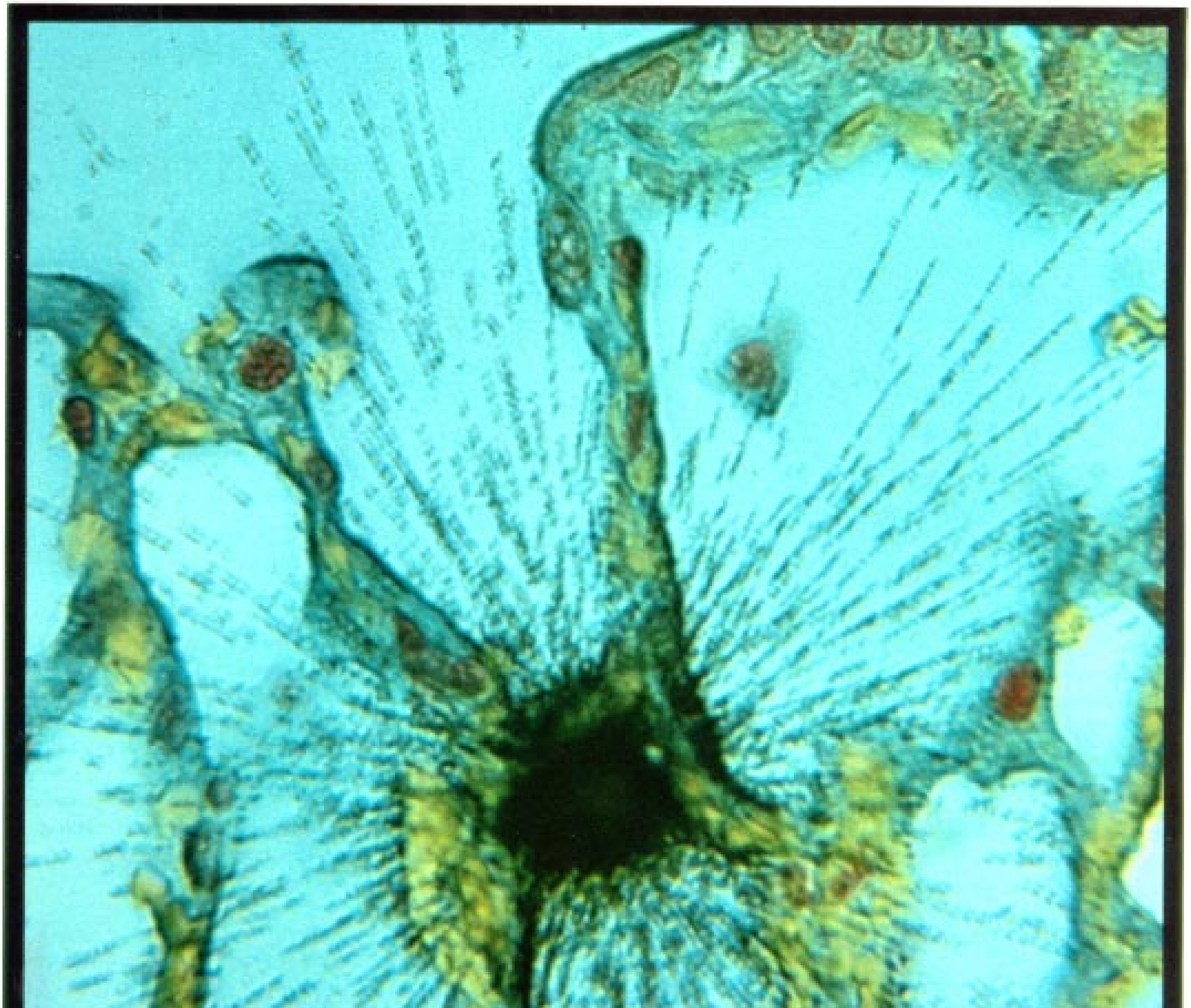


Autoradiograph of radioactive microsphere embedded in hamster lung tissue. Ceramic microspheres slightly larger than red blood cells and containing less than 1% plutonium-239 by weight lodge in pulmonary capillaries when injected into the jugular vein. The streaks emanating from the microsphere, forming an "alpha star," are alpha-particle ionization tracks in the film emulsion. Cell nuclei, here stained red-brown, contain DNA and are potential sites for initiation of radiation-induced cancer tumors, but there is no evidence of abnormalities in this tissue section despite an 18-month exposure to radiation from the microsphere. This example is from research by the Laboratory's Life Sciences Division on the role of internally deposited radionuclides in pulmonary diseases, including cancer.[1] (Photo by David M. Smith and James R. Prine)

LOW-LEVEL *How harmful is it?*

by Roger C. Eckhardt

RADIATION

"Last Friday, the Holsteins on the Lytle Farm started acting kind of touchy, lining up side by side at the fence and staring south. That was two days after the Three Mile Island nuclear power plant, five miles due south as the cow stares, started generating fear instead of electricity." —A journalist for *The New York Times.*

"If these cows start leaving town on their own, I'm getting out of here too."-Clarence Lytle 2nd, partner on the Lytle Farm.

"I've been working with this for ten years, and I have a pretty thorough familiarization. I'm not saying I'm brave. If you understand, your mind is at ease." —Edward Houser, Three Mile Island chemistry foreman and the worker who received the highest dose on the day of the accident.

"I don't know about that stuff that nuclear. Sounds to me so powerful man can't tame it right." -72-year-old resident of Yocumtown, Pennsylvania.

"The amount of radiation that escaped was no threat to the people in the area. . the radiation outside the plant was far less than that produced by diagnostic x rays."-Officials of the Nuclear Regulatory Commission.

"I don't think they're telling us the whole truth. They won't come out and say, 'Yes, everything is all right.'"-Resident of Highspire, Pennsylvania.

"Any dose is unsafe because there is no lower threshold for radiation." —George Wald, Nobel laureate and Emeritus Professor of Biology at Harvard University.

These reactions* to the accident at Three Mile Island make clear the fear and confusion regarding the potential radiation hazard from nuclear power plants. There are those who fear mutant babies and glowing cows and who oppose nuclear energy and its invisible radiation dangers no matter what safeguards are instituted. Others argue that nuclear energy can be rendered free of radiation hazards, but only at the expense of a nuclear police state. Still others feel that nuclear power is a pollution-free, benign source of energy, and the only viable solution to our nation's energy crisis.

Contributing to the fear and confusion is a range of scientific opinion about the long-term effects of low doses of ionizing radiation. There is no doubt that high doses have deadly results for man: a single dose of 600 reins of gamma radiation would likely result in death within a month to a majority of the exposed population.[2] For doses 100 or 1000 times less, which are relevant to radiation workers and the general public, respectively, the effect believed to be most important is an increased risk of cancer. But the extent of the risk is a subject of controversy, and estimates differ by as much as a factor of 100. For example, included in the most recent and most respected report on this subject,[3] familiarly known as BEIR III, are dissenting statements by two members of the preparing Committee. One member characterizes the published risk estimates as too low, and the other as too high.

The controversy has its basis in one simple fact. There are no unambiguous data on the incidence of effects at the low doses received by workers in the nuclear or medical industries, and the lack of data at doses characteristic of the general public is even more complete. To develop a reasonable model or make accurate predictions, scientists need data bearing directly on the phenomenon being considered; otherwise, the models are only educated guesses subject to further modification and the predictions are only extrapolations. This is the situation with the biological effects of low-level ionizing radiation.

The most widely accepted estimates for the effects of low-level radiation are based on extrapolation of data on survivors of the Nagasaki and Hiroshima bombings. These survivors experienced a single, moderate to high exposure (10 to 400 rads mean dose to the tissue). In the absence of a real theory, the correct technique for extrapolation to lower doses is unknown, and many factors, such as dose rate, are not considered in the data analysis. The data base itself is now being questioned because the relative amounts of gamma rays and neutrons released in the explosions may have been different than assumed.[4-6]

Many animal data are being gathered, but their relevance is

All quotations are from issues of* The New York Times *during the week following the Three Mile Island accident.

unknown. A dose accumulated over 30 years in humans cannot be duplicated in animals that live only several years. Also, how valid are extrapolations from animal to man when significant differences between radiation-induced effects in laboratory animals of different species are frequently observed?

Ideally, epidemiological studies of humans exposed to the doses, dose rates, and types of radiation of most concern should be the basis for risk estimates. Such data are not only difficult to acquire, but also include the effects of other causative agents, such as chemical carcinogens, natural background radiation, other manmade radiation sources, and even particular social and psychological habits.

Can a quantitative range be placed on the scientific uncertainty that results from these problems? Figure 1 depicts the currently expected number of deaths due to cancer among a million people in the United States and, also, two different estimates of excess cancer deaths resulting from an additional exposure to the population of one rad of x or gamma rays per person. One estimate represents those published in BEIR III and the other, greater by an order of magnitude, represents the typical range of scientific uncertainty. The fact that the estimated excess cancers from a l-rad dose cannot be shown on the same scale as the expected deaths illustrates the difficulty in detecting the effects of such exposures, much less of doses down to millirads. The figure also illustrates that the range of scientific uncertainty is much more circumscribed than the range of opinion among the general public,

Uncertainty about the hazards of low-level radiation is well--grounded and will persist, possibly indefinitely. Here we will attempt to answer some of the questions about ionizing radiation and discuss the rationale behind radiation protection standards. Perhaps the perspective we present will allay exaggerated fears. Although it may be true that no radiation dose is absolutely safe, in fact, the risk from doses comparable to those received by the public in the vicinity of the Three Mile Island accident is so low as to be undetectable.

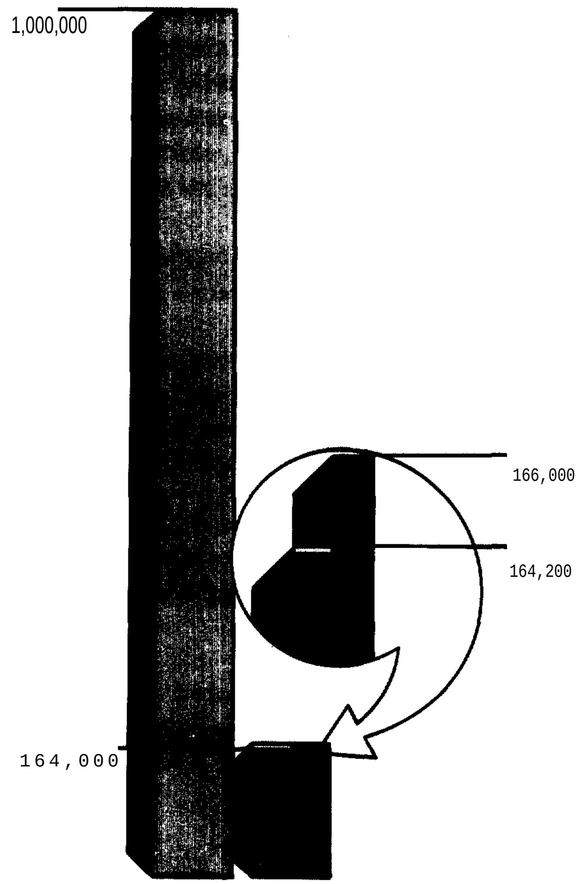


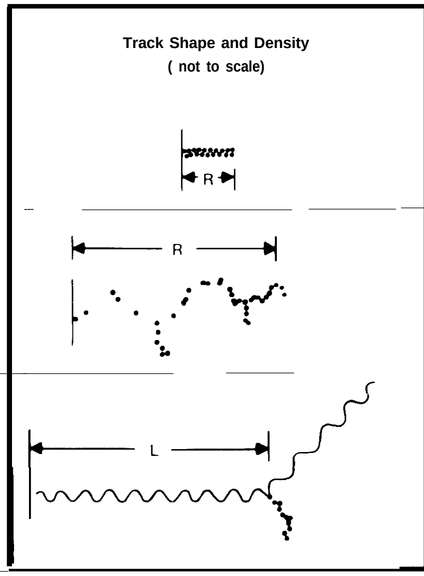
Fig. 1. Among a representative population in the United States of 1,000,000 (blue), the currently expected number of deaths due to all forms of cancer (green) is 164,000. The number of excess cancer deaths resulting from an additional 1-rad exposure of the population to x or gamma radiation (yellow) is, according to BEIR III, approximately 200. Also shown (red) is the number of deaths if the risk estimates are greater than those of BEIR III by an order of magnitude, a variation typical of current scientific uncertainty.

What are the Natural and Manmade Sources of Ionizing Radiation?

Natural background radiation has always been and still remains the greatest contributor of ionizing radiation to mankind. There are two main sources of this radiation. One is

Sidebar 1:

IONIZING RADIATION



Radiation	Radionuclide	Energy (MeV)	R or L (mm)
Alpha Particle	^{239}Pu	5.2	0.046 (average)
Beta Parttcle	^{14}C	0.15	0.3 mm
	^{90}Sr	2.2	11.0 mm
Gamma Ray	^{125}I	0.035	33 (average)
	^{60}Co	1.3	160 (average)

Characteristics of ionizing radiation from typical radionuclides. The dots in each track represent ionizations. For alpha and beta particles, R is the range in water; for gamna rays, L is the distance in water to the initial ionizing interaction.

The term ionizing radiation refers to electromagnetic radiation and particles with enough energy to cause ionization of the atoms or molecules of the irradiated material. Alpha particles, beta particles, and x rays are forms of ionizing radiation, but the ultraviolet light reaching the surface of the earth and microwave radiation are not. Of most concern is ionizing radiation with energies of millions of electron volts, including gamma rays and the particles ejected during the decay of such radionuclides as uranium-238 and strontium-90.

Charged particles, such as alpha and beta particles, cause ionization by direct Coulomb interaction with the irradiated material. Electromagnetic radiation, such as x and gamma rays, or uncharged particles, such as neutrons, generate secondary charged particles through absorption of electromagnetic energy or direct collisions. The secondary particles then ionize the irradiated material.

In a living cell, the sudden passage of the intense electric field of these particles disrupts the delicate orientation of water and protein molecules and generates organic free radicals, which react with enzymes, chromosomes, and other molecules necessary to the cell's life processes.

The critical element for understanding the interaction of ionizing radiation and matter is energy deposition. The amount of energy deposited, or the "absorbed dose," is measured in rads. In biological matter, however, different types of radiation can deposit the same total energy but produce different amounts of damage. For example, alpha particles, which produce high ionization densities along their paths, cause more cancer than do x or gamma rays. The unit used to quantify the degree of damage is the rem. The rem is the dose in rads times a quality factor appropriate to the type of radiation. ●

COMMON RADIATION UNITS

Unit	Measured Quantity	Definition
Curie	Radioactivity of source	1 curie = 3.7×10^{10} decays per second
Roentgen	Ionization produced by radiation (defined for x and gamma rays only)	1 roentgen produces 1 electrostatic unit of charge in 1 cubic centimeter of air at standard temperature and pressure
Rad	Energy deposited in matter by ionizing radiation	1 rad = 0.01 joules per kilogram of irradiated material
Rem	Energy deposited times a quality factor representing biological damage	reins = Q x rads Q = 1 for x and gamma rays Q = 10 for alpha rays

cosmic radiation produced by collisions of high-energy particles impinging continuously on the earth's atmosphere. The atmosphere serves as a shield, but a fraction of the radiation reaches the earth's surface and results in whole-body irradiation of the population. The thinner atmospheric shield present at higher altitudes and during airplane flights results in doses larger than those at sea level. Table I lists dose estimates for this and other radiation sources and notes the body portion exposed.

The other source of background radiation is naturally occurring radionuclides. These radionuclides surround us in the environment, particularly in the soil, and reside in our body after being ingested in air, food, and water. An individual's annual dose from terrestrial sources outside the body depends on the amounts of elements such as uranium, thorium, or potassium in the soil and can vary by an order of magnitude. The main contributor of internal beta and gamma radiation from ingested radionuclides is potassium-40, a radioactive isotope of an element vital to life. Another radionuclide currently of concern is radon. This element can diffuse out of brick, concrete, stone, soil, and water and build up in tightly sealed, energy-efficient homes.

To this pervasive background radiation must be added the manmade sources of ionizing radiation. One of the most significant of these is the medical use of x rays. Of comparable significance in 1963 was the radioactive fallout from atmospheric weapons testing. This source, however, has since declined markedly. Other sources include research activities

TABLE I

SOURCES OF IONIZING RADIATION[a]

Source	Body Portion Exposed	Average Annual Exposure (mrem/yr)
NATURAL		
Cosmic radiation		
Sea level	whole body	26
1.8 km (6000 ft)	whole body	52
External radionuclides		
Atlantic and Gulf coasts	whole body	15-35
Colorado Plateau	whole body	75-140
Internal radionuclides		
Potassium-40	gonads	19
Potassium-40	bone marrow	15
Uranium isotopes	gonads	12
Total Natural Radiation	whole body	100
	gonads	80
	bone marrow	80
	lungs	180-530
MANMADE		
Medical use of x rays	gonads	20
Atmospheric weapons testing		
1963	whole body	13
1980	whole body	4.4
Nuclear operations	whole body	<1
Cigarette smoking	localized points in lungs	≤8000

[a]All dose estimates are from Ref. 3, pp. 37-69.

and a wide range of consumer and industrial products, such as television, luminous watch and clock dials, airport x-ray devices, smoke detectors, static eliminators, tobacco products, fossil fuels, and building materials. These last collectively add only slightly to the average dose.

In light of public response to ionizing radiation, the last two sources listed in Table I are of particular interest. The average annual dose of an individual in the United States resulting from nuclear operations is estimated to be less than 1 millirem per year. In contrast, a cigarette smoker may be burdening the surface of his bronchial tract at highly localized points with up to 8000 millirems per year.

By keeping these doses due to natural and manmade sources in mind, the doses resulting from the Three Mile Island accident' can be put in reasonable perspective. The radionuclides released during the accident resulted in an average estimated dose of 1.4 millirems to the approximately 2,000,000 people living in the vicinity of the plant. This whole-body dose is lower than the typical bone-marrow dose of 10 millirems per chest X ray and is more than an order of magnitude lower than the average annual whole-body dose of 26 millirems from cosmic radiation at sea level. In the extreme case of an unclothed individual standing outdoors, 24 hours a day for 6 days, across the river from the plant in the path of the prevailing winds, the total dose received has been calculated to be below 100 millirems, that is, below the total whole-body dose due to natural background radiation. The highest exposures resulting from the accident were to several of the plant personnel who received doses of approximately 4 reins. These doses are the only potentially significant ones, being in excess of the quarterly limit of 3 reins allowed for radiation workers by the Nuclear Regulatory Commission.

What Biological Effects of Low-Level Ionizing Radiation Are of Most Concern?

The biological effects of primary concern are not the drastic and immediate effects of high doses but the more subtle late effects, such as cancer and gene mutation, that may result from prolonged or sporadic exposure at low levels. These effects are classified as genetic or somatic. Somatic effects, of which cancer is the most important, are experienced directly by those exposed, whereas genetic effects are experienced by their descendants. Genetic effects involve damage specifically to the germ cells in the gonads, whereas somatic effects involve a wide range of body cells.

Only the radiation dose received by the gonads of future parents during their reproductive span is of genetic significance. The average gonadal dose of manmade radiation to an individual in the United States is approximately 30 to 40 millirems per year. During a 30-year human reproductive span, this dose rate produces an additional genetically significant dose of roughly 1 rem. BEIR III estimates the increase in genetic disorders due to continued exposure of many generations at this level to range from 60 to 1100 disorders per million liveborn.[8] This estimate should be compared to the current incidence of 107,000 genetically related disorders per million liveborn.

Twenty years ago, genetic effects were believed to be far more important than somatic effects. However, this conclusion was drawn from animal experiments in which the dose was delivered at high rates. Further studies have shown that lower dose rates, such as those characteristic of occupational exposure, are less effective at inducing genetic effects. Also, estimates of the cancer induction rate have increased as the study populations age and more slowly developing cancers appear. The net result is that cancer is now considered to be the most important late effect of exposure to radiation.

Although members of the BEIR Committee disagreed about the risk of radiation-induced cancer, there were many points concerning this effect on which the Committee members were in complete accord. Some of the more important of these accepted points are listed below.

- The latent period of cancer (the time between exposure and the appearance of cancer) may be long—years or even decades.
- Nearly all tissues and organs of the human body are susceptible to radiation-induced cancer, but sensitivity to the induction of cancer varies considerably from site to site.
- Leukemia was at one time thought to be the principal type of radiation-induced cancer; however, solid cancers, such as lung, breast, and thyroid cancers, are the more numerous result.
- Age, both at irradiation and diagnosis, is a major factor in cancer risk; for example, a very high risk of leukemia was found in atomic-bomb survivors irradiated in the first years of life, and the highest risk of radiation-

induced breast cancer in women occurs for exposures in their second decade of life.

- Because of the greater incidence of breast and thyroid cancer in women, the total radiation-induced cancer risk for women is greater than for men.
- There is an increasing recognition that certain human genotypes are more susceptible than others to cancer after exposure to radiation (and other carcinogens), but the role of susceptibility in cancer induction is not yet well understood.
- There is evidence that the dose rate may change the radiation effect per unit dose, but the information currently available is insufficient to be used meaningfully when estimating the risk of cancer induction in man,

Although controversy surrounds the BEIR III risk estimates for radiation-induced cancer, we quote two of the estimates eventually published in that report.[9] A single whole-body dose of 10 rads of x or gamma radiation to a million persons is estimated to result in about 800 to 2200 deaths in excess of the normally expected 164,000 cancer deaths. A continuous lifetime exposure of 1 rad per year of this same type of radiation would result in 4800 to 12,000 excess deaths. It is not yet clear how the new information about the type of radiation released at Hiroshima and Nagasaki will affect these estimates.

How Are the Effects at Low Doses Estimated From the Known Effects at High Doses?

The problems inherent in quantifying the relationship between cancer incidence and ionizing radiation are numerous. To begin with, cancer is actually a group of diseases, and a particular site-specific cancer usually affects less than one person in a thousand each year. In addition, all available data indicate that the increase in incidence caused by radiation is small. We are therefore faced with the problem of detecting a small increase in an already low incidence.

Further, because radiation-induced cancers are indistinguishable from those due to other mechanisms, it is not possible to determine whether a given cancer was caused by radiation or would have occurred even in the absence of exposure. Therefore, evidence for cancer induction by radiation rests on a comparison of site-specific cancer incidence in an exposed group with the incidence in a similar unexposed, or control, group. Unfortunately, the sizes of the groups needed to detect a small absolute cancer excess become extremely large at low doses.

For example, let us assume that an excess cancer incidence is detectable with a particular statistical certainty in an exposed group of 1000 at a dose of 100 rads. Further assume that the excess incidence per rad is the same at all doses. Then, to obtain the same statistical certainty requires an exposed group of 100,000 at a dose of 10 rads and an exposed group of 10,000,000 at a dose of 1 rad. And, of course, similar numbers of people are required for the unexposed groups. Continuation of this reasoning should make it readily apparent why one cannot detect effects of doses in the range of millirads.

As mentioned above, studies of the Hiroshima and Nagasaki survivors have provided the largest data set pertaining to radiation exposure and cancer. Nearly 24,000 persons received doses estimated to be 10 rads or more.[10] To date, statistically significant excesses of various types of cancer have been established for such doses: first leukemia,[11-14] then thyroid cancer,[15] and now lung and breast tumors.[16] For other types of cancer, these studies may provide statistically significant correlations between excess cancer incidence and dose down to about 10 rads.

Other groups examined for radiation-induced cancer include medical patients given x-ray treatments, uranium miners, radium dial painters, radiologists, and nuclear workers. These groups are small and, in addition, have posed difficulties in obtaining correct dose estimates and matched control groups.

As a result, cancer incidence at low doses can generally only be estimated by extrapolating data at higher doses (Fig. 2). The linear, no-threshold hypothesis is the simplest approach to extrapolation. Here it is assumed that there is no threshold dose below which the effect does not occur and that the incidence is directly proportional to the dose. This method of extrapolation has been adopted by Government agencies until conclusive evidence for use of a more appropriate technique is presented.

Another method of extrapolation is to assume a "linear-quadratic" relationship between incidence and dose. Here the incidence is very nearly proportional to dose at low doses, but at high doses the incidence increases more rapidly, namely as the square of the dose. Applied to the same data in the high-dose region, a linear-quadratic extrapolation necessarily prediets lower risks at low doses than does a linear extrapolation. Likewise, a quadratic relationship with no linear term would predict even lower risks.

The BEIR Committee attempted to decide among the linear, linear-quadratic, and quadratic extrapolation techniques for the atomic-bomb data by applying statistical goodness-of-fit tests. They concluded that, in this respect, no one extrapolation technique was more satisfactory. Ultimately they chose to base their risk estimates for cancer on linear-quadratic extrapolation. A possible model for such a relationship attributes the linear term to cancer-inducing lesions, say in the form of broken DNA molecules, generated within a single ionizing track and therefore linearly dependent on dose. The quadratic term accounts for lesions formed through interactions between ionizing tracks, which are thus quadratically dependent on dose.

Another extrapolation method produces higher risk estimates at low doses than does linear extrapolation. Such a relationship may result from the existence of susceptible groups in the population who are harmed at much lower doses

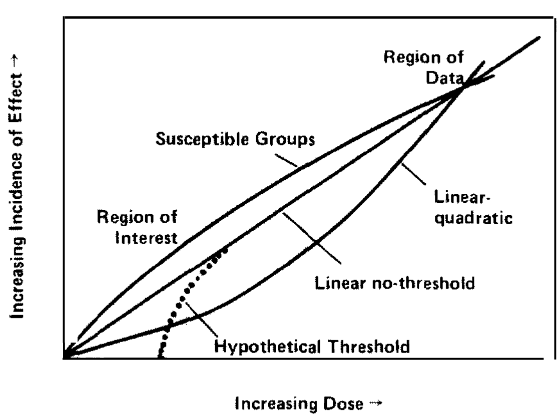


Fig. 2. Experimental data on the incidence of radiation-induced effects are available only at doses higher than those of primary concern. These data are extrapolated to low doses by various techniques. Scientific opinion currently favors linear, no-threshold or linear-quadratic extrapolation for radiation-induced cancer. The susceptible-groups curve illustrates the principle of representing a susceptible population with a higher extrapolation curve.

than are the majority. For instance, there is evidence of greater risk of radiation-induced thyroid cancer in Jewish children than in other ethnic groups." Because the size of these groups is currently believed to be small, this extrapolation technique is not widely used.

How is Low-Level Radiation Separated From Other Factors as the Determining Cause of an Effect?

Regardless of the extrapolation technique chosen, the epidemiologist must carefully assess the influence on the data themselves of many confounding and interactive factors. An especially important factor is the nature of the radiation exposure. Type of radiation, dose rate, dose, exposed organs, available shielding, and specific radionuclides involved-all influence the conclusions and should be accurately determined. For example, studies of the effects due to early medical x-ray treatments may require the rejuvenation and operation of old x-ray equipment to estimate the doses received by the patients.

Personal factors include the subject's size, race, genetic makeup, education, and smoking habits; there is evidence that stress can increase susceptibility to disease, including cancer. Age at time of exposure has already been mentioned as a well-established determinant for cancer risk. Similarly, the altitude and soil composition of the subject's habitat and the subject's occupational experience and exposure to carcinogenic chemicals play important roles.

The long latent period of cancer makes identification of cases and accurate quantification of their radiation exposures extremely difficult. The exposed population must be followed essentially through complete lifetimes, or the risks of late-developing cancers will be seriously underestimated. In fact, one of the first forms of cancer to be associated with radiation, leukemia, was identified primarily because it has a relatively short latent period, occurring as soon as 2 to 5 years after intense radiation exposure.[11]

An epidemiological study[18] of workers at the Hanford Works in Richland, Washington, well illustrates the problems that these factors may cause. (Valid risk estimates derived from studies of workers such as these are extremely important because the exposed group is subject to the highly fractionated, low-dose exposures of most relevance for establishing occupational radiation protection standards.) The investigators reported statistically significant associations between cumulative radiation-badge dose and excess mortality from cancers of many types, but particularly cancers of lung, pancreas, and bone marrow, Their estimates were markedly higher than those obtained from studies of acute, high-dose exposures.

Subsequent studies of the data revealed that the original analysis had not dealt adequately with certain of the confounding and interactive factors, such as age at dose and the demographic difference between exposed and nonexposed workers. After accounting for the neglected factors as best as possible, investigators found significant associations between dose and only two types of cancer, namely, multiple myeloma (a cancer of the bone marrow) and pancreatic cancer.[19]

The risk estimates for these two cancers were still high and implied an improbably large role for background radiation as the cause of the diseases among the general population. On the other hand, if the number of excess cancers of these two types had been low enough to yield reasonable risk estimates, the conventional requirements for statistical significance would not have been satisfied. This quandary is attributed to the limited sample size and low individual radiation doses of the Hanford workers.

To establish valid relationships between dose and effect, more extensive studies are obviously necessary. Since 1976, the Epidemiology Group of Los Alamos National Laboratory has been investigating the effects of plutonium on human health. This study began as a long-term clinical follow-up of the Manhattan Project plutonium workers[20] and was later expanded to a mortality study of 241 plutonium workers.[21] Neither of these efforts demonstrated a relationship between plutonium exposure and adverse health effects. These populations are included in a larger-scale epidemiological study of the approximately 100,000 past and present employees at 6 Department of Energy facilities. This study focuses on the incidence of and mortality due to cancer and other diseases among plutonium workers. Surveillance will continue through 1990 and will comprise a lifetime follow-up for many of the more heavily exposed early workers, Studies of populations residing in the vicinity of the same facilities are also underway.

At present, the mammoth amounts of data needed to establish the existence or nonexistence of excess diseases are being collected. The data include age, sex, ethnicity, chemical and medical x-ray exposures, smoking and other personal habits, and the dosimetry records for each employee. If excesses are demonstrated for the more heavily exposed workers, more data on important confounding factors and risk variables will be collected. Preliminary results are expected soon.

Concurrent with this study, the Laboratory is conducting a nationwide investigation of the deposition and distribution of plutonium and other transuranic elements in human tissue. Plutonium concentrations in the general population due to radioactive fallout are being determined from analyses of autopsy specimens provided by participating hospitals at various locations throughout the United States. In cooperation with the U. S. Transuranium Registry at Hanford, the Laboratory is also amassing data about plutonium concentrations in former nuclear workers, again by analysis of autopsy specimens.

It is hoped that these studies will avoid many of the problems of earlier epidemiological studies and will document the presence or absence of health effects due to plutonium deposition in the occupationally exposed.

How Have the Standards for Exposure to Ionizing Radiation Developed?

At the start of the Manhattan Project, only three radiation-exposure standards existed, all for occupational exposures. Radiation injury to radium dial painters from inhaled or ingested radioactive luminous compounds resulted in the establishment of limiting standards for radon in workroom air, 10^{-11} curies per liter, and for radium fixed in the body, 0.1 micrograms. Extensive occupational exposures to x rays led to the establishment of a limit of 0.1 roentgen per day for external x or gamma radiation. These standards were essentially tolerance doses based on observations of exposed individuals; their acceptance implied the existence of a threshold dose below which no effects occurred.

The years following World War II saw a rapid increase in exposures to a greater variety of radiation types. The National Committee on Radiation Protection (now the National Council on Radiation Protection and Measurements) was organized to examine the complex problems developing in radiation protection.[22] In the ensuing years, standards became more detailed as knowledge of the effects of radiation accumulated. By 1956, genetic hazard was considered the principal limitation on radiation exposure. Also, all exposures were considered cumulative since there appeared to be no cellular

BADGES THAT GLOW

Sidebar 2:

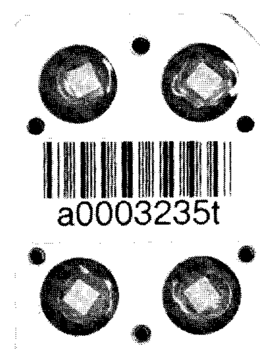
As a research institution, the Laboratory faces a greater variety of radiation exposure situations than do many employers, so demonstration of compliance with current radiation protection standards is not simple. Feeling that the older film badge was inadequate, the Health Division here designed a versatile thermoluminescent dosimeter badge (using Harshaw Chemical Company components) as the primary tool for monitoring radiation doses received by employees. The dosimeter badge can detect a dose as low as 0.01 rem and thus is more than sufficiently sensitive to prove compliance with the current standards. In fact, the badge; show a background dose of about 0.4 millirem per day in agreement with the expected background at Los Alamos from cosmic radiation and radionuclides in soil and building materials.

A thermoluminescent dosimeter consists of a lithium fluoride material that absorbs and stores energy when exposed to ionizing radiation. The material has been doped with suitable impurities; free electrons released by the ionizing radiation become trapped at impurity sites where they may remain stored for months or even years at room temperature. However, when the material is heated, the trapped electrons "thermoluminesce" and release energy as visible light. The amount of light released can be measured and is proportional to the radiation dose. In addition, if the material is enriched rather than depleted in ^{6}Li, it becomes much more sensitive to neutron radiation.

The badge includes three neutron-insensitive dosimeters, each covered by a different filter that allows passage of radiation with particular characteristics. A fourth dosimeter contains the neutron-sensitive material.

The measured responses (light outputs) of the four dosimeters provide the following information.

- The "penetrating" dose equivalent to that received about 1 centimeter into the body. This dose is due to gamma rays and high-energy x rays.
- The "nonpenetrating" dose equivalent to that received about 0.007 centimeter into the body. This dose is due to beta particles and lower-energy x rays.
- The neutron dose (to be accurate this reading must be supplemented with a knowledge of the source and any moderating materials).



A Los Alamos employee wearing the Laboratory's thermoluminescent dosimeter badge clipped to his collar. The dosimeter card that holds the four thermoluminescent chips inside each badge is shown on the right. The card is removed and "read" for absorbed dose each month.

A computer program has been written that, using the measured responses, can distinguish between the low-energy x rays and beta particles of the nonpenetrating dose, estimate the dose due to beta particles only, and determine the fraction of beta particles in a mixture of gamma rays and beta particles. Moreover, the badge acts as a crude spectrometer estimating the energy of low-energy x rays and the effective energy of a mixture of low-energy x rays and gamma rays. This is necessary since correction factors must be used to calculate doses due to photons below 100 kilo electron volts in energy.

Recently, dosimeter badges submitted by 60 different processors were judged according to a standard developed by the Health Physics Society Standards Committee. Performance was measured in eight categories of radiation type and energy; each radiation category was divided into several dose-range intervals. Only the Laboratory's thermoluminescent dosimeter badge performed satisfactorily in all eight categories. ■

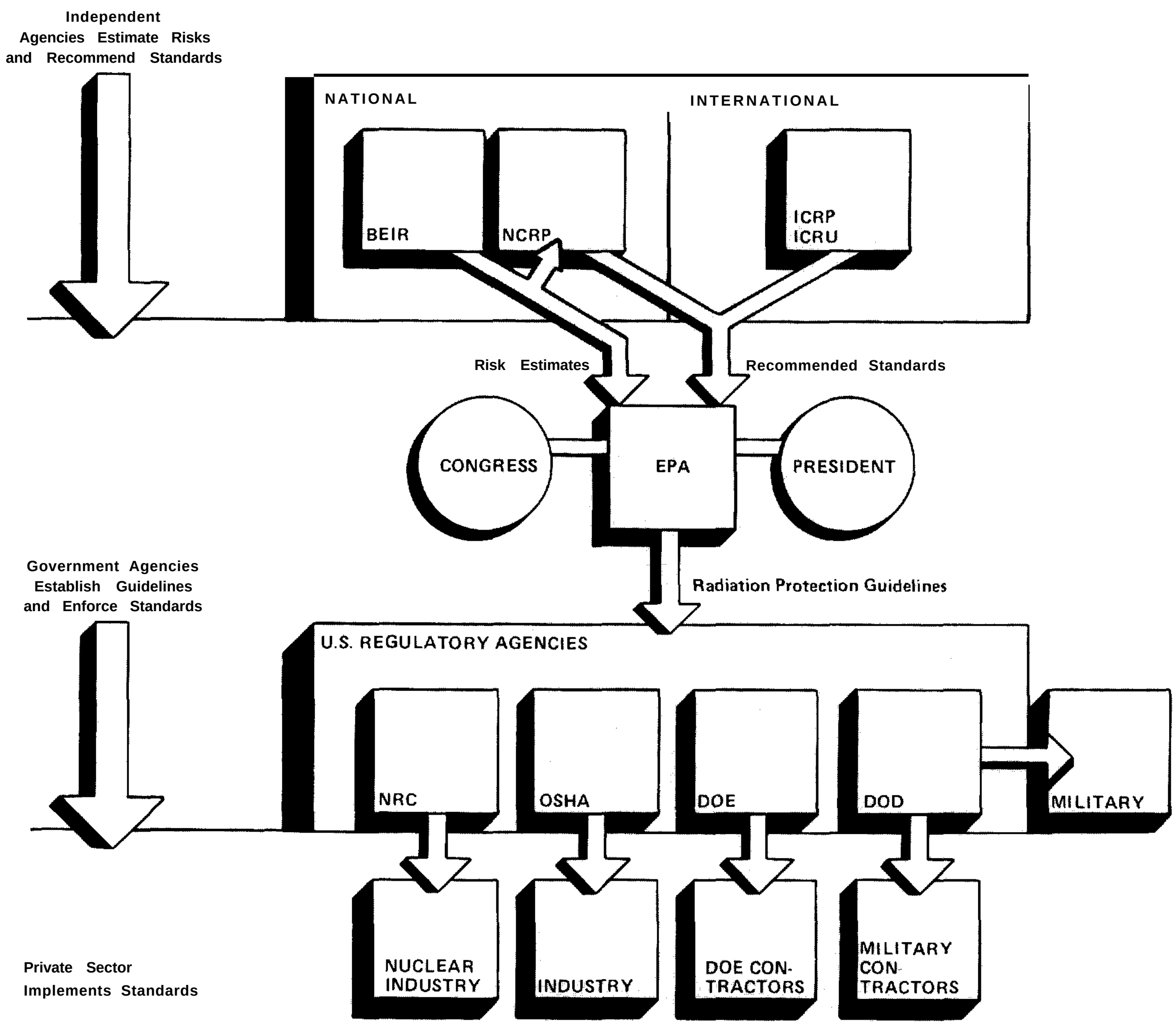


Fig. 3. The Environmental Protection Agency (EPA) is currently the focal point for development of radiation protection standards in the United States, being charged by Executive Order to advise the President and all Federal agencies on radiation matters affecting health. Other agencies involved include BEIR, the Committee on the Biological Effects of Ionizing Radiations established by the Congressionally chartered National Academy of Sciences; NCRP, the National Council on *Radiation Protection and Measurements chartered by Congress; ICRP, the International Commission on Radiological Protection; ICRU, the International Commission on Radiation Units and Measurements; NRC, the Nuclear Regulatory Commission; OSHA, the Occupational Safety and Health Administration; DOE, the Department of Energy; and DOD, the Department of Defense.*

recovery of genetic damage. Accordingly the Committee recommended a standard for occupational exposure of 5 reins per year and a standard for the general public of 0.5 rem per year. In recognition of the essentially linear relationship between dose and genetic damage down to zero dose, the Committee discarded the idea of a threshold dose and proposed a principle called "as low as practicable" or, in recent times, "as low as reasonably achievable." This principle states that radiation exposure must be avoided if unnecessary and should be kept as far below the standard as possible in light of social and economic considerations. Thus, present radiation standards consist of two parts: the exposure limit that is not to be exceeded, and the instruction to keep the actual exposure as low as reasonably achievable.

Acceptance of the no-threshold concept, which implies that any amount of radiation has some chance of causing harm, produces a dilemma about setting standards. One solution, used by both the International Commission on Radiological Protection[23] and the National Council on Radiation Protection and Measurements,[24] is to base standards on the concept of "acceptable risk." Application of the acceptable-risk concept will always be somewhat arbitrary, based as it is on decisions and judgments that take into account the benefits resulting from an activity as well as the risks.

Several points about radiation standards should be mentioned. First, a standard by no means represents a sharp dividing line between safety and disaster. But the tendency of much of the public to so regard a standard often results in concern, and sometimes panic, when even minor accidents occur.

Another point is the concern that standards may be set on the basis of ability to detect so that improved instrument sensitivity leads to lowered standards matching the new level of detection. However, the as-low-as-practicable regulations of the Nuclear Regulatory Commission for the general public are set at a level where direct measurement is not possible. Instead, proof of compliance is provided by calculations of radionuclide dispersion through the environment.

Finally, the standards recommended by the National Council on Radiation Protection and Measurements have no force in law and must be translated into legislated guidelines and standards by a number of Federal and state agencies (Fig. 3). Most importantly, the Environmental Protection Agency sets standards for all Federal agencies and the Nuclear Regulatory Commission issues regulations that are binding on all its licensees, that is, the nuclear industry.

An example of cooperative interaction between the groups that recommend, legislate, and administer the standards is their solution in 1956 to the problem of occasional occupational exposures above the 5-rems-per-year limit. Various averaging schemes were rejected by the lawyers and regulators who would be required to deal with such schemes. However, discussions among the groups led to the concept of age proration whereby a worker's cumulative exposure is related to his age N and is limited quantitatively by $5(N - 18)$ reins. Within this cumulative limit, Federal guidelines permit doses up to 3 reins per quarter or 12 reins per year. These guidelines allow a certain flexibility in the assignment of occupational exposures. For example, a worker's previous exposure history may permit performance during a year of several tasks requiring doses close to the quarterly limit of 3 reins. It should be noted that an Environmental Protection Agency survey showed that in 1975 99% of all radiation workers surveyed received an annual dose of less than 2.5 reins, and O. 15% a dose exceeding 5 rems.[25]

In January 1981 the Environmental Protection Agency proposed new guidelines for occupational exposures.[25] Included are changes in the requirements for the small number of workers who regularly receive large doses, recommendations for injested or inhaled radionuclides, weighting factors for nonuniform exposures of the body, and several alternative recommendations concerning pregnant women and exposures of the fetus. These proposals are currently under debate, but their passage appears uncertain. It is felt by many that the proposed guidelines pose technical difficulties and will not achieve significant reductions in actual occupational exposures.

Conclusions

The controversy over the hazards of low-level radiation is based on our inability to measure the risks directly. As epidemiological studies evolve that better eliminate confounding factors, more accurate risk estimates will be possible. In the meantime, standards are set by balancing risk estimates based on the best current scientific data against social and economic considerations.

The controversy will surely continue until definitive evidence for the effects of low-level radiation can be given, probably by unraveling the mysteries surrounding cancer and its causes. ■

References

1. D. M. Smith, R. G. Thomas, and E. C. Anderson, "Respiratory-Tract Carcinogenesis Induced by Radionuclides in the Syrian Hamster," in *Pulmonary Toxicology of Respirable Particles* (U. S. Department of Energy, 1980), pp. 575-590. Available from Technical Information Center, Springfield, Virginia 22161 as CONF-791OO2.

2. S. Glasstone and P. J. Dolan, *The Effects of Nuclear Weapons, 3rd Edition*, (U. S. Government Printing Office, Washington, D. C., 1977), pp. 580-581.

3. National Research Council Committee on the Biological Effects of Ionizing Radiations, *The Effects on Populations of Exposure to Low Levels of Ionizing Radiation: 1980* (National Academy Press, Washington, D. C., 1980).

4. E. Marshall, "New A-Bomb Studies Alter Radiation Estimates," Science 212,900-903 (May 22, 1981).

5. E. Marshall, "New A-Bomb Data Shown to Radiation Experts," Science 212, 1364-1365 (June 19, 1981).

6. S. Jablon, W. E. Loewe and E. Mendelssohn, R. L. Dobson and T. Staume, and D. C. Kaul, "Radiation Estimates," Science 212,6,8 (July 3, 1981).

7. Nuclear Regulatory Commission Special Inquiry Group, "Three Mile Island: A Report to the Commissioners and to the Public, Vol. l," U. S. Nuclear Regulatory Commission report NUREG/CR 1250, Vol. 1 (1980), pp. 153-154.

8. Ref. 3, pp. 96, 114.

9. Ref. 3, p. 209.

10. S. Jablon and H. Kate, "Studies of the Mortality of A-Bomb Survivors," Radiation Research 50,649-698 (1972).

11. S. Jablon, "Radiation," in *Persons at High Risk of Cancer*, J. Fraumeni, Ed. (Academic Press, New York, 1975), pp. 152-156.

12. A. B. Brill, M. Tomonaga, and R. M. Heyssel, "Leukemia in Man Following Exposures to Ionizing Radiation: Summary of Findings in Hiroshima and Nagasaki and Comparison with Other Human Experience," Annals of Internal Medicine 56,590-609 (1962).

13. A General Report on the ABCC-JNIH Joint Research Program, 1947-1975 (Atomic Bomb Casualty Commission-Japanese National Institute of Health, 1975).

14. G. W. Beebe, H. Kate, and C. E. Land, "Studies of the Mortality of A-Bomb Survivors," Radiation Research 75, 138-201 (1978).

15. L. N. Parker, J. L. Belsky, T. Yamamoto, S. Kawamoto, and R. J. Keehn, "Thyroid Carcinoma after Exposure to Atomic Radiation," Annals of Internal Medicine 80,600-604 (1974).

16. G. W. Beebe and H. Kate, "Cancers Other Than Leukemia," Journal of Radiation Research 16 (supplement), 97-107 (1975).

17. Ref. 3, pp. 268, 302.

18. T. F. Mancuso, A. Stewart, and G. Kneale, "Radiation Exposures of Hanford Workers Dying from Cancer and Other Causes," Health Physics 33,369-385 (1977).

19. G. B. Hutchinson, B. MacMahon, S. Jablon, and C. E. Land, "Review of Report by Mancuso, Stewart, and Kneale of Radiation Exposure of Hanford Workers," Health Physics 37,207-220 (1979).

20. G. L. Voelz, L. H. Hempelmann, J. Lawrence, and W. D. Moss, "A 32-Year Medical Follow-up of Manhattan Project Plutonium Workers," Health Physics 37,445-485 (1979).

21. G. L. Voelz, J. H. Stebbings, L. H. Hempelmann, L. K. Haxton, and D. A. York, "Studies on Persons Exposed to Plutonium," in *Proceedings of the International Symposium on the Late Biological Effects of Ionizing Radiation*, Geneva, March 13-17, 1978 (International Atomic Energy Agency, Geneva, 1978), pp. 353-367.

22. National Committee on Radiation Protection, "Permissible Dose from External Sources of Ionizing Radiation," National Bureau of Standards Handbook 59 (U.S. Government Printing Office, Washington, D. C., 1954).

23. International Commission on Radiological Protection, "Recommendations of the International Commission on Radiological Protection," ICRP Publication 26, pp. 14-26, in Annals of the ICRP 1-2 (1977-1979).

24. National Council on Radiation Protection and Measurements, "Basic Radiation Protection Criteria," NCRP Report No. 39 (NCRP Publications, Washington, D. C., 1974), pp. 58-61.

25. Federal Register 46,7836-7844 (January 23, 1981).

Further Reading

National Research Council Committee on the Biological Effects of Ionizing Radiations, *The Effects on Populations of Exposure to Low Levels of Ionizing Radiation: 1980* (National Academy Press, Washington, D. C., 1980). A review of all aspects of ionizing radiation, including estimates of risk.

D. J. Crawford and R. W. Leggett, "Assessing the Risk of Exposure to Radioactivity," American Scientist 68, 524-536 (1980). A description of models for the spread through the environment of radionuclides from uranium mining.

J. Rotblat, "Hazards of low-level radiation—less agreement, more confusion," Bulletin of the Atomic Scientists 37, 31-36 (1980). A discussion of the BEIR III controversy and the implications of the revised atomic-bomb data.

Scientific American 201 (September 1959). An issue devoted to ionizing radiation.

L. S. Taylor, *Radiation Protection Standards* (Chemical Rubber Co. Press, Cleveland, Ohio, 1977). A detailed history of the establishment of and rationale behind radiation protection standards.

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