Fallout from Nuclear Weapons Tests and Cancer Risks

Exposures 50 years ago still have health implications today that will continue into the future

Steven L. Simon, André Bouville and Charles E. Land

Prior to 1950, only limited consideration was given to the health impacts of worldwide dispersion of radioactivity from nuclear testing. But in the following decade, humanity began to significantly change the global radiation environment by testing nuclear weapons in the atmosphere. By the early 1960s, there was no place on Earth where the signature of atmospheric nuclear testing could not be found in soil, water and even polar ice.

Cancer investigators who specialize in radiation effects have, over the intervening decades, looked for another signature of nuclear testing—an increase in cancer rates. And although it is difficult to detect such a signal amid the large number of cancers arising from "natural" or "unknown" causes, we and others have found both direct and indirect evidence that radioactive debris dispersed in the atmosphere from testing has adversely affected public health. Frequently, however, there is misunderstanding about the type and magnitude of those effects. Thus today, with heightened fears about the possibilities of nuclear terrorism, it is worthwhile to review what we know about exposure to fallout and its associated cancer risks.

Historical Background

The first test explosion of a nuclear weapon, Trinity, was on a steel tower in south-central New Mexico on July 16, 1945. Following that test, nuclear bombs were dropped on Hiroshima and Nagasaki, Japan, in August of 1945. In 1949, the Soviet Union conducted its first test at a site near Semipalatinsk, Kazakhstan. The U.S., the Soviet Union and the United Kingdom continued testing nuclear weapons in the atmosphere until 1963, when a limited test ban treaty was signed. France and China, countries that were not signatories to the 1963 treaty, undertook atmospheric testing from 1960 through 1974 and 1964 through 1980, respectively. Altogether, 504 devices were exploded at 13 primary testing sites, yielding the equivalent explosive power of 440 megatons of TNT *(see Figure 2).*

The earliest concern about health effects from exposure to fallout focused on possible genetic alterations among offspring of the exposed. However, heritable effects of radiation exposure have not been observed from decades of follow-up studies of populations exposed either to medical x rays or to the direct gamma radiation received by survivors of the Hiroshima and Nagasaki bombs. Rather, such studies have demonstrated radiation-related risks of leukemia and thyroid cancer within a decade after exposure, followed by increased risks of other solid tumors in later years. Studies of populations exposed to radioactive fallout also point to increased cancer risk as the primary late health effect of exposure. As studies of biological samples (including bone, thyroid glands and other tissues) have been undertaken, it has become increasingly clear that specific radionuclides in fallout are implicated in fallout-related cancers and other late effects.

Nuclear Explosions: The Basics

Nuclear explosions involve the sudden conversion of a small portion of atomic nuclear mass into an enormous amount of energy by the processes of nuclear fission or fusion. Fission releases energy by splitting uranium or plutonium atoms, each fission creating on average two radioactive elements (products), one relatively light and the other relatively heavy. Fusion, triggered by a fission explosion that forces tritium or deuterium atoms to combine into larger atoms, produces more powerful explosive yields than fission. Both processes create three types of radioactive debris: fission products, activation products (elements that become radioactive by absorbing an ad-

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ditional neutron) and leftover fissionable material used in bomb construction that does not fission during the explosion.

A nuclear explosion creates a large fireball within which everything is vaporized. The fireball rises rapidly, incorporating soil or water, then expands as it cools and loses buoyancy. The radioactive debris and soil that are initially swept upwards by the explosion are then dispersed in the directions of the prevailing winds. Fallout consists of microscopic particles that are deposited on the ground.

How People Are Exposed to Fallout

The radioactive cloud usually takes the form of a mushroom, that familiar icon of the nuclear age. As the cloud reaches its stabilization height, it moves downwind, and dispersion causes vertical and lateral cloud movement. Because wind speeds and directions vary with altitude *(Figure 3),* radioactive materials spread over large areas. Large particles settle locally, whereas small particles and gases may travel around the world. Rainfall can cause localized concentrations far from the test site. On the other hand, large atmospheric explosions injected radioactive material into the stratosphere, 10 kilometers or more above the ground, where it could remain for years and sub-

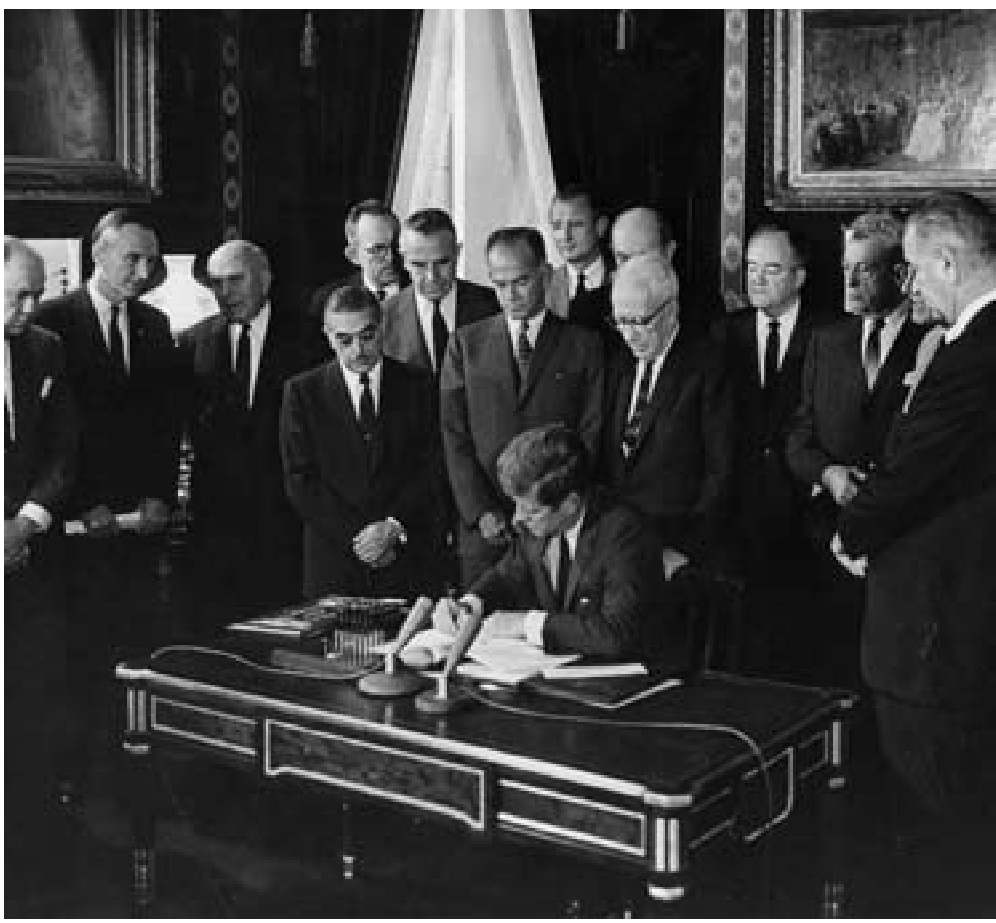


Figure 1. Between 1945 and 1980, the U.S., the U.S.S.R, the U.K., France and China carried out more than 500 atmospheric tests of nuclear weapons totaling the explosive equivalent of 440 megatons of TNT. These tests injected radioactive material into the atmosphere, much of which became widely dispersed before being deposited as fallout. Cancer investigators have been studying the health effects of radioactive fallout for decades, making radiation one of the best-understood agents of environmental injury. The legacy of open-air nuclear weapons testing includes a small but significant increase in thyroid cancer, leukemia and certain solid tumors. Mushroom clouds, such as the one from the 74-kiloton test HOOD on July 5, 1957 (detonated from a balloon at 1,500 feet altitude), are a universally recognized icon of nuclear explosions. The characteristic cap forms when the fireball from the explosion cools sufficiently to lose buoyancy. HOOD was the largest atmospheric test conducted at the Nevada Test Site (and in the continental U.S.). Fortunately, the U.S., the Soviet Union and the U.K. stopped atmospheric testing in 1963, when the nations signed the Limited Test Ban Treaty. (France ceased atmospheric testing in 1974 and China in 1980.) President John F. Kennedy signed the treaty on October 5, 1963 *(bottom)*. (Top photograph from the Nevada Test Site, U.S. Department of Energy. Bottom photograph from the National Archives.)

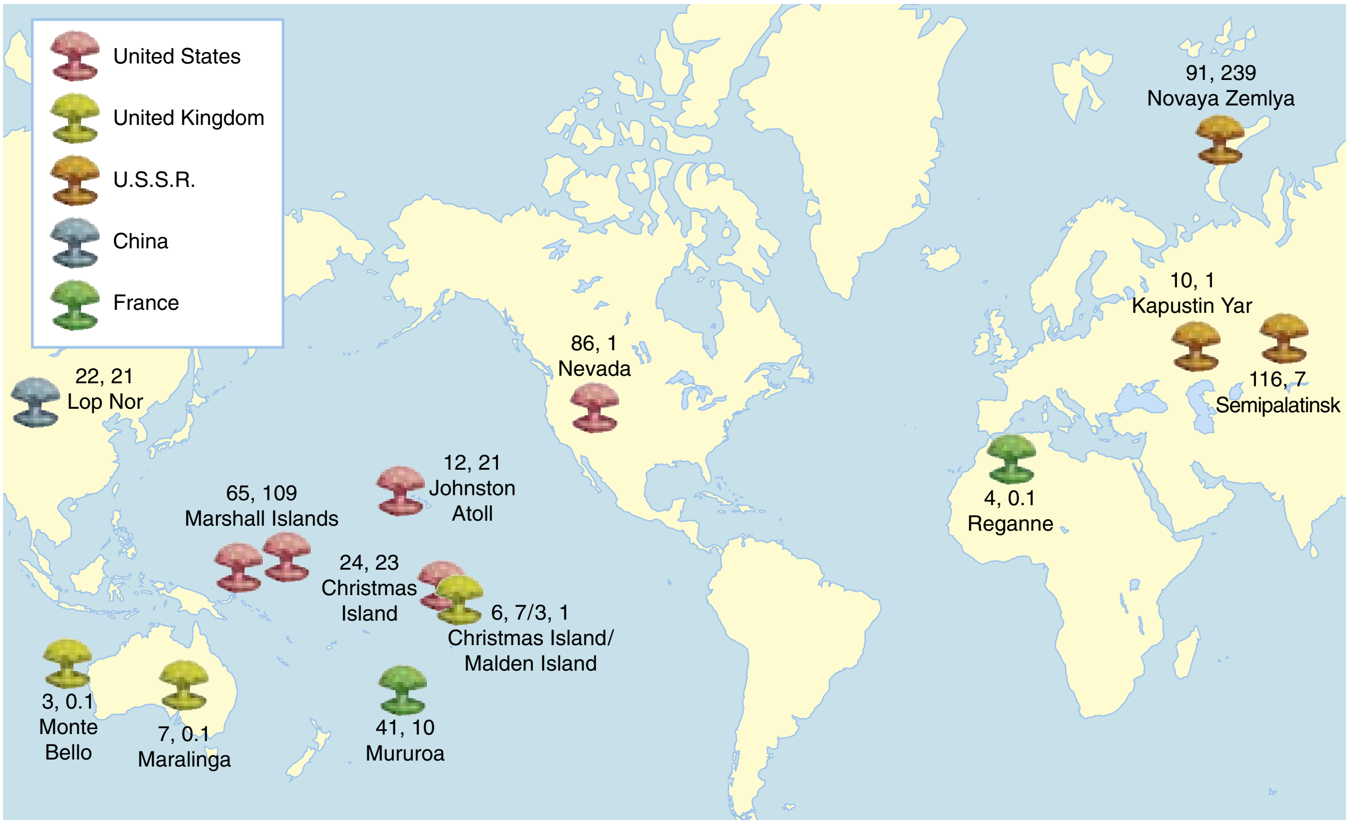


Figure 2. Primary atmospheric nuclear weapons test sites were widely distributed around the globe, with South America and Antarctica the only continents to be spared. No spot on Earth escaped the fallout, however, as larger tests injected radioactive material into the stratosphere, where it could remain for several years and disperse globally. The numbers shown at each test site indicate the number of tests and (following the comma) the total yield in the equivalent of megatons of TNT. (Data here and in Figures 3 and 7–10 from NCI 1997.)

sequently be deposited fairly homogeneously ("global" fallout). Nuclear tests usually took place at remote locations at least 100 kilometers from human populations. In terms of distance from the detonation site, "local fallout" is within 50 to 500 kilometers from ground zero, "regional fallout" 500–3,000 kilometers and global fallout more than 3,000 kilometers. Because the fallout cloud disperses with time and distance from the explosion, and radioactivity decays over time, the highest radiation exposures are generally in areas of local fallout.

Following the deposition of fallout on the ground, local human populations are exposed to external and internal irradiation. External irradiation exposure is mainly from penetrating gamma rays emitted by particles on the ground. Shielding by buildings reduces exposure, and thus doses to people are influenced by how much time one spends outdoors.

Internal irradiation exposures can arise from inhaling fallout and absorbing it through intact or injured skin, but the main exposure route is from consumption of contaminated food. Vegetation can be contaminated when fallout is directly deposited on external surfaces of plants and when it is absorbed through the roots of plants. Also, people can be exposed when they eat meat and milk from animals grazing on contaminated vegetation. In the Marshall Islands, foodstuffs were also contaminated by fallout directly deposited on food and cooking utensils.

The activity of fallout deposited on the ground or other surfaces is measured in becquerels (Bq), defined as the number of radioactive disintegrations per second. The activity of each radionuclide per square meter of ground is important for calculating both external and internal doses. Following a nuclear explosion, the activity of short-lived radionuclides is much greater than that of long-lived radionuclides. However, the short-lived radionuclides decay substantially during the time it takes the fallout cloud to reach distant locations, where the long-lived radionuclides are more important.

Iodine-131, which for metabolic reasons concentrates in the thyroid gland, has a half-life (the time to decay by half) of about eight days. This is long enough for considerable amounts to be deposited onto pasture and to be transferred to people in dairy foods (*Figure 4*). In general, only those children in the U.S. with lactose intolerance or allergies to milk products consumed no milk products, particularly in the 1950s and 1960s when there were fewer choices of prepared foods. Radioiodine ingested or inhaled by breast-feeding mothers can also be transferred to nursing infants via the mother's breast milk.

The two nuclear weapons dropped on Hiroshima and Nagasaki were detonated at relatively high altitudes above the ground and produced minimal fallout. Most of the injuries to the populations within 5 kilometers of the explosions were from heat and shock waves; direct radiation was a major factor only within 3 kilometers. Most of what we know about late health effects of radiation in general, including increased cancer risk, is derived from continuing observations of survivors exposed within 3 kilometers.

Understanding Radiation Dose

Radiation absorbed dose is the energy per unit mass imparted to a medium (such as tissue). Almost all radionuclides in fallout emit beta (electron) and gamma (photon) radiation. A cascade of events follows once tissue is exposed to radiation: The initial radiation scatters, and atoms in the body are ionized by removal of weakly bound electrons. Radiation can damage DNA by direct interaction or by creating highly reactive chemical species that interact with DNA.

The basic unit of the system used internationally to characterize radiation dose is the gray (Gy), defined as the absorption of 1 joule of energy per kilogram of tissue. (The international system of units is gradually supplanting the previous system based on dose units of rad, but conversion is easy: 1 Gy = 100 rad.) For perspective, it is helpful to remember that the external dose received from natural sources of radiation—from primordial radionuclides in the earth's crust and from cosmic radiation—is of the order of 1 milligray (mGy, one-thousandth of a gray) per year; the dose from a whole-body computer-assisted tomographic (CT) examination is about 15–20 mGy, and that due to cosmic rays received during a transatlantic flight is about 0.02 mGy.

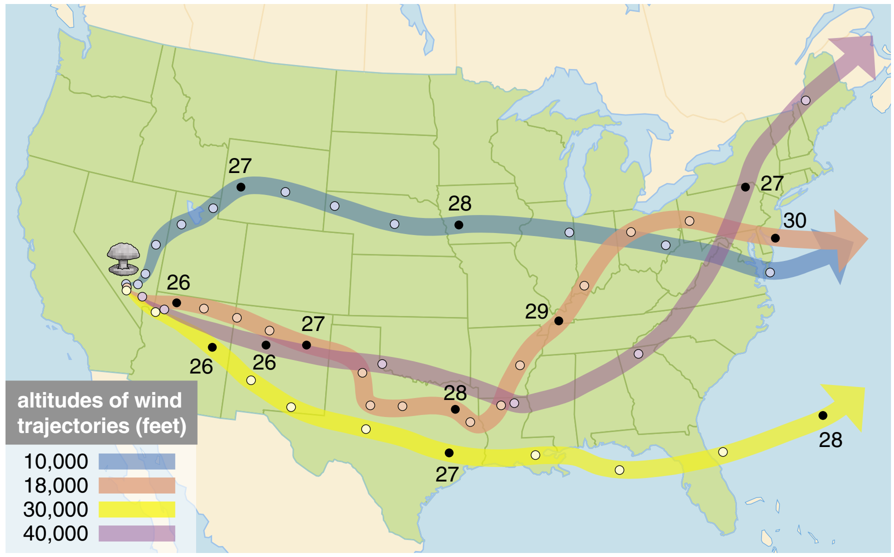


Figure 3. Wind shear (variations in wind speed and direction with altitude) causes fallout to spread over large areas. The 43-kiloton test SIMON was detonated at 4:30 a.m. local time on April 25, 1953, at the Nevada Test Site. Trajectories of the fallout debris clouds across the U.S. are shown for four altitudes. Each dot indicates six hours. The numbered dots are the date in April.

Examples of Fallout Exposures

Doses from fallout received in the 1950s and 1960s have been estimated in recent years using mathematical exposure assessment models and historical fallout deposition data. There have been only a few studies involving detailed estimation of the doses received by local populations; the exceptions include some towns and cities in Nevada and adjacent states, a few villages near the Soviet Semipalatinsk Test Site (STS), and some atolls in the Marshall Islands.

Marshall Islands. One of the 65 tests conducted in the Marshall Islands, the explosion of a U.S. thermonuclear device code-named BRAVO (March 1, 1954), was responsible for most—although not all—of the radiation exposure of local populations from all of the tests. The fallout-related doses received as a result of that one test at Bikini Atoll are the highest in the history of worldwide nuclear testing.

Wind shear (changes in direction and speed with altitude) and an unexpectedly high yield resulted in heavy fallout over populated atolls to the east of Bikini rather than over open seas to

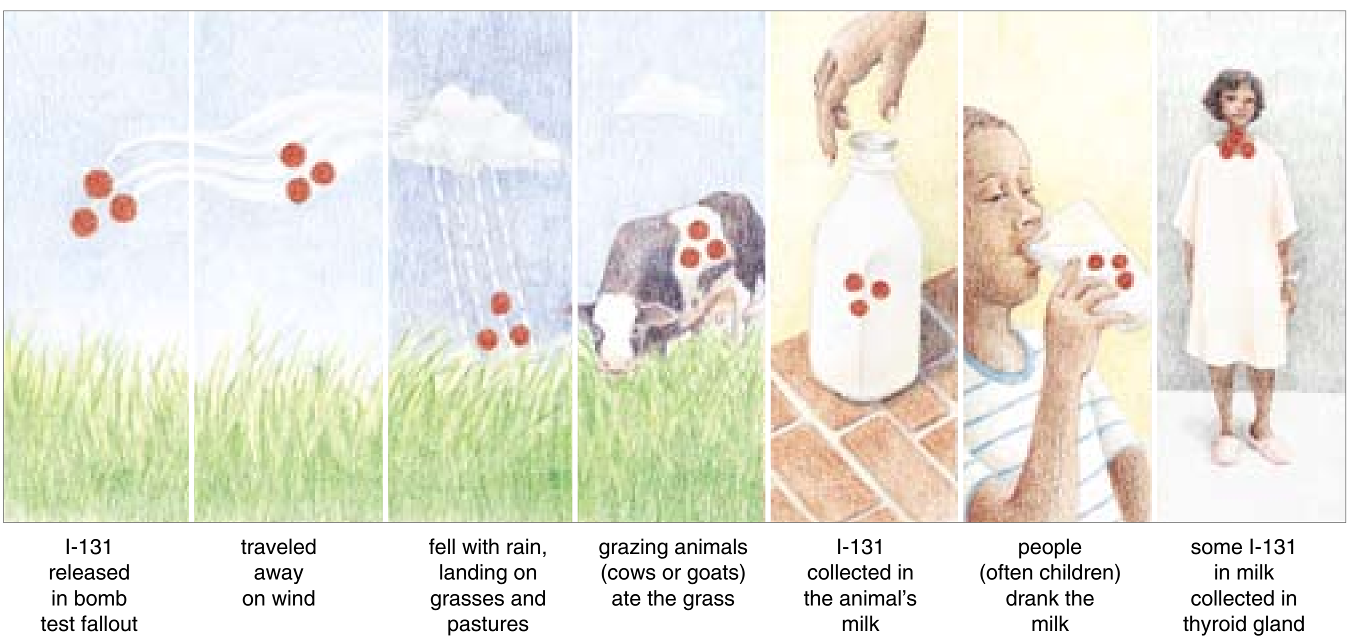


Figure 4. One major means by which fallout and nuclear debris are transferred through the atmosphere to people is via the production and consumption of dairy products. Fallout descends onto vegetation, which is eaten by dairy animals. The fallout passes into the animals' milk, which is prepared for human consumption. This pathway is the single largest means by which people in the U.S. were exposed to iodine-131 from fallout generated by nuclear weapons testing. (Figure adapted from the National Cancer Institute).

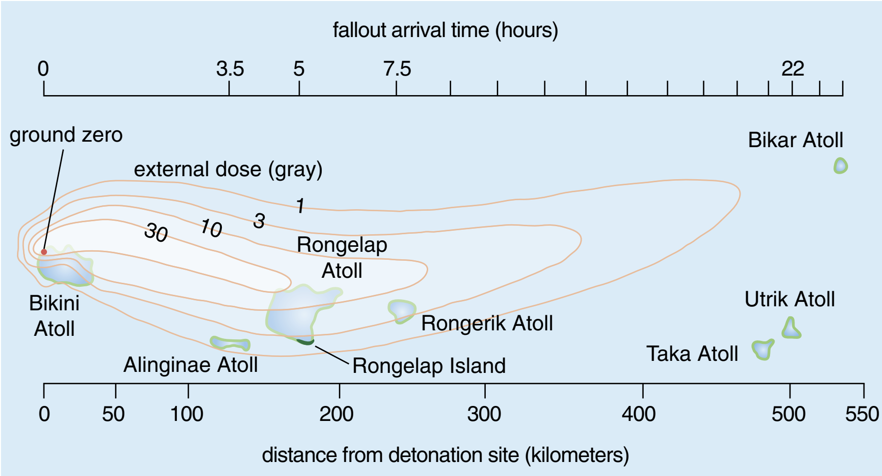


Figure 5. BRAVO, detonated on March 1, 1954, was a 15-megaton thermonuclear device that resulted in the highest radiation exposures to people of any nuclear test. Unanticipated wind direction and an explosive yield higher than expected sent a fallout cloud from the Bikini test site towards the inhabited atolls of Rongelap, Ailinginae, Rongerik and Utrik in the Marshall Islands. Doses from external exposure were about 1–2 Gy on Rongelap and Ailinginae.

the north and west. About $3\frac{1}{2}$ hours after the detonation, the radioactive cloud began to deposit particulate, ash-like material on 18 Rongelap residents who were fishing and gathering copra on Ailinginae Atoll about 135 kilometers east of the detonation site, followed 2 hours later by deposition on Rongelap Island 65 kilometers farther to the east, affecting 64 residents. The fallout arrived $2\frac{1}{2}$ hours later at Rongerik Atoll another 40 kilometers to the east, exposing 28 American weathermen; about 22 hours after detonation, it reached the 167 residents of Utrik Atoll.

Doses received by the Rongelap group were assessed by ground and aerial exposure rate measurements and radioactivity analysis of a community-pooled urine sample. The doses received before evacuation were essentially due to external irradiation from short-lived radionuclides and internal irradiation from ingestion of short-lived radioiodines deposited on foodstuffs and cooking utensils. Thyroid doses, in particular, were very high: At Rongelap they were estimated to be several tens of Gy for an adult and more than 100 Gy for a one-year old. Estimated thyroid doses at Ailinginae were about half those at Rongelap, and doses at Utrik were about 15 percent of those at Rongelap. The external whole-body doses estimated were about 2 Gy at Rongelap, 1.4 Gy at Ailinginae, 2.9 Gy at Rongerik and 0.2 Gy at Utrik. Much lower exposures have been estimated for most of the other Marshall Islands atolls.

Twenty-three Japanese fishermen on the fishing vessel *Lucky Dragon* were also exposed to heavy fallout. Their doses from external irradiation were estimated to range from 1.7 to 6 Gy. Those doses were received during the 14 days it took to return to harbor; about half were received during the first day after the onset of fallout.

Semipalatinsk, Kazakhstan. The Semipalatinsk Test Site, in northeastern Kazakhstan near the geographical center of the Eurasian continent, was the Soviet equivalent of the U.S. Nevada Test Site; 88 atmospheric tests and 30 surface tests were conducted there from 1949 through 1962. The main contributions to local and regional environmental radioactive contamination are attributed to particular atmospheric nuclear tests conducted in 1949, 1951 and 1953.

Doses from local fallout originating at the STS depended on the location of villages relative to the path of the fallout cloud, the weather conditions at the time of the tests, the lifestyles of residents, which differed by ethnicity (Kazakh or European), and whether they were evacuated before the fallout arrived at the village. Some unique circumstances included strong winds that resulted in short fallout transit times and little radioactive decay before deposition for at least one test. Also, the residents of the area were heavily dependent on meat and milk from grazing animals, including cattle, horses, goats, sheep and camels.

Dose-assessment models predict a decreasing gradient in the ratio of external radiation doses to internal doses from inhalation and ingestion with increasing time from detonation to fallout arrival. The relatively large particles that tend to fall out first are not efficiently transferred to the human body. At more distant locations in the region of local fallout, internal dose is relatively more important because smaller particles that predominate there are biologically more available. For example, in rural villages

Figure 6. Subsequent to the explosion of BRAVO at the Bikini test site, teams of medical doctors and health physicists made annual trips to the Marshall Islands to check on the health of islanders accidentally exposed to radioactive fallout. In this photograph, Dr. Robert Conard is examining a Marshall Islander for any thyroid abnormalities. (Photograph courtesy of Brookhaven National Laboratory.)

along the trajectory of the first test (August 1949) at the Semipalatinsk Test Site, average estimated radiation dose from fallout to the thyroid glands of juvenile residents decreased with increasing distance from the detonation, but the proportion of that total due to internal radiation sources increased with distance. At 110 kilometers from the detonation site, the average dose was 2.2 Gy, of which 73 percent was from internal sources, whereas at 230 kilometers, 86 percent of the average dose of 0.35 Gy was from internal sources

Nevada Test Site (NTS). The NTS was used for surface and above-ground nuclear testing from early 1951 through mid-1962. Eighty-six tests were conducted at or above ground level, and 14 other tests that were underground involved significant releases of radioactive material into the atmosphere.

In 1979 the U.S. Department of Energy described a methodology for estimating radiation doses to populations downwind of the NTS. Doses from internal irradiation within this local fallout area were ascribed mainly to inhalation of radionuclides in the air and to ingestion of foodstuffs contaminated with radioactive materials. Doses from internal irradiation were, for most organs and tissues, substantially smaller than those from external irradiation, with the notable exception of the thyroid, for which estimated internal doses were substantially higher. Estimated thyroid doses were ascribed mainly to consumption of foodstuffs contaminated with iodine-131 (I-131) and, to a lesser extent, iodine-133 (I-133), and to inhalation of air contaminated with both I-131 and I-133. Thyroid doses varied according to local dairy practices and the extent to which milk was imported from less contaminated areas. Bone-marrow doses less than 50 mGy were estimated for communities in a local fallout area within 300 kilometers of the NTS, where ground-monitoring data were available, and an order of magnitude less for other communities in Arizona, New Mexico, Nevada, Utah and portions of adjoining states.

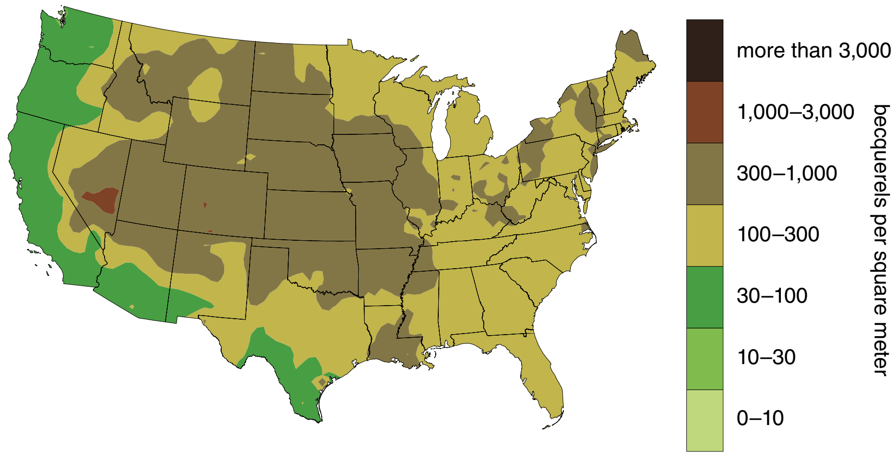


Figure 7. Cesium-137 deposition density resulting from the cumulative effect of the Nevada tests generally decreases with distance from the test site in the direction of the prevailing wind across North America, although isolated locations received significant deposition as a result of rainfall.

Investigators at the University of Utah estimated radiation doses to the bone marrow for 6,507 leukemia cases and matched controls who were residents of Utah. Average doses were about 0.003 Gy with a maximum of about 0.03 Gy. Subsequently, thyroid doses were estimated to members of a cohort exposed as school children in southwestern Utah and who are part of a long-term epidemiology study. The mean thyroid dose was estimated to be 0.12 Gy, with a maximum of 1.4 Gy. Among children who did not drink milk, the mean thyroid dose was on the order of 0.01 Gy.

In response to Public Law 97-414 (enacted in 1993), the U.S. National Cancer Institute (NCI) estimated the absorbed dose to the thyroid from I-131 in NTS fallout for representative individuals in every county of the contiguous United States. Calculations emphasized the pasture-cow-milk-man food chain, but also included inhalation of fallout and ingestion of other foods. Deposition of I-131 across the United States was reconstructed for every significant event at the NTS using historical measurements of fallout from a nationwide network of monitoring stations operational between 1951 and 1958. Thyroid doses were estimated as a function of age at exposure, region of the country and dietary habits. For example, for a female born in St. George, Utah, in 1951 and residing there until 1971, the thyroid doses are estimated to have been about 0.3 Gy if she had consumed commercial cow's milk, 2 Gy if she had consumed goat's milk, and 0.04 Gy if she had not

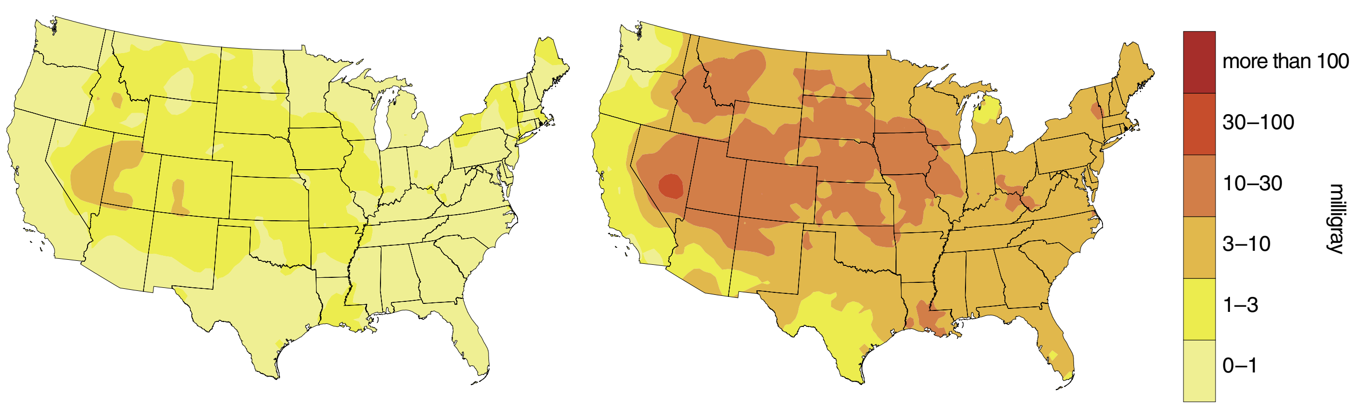


Figure 8. Total external and internal dose to the red bone marrow of persons born on January 1, 1951, from all Nevada tests is shown at left. Total external and internal dose to the thyroid of adults in 1951 from all Nevada tests is shown at right. Note that the dose is roughly proportional to the deposition density shown in Figure 7.

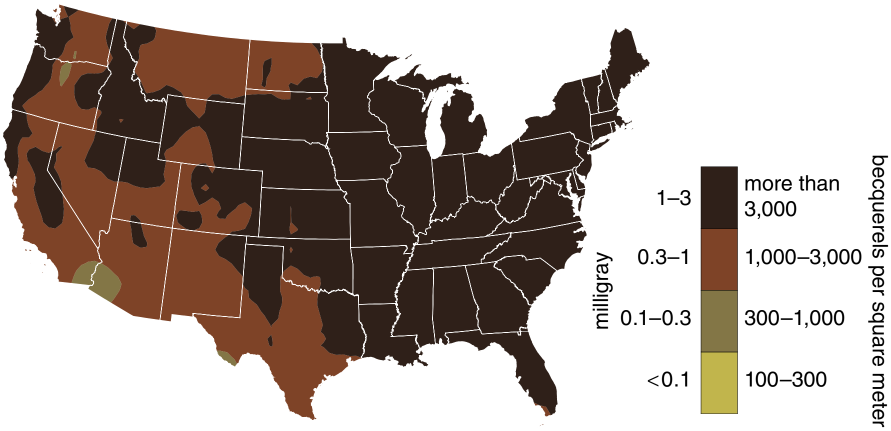


Figure 9. Cesium-137 deposition density *(right scale)* and dose to red bone marrow *(left scale)* from global fallout for persons born on January 1, 1951, show a different pattern than that from the Nevada tests, as they are strongly influenced by rainfall amounts.

consumed milk. For a female born in Los Angeles, California, at the same time, the corresponding values would have been 0.003, 0.01, and 0.0004 Gy. (A link to these data is available in the bibliography.)

Following the publication of the NCI findings in 1997, the U.S. Congress requested that the Department of Health and Human Services extend the study to other radionuclides in fallout and to consider tests outside the U.S. that could have resulted in substantial radiation exposures to the American people. Examples of results extracted from the report (a link is available in the bibliography) are shown in Figures 7 through 9 and 11. Figure 7 shows the pattern of deposition of cesium-137 (Cs-137), a radionuclide traditionally used for reference, resulting from all NTS tests in the entire United States. Fallout decreased with distance from the NTS along the prevailing wind direction, which was from west to east. Very little fallout was observed along the Pacific coast, which was usually upwind from the NTS. Estimated bone-marrow and thyroid doses are illustrated in Figure 8. The fact that both external and internal doses were roughly proportional to the deposition density is reflected in similarities between the two figures. Estimates of average thyroid and of bone-marrow doses for the entire U.S. population are presented in Figure 11; the thyroid doses from I-131 are much higher than the internal doses from any other radionuclide and also much higher than the doses from external exposure.

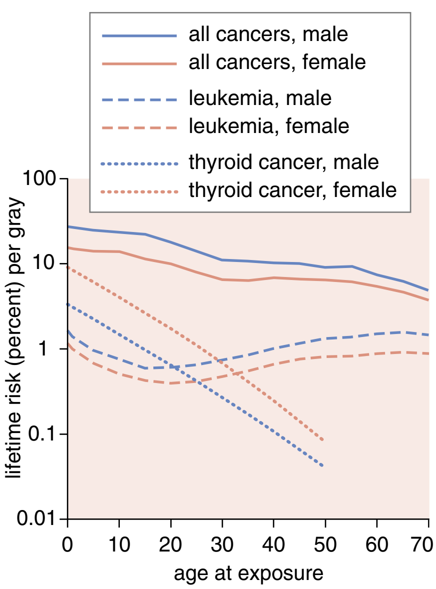


Figure 10. Lifetime risk per gray of absorbed radiation dose can be calculated as a function of age at exposure; here these risks are graphed on a logarithmic scale. The curves for leukemia refer to the absorbed doses to red bone marrow, whereas the curves for thyroid cancer refer to the absorbed doses to the thyroid gland, and the curves for all cancers refer to whole-body absorbed doses.

Global fallout within the U.S. Global fallout originated from weapons that derived much of their yield from fusion reactions. These tests were conducted by the Soviet Union at northern latitudes and by the U.S. in the mid-Pacific. For global fallout, the mix of radionuclides that might contribute to exposure differs from that of NTS fallout, largely because radioactive debris injected into the stratosphere takes one or more years to deposit, during which time the shorter-lived radionuclides largely disappear through radioactive decay. Of greater concern are two longer-lived radionuclides, strontium-90 and cesium-137, which have 30-year half-lives and did not decay appreciably before final deposition. Examples of the doses received from global fallout are shown in Figures 9 and 11. Figure 9 shows the pattern of deposition of Cs-137 from global fallout, as well as the total dose to red bone marrow, which is roughly proportional to the deposition. A comparison of Figures 9 and 7 shows very different patterns of Cs-137 in global fallout (related to rainfall patterns) and NTS fallout, which depended mainly on the trajectories of the air masses originating from the NTS. Estimates of average thyroid and bone-marrow doses for the entire U.S. population from global fallout are presented in Figure 11; the thyroid dose from I-131 is higher than the internal doses from any other radionuclide, but it is no greater than the doses from external irradiation.

Fallout and Cancer Risk

Increased cancer risk is the main long-term hazard associated with exposure to ionizing radiation. The relationship between radiation exposure and subsequent cancer risk is perhaps the best understood, and certainly the most highly quantified, dose-response relationship for any common environmental human carcinogen. Our understanding is based on studies of populations exposed to radiation from medical, occupational and environmental sources (including the atomic bombings of Hiroshima and Nagasaki, Japan), and from experimental studies involving irradiation of animals and cells. Numerous comprehensive reports from expert committees summarize information on radiation-related cancer risk using statistical models that express risk as a mathematical function of radiation dose, sex, exposure age, age at observation and other factors. Using such models, lifetime radiation-related risk can be calculated by summing estimated age-specific risks over the remaining lifetime following exposure, adjusted for the statistical likelihood of dying from some unrelated cause before any radiation-related cancer is diagnosed.

Relatively little of the information on radiation-related risk comes from studies of populations exposed mostly or only to radioactive fallout, because useful dose-response data are difficult to obtain. However, the type of radiation received from external sources in fallout is similar to medical x rays or to gamma rays received directly by the Hiroshima and Nagasaki A-bomb survivors, allowing information from individuals so exposed to be used to

radionuclide	half-life	Nevada Test Site fallout: thyroid or red bone marrow external dose (mGy)	Nevada Test Site fallout: thyroid internal dose (mGy)	Nevada Test Site fallout: red bone marrow internal dose (mGy)	global fallout: thyroid or red bone marrow external dose (mGy)	global fallout: thyroid internal dose (mGy)	global fallout: red bone marrow internal dose (mGy)
carbon-14	5730 y	-	-	-	-	0.1	0.1
cesium-137	30 y	0.01	0.009	0.009	0.3	0.1	0.1
strontium-90	28.5 y	-	-	0.02	-	0.0009 [0.002][a]	0.2 [0.5][a]
tritium	12.3 y	-	-	-	-	0.07	0.07
antimony-125	2.7 y	-	-	-	0.03	-	-
ruthenium-106	368 d	-	0.001	0.002	0.04	-	-
manganese-54	313 d	-	-	-	0.04	-	-
cerium-144	284 d		-	-	0.02	-	-
zirconium/niobium-95	64 d	0.08	-	-	0.2	-	-
strontium-89	52 d	-	0.001	0.03	-	-	-
ruthenium-103	39 d	0.03	-	-	0.02	-	-
cesium-136	13 d		0.002	0.002	-	-	-
barium/lanthanum-140	13 d	0.2	-	0.006	0.05	-	-
iodine-131	8 d	0.02	5 [30][a]	0.001	-	0.4 [2][a]	0.00009 [0.0002][a]
tellurium/iodine-132	3.3 d	0.1	0.06	0.001	-	-	-
neptunium-239	2.4 d	0.02	-	-	-	-	-
iodine-133	0.9 d	0.02	0.04	-	-	-	-
zirconium/niobium-97	17 h	0.02	-	-	-	-	-
rounded totals:		0.5	5 [30][a]	0.1	0.7	0.7 [2][a]	0.6 [0.9][a]

Figure 11. Average doses in milligray (mGy) for adults (unless accompanied by a superscripted "a," which denotes a child born January 1, 1951) living in the contiguous United States during the era of atmospheric testing are shown for the most important radionuclides. Note that the radionuclides are organized by half-life, from longest to shortest (in years, *y*, or days, *d*), descending, rather than by atomic weight.

estimate fallout-related risks from external radiation sources. Estimates of radiation-related lifetime cancer risk per unit dose from external radiation sources to the organs and tissues of interest are shown in Figure 10 for leukemia, thyroid cancer and all cancers combined. Estimated risks, in percent, are given separately by sex, as functions of age at exposure.

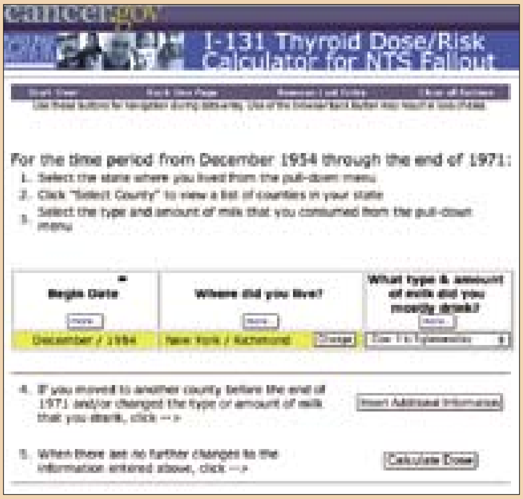
Thyroid cancer is a rare disease overall—with U.S. lifetime rates estimated to be 0.97 percent in females and 0.36 percent in males—and it is extremely rare at ages younger than 25. Furthermore, the malignancy is usually indolent, may go long unobserved in the absence of special screening efforts and has a fatality rate of less than 10 percent. These factors make it difficult to study fallout-related thyroid cancer risk in all but the most heavily exposed populations. Thyroid cancer risks from external radiation are related to gender and to age at exposure, with by far the highest risks occurring among women exposed as young children.

The applicability of risk estimates based on studies of external radiation exposure to a population exposed mainly to internal sources, and to I-131 in particular, has been debated for many years. This uncertainty relates to the uneven distribution of I-131 radiation dose within the thyroid gland and its protraction over time. Until recently, the scientific consensus had been that I-131 is probably somewhat less effective than external radiation as a cause of thyroid cancer. However, observations of thyroid cancer risk among children exposed to fallout from the Chornobyl reactor accident in 1986 have led to a reassessment. An Institute of Medicine report concluded that the Chornobyl observations support the conclusion that I-131 has an equal effect, or at least two-thirds the effect of internal radiation. More recent data on thyroid cancer risk among persons in Belarus and Russia exposed as young children to Chornobyl fallout offer further support of this inference.

In 1997, NCI conducted a detailed evaluation of dose to the thyroid glands of U.S. residents from I-131 in fallout from tests in Nevada. In a related activity, we evaluated the risks of thyroid cancer from that exposure and estimated that about 49,000 fallout-related cases might occur in the United States, almost all of them among persons who were under age 20 at some time during the period 1951–57, with 95-percent uncertainty limits of 11,300 and 212,000. The estimated risk may be compared with some 400,000 lifetime thyroid cancers expected in the same population in the absence of any fallout exposure. Accounting for thyroid exposure from global fallout, which was distributed fairly uniformly over the entire United States, might increase the estimated excess by 10 percent, from 49,000 to 54,000. Fallout-related risks for thyroid cancer are likely to exceed those for any other cancer simply because those risks are predominantly ascribable to the thyroid dose from internal radiation, which is unmatched in other organs.

External gamma radiation from fallout, unlike beta radiation from I-131,

Estimating Your Thyroid Cancer Risk



A Web-based calculator developed by the National Cancer Institute is available to anyone wishing to estimate individual thyroid cancer risks associated with exposure to I-131 radiation in fallout from the Nevada Test Site, for persons who lived in the U.S. during the 1950s. The calculator can be accessed through the Internet at its stand-alone web page (http://ntsi131.nci.nih.gov/) or through the main NCI website (http://www.cancer.gov/i131), which provides more general information about the NTS, I-131 and radioactive fallout. Information required for the calculation includes gender, age at exposure, places of residence during the years 1951–71, and sources and approximate amounts of milk consumed.

is penetrating and can be expected to affect all organs. Leukemia, which is believed to originate in the bone marrow, is generally considered a "sentinel" radiation effect because some types tend to appear relatively soon after exposure, especially in children, and to be noticed because of high rates relative to the unexposed. Lifetime rates in the general population, however, are comparable to those for thyroid cancer (on the order of one percent), whereas those for all cancers are about 46 percent in males and 38 percent in females.

A total of about 1,800 deaths from radiation-related leukemia might eventually occur in the United States because of external (1,100 deaths) and internal (650 deaths) radiation from NTS and global fallout. For perspective, this might be compared to about 1.5 million leukemia deaths expected eventually among the 1952 population of the United States. About 22,000 radiation-related cancers, half of them fatal, might eventually result from external exposure from NTS and global fallout, compared to the current lifetime cancer rate of 42 percent (corresponding to about 60 million of the 1952 population).

The risk estimates in Figure 10 do not apply to the extremely high-dose fallout exposures experienced by 82 residents of the Marshall Islands exposed to BRAVO fallout on Rongelap and Ailinginae in 1954, because the total dose to the thyroid gland (88 Gy on average) far exceeded those in any of the studies on which the estimates are based. Other islands in the archipelago, with about 14,000 residents in 1954, had average estimated doses of 0.03 Gy to bone marrow and 0.68 Gy to the thyroid gland. Altogether, excess lifetime cancers are estimated to be three leukemias (compared to 122 expected in the absence of exposure, an excess of 2.5 percent), 219 thyroid cancers (compared to 126 expected in the absence of exposure, an excess of 174 percent) and 162 other cancers (compared to 5,400 expected, an excess of 3 percent).

It is important to note that, even though the fallout exposures discussed here occurred roughly 50 to 60 years ago, only about half of the predicted total numbers of cancers have been expressed so far. The same can be said of the survivors of the atomic bombings of Hiroshima and Nagasaki. Most of the people under study who were exposed to fallout or direct radiation—for example, A-bomb survivors—at very young ages during the 1940s, 1950s and 1960s are still alive, and the cumulative experience obtained from all studies of radiation-exposed populations is that radiation-related cancers can be expected to occur at any time over the entire lifetime following exposure.

Fallout and Radiological Terrorism

Concern about the possible use of radioactive materials by terrorists has been heightened following the attacks on the World Trade Center and the Pentagon on September 11, 2001, and other acts elsewhere in the world. Conventional attacks, including use of a *dirty bomb*—that is, a conventional explosive coupled with radioactive material—seem more likely (because they are easier to carry out) than a fission event, but it is still useful to ask ourselves "What lessons from our research on fallout are applicable to events of radiological terrorism?" The potential for health damage downwind of a terrorist event involving any degree of fission will be dominated by exposure to early highly radioactive fallout.

Accurately projecting fallout patterns requires knowledge of the location and altitude at which the device is exploded, and the local meteorology—particularly a three-dimensional characterization of the wind field in the vicinity of the explosion. Logistics would likely lead a terrorist organization to explode a small-scale, fission-type nuclear device at ground level. According to the National Council on Radiation Protection and Measurements, an explosive yield of only 0.01 kiloton would cause more physical damage than the explosion that destroyed the Oklahoma City Federal Building in 1995. Persons within 250 meters of a 0.01-kiloton nuclear detonation would receive whole-body doses of 4 Gy from the initial radiation, resulting in the mortality of almost half of those exposed. The same dose would be received within one hour from exposure to fallout by those who remained within 1.3 kilometers of the detonation.

Acute life-threatening effects would dominate treatment efforts within the initial weeks of a terrorist event. Later, increase levels of chronic disease, including cancer, would be expected to contribute to radiation-related mortality and morbidity among survivors, including those with lesser exposures. Among all persons in the U.S. and most other developed countries, cancer causes about 1 in 4 deaths. The total additional cancer risk from exposure to radioactive fallout is relatively small, although follow-up of the Japanese atomic bomb survivors has shown that elevated cancer risks continue throughout the remainder of life.

Fallout—What We've Learned

Over the more than five decades since radioactive fallout was first recognized as a potential public-health risk, it has stimulated interdisciplinary research in areas of science as diverse as nuclear and radiation physics, chemistry, statistics, ecology, meteorology, genetics, cell biology, physiology, exposure and risk assessment, and epidemiology.

Individual radionuclides in fallout were recognized early on as opportune tracers by which the kinetic behavior of elements could be studied, both among components of ecosystems and in their transport to people. The phenomenon of fallout, while contributing only modestly to our overall understanding of radiation risks, has taught us much about pathways of exposure and about cancer risks to the public in settings outside the medical and occupational arenas. And in particular, fallout studies helped increase our understanding of health risks from specific radionuclides, for example, I-131. This has made possible the development of the National Cancer Institute's thyroid dose and risk calculator *(see "Estimating Your Thyroid Cancer Risk," facing page).*

In the U.S., it took a number of years for the differences in dose and cancer risk from regional and global fallout to be understood. We have learned that the internal doses from global fallout were considerably smaller for the thyroid, but greater for the red bone marrow, than those from Nevada fallout, whereas the doses from external irradiation were similar for Nevada and for global fallout.

We estimate that in the U.S. the primary cancer risks from past exposure to radioactive fallout are thyroid cancer and leukemia, whereas in a very few cases—for example, the Marshall Islands—large internal doses as a result of ingestion of radionuclides have led to significant risks of cancers in the stomach and colon. Our research has quantified the likely number of cancer cases to be expected in the U.S. from Nevada exposures and has contributed to the assessment of risk at other worldwide locations.

Nuclear testing in the atmosphere began 60 years ago. It ended in 1980, in part because of public concerns about involuntary exposure to fallout. By that time, increased cancer risk had been established as the principal late health effect of radiation exposure, based primarily on studies of populations exposed to medical x rays, to radium and radon decay products from the manufacture of luminescent (radium) watch dials and in uranium mining, and to direct radiation from the atomic bombings of Hiroshima and Nagasaki. Since then, organ-specific dose-response relationships for radiation-related risks of malignant and more recently benign disease (for example, cardiovascular disease and benign neoplasms of various organs) have been increasingly well quantified with further follow up of these and other populations, and it is increasingly clear that radiation-related risk may persist throughout life. Fallout studies have substantially clarified the consequences of exposure to specific organs from internal contamination with radioactive materials—for example, I-131 in the thyroid gland—and there is every reason to believe that, on a dose-specific basis, increased risks from fallout should be similar to those from other radiation sources. Our improved understanding of individual radionuclides, radiation dose and related health risk is due in part to decades of study of fallout from nuclear testing; that same understanding today makes us better prepared to respond to nuclear terrorism, accidents or other events that could disperse radioactive materials in the atmosphere.

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