Articles

The Global Impact of the Chernobyl Reactor Accident

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Radioactive material was deposited throughout the Northern Hemisphere as a result of the accident at the Chernobyl Nuclear Power Station on 26 April 1986. On the basis of a large amount of environmental data and new integrated dose assessment and risk models, the collective dose commitment to the ~3 billion inhabitants is calculated to be 930,000 person-gray, with 97% in the western Soviet Union and Europe. The best estimates for the lifetime expectation of fatal radiogenic cancer would increase the risk from 0 to 0.02% in Europe and 0 to 0.003% in the Northern Hemisphere. By means of an integration of the environmental data, it is estimated that ~100 petabecquerels of cesium-137 (1 PBq = 10^{15} Bq) were released during and subsequent to the accident.

ON 26 APRIL 1986, A MAJOR ACCIDENT OCCURRED AT reactor 4 of the Chernobyl Nuclear Power Station in the Soviet Union. The resulting release of radioactive material was initially reported by the Soviets to be about 4 EBq (100 MCi) (1 exabecquerel = 10^{18} becquerels) of fission products, but (except for the noble gases) that estimate included only material deposited within the European part of the Soviet Union (*1*). This is the largest reported accidental release of radioactive material. As a result, radionuclides were deposited throughout the Northern Hemisphere.

The purpose of this article is to present a global perspective of the significance of the release (*2, 3*). Reported measurements of the external gamma-exposure rate or the deposition of specific radionuclides (or both) are combined with a general model of radiation-dose assessment to estimate collective dose commitment. From this base we estimate the expectation of radiogenic cancers and genetic disorders and present the uncertainties in our calculations.

The dominant concern for the world's citizenry after the Chernobyl accident has been future risks to health. This concern continued even after it was clear that the individual risks outside the Soviet Union would be quite small (*3*). Our goal is to calculate the expectation of possible latent health effects to people in the Northern Hemisphere.

Release and Dispersion of Radioactive Material

At the time of the accident, reactor 4 contained 1659 fuel assemblies, each with 114.7 kg of uranium, with an average burnup of 10.3 MW-day/kg (*1*). From these and other data (*1, 4*), we calculate that the reactor core contained the residue of 5.6×10^{27} fissions and that the average age of the fuel assemblies was 610 days. During the fissioning process, more than 200 different radionuclides are produced with half-lives varying from less than a second to more than a billion years. As the average age of the fuel was nearly 2 years, the majority of the short-lived radionuclides created in the core, including ^{131}I and ^{132}I, had already decayed. In contrast, essentially all of the long-lived fission products, such as ^{90}Sr and ^{137}Cs, remained in the core.

The immediate cause of the accident was an uncontrolled power excursion that overheated the reactor and expelled the upper shield, causing a complete loss of cooling. A large initial release of radioactive material, which included fragments of the fuel, resulted. After this large, explosive release, the emissions from the damaged reactor fell to a low level. After several days, however, heat from the decay of the residual fission products caused the temperature within the remaining core to rise to a level where fission products began to distill out of the reactor. Nine days after the initial accident, the daily release rate of radioactive material was nearly as high as it was at the time of the initial release (*1*). This secondary period of increased release rate was then terminated abruptly by successful remedial measures.

Because the emission of radioactive material from the reactor resulted from two important but different controlling processes, the release fraction of the core inventory of radionuclides varied substantially according to the volatility of each chemical element. Essentially all of the noble gases, roughly half of the volatile elements including ^{131}I and ^{134,137}Cs, and only a small percentage of the refractory materials including ^{89,90}Sr, ^{141,144}Ce, and ^{238,239,240}Pu were released (*3*).

After the accident, the initial plume dispersed to the northwest and reached Finland and Sweden. Early detection alerted the European nations to the occurrence of a major nuclear reactor accident, until then unannounced by the Soviets. Because the release occurred over many days under changing meteorological conditions, the overall trajectory of the plume was complex. Scandinavia, eastern Europe, and, at later times, southern Europe were more heavily impacted. Several different atmospheric transport models, for example, MESOS (*5*), GRID (*6*), and PATRIC (ARAC) (*7*), have been used to derive the evolution and characteristics of the plumes.

Once the accident became known, the International Atomic Energy Agency (IAEA) and the World Health Organization (WHO) organized the collection and collation of radiological

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Table 1. Radiogenic risk factors (*25*).

Cancer site or effect	Risk coefficient*
Leukemia	$2.24/10^4$ PY-Gy × F
Bone	$0.1/10^4$ PY-Gy × F
Breast (female)	45%/Gy
Lung	18%/Gy × F
Gastrointestinal tract	39%/Gy × F
Thyroid (external)	$0.25/10^4$ PY-Gy (age < 20 years)
	$0.125/10^4$ PY-Gy (age ≥ 20 years)
Thyroid (^{131}I)	(One-third of external values)
Other cancers	20%/Gy × F
In utero cancer	$21/10^4$ PY-Gy (to fetus)
Severe mental retardation	40%/Gy (incidence) (8- to 15-week-old fetus)
Genetic ill health	$30/10^4$ Gy (effects per generation)

*Best or central estimate, where PY is person-years and F is reduction factor (Table 2).

measurement results from member countries. Seven summary reports were issued by WHO, with the final report (*8*) issued on 12 June 1986. We used these reports plus additional data sources (*3*) to estimate radiation doses and commitments to people in the Northern Hemisphere. For the Soviet Union, estimates are taken directly from the recent reports by Ilyin and Pavlovski (*9*) and by Ilyin (*10*), which update estimates reported earlier by the Soviets (*1, 11*).

Methods of Calculating Dose, Dose Commitment, and Collective Dose Commitment

Radiation dose to humans can occur through four primary mechanisms or pathways: (i) external exposure from the passing cloud; (ii) inhalation of radionuclides in the passing cloud; (iii) continuing external exposure from radionuclides deposited on surfaces (mainly soil) during the cloud passage; and (iv) ingestion of radionuclides, either through direct contamination of foodstuffs or from transfer through more complex food chains. For the Chernobyl accident, only the latter two pathways are significant in delivering radiation dose to the total body (*3*). The inhalation pathway can convey significant dose to the human thyroid, but in this case its relative global significance as a source of potential cancer mortality is negligible.

To calculate the dose commitment from external exposure caused by surface deposition of radionuclides on soil, a presently measured or inferred external gamma-exposure rate must be projected into the future. A reasonable way of calculating this projection is with a model based on both empirical and theoretical parameters. The empirical information needed is the relative mixture of radionuclides deposited and the average depth of penetration within the soil. The theoretical information needed is the calculated external gamma-exposure rate per unit deposition for each radionuclide. This is a function of the energy and intensity of gamma emissions and the depth of penetration into soil. Beck (*12*) has published the needed calculations for many different radionuclides and for several different relaxation depths (*13*).

For the relative mixture of radionuclides from Chernobyl, we have used as reference the concentrations in air in Nurmijarvi, Finland, measured on 28 April 1986 between 1500 and 2100 (*14*). The mean time of this sample collection period was 66 hours following the accident. Values for 23 different radionuclides were reported, from which ten additional daughter radionuclides can be inferred. Values for the mixture at other time periods were calculated on the basis of radioactive decay.

We assumed the following relaxation coefficients as a function of half-life of the radionuclides: for half-lives <14 days, 0.16 g/cm^2; for half-lives >14 days but <200 days, 1.6 g/cm^2; and for half-lives >200 days, 4.8 g/cm^2. For a nominal soil density of 1.6 g/cm^3, these values correspond to relaxation depths of 1 mm, 1 cm, and 3 cm, respectively. This is consistent with observation (*15*), and matches the 3-cm depth historically used by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) (*16*) for long-lived radionuclides.

Results of the calculated external gamma-exposure rate from all radionuclides as a function of time are shown in Fig. 1, starting with an external gamma-exposure rate of 1 mR/hour at 66 hours after the accident. The contributions from ^{134}Cs and ^{137}Cs are also shown. From Fig. 1 it is apparent that, owing to the mixture of radionuclides, the curves are not well approximated by single power functions (such as $Ct^{-1.2}$); exposures will continue long into the future; and exposures will be dominated by contributions from the two cesium radionuclides at times beyond a few weeks.

The calculations for Fig. 1 were based on the assumption that deposited radionuclides do not migrate laterally. This assumption is reasonable for rural areas and for grassy lawns in urban areas. However, several investigators noted a rapid loss from urban surfaces of radionuclides deposited from the plume (*17*), as well as the rapid appearance of fresh Chernobyl debris in sewage sludge. These observations are consistent with the assumption that half of the radionuclides deposited in an urban environment are removed with a half-time of 7 days. We also assumed that 30% of each country's population lives in an urban environment. This estimate was derived by averaging for several countries the fraction of populations living in cities with populations larger than 100,000.

The upper curve in Fig. 1 represents the combined decay of individual radionuclides, from which the exposure rates to calculate exposure over any given time period may be integrated. We used a time period of 50 years, a standard interval over which to calculate the doses for lifetime cancer risks. Exposures over the first-year period and over infinite time were also derived. As an approximation, the first-year exposure is 10% of the 50-year exposure, and the 50-year exposure is more than 75% of the exposure over infinite time.

Absorbed dose, not exposure, is needed to estimate risks. For this conversion, we used a factor of 0.0087 Gy per R to convert from exposure to absorbed dose in air. For a rural environment, another factor of 0.3 was used to convert from absorbed dose in air to organ dose, including the effects of building shielding and occupancy. These factors are from UNSCEAR (*16*); the 0.3 factor was stated to be an average value for the Northern Hemisphere. For an urban environment, we reduced the shielding and occupancy factor to 0.15, as it is probable that shielding is more substantial and people spend more time indoors.

For the calculation of dose from ingested radionuclides, we have used the PATHWAY model of Whicker and Kirchner (*18*) as an estimator of the total intake of a radionuclide per unit deposition. This model includes seasonal dependence, and it has been validated thoroughly by comparison of predicted results with measurements. The final factor in the calculation is the dose per unit intake of ingested radionuclides; we have used values determined by Ng (*19*) for the thyroid and the total body. For Ng's calculations, ICRP-30 methodology (*20*) was used, modified as needed to calculate absorbed dose (rather than dose equivalent or effective dose equivalent) to the total body.

We used the output from Whicker and Kirchner's example (*18*) in which exposure begins on 25 April 19XX (any year in the century) in the western United States. The assumption is that cows are not on pasture but subsequently move onto pasture or derive about 20% of their dry matter intake from pasture or green chop beginning on 1

Table 2. Reduction factor (F) (best or central estimate) for radiogenic risk models (*25*). At a dose rate of <0.05 Gy/day, F is 0.3; at a rate of ≥0.05 Gy/day, F is 0.30 + 0.47 D(Gy).

Total dose D(Gy)	F
0.01	0.30
0.10	0.35
0.25	0.42
0.50	0.54
0.75	0.65
1.00	0.77
1.25	0.89
≥1.50	1.00

May 19XX. This closely mimics the actual situation in much of northern Europe at the time of the accident, although more substantial use of pasture was being made in parts of southern Europe. Also, because this is a model simulating agriculture in the western United States, it does not include all pathways, such as that of lichen-reindeer-meat.

From sensitivity studies with the PATHWAY model (*21*), it is known that p, the fractional retention of fallout deposition in vegetation, is a critical parameter. This is frequently estimated from the following equation derived by Chamberlain (*22*)

$$1 - p = e^{-\mu w}$$

where μ is a constant and w is the plant biomass (*23*). For these calculations, we have used a value for μ of 0.39 m^2/kg, which is used in the PATHWAY computer program in Utah and Nevada for the reconstruction of doses from fallout from weapons tests. Chamberlain calculated values of μ about ten times higher for the dry deposition of vapors and very small aerosols. However, most of the heavy deposition from the Chernobyl plume was caused by rain, and under these circumstances the value of μ (and p) is known to decrease with rainfall rate. Limited data available are consistent with the chosen value for μ of 0.39 m^2/kg (*3*). After the external 50-year dose commitment and the ingested radionuclide dose commitment were calculated for the "average" individual in a country, the results were summed and then multiplied by that country's population in order to calculate the collective dose commitment.

Methods of Calculating the Expectation of Biological Effects

Although the exact radiation dose received by each person in the Northern Hemisphere will never be known, the models and measurements used provide a reasonably accurate estimate of collective doses and consequences. For latent health effects such as fatal cancers and genetic disorders, the scientific community has reached general consensus on a model derived from a linear-quadratic dose-risk relation for low dose, low–linear energy transfer exposures (*24, 25*). It is assumed that no threshold dose exists below which there is no risk, although the data do not eliminate the possibility of zero risk at low doses. There has been a move toward a relative risk model for most primary cancer sites and away from the more prevalent, older absolute risk model. For a given dose, the projected relative risk for a given cancer is considered to be proportional to the age-adjusted cancer risk of the unexposed population, rather than added to the natural risk. The significance of this change has been to increase the risk from a small dose generally by about a factor of 2 to 3.

To calculate the expectation of cancers, we have considered three recent reports: the U.S. Congress–mandated National Institutes of Health (NIH) report on the development of radioepidemiological tables (*24*); the Nuclear Regulatory Commission NUREG report on the "summed site" health effects model for nuclear power plant accident-consequence analysis (*25*), which was prepared by the Harvard School of Public Health, Sandia National Laboratories, and others; and the recent UNSCEAR report on the genetic and somatic effects of ionizing radiation (*26*). Our judgment is that these three studies are basically consistent and provide similar results. The NUREG approach is to derive three estimates of the top of the risk range: an upper estimate, a best (central) estimate that is considered to be the most realistic, and a lower estimate. For the best estimate, an absolute risk–projection model is used for leukemia, bone, and thyroid cancers; a relative risk–projection model is used for breast, lung, gastrointestinal tract, and "other" cancers. We have taken the bottom of the range to be zero, which is consistent with the NUREG report. A summary of the radiogenic risk parameters used for the preferred or best estimate derivations is given in Tables 1 and 2.

We used the latest assessments of doses, risks, and consequences in our analysis. The collective dose commitments for subgroups of the Soviet population were obtained according to average individual dose commitments (*10*). For each primary cancer site, a dose-dependent risk coefficient was applied to the subgroup's collective dose commitment to obtain an estimate of lifetime incremental cancer mortality. The increments were summed across the population to obtain an overall increment for each primary cancer site. These overall increments were then summed to get an expectation of additional lifetime cancer mortality for the entire population of the

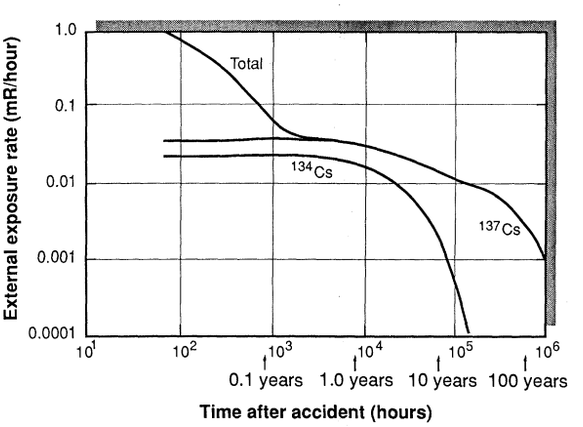

Fig. 1. Calculated external gamma-exposure rate from all radionuclides as a function of time, as indicated by "total" curve. Individual rates of ^{134}Cs and ^{137} Cs are also shown.

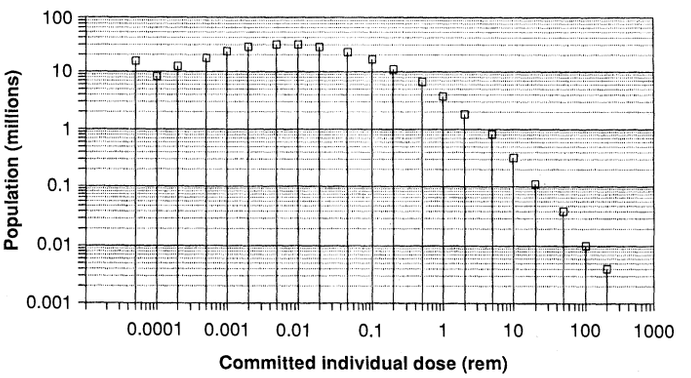

Fig. 2. Individual dose commitment distribution from Chernobyl over the U.S.S.R. population (*10*).

Soviet Union in terms of an upper, a best, and a lower estimate of the top of the range, and with zero effects as an estimate of the bottom of the range. Our estimates are based on four factors: the estimated specific distributions of collective dose commitments in exposed populations, the assumption of a general distribution of age and sex, the assumption that the risk models used apply equally to all populations, and the use of a 50-year risk projection.

Results

Our calculations of the 50-year radiation-dose commitments are listed in Table 3 by country. Populations and areas were taken from a standard source (*27*). Exposure rate and ^{137}Cs deposition data were taken from national and WHO reports (*3, 8*). In many cases only the exposure rates were reported. From these data and the reference radionuclide mix, we inferred the arrival time of the main plume and the ^{137}Cs deposition. Where only the deposition of ^{137}Cs, ^{134}Cs plus ^{137}Cs, or perhaps ^{131}I was reported, the peak exposure rate was inferred from the deposition and the time of arrival on the basis of data from neighboring countries.

Our calculated results include the estimated individual 50-year radiation dose commitment to the total body from the external pathway and the individual infinite dose commitments from the ingestion pathway for the thyroid and the total body. The individual external and internal dose commitments were summed and multiplied by the country's population to obtain national collective 50-year dose commitments. The fractional contribution from the external exposure pathway is also shown in Table 3.

The data for the Soviet Union in Table 3 are from the papers by

Table 3. Distribution of Chernobyl fallout and doses.

Region or country	Population	Area (km^2)	Peak exposure rate (μR/hour)	Time of plume arrival (hour)*	^{137}Cs deposition (Bq)	Individ. 50-year external dose (Gy)	Individ. thyroid ingestion dose (Gy)	Individ. total-body ingestion dose (Gy)	Collective 50-year total-body dose (person-Gy)	Fraction due to external dose (%)
Europe										
Albania	2.9×10^6	2.9×10^4	5.0×10^1	204	3.9×10^{14}	9.8×10^{-4}	3.1×10^{-3}	9.3×10^{-4}	5.5×10^3	52
Austria	7.5×10^6	8.4×10^4	7.6×10^1	114	1.1×10^{15}	9.5×10^{-4}	3.7×10^{-3}	8.8×10^{-4}	1.4×10^4	52
Belgium	9.9×10^6	3.0×10^4	2.1	228	1.9×10^{13}	4.6×10^{-5}	1.3×10^{-4}	4.3×10^{-5}	8.8×10^2	51
Bulgaria	9.0×10^6	1.1×10^5	1.3×10^2	132	2.7×10^{15}	1.8×10^{-3}	6.7×10^{-3}	1.7×10^{-3}	3.1×10^4	52
Czechoslovakia	1.5×10^7	1.3×10^5	2.5×10^1	132	5.9×10^{14}	3.5×10^{-4}	1.3×10^{-3}	3.2×10^{-4}	1.0×10^4	52
Denmark	5.2×10^6	4.3×10^4	4.6	180	4.7×10^{13}	8.1×10^{-5}	2.7×10^{-4}	7.6×10^{-5}	8.2×10^2	52
Finland	4.8×10^6	3.4×10^5	5.0×10^1	66	1.9×10^{15}	4.3×10^{-4}	1.9×10^{-3}	4.0×10^{-4}	4.0×10^3	52
France	5.4×10^7	5.5×10^5	8.2	132	8.3×10^{14}	1.1×10^{-4}	4.2×10^{-4}	1.1×10^{-4}	1.2×10^4	52
East Germany	1.7×10^7	1.1×10^5	3.5×10^1	102	5.8×10^{14}	4.0×10^{-4}	1.6×10^{-3}	3.7×10^{-4}	1.3×10^4	52
West Germany	6.2×10^7	2.5×10^5	3.1×10^1	156	1.6×10^{15}	4.9×10^{-4}	1.7×10^{-3}	4.6×10^{-4}	5.8×10^4	52
Greece	9.9×10^6	1.3×10^5	1.4×10^1	180	4.4×10^{14}	2.5×10^{-4}	8.2×10^{-4}	2.3×10^{-4}	4.7×10^3	52
Hungary	1.1×10^7	9.3×10^4	4.0×10^1	156	7.9×10^{14}	6.3×10^{-4}	2.2×10^{-3}	5.9×10^{-4}	1.3×10^4	52
Iceland	2.4×10^5	1.0×10^5	Very low		Very low	Very low	Very low	Very low	Very low	
Ireland	3.5×10^6	7.0×10^4	1.5×10^1	180	2.5×10^{14}	2.6×10^{-4}	8.7×10^{-4}	2.5×10^{-4}	1.8×10^3	52
Italy	5.7×10^7	3.0×10^5	3.0×10^1	156	1.9×10^{15}	4.7×10^{-4}	1.7×10^{-3}	4.4×10^{-4}	5.2×10^4	52
Luxembourg	3.6×10^5	2.6×10^3	8.0	132	3.8×10^{12}	1.1×10^{-4}	4.1×10^{-4}	1.0×10^{-4}	7.6×10^1	52
Malta	3.6×10^5	3.2×10^2	3.0×10^1	156	2.0×10^{12}	4.7×10^{-4}	1.7×10^{-3}	4.4×10^{-4}	3.3×10^2	52
Monaco	2.7×10^4	1.5	8.2	132	2.3×10^9	1.1×10^{-4}	4.2×10^{-4}	1.1×10^{-4}	5.9	52
Netherlands	1.4×10^7	4.1×10^4	6.2	204	6.8×10^{13}	1.2×10^{-4}	3.8×10^{-4}	1.1×10^{-4}	3.4×10^3	52
Norway	4.1×10^6	3.9×10^5	2.2×10^1	78	1.1×10^{15}	2.1×10^{-4}	9.0×10^{-4}	1.9×10^{-4}	1.7×10^3	52
Poland	3.6×10^7	3.1×10^5	2.3×10^2	78	9.2×10^{15}	2.2×10^{-3}	9.5×10^{-3}	2.0×10^{-3}	1.5×10^5	52
Portugal	1.0×10^7	8.9×10^4	Very low		Very low	Very low	Very low	Very low	Very low	
Romania	2.3×10^7	2.4×10^5	2.0×10^2	90	6.7×10^{15}	2.1×10^{-3}	8.8×10^{-3}	2.0×10^{-3}	9.2×10^4	52
San Marino	2.4×10^4	6.1×10^1	3.0×10^1	156	3.9×10^{11}	4.7×10^{-4}	1.7×10^{-3}	4.4×10^{-4}	2.2×10^1	52
Spain	3.8×10^7	5.1×10^5	Very low		Very low	Very low	Very low	Very low	Very low	
Sweden	8.3×10^6	4.5×10^5	6.0×10^1	78	3.4×10^{15}	5.8×10^{-4}	2.5×10^{-3}	5.3×10^{-4}	9.2×10^3	52
Switzerland	6.3×10^6	4.1×10^4	3.0×10^1	114	2.0×10^{14}	3.7×10^{-4}	1.5×10^{-3}	3.5×10^{-4}	4.5×10^3	52
United Kingdom	5.6×10^7	2.4×10^5	7.6	180	4.4×10^{14}	1.3×10^{-4}	4.4×10^{-4}	1.3×10^{-4}	1.5×10^4	52
Yugoslavia	2.3×10^7	2.6×10^5	1.0×10^2	180	6.1×10^{15}	1.8×10^{-3}	5.8×10^{-3}	1.7×10^{-3}	7.9×10^4	52
U.S.S.R. (Europe)†	2.0×10^8	5.3×10^6			3.7×10^{16}	9.1×10^{-4}		6.8×10^{-4}	3.2×10^5	57
(Subtotal)	6.9×10^8	1.0×10^7			7.7×10^{16}				9.0×10^5	
Asia										
China	1.0×10^9	9.6×10^6	1.2×10^{-1}	372	5.4×10^{14}	4.4×10^{-6}	9.5×10^{-6}	4.2×10^{-6}	8.9×10^3	51
India	7.0×10^8	3.2×10^6	Very low		Very low	Very low	Very low	Very low	Very low	
Israel	4.0×10^6	2.0×10^4	1.0	204	5.3×10^{12}	2.0×10^{-5}	6.1×10^{-5}	1.9×10^{-5}	1.5×10^2	52
Japan	1.2×10^8	3.7×10^5	2.9×10^{-1}	180	2.6×10^{13}	5.1×10^{-6}	1.7×10^{-5}	4.8×10^{-6}	1.2×10^3	52
Kuwait	1.5×10^6	1.8×10^4	1.6×10^{-1}	276	1.0×10^{12}	4.2×10^{-6}	1.1×10^{-5}	4.0×10^{-6}	1.2×10^1	51
Mongolia‡	1.9×10^6	1.5×10^6			3.8×10^{14}	1.9×10^{-5}		6.3×10^{-6}	4.9×10^1	75
Turkey	4.9×10^7	7.7×10^5	1.0×10^1	180	1.8×10^{15}	1.8×10^{-4}	5.8×10^{-4}	1.7×10^{-4}	1.7×10^4	52
U.S.S.R. (Asia)†	7.9×10^7	1.7×10^7			1.8×10^{16}	8.0×10^{-5}		9.4×10^{-6}	6.9×10^3	89
(Subtotal)	2.0×10^9	3.2×10^7			2.0×10^{16}				3.4×10^4	
Other										
Canada	2.4×10^7	9.9×10^6	5.4×10^{-2}	372	2.5×10^{14}	2.0×10^{-6}	4.3×10^{-6}	1.9×10^{-6}	9.4×10^1	51
United States	2.3×10^8	9.5×10^6	6.4×10^{-2}	372	2.8×10^{14}	2.4×10^{-6}	5.1×10^{-6}	2.2×10^{-6}	1.1×10^3	51
(Subtotal)	2.6×10^8	1.9×10^7			5.3×10^{14}				1.2×10^3	
Total	2.9×10^9	6.2×10^7			9.8×10^{16}				9.3×10^5	

*Hours after the accident. †Dosimetric values taken directly from Ilyin and Pavlovski (*9*). ‡Interpolated from data for China and the Asian portion of the Soviet Union.

Ilyin and Pavlovski (*9, 10*). We divided the Soviet Union into the European and Asian portions. As direct measurements were not available for Mongolia, individual dose commitments were linearly interpolated from the logarithms of the values for the Asian portion of the Soviet Union and for China. Similar interpolations were used to derive values for Albania and Romania.

Our calculations indicate that about 52% of the dose commitment is attributable to the external pathway (*28*). The value of 57% for the European part of the Soviet Union is similar and indicates that the methods used by us and by Ilyin and Pavlovski (*9*) are reasonably consistent. Their value of 89% for the Asian portion of the Soviet Union reflects a more detailed analysis of this region, which at the time of the accident had very few food crops that had grown to the point where they could be contaminated directly.

The most significant result for the Northern Hemisphere is the total collective 50-year dose commitment of 930,000 person-Gy. Of this, about 900,000 person-Gy is calculated to occur in Europe, about 30,000 in Asia, and only about 1,000 in North America.

The total deposition of ^{137}Cs was also determined. Each country's area was multiplied by its ^{137}Cs deposition to obtain the values in Table 3. The summation of national values is 98 PBq, of which 77 PBq is in Europe, 20 PBq in Asia, and 0.5 PBq in North America. Our calculated value is compared with other derived values in Table 4.

A set of best estimates of cancer risk increment have been derived by using the committed dose distribution within the Soviet Union (*10*) plus calculated values for other regions from Table 3 and the risk coefficients from Tables 1 and 2. As shown in Table 5, of the almost 3 billion people in the Northern Hemisphere receiving Chernobyl radiation, 26%, or about 800 million people, account for 97% of the total risk increment. The remaining 3% of the dose commitment in Asia and North America represents a miniscule risk increment. Outside of the 30-km zone surrounding Chernobyl, the incremental increase in fatal cancer risk is a fraction of a percent and is not likely to ever be detected epidemiologically (*3, 29*).

Those workers and populace in the 30-km zone represent a special cohort, which may present some detectable increase in health effects in the years to come. Of the 115,000 persons evacuated, some 24,000 were estimated to have received an average of 0.43 Sv (43 rem) (*1, 9*). Over the next 50 years about 122 spontaneous leukemias would be expected in this group, that is, about 2 per year or 25 to 30 over the next 12 years. On the basis of current epidemiological data, acute myeloid leukemia appears to have a 2-year latency and a 10-year "plateau of risk" during which the fatal radiogenic cases will be expressed (*25*). The irradiated group would be expected to show up to 26 additional fatal leukemias or roughly a doubling of the risk during the decade starting in 1988. The absence of such a doubling would indicate that either our risk estimates overstate the case for low dose rate exposures or the basic model may be too conservative, or both, a point that can be clarified over the next few years.

Table 4. Estimates of total ^{137}Cs deposition.

Source	Activity (PBq)
This article	98
U.S.S.R. early estimate (*1*)	37
PATRIC (ARAC) (*7*)	89
MESOS (*5*)	26
GRID (*6*)	50
Cambray *et al.* (*36*)	70
Sorensen (*37*)	100
Aarkrog (*38*)	100

At a recent conference in Kiev, Ilyin presented updated dose estimates for the Soviet "accident" population (*10*), as shown in Fig. 2, which is derived from Ilyin's data. Of the ~50,000 people who received 0.5 Gy (50 rads) or more, some 4,000 persons apparently received an average of 2 Gy (200 rads). Over the next decade, the fatal leukemia risk of this latter group is projected to increase by ~150%. For the entire group of ~50,000 persons, the corresponding increase would be ~40%.

The irradiated populations are also at risk for genetic disorders in future generations. For all of Europe including the Soviet Union, we estimate that up to 1,500 additional cases might be added to the 35 to 40 million normally expected in the population (that is, about 0.005% risk increment). It would not be possible to determine such small increases by epidemiological study.

On the basis of a follow-up study of children irradiated in Hiroshima and Nagasaki during their 8th to 15th week of gestation, Otake and Schull have produced a risk model for radiation-induced severe mental retardation (*30*). Using their risk factors (Table 1) and our estimates of collective dose commitment, we project up to a doubling of cases in the evacuated population near Chernobyl (15 radiogenic plus 15 spontaneous), and up to 500 additional cases in Europe added to a spontaneous expectation of more than 65,000. As the doses and rates were relatively small and a more recent analysis suggests a threshold for the response at 0.20 to 0.40 Gy (*31*), our estimate probably seriously overstates the risk.

Our best current estimate of the global impact of the accident is additional to the 237 confirmed cases of acute radiation sickness, including the 31 acute fatalities, in the Soviet Union. Most of the radiological impact is in Europe (including the European portion of the Soviet Union), which is projected to receive 97% of the collective dose commitment. Outside of the Chernobyl region, the magnitude of individual doses is relatively small, and in terms of increased lifetime fatal cancer risk represents an increment of about 0.01 to 0.02%. Alternatively, one might project up to about 17,000 additional fatal radiogenic cancers in Europe where some 123

Table 5. Projected health effects from Chernobyl. Estimates of spontaneous and radiation-induced cancer mortality.

Region	Population (millions)	Collective lifetime dose (thousands of person-Gy)	Fatal cancers (lifetime)		Excess over natural or spontaneous (%)
			Natural or spontaneous (thousands)	Radiation induced* (thousands)	
U.S.S.R.	279	326	35,000	6.5†	0.02†
Europe (non-U.S.S.R.)	490	580	88,000	10.4	0.01
Asia (non-U.S.S.R.)	1,900	27	342,000	0.5	0.0001
United States and Canada	250	1.2	48,000	0.02	0.00004
Northern Hemisphere‡	2,900	930	513,000	17.4	0.003

*Best or central estimate values. The possibility of zero health effects at very low doses and dose rates cannot be excluded. †The upper and lower mortality estimates are 17,000 and 2,000 fatal cancer cases, respectively, giving corresponding ratios of excess over natural or spontaneous cancers of 0.05 and 0.006%. ‡Some columns do not match total because of rounding of numbers.

million are normally expected, an increment of about 0.01%.

Numbers of this magnitude cannot be determined by direct epidemiological study of the populations. Thus, as one cannot prove the risk, does it really exist? This dilemma has led some to translate the above statement to mean literally that there is no risk, akin to a threshold. One of the most misunderstood concepts encountered in the analysis is the way in which probabilistic or stochastic risks are perceived and presented. The numbers we derive are increments in a probability distribution, and not the certainty frequently reported in the media. Thus we reiterate that these risk estimates do not rule out zero as a possibility.

The estimates of global deposition of fission products from Chernobyl used in these analyses have a probable error well within a factor of 2, as do the projections of external and ingestion doses to individuals. Calculations of collective whole-body doses reflect these uncertainties. Use of these collective doses to calculate possible mortality on the basis of primary cancer sites may overestimate fatal cancers by as much as 50% because whole-body dose was equated to organ dose. In respect to the risk conversion factors, two types of uncertainty arise: (i) those associated with the use of three levels for the upper bound of risk (that is, lower, best or central, and upper values), all of which range down to zero; and (ii) those associated with each of the upper bound levels (that is, lower, best, and upper levels). In the first case, lower and upper levels bound the central estimate by a factor of about 3. However, the probability distribution between zero and any one of the levels is not known. In the second case, each of the upper bound levels has an uncertainty of about ±50%. Overall, it is unlikely that we have underestimated the risk; our best value may overestimate the risk by a factor of 2 or more.

The economic cost of the accident is still not fully calculated. It was recently stated (*32*) that there was a direct cost of 4 billion rubles (about $6.8 billion) (for example, loss of the reactor, relocations, medical care, and decontamination) plus an equal amount for indirect costs (for example, replacement of lost power, new construction, and food surveillance). With additional costs within other countries, the total may be about $15 billion.

Less quantifiable are the psychological stresses of the accident engendered in world populations as a result of various causes, such as fear, anxiety, ignorance, misinformation, or lack of information. Such stresses are being addressed by physicians and public health and radiological protection authorities. In the Soviet Union, public concerns and phobias about radiation have led to public information activities by nuclear plant management, public officials, and scientific bodies to inform and educate the workers and the general populace on Chernobyl risks and the actions taken to control them (*10, 33, 34*). Perhaps the greatest concern illustrated by the Soviet experience was the lack of an understanding of radiological risks by the general population and of sufficient medical personnel knowledgeable about such risks to act as advisers to the general public.

Summary

Global impacts to health from the Chernobyl accident may be characterized as acute (nonstochastic) effects or as delayed, stochastic effects predicted on a probabilistic basis. No acute effects have occurred outside of the Soviet Union where 237 cases of acute radiation sickness, including 31 deaths, were reported.

Outside of the immediate Chernobyl region, the magnitude of radiation doses to individuals is quite small, leading to extremely low incremental probabilities of any person developing a fatal radiogenic cancer over a lifetime. Given present dose data, a doubling of leukemia risk might be expected for the period 1988 to 1998 in the highly exposed Soviet populace in the 30-km zone around the reactor site. Some possibility also exists of a few added cases of severe mental retardation in recent progeny of this exposed group. No adverse genetic effects are expected to be observed in the entire group.

Probably no adverse health effects will be manifest by epidemiological analysis in the remainder of the Soviet population or the rest of the world. Projections of excess cancer risk for the Northern Hemisphere range from an incremental increase of 0% to 0.003%. An upper bound estimate would range from 0% to about 0.01%, still undetectable. Projections of other adverse health effects such as severe mental retardation or genetic disorders are so low as to be unobservable, compared to natural or spontaneous incidence.

The major global impacts from Chernobyl appear to be economic and social. On the basis of extrapolations from initial Soviet estimates, direct and indirect monetary costs may reach $15 billion, 90% of which would be in the Soviet Union. The social consequences are more difficult to quantify, but public concerns, whether justified or not, have increased, necessitating attention by medical, public health, and other authorities. Estimates of health and environmental effects, as well as economic and social impacts predicted in this article, are reasonable but early projections. Their evaluation and, where possible, validation in highly exposed populations and the environment will require study for some period of years (*35*).

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Chemistry of High-Temperature Superconductors

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Spectacular advances in superconductors have taken place in the past two years. The upper temperature for superconductivity has risen from 23 K to 122 K, and there is reason to believe that the ascent is still ongoing. The materials causing this excitement are oxides. Those oxides that superconduct at the highest temperatures contain copper-oxygen sheets; however, other elements such as bismuth and thallium play a key role in this new class of superconductors. These superconductors are attracting attention because of the possibility of a wide range of applications and because the science is fascinating. A material that passes an electrical current with virtually no loss is more remarkable when this occurs at 120 K instead of 20 K.

SUPERCONDUCTIVITY WAS FIRST DISCOVERED IN MERCURY metal in 1911. The temperature at which mercury becomes superconducting (T_c) is 4.1 K, very close to the boiling point of liquid helium. Subsequently, other materials were discovered to be superconducting, with the highest T_c's generally in the intermetallic compounds of niobium (*1*). A slow but steady rise of highest T_c took place resulting in a T_c of 23 K for Nb_3Ge in 1975 (Fig. 1). Subsequently, a period of some disenchantment set in, reinforced by theoretical predictions that T_c would never rise above 30 K.

The field of oxide superconductors starts in the early 1960s (Fig. 1 and Table 1) (*2–14*). Oxides are not generally viewed as having good metallic properties although some such as ReO_3 and RuO_2 are excellent metals. On the other hand, we know that superconductors when above T_c generally do not possess the properties of good metals. The first oxides found to be superconducting were NbO and TiO (*2*). These oxides however may be viewed merely as metals which have dissolved some oxygen. They have NaCl-related struc-

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Table 1. History of oxide superconductors.

Compound	T_c	Date discovered	Reference
TiO,NbO	1 K	1964	(*2*)
$SrTiO_{3-x}$	0.7 K	1964	(*3*)
Bronzes			
A_xWO_3	6 K	1965	(*4*)
A_xMoO_3	4 K	1969	(*5*)
A_xReO_3	4 K	1969	(*5*)
Ag_7O_8X	1 K	1966	(*6*)
$LiTi_2O_4$	13 K	1974	(*7*)
$Ba(Pb,Bi)O_3$	13 K	1975	(*8*)
$(La,Ba)_2CuO_4$	35 K	1986	(*9*)
$YBa_2Cu_3O_7$	95 K	1987	(*10*)
Bi/Sr/Cu/O	22 K	1987	(*11*)
Bi/Sr/Ca/Cu/O	90 K	1987	(*12*)
Tl/Ba/Ca/Cu/O	122 K	1988	(*13*)
K/Ba/Bi/O	30	1988	(*14*)