. The remainder was presumably still airborne and much of it had by then probably drifted over the regions surrounding Europe. About one-third of the radioactivity was estimated to have been deposited in the Soviet Union—mostly in Belorussia.

IN CALCULATING the consequences of the radiation exposure to the population in Europe, we have made the usual assumption used in estimating numbers of cancer and thyroid tumor cases resulting from low-dose radiation exposures: that the probability of incurring the consequence is proportional to the radiation dose. This "linear hypothesis" is in rough accord with the available epidemiological data on most radiation-caused cancer and thyroid tumors in the dose range of tens and hundreds of rads. It has not been possible, however, to test it at the lower doses of tenths of rads to rads to which much of the population of Europe was exposed by the Chernobyl accident, because the predicted incidence of effects in this dose range is well below 1 percent and is therefore hard to detect statistically.

One important implication of the linear hypothesis is that the number of cancers and thyroid tumor cases resulting from Chernobyl can simply be calculated by summing the radiation doses of the entire exposed population. This greatly simplifies the task of calculating the long-term consequences of large releases of radioactivity, because the details of the distribution of doses will determine who was at greatest risk but will not effect the total estimated consequences.

For purposes of estimating the risks, we have assumed average population densities for the regions of the Soviet Union, Scandinavia, and the other countries involved. It would have been possible to calculate the overlaps of the computer-generated radiation exposure distributions with the real nonuniform population distribution, but because the computer maps do not accurately capture the great local variations in exposure, we have left this task to a time when the thousands of measurements of actual exposures may be collected in one place and analyzed.

We calculate the individual doses in a given area by the computer-estimated level of land contamination or the level and duration of air contamination in that area multiplied by the appropriate exposure-dose coefficient. The popula-

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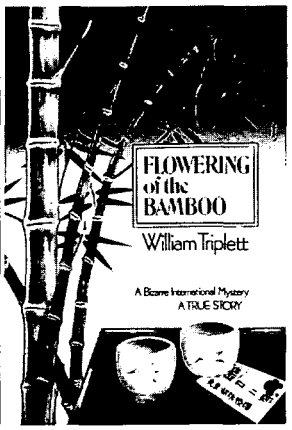

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FROM THE MARCH 1986 REVIEW OF *FLOWERING OF THE BAMBOO*. JOHN W. POWELL, AUTHOR, "A HIDDEN CHAPTER IN HISTORY" *THE BULLETIN OF THE ATOMIC SCIENTISTS*, VOL. 37, NO. 8, OCTOBER 1981

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tion dose is then estimated by using the assumed regional average population density and adding up the individual doses. Finally, the consequence numbers are calculated by multiplying the population doses by the appropriate dose-consequence coefficients. Ranges of values for all the exposure-dose and dose-consequence coefficients have already been quoted above. In estimating the uncertainties of the final estimates, we have assumed an uncertainty of a factor of four in the total population doses due to uncertainties in the Imperial College maps and the use of averaged population densities. The errors in local population doses will be much larger, but these errors will tend to average out.

We estimate:

- 2,000–40,000 thyroid tumor cases from iodine 131 inhalation, of which a few percent might be fatal. The average dose associated with these thyroid tumor cases is only about one rad, corresponding to an individual risk of less than one in one thousand.
- 10,000–250,000 potential thyroid tumor cases from iodine 131 absorbed via the grass-cow-milk route *in the absence of actions by the public health authorities to block this exposure route.* These actions would have greatly reduced the actual numbers of thyroid tumor cases, but our estimates explain their importance.
- 3,500–70,000 cancer cases from the whole-body doses of cesium 137 (external and internal), of which approximately half might be fatal. This number would be very little reduced by evacuation and decontamination efforts because most of the extra cancer deaths would be due to relatively low radiation doses hundreds of miles downwind from Chernobyl where costly mitigation measures will not be considered.* If, before the accident, the lifetime risk of cancer death in such an area were 20 percent, then after the accident, it might be increased by only 0.1 percent, that is, to 20.1 percent. Nevertheless, it is the addition of such small extra risks over many millions of individuals that results in our estimate of thousands to tens of thousands of extra cancer deaths.

As a result of all the compounding uncertainties in the factors involved, our estimates of the long-term health consequences of the Chernobyl accident are uncertain even as to order of magnitude. They serve to indicate, however, that the short-term health consequences may be only the visible tip of a very large iceberg. Because of the radioactive pollution of Europe by the Chernobyl accident, thousands to tens of thousands of people may develop thyroid tumors or cancer over the next few decades. □

1. *New York Times,* June 4, 1986, p. A12; according to Dr. Robert Gale, the U.S. marrow transplant expert, an additional 200 persons were hospitalized in Kiev: *New York Times,* July 3, 1986, p. A4.

2. Jan Beyea and Frank von Hippel, "Containment of a Reactor Meltdown," *Bulletin* (Aug./Sept. 1982), pp. 52–59.

*The average dose to the 200 million most exposed people would be the equivalent to that from about one year's extra background radiation or approximately the dose absorbed one generation earlier from the cesium 137 deposited by the global fallout from atmospheric nuclear tests (0.1 rad).

3. U.S. Nuclear Regulatory Commission, *Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants* (Springfield, Va.: National Technical Information Service, Report # WASH-1400 [NUREG-75/014], 1975); appendix 6, sec. 3. This same reference is the source of all the fission yields and reactor inventories quoted in this article.

4. D.C. Aldrich, P. McGrath, and N.C. Rasmussen, *Examination of Offsite Radiological Emergency Protective Measures for Nuclear Reactor Accidents Involving Core Melt* (Washington, D.C.: U.S. Nuclear Regulatory Commission Report # NUREG/CR-1131), fig. 5.14.

5. Committee on the Biological Effects of Ionizing Radiation, *The Effects on Populations of Exposure to Low Levels of Ionizing Radiation: 1980* (Washington, D.C.: National Academy Press, 1980), p. 304; *Induction of Thyroid Cancer by Ionizing Radiation* (Washington, D.C.: National Council on Radiation Protection and Measurement, 1985), table 11.3. We assume that three benign tumor cases will occur for each malignant one.

6. Robert A. Conard et al., *Review of Medical Findings in a Marshallese Population Twenty-Six Years after Accidental Exposure to Radioactive Fallout* (Upton, N.Y.: Brookhaven National Laboratory Report BNL-5161, 1980), appendix 4, table 1.

7. Food and Drug Administration, "Potassium Iodide as a Thyroid-Blocking Agent in a Radiation Emergency: Final Recommendations on Use" (Washington, D.C.: Food and Drug Administration, Bureau of Radiological Health and Bureau of Drugs, April 1982).

8. Frank von Hippel, "The NRC and Thyroid Protection—One Excuse after Another," *Bulletin* (Oct. 1980), pp. 44–45; House Subcommittee on Oversight and Investigations, *Emergency Preparations for Radiological Accidents: The Issue of Potassium Iodide,* 97th Cong., 2d sess., March 5, 1982.

9. L. Devell et al., "Initial Observations of Fallout from the Reactor Accident at Chernobyl," *Nature,* 321 (May 15, 1986), pp. 192–93; C. Hohenemser et al., "An Early Report on the Reactor Accident at Chernobyl," *Environment* (June 1986).

10. U.N. Scientific Committee on the Effects of Atomic Radiation, *Ionizing Radiation: Sources and Biological Effects* (New York: United Nations, 1982), p. 102, table 17.

11. Felicity Barringer, "From Children of Chernobyl, Stories of Flight and of Fears," *New York Times,* June 5, 1986, p. 1, quotes *Pravda* as saying that 60,000 children had been evacuated from contaminated areas of Belorussia—many from outside the 30-kilometer evacuation zone.

12. *The Effects on Populations,* pp. 147, 246; David A. Hoffman and Edward P. Radford, *A Review of the Carcinogenic Effects of Low-Dose Ionizing Radiation* (Philadelphia: Three Mile Island Public Health Fund, 1985), p. 124.

13. *Ionizing Radiation,* p. 241, table 30.

14. L. Devell et al., p. 193.

15. *Reactor Safety Study,* tables VI-D-2 and VI-D-5; "Report to the American Physical Society by the Study Group on Light-Water Reactor Safety," *Reviews of Modern Physics,* 47, p. S99, table 36.

16. *Activities of the Swedish Authorities Following the Fallout from the Soviet Chernobyl Reactor Accident* (Stockholm: Swedish Institute of Radiation Protection, May 12, 1986), fig. 2.

17. *Ionizing Radiation,* pp. 220, 234, table 13; U.S. Food and Drug Administration, "Accidental Radioactive Contamination of Human Food and Animal Feeds; Recommendations for State and Local Agencies," *Federal Register* (Oct. 22, 1982), pp. 47,073–47,084.

18. F.A. Fry, R.H. Clarke, and M.C. O'Riordan, "Early Estimates of UK Radiation Doses from the Chernobyl Reactor," *Nature,* 321 (May 15, 1986), pp. 193–95.

19. Joseph B. Knox and Marvin B. Dickerson ("technical contacts"), "ARAC [Atmospheric Release Advisory Capability] Preliminary Dose Estimates for Chernobyl Reactor Accident." The dispersion model is described in M.B. Dickerson et al., *ARAC Status Report, 1985* (Livermore, Calif.: Lawrence Livermore National Laboratory, UCRL-53641, May 1985). H.M. ApSimon and J.J.N. Wilson, "Preliminary Analysis of Dispersion of the Chernobyl Release, Paper Given at the [U.K.] Nuclear Inspectorate on 20th May 1986" and Helen ApSimon, personal communication to Frank von Hippel, June 19, 22, July 16, 1986. See also Helen ApSimon and Julian Wilson, "Tracking the Cloud from Chernobyl," *New Scientist* (July 17, 1986), pp 42–45. The atmospheric dispersion model is described in H.H. ApSimon, A.J.H. Goddard, and J. Wrigley, "Long-Range Atmospheric Dispersion of Radioisotopes," *Atmospheric Environment,* 19 (1985), pp. 99–125. A deposition velocity of 0.1 centimeter per second was assumed in calculating the inhalation thyroid doses from the iodine 131 dry deposition levels.