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Energy AND Security

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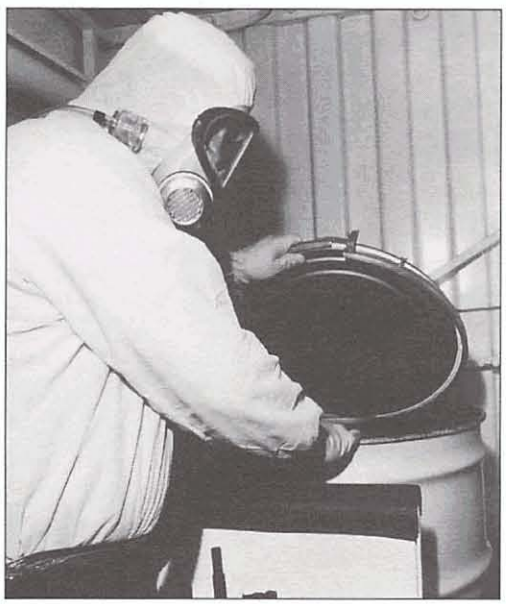
Health Risks of Ionizing Radiation

BY DAVID SUMNER, HOWARD HU, AND ALISTAIR WOODWARD*



▲ *A worker at the nuclear weapons production plant near Fernald, Ohio, loading thorium into drums.*

Ionizing radiation can cause stochastic (random) and deterministic (or nonstochastic) effects. Deterministic effects appear if a minimum radiation dose is exceeded. Above that threshold, the effects are readily observed in most or all exposed people and the severity increases with dose. The occurrence and severity of a deterministic effect in any one individual are reasonably predictable. A radiation burn is an example of a deterministic effect.

In adults, nonstochastic effects dominate when the dose to the entire body is more than about one sievert. An exception is temporary sterility in the male, which can occur with a single absorbed dose to the testis of about 0.15 grays.[1] With respect to children, the threshold for congenital malformations and other developmental abnormalities has been estimated to be 0.25 grays of radiation exposure up to 28 days of gestation.

Single radiation doses over about 1 gray cause radiation sickness; acute effects include nausea, vomiting, and diarrhea, sometimes accompanied by malaise, fever, and hemorrhage. The victim may die in a few hours, days, or weeks. Other acute effects can include sterility and radiation burns, depending on the absorbed dose and the rate of the exposure. The dose at which half the exposed population would die in sixty days without medical treatment is called the LD50 dose (LD for lethal dose, and 50 for 50 percent). It is about 4 sieverts for adults [see p. 7 for dose definitions]. The sixty-day period is sometimes explicitly identified, and the dose is then called the LD50/60 dose. In general, a number of different LD50 doses can be specified, depending on the number of days, T, after which the observations of death are cut off.

For radiation doses less than about 1 sievert, stochastic effects have been the greatest concern. The most important stochastic effects, cancer and inheritable genetic damage, may appear many years or decades after exposure. It is thought that there is no minimum threshold for these effects; as dose decreases the effects are still expected to occur, but with lower frequency. However, the uncertainties at low doses (10 millisieverts or less) are very large. Estimates of the magnitude of low-dose radiation effects have tended to rise

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IEER staff are frequently asked about the health effects of radiation. In this issue of *Energy & Security* we have compiled some basic technical information on how those effects are calculated, and regulations limiting radiation doses to workers and the public. On p. 6, you will find an expanded "Science for the Critical Masses" section which includes basics of radioactive decay, dose and dose units, international radiation protection standards, and U.S. limits on emissions of some radionuclides to the air and water. The article on p. 3 discusses uranium mining and milling, which has been the most damaging step of the nuclear fuel cycle, affecting large numbers of people, including many in countries without nuclear power or nuclear weapons. The article on p. 2 outlines different kinds of health studies, along with some of the uncertainties and complications inherent in interpreting their results. The results of a recent study on cases of leukemia near the La Hague reprocessing facility in France are outlined on p. 14.

Epidemiological and Dose Reconstruction Studies

BY ANITA SETH AND ARJUN MAKHIJANI

Epidemiological studies analyze the occurrence and distribution of disease among populations. In general, these studies aim to determine the association (if any) between exposures to suspected disease-causing agents and health effects by comparing populations. There are three types of common epidemiological studies. Case-control studies compare exposures of people who have a certain disease against those who don't. Cohort studies examine the differences in disease rates between exposed and non-exposed populations. Ecological studies study the rate of disease of a population in a given geographical area based on average measures of exposure. Because ecological studies are not based on the actual exposure of individuals, they are less sophisticated than the other two types of studies, and results should be treated with caution.

In cohort studies, where a well-defined exposed population exists, epidemiologists calculate the *relative risk* or risk ratio of the exposed population by examining the rate of disease or death among exposed populations and dividing it by the rate in non-exposed populations. Epidemiological studies may also compare the number of cancer deaths in a studied population with the rates among the general population. The attributable or excess risk is calculated by taking the difference (as opposed to ratio) between disease or death rates in exposed and non-exposed populations. In all epidemiological studies, it is important that the populations studied be adjusted for factors such as age, gender, and lifestyle habits (such as smoking), because disease rates can differ greatly across different groups.

Dose reconstruction studies estimate the exposure of individuals or of a population to a disease-producing agent like radiation. In order to estimate exposure, it is essential to know the amount of a pollutant released to a particular medium, such as air or water, from a source of pollution (called a source term), or to have an accurate history of concentrations of pollutants in air, water, and soil. Pathway analysis clarifies the often complex ways in which pollutants reach people through the environment, allowing release estimates to be converted to dose estimates. For example, pollutants can be both inhaled from the air, and ingested through drinking contaminated water or eating contaminated food. In addition, a population may receive both external and internal doses. Dose reconstruction studies can be conducted independently of epidemiological studies, but they can also help epidemiologists group together exposed populations more precisely.

Dose reconstruction and epidemiological studies can be powerful tools in determining the relationship between a pollutant and a health outcome. However, there are a number of complications which can cloud their results.

- Incorrect or incomplete data on pollutants. In general, it is easier to estimate doses to workers, who are often

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The Uranium Burden

BY ROBERT BROOKS AND ANITA SETH

From the time of its discovery in 1789 to the early 1900s uranium was used for color and glazing in ceramics and glass-making.[1] From the early 1900s to the 1930s, it was discarded as a waste from radium production (which was used in medical applications and to make instrument and watch dials luminous). It was only with the discovery of nuclear fission in 1938 that uranium was mined on a large scale. Though found throughout the world in trace quantities, uranium is often mined where concentrations are 0.1 to 0.5 percent of ore. On rare occasions it can be found in concentrations over 10 percent, such as in the Saskatchewan reserves of Canada, or even greater. There are four common methods for mining:

- open pit;
- underground;
- *in situ* leach mining which consists of injecting solvents such as hydrochloric acid, alkaline carbonate and hydrogen peroxide underground to dissolve the uranium from the ore body. Waste solutions are pumped back into the ground; and
- heap leaching, which is used to recover uranium as a by-product from extremely low-grade ores resulting from gold and phosphate mining. This process involves repeatedly percolating a solution (typically sulfuric acid or ammonium carbonate) through an ore pile to dissolve uranium, until its content in the solution becomes high enough for extraction.

PHOTO BY ROBERT TREDICI

Uranium tailings pile (Starock Tailings Wall), Elliot Lake, Ontario Canada. Mill tailings make up over 95 percent of the volume of radioactive wastes from the nulcear fuel cycle (excluding mine wastes).

Uranium milling consists of extracting the uranium from the ore and processing it into an oxide powder that can be shipped. Both the mining and milling process expose the workers, nearby residents and the environment to various hazards. To understand these it is first necessary to understand the make-up of uranium ore.

Natural uranium consists of three alpha-emitting isotopes: U-238, U-235 and U-234. These isotopes also emit some gamma radiation. U-238, the most prevalent of these isotopes (almost 99.3 percent in natural uranium) has a half life of about 4.5 billion years. The half lives of U-235 (about 0.7 percent) and U-234 (which is only 0.005 percent of content but accounts for almost half of uranium's radiation) are 704 million years and 245,000 years respectively. Decay of uranium-238 gives rise to many radioactive decay products, including thorium-234 and -230, radium-226, radon-222 and polonium-218 and -214. These decay products are always found together with natural uranium in ores.

Uranium is both radioactive and a chemical toxin. Outside the body, natural uranium poses a slight hazard because of its relatively weak gamma ray emissions (unless exposure is prolonged). Once inhaled or ingested, it can increase the risks of lung and bone cancer due to its alpha emissions. The decay products of uranium-238 pose additional health hazards. Thorium-234 decays in place while thorium-230 tends to be taken up in the bone. Polonium is distributed in soft tissues as well as bone. Radium is similar to calcium and accumulates on the surface of the bones and later in the matrix of bone structure. It is a known agent of bone cancer, as was discovered in the 1920s through the unfortunate fate of radium dial painters who inadvertently ingested radium when licking the tips of their brushes to produce a fine point.

The gas radon-222 is a decay product of radium-226, and has a half life of 3.82 days. Conventional underground mining is the most dangerous to workers because of higher exposure to radon decay products. Workers inhale the polonium-218, lead-214, bismuth-214 and polonium-214 in the air. The decay of these radionuclides in the lung has been the chief route of exposure of uranium miners and is historically responsible for the elevated levels of cancer they incur. Exposure to radon and its decay products is measured in working levels and working level months (see p. 7).

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over the years, but remain the subject of controversy.

Because ionizing radiation can damage the genetic material of virtually any cell, cancer can occur in many sites or tissues of the body. The actual effect depends in part on the route of exposure. For example, external radiation, such as X rays or gamma radiation, can affect DNA in blood-forming cells or in many organs in ways that cause cancers of these organs decades later. It should be noted that tissues vary in their sensitivity to radiation damage. For instance, muscles are less sensitive than bone marrow.

There are many pathways by which the body can be exposed to internal irradiation. Decay products of radon, which are present in an underground uranium mine, may be inhaled by miners and end up in their lungs. Particles of plutonium-239 or other actinides, which emit mostly high-LET alpha particles, may be inhaled and deposited on the epithelial lining of bronchi in the lung. A radiation dose from such exposure pathways increases the risk of lung cancer. In addition, soluble particles may be absorbed and distributed through the blood or lymph systems to other parts of the body. Some elements, such as radium, strontium, or iodine, tend to accumulate in certain organs. For example, iodine-131 delivers its principal ionizing radiation dose to the thyroid gland, making that the most likely site of a resultant cancer. Iodine-131 is also used to combat thyroid cancer, since the emitted radiation destroys the cancerous cells along with healthy ones. But when there is no disease in the thyroid, the radiation affects only healthy cells.

Estimating the Risk of Cancer from Ionizing Radiation

Various institutions have estimated the risk of cancer following exposures to ionizing radiation, particularly the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the U.S. National Academy of Sciences Committee on the Biological Effects of Ionizing Radiation (BEIR), and the International Commission on Radiological Protection (ICRP). These estimates are derived mainly from studies of the survivors of the Hiroshima and Nagasaki bombings, and also from various groups of people given radiation for therapeutic and diagnostic purposes or who have been exposed at work, such as radium dial painters and uranium miners.

Studies of survivors of the atomic bombings of Hiroshima and Nagaski indicate statistically significant excess cancers for doses greater than 0.2 grays. These doses were delivered suddenly, following explosions. A number of problems arise when using such data to estimate cancer risks for lower doses of ionizing radiation or doses delivered in gradual increments.

The first problem is how to extrapolate the dose-response relationship down to low doses. It is usually assumed that a "linear no-threshold" model applies—

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LOW-LEVEL RADIATION

Radiation doses at which biological effects cannot be immediately observed are classified under the general rubric of "low-level radiation." Since different physical effects are observed at different radiation levels, this has given rise to some confusion about what levels constitute low-level radiation.

Depressed white blood cell count can occur with doses as low as 0.1 gray (Gy). However, since stochastic effects, notably cancer, are the predominant long-term effect of doses below 1 Gy given at one time, many authorities use this level below this as "low-level radiation." Larger doses given over long periods of time also fall into the category of low-level radiation so long as they do not produce immediately observable effects. For instance, radiation doses of .05 Gy per year over 30 years amount cumulatively to 1.5 Gy, but would still count as low-level radiation, because there are no deterministic effects. In sum, the term low-level radiation should not be understood to mean the absence of risk or low levels of total energy deposited in the body, but levels of radiation dose that do not produce immediate observable effects.

The rate so far experienced by Hiroshima and Nagasaki survivors is about 0.08 fatal cancers per sievert of dose, as estimated in the BEIR V report. This is called the unadjusted risk rate for low-level radiation because it is the rate for a single dose experienced in a short time. It is common practice, based mainly on animal studies, to assume a lower risk rate—about 0.04 to 0.05 fatal cancers per sievert when doses are experienced over long periods of time. This is the adjusted risk factor. While there is published literature that claims both higher and lower risks per unit of radiation exposure, our view is that these unadjusted and adjusted coefficients are a reasonable set to use. Lower estimates of risk, advocated by some in academia and industry would, in our view not be sound public health practice because they resolve uncertainties in favor of higher exposures.

—ARJUN MAKHIJANI

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that is, the risk is directly proportional to dose, with no threshold. Because the main effect of low-dose radiation is the induction of cancer, and cancer is a common disease with many causes, it is not yet possible to verify the linear no-threshold model; nevertheless, there is considerable radiobiological evidence for this theory and it is generally used for public health protection purposes, such as setting standards.

The second problem is that some assumption has to be made about how calculations of cancer risk will change in the future. After all, more than half the Hiroshima and Nagasaki survivors are still alive. At present, the data best fit a relative-risk model-that is, the cancer risk is proportional to the «spontaneous» or «natural» cancer risk. If this is correct, there will be an increasing number of radiation-induced cancers later in life.

A third problem is that the relative biological effectiveness of radiation depends partly on the energy of the radiation. For instance, data indicate that low energy neutrons and alpha particles may be more effective in producing biological damage than high energy particles (per unit of absorbed energy).[2] Thus, assuming a constant quality factor, as is common practice, can sometimes yield an inaccurate estimate of the dose.

Finally, there are uncertainties related to the effect of low doses and low dose rates of low-LET radiation. The conclusion of the BEIR Committee, ICRP, and others is that low doses and dose rates of low-LET radiation are less effective in producing cancer, particularly leukemia, than would be expected based on linear extrapolation of data for low-LET radiation at high doses and high dose rates (i.e., the effect is nonlinear at low doses and dose rates). Unfortunately, the epidemiological database for evaluating the validity of DREF adjustments is sparse.

Despite these potential limitations, most cancer projections continue to utilize the cancer risk factors estimated by established radiological protection committees. Their current estimates are as follows:

- UNSCEAR, 1993:[3] 0.11 fatal cancers per person-sievert for high doses (comparable to those experienced by the survivors of the Hiroshima and Nagasaki bombings). For low doses, UNSCEAR states that "no single figure can be quoted" for the risk reduction factor, "but it is clear that the factor is small. The data from the Japanese studies suggest a factor not exceeding 2."[4] For a population between the ages of 18 and 64 (corresponding to the ages of people in a typical industrial work force), a factor of 2 yields a fatal cancer risk at low dose rates of 0.04 per person-sievert.
- BEIR Committee, 1990:[5] 0.08 fatal cancers per person-sievert for a single dose of 0.1 sievert, based on Hiroshima and Nagasaki survivor data. This figure is unadjusted for any reduction of risk at low dose rates.
- ICRP, 1991:[6] 0.05 fatal cancers per person-sievert for the entire population and 0.04 fatal cancers per person-sievert for adult workers, with both estimates being for low doses and incorporating a dose rate reduction factor of 2.
- The U.S. Environmental Protection Agency uses a cancer incidence risk factor of 0.06 per person-sievert.[7] Since the cancer incidence rate is about 50 percent greater than the cancer fatality rate, the implicit risk for fatal cancers is about 0.04 per person-sievert.

Estimates of the risk per unit dose may be revised substantially again (upward or downward). As the BEIR committee points out:

Most of the A-bomb survivors are still alive, and their mortality experience must be followed if reliable estimates of lifetime risk are to be made. This is particularly important for those survivors irradiated as children or in utero who are now entering the years of maximum cancer risk.[8]

* Used with permission from *Nuclear Wastelands*, Arjun Makhijani, Howard Hu, and Katherine Yih, eds. (Cambridge: MIT Press, 1995), Chapter Four "Health Hazards of Nuclear Weapons Production." Explanatory footnotes not reproduced.

1 1990 Recommendations of the International Committee on Radiological Protection. ICRP Publication 60. *Annals of the ICRP*, vol. 21, no. 1–3. Oxford, New York: Pergamon Press, 1991, p. 15.

2 National Research Council, Committee on the Biological Effects of Ionizing Radiations. *Health Effects of Exposures to Low Levels of Ionizing Radiation, BEIR V*. Washington, D.C.: National Academy Press, 1990, pp. 27–30.

3 United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR). *Sources, Effects, and Risks of Ionizing Radiation*. New York: United Nations, 1993, pp. 16–17.

4 Ibid, p. 17.

5 National Research Council 1990, pp. 5–6.

6 ICRP 1991, pp. 69–70.

7 U.S. Environmental Protection Agency. *Issues Paper on Radiation Site Cleanup Regulations*. EPA 402-R-93-084. Washington, D.C.: Office of Radiation and Indoor Air, September 1993, p. 7.

8 National Research Council 1990, p. 8.

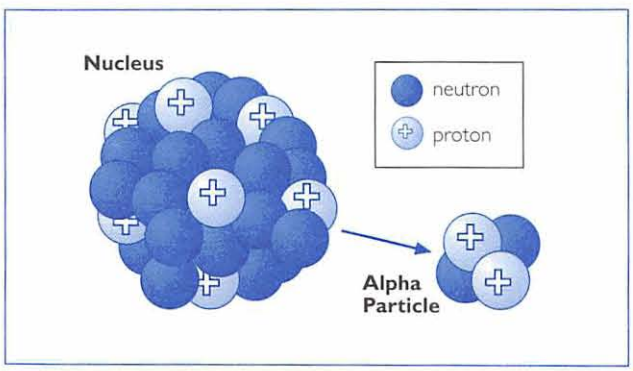
Radioactive Decay

Radioactive elements have unstable nuclei, meaning they are transformed into other elements, typically by emitting particles (and sometimes by absorbing particles). This process, called radioactive decay, generally consists of the emission of alpha or beta particles from the nucleus. Some radionuclides transmute into stable elements after one decay, but in the case of others, the new elements formed by the process of decay are also unstable. With heavy isotopes like uranium-238 a series of decays into new elements occurs before a final stable element is formed. This is known as a decay chain. The half-life of a radionuclide refers to the amount of time it takes for half of the atoms in any sample to undergo radioactive decay.

An alpha particle is the nucleus of a helium atom (with two neutrons and two protons each). Many heavy radionuclides, such as uranium-238 and plutonium-239, decay mainly by emitting alpha particles.

For example the decay of plutonium-239 results in uranium-235 with the emission of an alpha particle:

$_{94}$Pu-239 —— $_{92}$U-235 + $_{2}$He-4

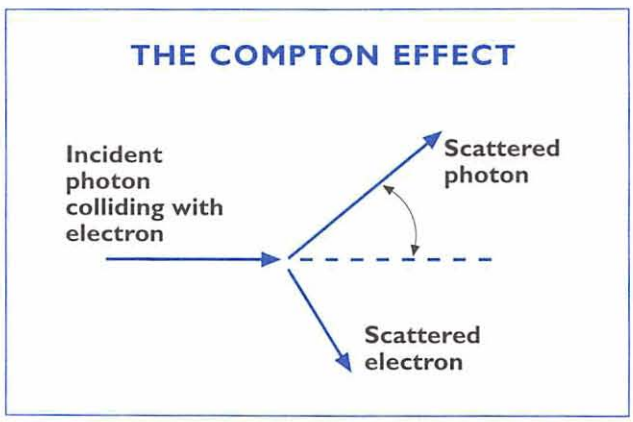


The alpha particles emitted carry a lot of energy, averaging about 5 million electron volts. A helium atom at room temperature has an energy of .025 electron volts. It is the large amount of energy associated with particles emitted by radioactive decay being deposited in cells that causes biological damage through ionization.

Alpha particles, being heavy, transfer their energy to other atoms and molecules within a shorter distance than the far lighter electrons which are the primary means of radiation damage for both gamma and beta radiation. Outside of the body, alpha particles do not pose a health hazard, since they do not penetrate the outer, dead layer of skin. However, once inside the body through ingestion, inhalation or through cuts and abrasions, alpha particles are very damaging, because they travel only a short distance within living tissue, repeatedly bombarding the cells and tissue nearby.

A beta particle is an electron or a positron (a positively charged particle otherwise identical to an electron). Beta particles are much lighter than alpha particles, and travel much further. If they are sufficiently energetic, they can penetrate the skin. Some beta-emitters therefore can pose a health hazard, especially to the lymphatic system, even when outside of the body. Most beta radiation can be stopped by light shielding, such as a piece of wood, though some, such as that from sodium-24 requires heavier shielding.

Radioactive decay is often also accompanied by emission of gamma radiation, which is very high frequency electromagnetic radiation, like X-rays. It takes heavy shielding such as lead to stop gamma rays. Gamma rays consist of photons, which are "packets" or quanta of electromagnetic energy. Emission of photons from a nucleus does not result in a transmutation. Gamma ray photons produce ionization (and hence biological damage). The incident photon collides with an electron in an atom (or molecule) and knocks it out, imparting some energy to it. A less energetic photon (the "scattered" photon) is also emitted in this process, which is called the Compton Effect.



These electrons, the electrons generated by further collisions, as well as electrons produced by the new photons, are responsible for the damage caused by gamma radiation.

Alpha, beta, and gamma radiation have very different properties in some respects, but are all ionizing radiation—that is, each is energetic enough to break chemical bonds, and thus possess the ability to damage or destroy living cells. Visible light, like gamma rays, is also electromagnetic energy, but of lower frequency. Visible light photons are not energetic enough to cause ionization. Radio waves are of even lower frequency than visible light.

Radiation Doses

Radiation exposures to individuals are measured by the amount of energy deposited in their bodies; exposures to populations are measured by adding up the individual doses in that population.[1] The unit of radiation dose is the gray. It is a measure of the amount of ionization caused by the radiation and is a strictly physical unit. Other factors such as the type of radiation involved (alpha, beta, etc.) and the parts of the body exposed affect the biological effect of the radiation. When corrections are made for these factors, the unit used is the sievert . . . .Where the total dose to groups or populations is being considered, units such as person-sieverts are used. Population doses are measured in person-grays and person-sieverts (person-Sv), depending on whether energy deposition or biological damage is being measured.

Two further units apply to uranium mines. The working level (WL) is the quantity of radon decay products (also called radon daughters or radon progeny) in one liter of air that will result in the emission of 130,000 million electron volts of alpha-particle energy. If the radon progeny are in equilibrium with radon in the air (that is, if the radon has remained in the air for some time), then about 100 picocuries (3.7 becquerels) of radon per liter of air equals one working level. The working level month (WLM) measures the total radiation dose a miner would receive by breathing air containing a concentration of 1 working level for one working month (170 hours).

Radiation doses may be due to sources outside the body or to substances that have entered the body in the course of eating, drinking, or breathing, or through a wound. It is relatively straightforward to estimate radiation doses due to gamma rays and beta particles from outside the body, provided a person wears appropriate measuring equipment, such as a film badge. However, it is generally much harder to estimate doses from substances inside the body. The size of the dose will depend on the chemical form of the material, its pathways and distribution in the body, and the rate of its elimination from the body, among other factors. The elimination of a radionuclide from the body is generally quite a complex phenomenon; it can be very approximately described by the concept of "biological half-life"-the time it takes for half the material to be eliminated from the body.

When estimating doses from environmental radioactivity, direct measurements are almost never available for the amounts of particular radionuclides in the body. Complex computer models have to be used, often with large numbers of parameters and associated uncertainties. This is especially true of dose estimation for off-site populations where there are no direct measurements for dose or for body-burdens of radioactive materials. However, radionuclides in food, water,

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UNITS OF RADIATION AND DOSE

Becquerel (Bq): The standard international (SI) unit of radioactivity equal to one disintegration per second. It is a very small unit equal to about 27 picocuries.

Curie (Ci): The traditional unit of radioactivity equal to the radioactivity of one gram of pure radium. It is equal to 37 billion disintegrations per second (37 billion becquerels).

Rad (radiation absorbed dose): a unit of absorbed dose of radiation defined as deposition of 100 ergs of energy per gram of tissue.

Gray (Gy): A unit of absorbed radiation dose equal to 1 joule per kilogram or 100 rads.

Roentgen: The old unit of radiation exposure. It is a unit of gamma radiation measured by the amount of ionization in air. In non-bony biological tissue, a roentgen delivers a dose equal to about 0.93 rad.

Rem (radiation equivalent man): A unit of absorbed dose of radiation, which takes into account the varying amounts of biological damage caused by different kinds of ionizing radiations (known as relative biological effectiveness or RBE). While rads measure deposition of energy in tissue, rems measure biological damage. Rems are derived from rads by multiplying rads by a "quality factor" which approximates the RBE. For beta and gamma radiation the quality factor is taken as one—that is, rems equal rads. For alpha radiation, the quality factor is taken as 20—that is rems equal 20 times rads.

Sievert (Sv): The unit for measuring biological damage of 1 gray; equal to 100 rems.

Person-Sievert: The unit used to measure the population dose, which is the sum of individual doses in a defined population.

Working level (WL): Unit of dose used in uranium mining. A working level measures the alpha energy released from radon and its decay products in one liter of air. If the radon has remained in the air for some time, then 1 WL is equal to about 100 picocuries of radon per liter of air.

Working level month (WLM): The exposure to an average of 1 WL for a working month of 170 hours.

Effective Dose Equivalent

When radioactivity is taken into the body, the dose received is due to the energy imparted to internal organs such as the lung, thyroid, or bones.[1] A *dose conversion factor* (DCF) coverts an amount of radioactivity (expressed in curies or becquerels) into a dose (expressed in rems and sieverts). The DCFs used for regulatory purposes are derived from a combination of experimental data and mathematical models. The DCF for a given radionuclide depends upon the half-life of the radioactive material and the type of radiation emitted (alpha, beta, gamma). It also depends on how easily that radioactive material passes through the body. For inhaled materials, this is indicated by the solubility of the radioactive material. For ingested material, this is indicated by the uptake fraction; the fractional amount taken up by the blood from the small intestine.

Solubility refers to how likely a material is to dissolve in water. Once absorbed, insoluble material generally spends more time in the body, and therefore does more damage. This explains why, for most radionuclides, insoluble forms have greater DCFs than more soluble forms. Similarly, radionuclide forms with smaller uptake fractions will spend less time in the body, resulting in less damage and a smaller DCF for a given intake of radioactivity.

Radiation standards for workers and non-workers are expressed as whole-body dose equivalents. But in reality, the body is rarely if ever uniformly irradiated, and certain parts of the body or organs are often more affected than others. This is because radionuclides taken into the body are distributed unequally among organs (for example, radioactive iodine concentrates in the thyroid, inhaled plutonium disproportionately affects the lungs, and strontium is deposited in bones). In addition, it is possible that only a portion of the body might be exposed to an external radiation source.

The *effective dose equivalent* is a way of converting the actual complicated process of radioactive intake into a simplifed concept of a uniform whole-body dose—that is, an equivalent of what an actual localized dose means to the overall body. It is a way of quantifying the increased chance of harm expected as a result of the dose, measured mainly by excess fatal cancers and hereditary disease. Effective dose is meant to allow the comparison between different types of radiation exposure and exposure to different organs.

To determine if a person has received a radiation dose above a recommended limit, a single DCF, pertaining to a particular organ or the "effective" DCF, is used. The organ chosen is then referred to as the "standard-setting organ." The effective dose is calculated by taking doses to individual organs and converting them to equivalent whole-body doses by using weighting factors. These figures are then added up to calculate the total dose. These weighting factors are shown in the box below. So, for example, a dose of 20 rem to the thyroid is equivalent to an effective dose equivalent to 0.6 rem.

WEIGHTING FACTORS FOR ORGAN DOSES

Organ or tissue	Weighting factor (W_T)
Gonads	0.25
Breast	0.15
Red bone marrow	0.12
Lung	0.12
Thyroid	0.03
Bone surfaces	0.03
Remainder*	0.30

* The five remaining organs or tissues receiving the highest dose equivalents are each assigned a weighting factor of 0.06 (excluding the skin, lens of the eye, and the extremities).

It is possible to have single or continuous intake of radiation. Single intakes tend to happen in unusual circumstances, such as accidents. A continuous intake could result from living near a nuclear facility that regularly releases radioactivity into the air or water.

Even when intake of radioactivity into the body takes place in a very brief period of time (as in a single intake), the material remains in the body for some time and hence the dose from that material is imparted over a period of time. The period of time depends on the half-life of the material that is taken into the body and the amount of time it stays in the body (dominated by the smaller of these numbers). The dose expected over the effective lifetime of the radioactivity in the body is the *committed dose*. The *committed dose equivalent*, established by the ICRP, is the dose equivalent deposited over the 50 years after the intake of the radionuclide.

1 This article is adapted from Kevin Gurney, "DCFs," *Science for Democratic Action*, vol. 2, no. 3 (Fall 1993), p. 8.

U.S. NRC Concentration Limits for Air and Water

The table below lists the limits set by the United States Nuclear Regulatory Commission (NRC) on concentration in air and water of some isotopes commonly found around nuclear facilities. These standards apply to facilities licensed by the NRC (such as commerical uranium processing facilities and nuclear power plants), and are applied to members of the public. Occupational exposure limits for nuclear facility workers are higher.

These concentration limits are calculated such that a dose limit of 50 millrems per year is not exceeded for each radionuclide. They assume that a given radionuclide is the only one inhaled or ingested; allowable concentrations are proportionately reduced if more than one radionuclide is present.

These standards exclude background radiation, which is defined as "radiation from cosmic sources; naturally occurring radioactive materials, including radon (except as a decay product of source or special nuclear material) and global fallout as it exists in the environment from the testing of nuclear explosive devices."[1] In other words, background radiation is counted in addition to these allowable limits. However, if another facility is located nearby (such as multiple plants in a complex), *the combined* emissions from these facilities must be lower than the allowable limit.

1 Nuclear Regulatory Commission, 10 CFR Part 20.1002, (Washington, D.C.: US Government Printing Office, 1994), p. 304.

Radionuclide	Solubility	Air Conc. Limits (pCi/l)	Water Conc. Limits (pCi/l)	Health effects
Hydrogen-3 (Tritium)	Insoluble Soluble	100 100	1,000,000* 1,000,000	Low-energy beta-emitter. When in the form of water, it can become organically bound by hydrogen atoms in a body's cells. As water, it crosses the placenta and irradiates the fetus when a pregnant woman is exposed.
Strontium-90	Insoluble Soluble	0.006 0.03	— 500	Beta-emitter. Behaves like calcium and concentrates in bones.
Iodine-131	Insoluble Soluble	0.2 0.2	1000 1000	Beta-emitter. Concentrates in the thyroid, especially via the milk pathway.
Cesium-137	Insoluble Soluble	0.2 0.2	1000 1000	Beta- and gamma-emitter. Resembles potassium and collects in muscles.
Radon-222	no decay products with decay products	10 0.1	— —	Damage mostly from short-lived alpha-emitting decay products deposited in bronchial walls and can cause lung cancer.
Radium-226	Insoluble Soluble	0.0009 0.0009	60 60	Alpha-emitter. Similar to calcium, concentrates in bones. Primary route of exposure is ingestion.
Natural uranium	Insoluble Somewhat soluble Soluble	0.00009 0.0009 0.003	— — 300	Primarily alpha-emitter, also chemically toxic, esp. to kidney. Inhalation or ingestion increases chances of lung and bone cancer.
Plutonium-239	Insoluble Somewhat soluble Soluble	0.00002 0.00002 —	— 20 —	Alpha-emitter. Main health danger comes from inhalation of fine particles or incorporation in cuts.
Americium-241	Insoluble Soluble	0.00002 0.00002	20 20	Alpha- and gamma-emitter. Decay product of pu-241; of special concern for workers handling reactor-grade pu.

Source: Nuclear Regulatory Commission, 10 CFR Part 20, Appendix B (Washington, D.C.: US Government Printing Office, 1994).

* Drinking water standards set by the Environmental Protection Agency (EPA) are based on a limit of 4 millirem per year via drinking water pathway only. So allowable concentrations under the EPA would be generally less than 1/10 of those given in the table. In the case of a few radionuclides, like tritium, the allowable limit is even lower (20,000 pCi/l).

Radiation Protection

Radiation protection regulations are based on three basic recommendations originally made in 1977 by the ICRP and reaffirmed later:[1, 2]

- **Justification:** No practice involving exposures to radiation should be adopted unless it produces enough benefit to the exposed individuals or to society to offset the radiation detriment it causes.
- **Optimization:** Exposures to radiation should be as low as reasonably achievable.
- **Individual dose and risk limitation:** No individual should receive radiation doses higher than the maximum allowable limits.

The most difficult of these principles, and certainly the one that is rarely adequately addressed, is justification. Assessing the likelihood that any practice will produce a net benefit involves many value judgments that are difficult, if not impossible, to quantify. ICRP recognizes this:

> The Commission recommends that, when practices involving exposure, or potential exposure, to radiation are being considered, the radiation detriment should be explicitly included in the process of choice. The detriment to be considered is not confined to that associated with radiation-it includes other detriments and the costs of the practice. Often, the radiation detriment will be a small part of the total. The justification of a practice thus goes far beyond the scope of radiological protection . . . . To search for the best of all the available options is usually a task beyond the responsibility of radiological protection agencies.[3]

This point is expanded in a statement by the Committee on Radiation Protection and Public Health of the OECD Nuclear Energy Agency:

> Decisions about the justification of a practice or activity involving radiation exposure usually involve a broad range of social, economical and political issues in addition to those concerning radiological protection . . . . Justification is essentially a political decision-making process, in which the technical and purely radiation-related advantages or detriments play an important, but relatively limited role.[4]

In the early years of nuclear weapons development, the scientists and administrators involved implicitly assumed that national security justified the risks of the enterprise. According to J. Newell Stannard, "In 1947, the data for plutonium and the other actinides were used at a series of three-nation conferences on radiation exposure limits . . . . They required careful interpretation, for the most conservative interpretation could have closed Los Alamos." [5]

The principle of justification continues to be a cornerstone of ICRP philosophy, but the application of this principle to a particular situation in the nuclear industry, whether civil or military, is rarely discussed.[6] Optimization implies that measures will be taken to reduce exposures until the benefits of further reductions do not justify their cost. It is not clear how this principle can be rigorously applied, particularly as it requires some quantitative estimate of the monetary value of a life saved. In practice, optimization is applied in two ways: as an exhortation to use "best available technology" and as a recognition that merely complying with dose limits is not enough. If further dose reductions are practicable at reasonable cost, they should be made. Optimization generally refers to collective rather than individual radiation doses.

The principal dose limits recommended in ICRP Publication 26 (1977) were 50 millisieverts (5 rem) per year for radiation workers and 5 millisieverts (500 millirem) per year for members of the public. A subsidiary recommendation to keep doses to the public below 1 millisievert per year if possible has slowly become the primary long-term dose limit for the public, with short-term exposures of 5 millisieverts per year allowed.

The ICRP intended these limits to apply to the total exposure from all sources except natural background radiation. It has developed a methodology for combining the doses from different sources-such as combining exposures from inhaling ore dust with those from gamma exposure-and it is this total that should be compared with the appropriate limit.

In 1991, the ICRP revised its radiation protection standards, largely in response to reevaluation of dosimetry and cancer risk among atomic bomb

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RADIATION DOSES

FROM PAGE 7

and air can be measured. If done carefully, such measurements can provide a basis for estimating doses. If internal burdens are large, techniques such as whole-body counting (called *in vivo* measurements) and urine sampling can also be used.

1 Used with permission from *Nuclear Wastelands*, Arjun Makhijani, Howard Hu, and Katherine Yih, eds. (Cambridge: MIT Press, 1995), Chapter Four "Health Hazards of Nuclear Weapons Production."

RADIATION PROTECTION

FROM PAGE 10

survivors.[7] The most significant change lowered the worker's annual limit to 20 millisieverts. (Public dose limits were lowered to 100 mrem.) Regulations do not yet widely reflect this change.

1 Recommendations of the International Committee on Radiological Protection. ICRP Publication 26. *Annals of the ICRP*, vol. 1, no. 3. Oxford, New York: Pergamon Press, 1977, p. 3.

2 ICRP 1991, p. 28.

3 ICRP 1991, para.115.

4 Nuclear Energy Agency, Committee on Radiation Protection and Public Health. Applicability of the ICRP principle of justification of a practice to radiological protection standards. *Journal of the Society for Radiological Protection*. vol. 2, no. 4 (1982), p. 15.

5 J. N. Stannard. Radioactivity and Health: A History. Prepared for the U.S. Department of Energy, Office of Health and Environmental Reserach. Oak Ridge, Tennessee: Office of Scientific and Technical Information, U. S. DOE. October 1988.

6 QUEST Radiation Database (1992) gave just 5 references to "justification" but 91 to the principle of optimization. (*QUEST Radiation Data Base*. Vol 2.6, 1992. [Produced and distributed by Radiation Technology, Inc., P;. O. Box 10457, Silver Spring, MD 20914, USA.])

7 ICRP 1991.

PUZZLE

Keeping track of units of dose can be very complicated. Sharpen your dose calculating skills in the following problem.

In the Deep Canyon uranium mine, radon levels are 100 picocuries per liter of air. What would be the absorbed dose in rad to the lung of a miner working there for one month? For one year? The answer will be published in the next issue.

Some useful information and assumptions (also see the definition of working level on p. 7):

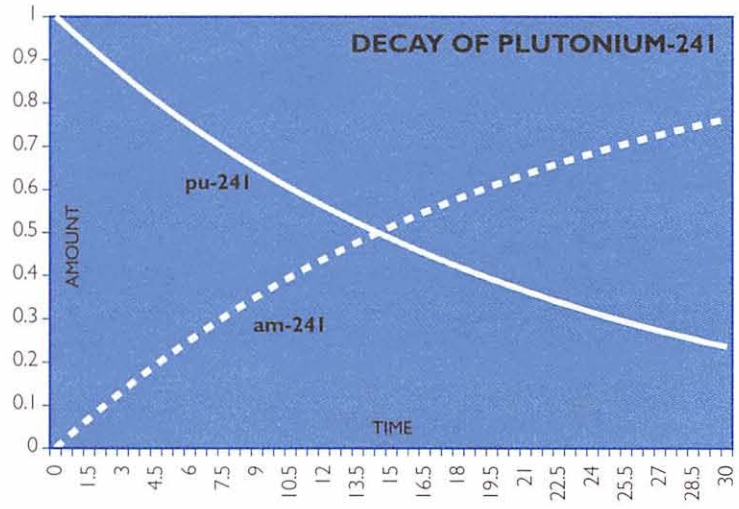
- 1 WL = 2.08 x 10^{-8} joules (J)/liter
- The amount of air breathed for one hour by a miner doing heavy work is estimated to be 2000 liters.
- 1 WLM = exposure to 1 WL for 170 hours.
- 1 gray = 100 rads = 1 J/kg
- The weight of an adult's lungs is estimated to be 1.2 kg

ANSWER FROM LAST ISSUE

Whoops! We failed to provide adequate information for readers to be able fill in the missing values of the table on p. 8 in the last Science for the Critical Masses. Below you will find a chart showing the decay of plutonium-241, and accumulation of americium-241. As we mentioned in the last issue, we have ignored the decay of americium-241 for simplicity and because 28.8 years is short compared to its half-life of 432 years. Looking at the chart, you can find the values that were missing from the table (now in bold).[1]

Answer from *Energy & Security* no. 3

Isotope	Initial composition	after 2 years	after 5 years	after 14.4 years	after 28.8 years
plutonium-241	1	0.91	**0.79**	0.5	**0.25**
americium-241	0	0.09	**0.21**	0.5	**0.75**



1 For the die-hard math fans in the audience, the equation used to calculate decay is $N=N_0*\exp(-0.63*t/\tau)$ where N_0 is the original amount of the isotope, t is the time in years, and τ is the half-life.

URANIUM BURDEN

FROM PAGE 3

Uranium miners also face many non-radiation-related hazards. Soluble uranium affects the kidneys if ingested or inhaled because of its chemical toxicity as a heavy metal. The ore in which uranium is found also contains non-radioactive toxic heavy metals. These vary from site to site but may include arsenic, lead, molybdenum, and manganese. Silica dust is created in the drilling process and can cause the gradual development of scarring in the lungs, which restricts lung function and can lead to cancer and an increased risk of tuberculosis, rheumatoid arthritis and kidney disease. As with all types of mining, uranium miners face a high risk of injury; however, these risks have declined in most countries over the years as safety measures have improved.

Doses to workers in uranium mines can be reduced through proper ventilation, careful planning, and good design and work practices. Yet, many mine operators throughout the world have resisted steps to ameliorate working conditions. It took the U. S. until the mid 1960s to establish protections against known health hazards, even though studies conducted by the United States Public Health Service (USPHS) in the early 1950s showed that hazards to American workers were similar to those in Europe, where elevated levels of lung cancer had already been demonstrated. Canada, prompted by the US race for the bomb, began mining and processing on a large scale in the early 1940s. There was no regulatory upper limit to radiation exposure for Canadian miners until 1968. The Soviet Union operated its East German mines with no radiation protection measures until 1954; they continued to be radioactive disaster areas for decades. Worker health and safety has been neglected at Namibia's Rössing mine as well. For the first three years of operation it wasn't compulsory for workers to wear film badges and then only in the final stages of uranium extraction. A 1992 study found that, "throughout [the 1980s] the Rössing industrial hygiene standard for airborne uranium was nearly 6 times the ICRP [recommended maximum] Derived Air Concentration for natural uranium, and 36 times the limit implied by current scientific evidence."[2]

A number of health studies of uranium miners have been conducted, documenting elevated levels of lung cancer. In Czechoslovakia, follow-up studies on several cohorts of miners have been conducted since 1970. A study of 4042 miners who began working underground between 1948 and 1957 found that the number of lung cancer deaths as of 1985 was five times the expected number.[3] In Canada, an Ontario study examining data from 1955 to 1986 on 50,201 miners (including 15,000 miners who worked exclusively in Ontario uranium mines) discovered an excess of 120 lung cancer deaths over the 171.8 expected in the non-exposed population. In the United States, numerous follow-up studies have been conducted on the USPHS cohort. A 1988 study by Hornung and Meinhardt suggested synergistic effects of cigarette smoking and exposure to radon

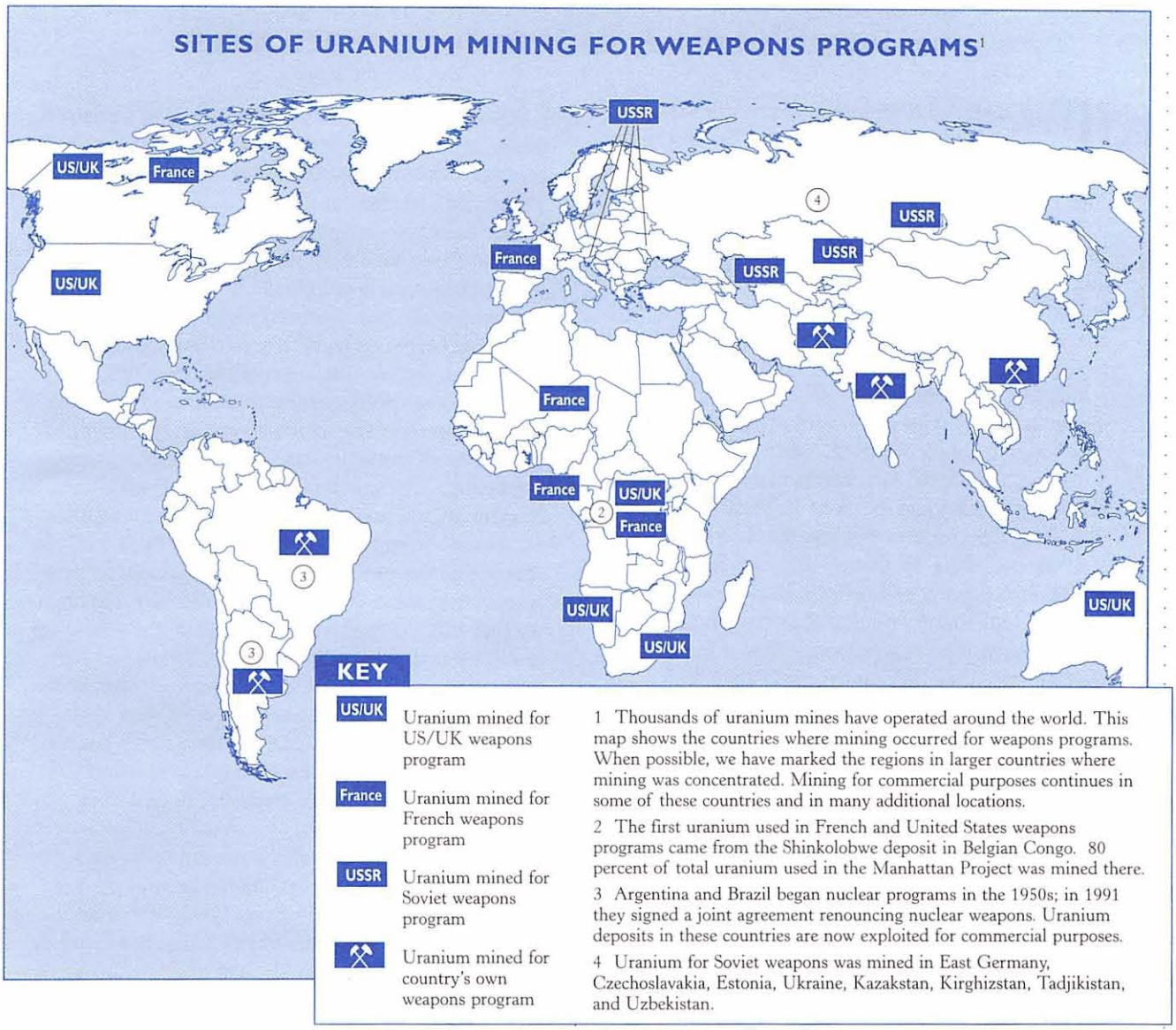
SEE **URANIUM BURDEN** ON PAGE 13

TOP TEN URANIUM MINES, 1996

("Western world" only)

Country	Mine	Owner	Mine type	production (metric tons)	% of world production
Canada	Key Lake	Cameco/Uranerz	Open pit	5,429	15.4
Canada	Rabbit Lake	Cameco/Uranerz	Open pit/ underground	3,972	11.3
Australia	Ranger	ERA	Open pit	3,508	10.0
Namibia	Rössing	RTZ	Open pit	2,452	7.0
Niger	Akouta	Cogema/Onarem	underground	2,120	6.0
Canada	Cluff Lake	Cogema	Open pit/ underground	1,963	5.6
Australia	Olympic Dam	WMC	by-product (copper) underground	1,466	4.1
Niger	Arlit	Cogema/Onarem	Open pit	1,200	3.4
S. Africa	Vaal Reefs	Anglo-American	By-product (gold) underground	914	2.6
Gabon	Okelobondo	Cogema/ Gabon State	Underground	565	1.6
			TOTAL	**23,589**	**67.0**

Source: The Uranium Institute. Web page http://www.uilondon.org/utopmin.html



URANIUM BURDEN

FROM PAGE 12

decay products. Lung cancer deaths in excess of those expected have also been found in studies of Australian, East German, and French miners. Information about the health and environmental effects in many regions, including Africa, the former Soviet Union, and China is not easily available, and fewer studies have been conducted in these regions.

Waste from the milling process, which involves the chemical separation of uranium from other ore components, also poses significant health and environmental hazards. For a typical uranium concentration of 0.2 percent, 1,000 metric tons of ore are needed in order to get 2 metric tons of uranium, leaving behind 998 tons of waste. This waste, called mill tailings, contains over 85 percent of the radioactivity from the original ore along with heavy metals and chemical toxic materials from mill reagents such as sulfuric acid and ammonium chloride. The principal radioactive components of mill tailings are radium-226 and thorium-230.

When discharged from the mill, the tailings are roughly 40 percent solids and 60 percent liquid. The liquid can eventually percolate into the soil, posing a threat of groundwater contamination. Wind scatters fine respirable radioactive particles from dry tailings areas, exposing workers and nearby residents. Mill tailings have also been frequently used in construction of houses, leading to high radon doses to inhabitants. Mill tailings make up over 95 percent of the total volume of radioactive wastes coming from the nuclear fuel cycle (excluding mine waste), and are very long-lived (although account only a small fraction of the radioactivity).

In the early decades, mill tailings were left in unlined tailings ponds, leading to contamination of groundwater. Tailings dams have ruptured, leading to release of impounded tailings and widespread contamination. In 1979, a United Nuclear uranium mill tailings dam

SEE **URANIUM BURDEN** ON PAGE 16

LEUKEMIA CLUSTERS NEAR LA HAGUE AND SELLAFIELD

The La Hague reprocessing plant in France is the largest facility of its kind in the world (see *Energy & Security* no. 2), with a capacity of 1650 tons of spent fuel per year. A study, published in January 1997 in the British Medical Journal by two French scientists, showed a potential link between an increased incidence of childhood leukemia in the area around La Hague and discharges from the plant.[1] Dominique Pobel and Jean-Francois Viel conducted a case-control study, covering a 35-kilometer radius around the plant. Their study considered 27 cases of leukemia diagnosed in people under 25 years of age between 1978 and 1993 and 192 controls matched for such factors as gender, age, place of birth, and place of residence. The parents of these subjects were also studied, including for factors such as lifestyle, radiation exposure, and occupational exposure.

Pobel and Viel found that children who had spent time at local beaches more than once a month were almost three times more likely than the controls to develop leukemia. They also found an increased risk when mothers went regularly to these beaches during pregnancy. A similarly increased risk to children was shown from eating local fish and shellfish, although mothers' eating habits appeared to pose no increased risk to their children. Parents' occupational exposure (not just to radiation, but also to chemicals and wood dust) or exposure to radiation did not seem to significantly influence the risk of leukemia in their children. They found some evidence of increased risk from exposure to radon in the home.

They concluded that their study shows some convincing evidence for a causal role for environmental radiation exposure, and that study into environmental pathways particularly on marine ecosystems is warranted. In fact, monitoring in June 1997 of the area around the drainage pipe from the reprocessing plant by Greenpeace, followed by an independent analysis on samples conducted by the Department of Labor, Health and Social Service of the Federal State of Hamburg (Germany) showed levels of tritium of up to 160 million becquerels per liter and sediments that could be classified as "waste containing nuclear fuel." In July, French Environmental Minister Dominique Voynet called an indefinite ban on fishing and bathing near the La Hague facility.

Pobel and Viel's study was the first case-control study (where an exposed population was compared to a non-exposed population) to be conducted in France (few studies on the effects of radiation on health have been conducted at all in France, and most of these have been the less sophisticated studies which compare mortality rates between different geographical areas.) However, in Britain there has been a series of studies conducted since 1983, with the identification of the "Seascale cluster." A ten-fold increase in childhood leukemia rate compared to the national average was found in the village of Seascale, near the Sellafield reprocessing facility. The government commissioned a study to estimate the probable radiation doses to children in Seascale from the Sellafield discharges. It was found that the probable doses were too low to have caused the excess leukemias, but there is a possibility that this study was flawed. One of the follow-up studies was conducted in 1990 by Martin Gardner and others, which showed a link between radiation doses received by fathers before conception, and leukemia in children. There has been much controversy over this finding, because it was the first study to correlate fathers' exposure to radiation with childhood leukemia.

Following discovery of the Seascale cluster, a number of studies were conducted around other nuclear facilities. In 1989 Paula Cook-Mozaffari and others found a slight, but significant increase in leukemia in people under the age of 25 in the areas around 15 nuclear facilities in England and Wales. Most significant of these was the increase of leukemia around nuclear weapons plants at Aldermaston and Burghfield, which are located near eachother, because the area around these plants is more densely populated. It is difficult to explain in terms of official estimates of environmental exposure to radioactivity, as the estimated doses to this population do not match the increase in leukemia. There has been no independent evaluation of radioactive releases and dose estimates in other countries as most documents are still secret. Further, IEER's work in the US has shown that official dose estimates from weapons plants are often wrong and seriously understate public exposure.

—ANITA SETH

1 Dominique Pobel and Jean-Francois Viel, "Case-control study of leukaemia among young people near La Hague nuclear reprocessing plant: the environmental hypothesis revisited," British Medical Journal 314:7074 (January 11, 1997).

EDIDEMIOLOGICAL STUDIES

FROM PAGE 2

subject to some kind (if often inadequate) monitoring, than to neighboring populations, for whom data are generally not available. However, data on non-radioactive toxic materials are often lacking for workers, as well as for off-site populations.

- Difficulty in separating exposed from non-exposed populations. Populations may be incorrectly grouped because of poor or incomplete records. For example, worker groups have been grouped based on external doses from beta and gamma radiation, often because internal dose data are lacking. If the exposed people cannot be grouped into appropriate dose ranges, then estimation of increase in risk becomes very difficult. This is especially the case if a small proportion of highly exposed people are mixed in with a far larger number of people with relatively low exposure.
- Difficulty in tracking individuals over long periods. The period of time between exposure and the onset of disease (known as latency) can stretch over many decades, such as in the case of cancers or generational effects like birth defects. It is easy to lose track of individuals in these periods as they move, marry, change jobs, etc.
- Misdiagnosis and/or incorrect documented cause of death.
- Uncertainties posed by interaction between environmental or occupational exposure and other factors like gender, age, diet, smoking and other lifestyle habits.
- Synergistic effects. Populations are often exposed to more than one disease-producing agent, and the synergistic effects of these agents are not well-known.
- A disproportionate focus on cancer effects. Non-cancer effects of toxic materials, like birth defects and immune system damage, are only now beginning to be understood, and are therefore often overlooked.
- Small sizes of exposed populations combined with the low background occurrence of many diseases lead to large statistical uncertainties. Since there are considerable differences in they way different people respond to disease-producing agents, there must be sufficient numbers of people in an epidemiological study to determine with a reasonable certainty if there is an increased risk.
- For a variety of reasons, there are usually large uncertainties about the health effects of low levels of exposure to radiation and other toxic materials.

GLOSSARY

Absorbed Dose: the amount of energy deposited in a unit weight of biological tissue. The units of absorbed dose are the rad and gray.

Cohort: a group of individuals having a statistical factor (such as age) in common in a demographic or epidemiological study.

Dose Limit: regulatory limit set on the amount of radiation that an individual may receive from artificial sources (excluding medical sources). Worker limits are set higher than general population limits.

Dose Reconstruction: estimating exposure by considering emissions, environmental measurements, and routes of exposure.

External Radiation Dose: the dose from sources of radiation outside the body. This is most often from gamma rays, though beta rays can contribute to dose in the skin and other tissues near the skin.

Linear energy transfer (LET): refers to the rate of energy transfer (and thus damage) per unit at distance travelled. For example, alpha is high-LET radiation, while photons and electrons are low-LET radiation.

Internal Radiation Dose: the dose to the organs of the body from radioactive material that has entered the body through inhalation, ingestion or through cuts and wounds. It may consist of any combination of alpha, beta, gamma radiation, and neutrons.

Pathway Analysis: an analysis of the ways in which toxic or radioactive substances can reach human beings from a factory, place, or process in which they are made, used, stored or dumped via air, water, soil, the food chain, or some combination of these pathways.

Relative Biological Effectiveness (RBE): a factor that measures the relative effectiveness of various kinds of radiation in causing damage. It is complex and organ-specific. Due to its complexity, a simple parameter, called the quality factor, is used in regulatory practice.

Relative Risk: the ratio of disease incidence (or mortality) in an exposed population to that in an unexposed population.

Solubility: the ability to dissolve in water. For instance the less soluble a given amount of material the more difficult it is for the body to remove it. An insoluble material inhaled into the lungs for example would have more time to do damage to the lungs.

Source Term: The amount of a specific pollutant emitted or discharged to a particular medium, such as the air or water, from a particular source.

URANIUM BURDEN

FROM PAGE 12

broke near Churchrock, New Mexico, releasing 94 million gallons of tailings and 1,100 tons of tailings solids which spread 60 miles from the facility. In the Elliot Lake area of Ontario, Canada, 80 kilometers of the Serpent River system including 10 local lakes have been contaminated. Elliot Lake has also experienced over 30 tailings dam breaches and 125 radioactive spills in Saskatchewan have been reported. In the United States, tailings areas are being remediated by putting plastic liners under the tailings to prevent seepage and by keeping them under water to reduce emissions of radon decay products.

The burden from the effects of uranium production, driven by a few countries seeking nuclear weapons and nuclear power, has been disproportionately carried by indigenous, colonized and other dominated peoples. Approximately two-thirds of the United States' uranium deposits are on Native American land, and almost a third of all mill tailings produced in the U.S. from abandoned mill operations are on Navajo land. Northern Saskatchewan, home to some of the richest reserves, and where over 20% of uranium in the world is mined, is inhabited by the Cree and Dene.

Much of the uranium used in French weapons and reactors has been mined in Niger and Gabon. Although the mines are run by the French company Cogema, they are not subject to the same health and environmental regulations that are enforced in France. The conditions in Niger prompted BBC producer Chris Olgiati to remark: "Some of the poorest people on earth labor in one of the deadliest environments to power the electric train sets and fuel the bombs of the world"s richest nations."[4] Other European states and Japan also buy uranium from Niger and Gabon. The British company Rio Tinto Zinc began mining operations in Namibia, at Rössing in 1976 in violation of a 1974 UN decree that no Namibian natural resources could be extracted without the consent of the UN Council for Namibia. Until 1990, Namibia was a colony of South Africa. A significant amount of this uranium went to facilitate Britain's nuclear weapons program and Japan's civilian nuclear power operations.

In most countries, uranium mining has been the most hazardous step of nuclear materials production, both in terms of doses and in the number of people affected. Greater efforts are needed to identify populations affected by uranium mining and milling activities, to assess the extent to their exposures, and provide them with health monitoring and related assistance. Countries should protect both uranium miners and those living nearby mining and milling sites by establishing standards based on the recommendations of the International Committee on Radiological Protection (2 rem maximum worker exposure per year). Given the disproportionate burden borne by non-nuclear countries and dominated peoples, they should be provided adequate health and environmental monitoring, environmental remediation of damaged areas, and compensation for past injustices in order to redress the manifest inequity of the pollution.

1 In the writing of this article, we have drawn extensively on Arjun Makhijani, Howard Hu, and Katherine Yih, eds., Nuclear Wastelands, A Global Guide to Nuclear Weapons Production and its Health and Environmental Effects, Cambridge: MIT Press, 1995. Of special relevance are chapter four "Health Hazards of Weapons Production," by David Sumner, Howard Hu and Alistar Woodward, and chapter five "Uranium Mining and Milling for Military Purposes," by Katherine Yih, Albert Donnay, Annalee Yassi, A. James Ruttenber, and Scott Saleska.

2 G. Dropkin and D. Clark, Past exposure: Revealing health and environmental risks of Rossing uranium. Partizans, London, 1992, (as cited in *Nuclear Wastelands*, p 144).

3 J. Sevc, L. Tomasek, E. Kunz, V. Placek, D. Chmelevsky, D. Barclay, and A. M. Keller, A survey of the Czechoslovak follow-up of lung cancer mortality in uranium miners, *Health Physics*, vol. 64, pp. 355-369, (as cited in *Nuclear Wastelands*, p 159).

4 As quoted in *Nuclear Wastelands*, p. 106.

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