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Science FOR Democratic Action

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The Uranium Burden

BY ROBERT BROOKS AND ANITA SETH[1]

From the time of its discovery in 1789 to the early 1900s uranium was used for color and glazing in ceramics and glass-making.[2] From the early 1900s to the late 1930s, it was discarded as a waste from radium production (which was used in medical applications and to make instrument and watch dials luminous). 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 leachate 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.

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

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US VANADIUM CO. FROM THE AEC COLLECTION AT THE NATIONAL ARCHIVES & RECORDS ADMINISTRATION

Uranium miners use a mine car to transport uranium ore (circa 1955). In terms of adverse health effects, uranium mining has been one of the most damaging steps of nuclear materials production.

Health Risks of Ionizing Radiation

BY DAVID SUMNER, HOWARD HU, AND ALISTAIR WOODWARD[1]

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.[2] [See *Science for for the Critical Masses*, beginning on page 8, for a description of radiation units and terms.] With respect to children, the threshold for congenital

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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. [See glossary on page 10.] 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. [See table below.] 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. [See uranium decay chain, page 3.]

ISOTOPES FOUND IN NATURAL URANIUM

Isotope	Percent of natural uranium by weight	Half-life (in years)
Uranium-238	99.284	4.46 billion
Uranium-235	0.711	704 million
Uranium-234	0.0055	245,000

Uranium is both radioactive and a chemical toxin. Outside the body, natural uranium poses only 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 mostly 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. Radium is dangerous when ingested. It is a known agent of bone cancer as was discovered in the 1920s through the unfortunate fate of the 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. Radon and its decay products are historically responsible for the elevated levels of lung cancer incurred by uranium miners. Conventional underground mining is most dangerous to workers because of higher exposure to radon decay products. Workers breathe in 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.[3]

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SCIENCE FOR DEMOCRATIC ACTION

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Editor: Lisa Ledwidge

URANIUM BURDEN

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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 of 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. For instance, 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 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 a radioactive disaster area 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 [International Commission on Radiation Protection's recommended maximum] Derived Air Concentration for natural uranium, and 36 times the limit implied by current scientific evidence."[4]

URANIUM DECAY CHAIN

(principle branch only)

Uranium-238
(half-life: 4.46 billion years)
alpha decay
↓
Thorium-234
(half-life: 24.1 days)
beta decay
↓
Protactinium-234m
(half-life: 1.17 minutes)
beta decay
↓
Uranium-234
(half-life: 245,000 years)
alpha decay
↓
Thorium-230
(half-life: 75,400 years)
alpha decay
↓
Radium-226
(half-life: 1,600 years)
alpha decay
↓
Radon-222
(half-life: 3.82 days)
alpha decay
↓
Polonium-218
(half-life: 3.11 minutes)
alpha decay
↓
Lead-214
(half-life: 26.8 minutes)
beta decay
↓
Bismuth-214
(half-life: 19.9 minutes)
beta decay
↓
Polonium-214
(half-life:
163 microseconds)
alpha decay
↓
Lead-210
(half-life: 22.3 years)
beta decay
↓
Bismuth-210
(half-life: 5.01 days)
beta decay
↓
Polonium-210
(half-life: 138 days)
alpha decay
↓
Lead-206
(stable)

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.[5] 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 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, like 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 85 percent of the radioactivity in the original ore along with heavy metals and chemical toxic materials from mill reagents such as sulfuric acid and ammonium chloride.

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 ground water 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,

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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 discharges and widespread contamination. In 1979, a United Nuclear uranium mill tailings dam broke near Churchrock, New Mexico, releasing 94 million gallons of tailings liquids 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 30 tailings dam breathings 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 US 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

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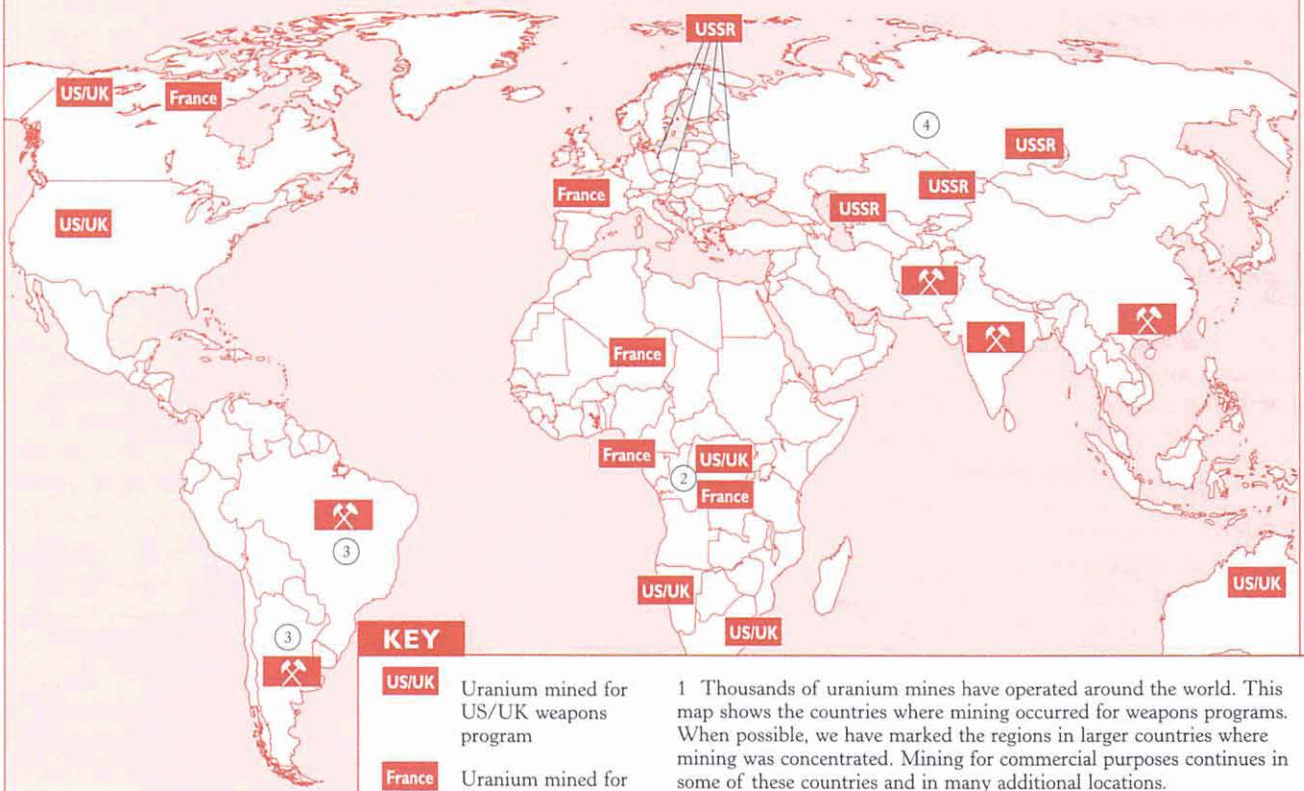
SITES OF URANIUM MINING FOR WEAPONS PROGRAMS[1]



1 Thousands of uranium mines have operated around the world. This map shows the countries where mining occurred for weapons programs. When possible, we have marked the regions in larger countries where mining was concentrated. Mining for commercial purposes continues in some of these countries and in many additional locations.

2 The first uranium used in French and United States weapons programs came from the Shinkolobwe deposit in Belgian Congo. 80 percent of total uranium used in the Manhattan Project was mined there.

3 Argentina and Brazil began nuclear programs in the 1950s; in 1991 they signed a joint agreement renouncing nuclear weapons. Uranium deposits in these countries are now exploited for commercial purposes.

4 Uranium for Soviet weapons was mined in East Germany, Czechoslavakia, Estonia, Ukraine, Kazakstan, Kirghizstan, Tadjikistan, and Uzbekistan.

Reprinted from IEER's international newsletter, *Energy & Security*, no. 4 (1997).

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electric train sets and fuel the bombs of the world's richest nations."[6] 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 born 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 This article appeared originally in IEER's global newsletter *Energy & Security*, no. 4 (1997).

2 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.

3 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).

4 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).

5 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).

6 As quoted in Nuclear Wastelands, p. 106.

TOP TEN URANIUM MINES, 1997 ("WESTERN WORLD" ONLY)

Mine	Country	Owner	Mine Type	Production (tU)	% of world production
Key Lake	Canada	Cameco/Uranerz	Open pit	5433	15.2
Rabbit Lake	Canada	Cameco/Uranerz	Underground	4632	13.0
Ranger	Australia	ERA	Open pit	4095	11.5
Rössing	Namibia	RTZ (69%)	Open pit	2905	8.1
Akouta	Niger	COGEMA/Onarem	Underground	2139	6.0
Cluff Lake	Canada	COGEMA	Open pit/underground	1964	5.5
Olympic Dam	Australia	WMC	Byproduct (copper) underground	1425	4.0
Arlit	Niger	COGEMA/Onarem	Open pit	1358	3.8
Vaal Reefs	South Africa	Anglo-American (27.6%)	Byproduct (gold) underground	677	1.9
Highland	USA	Cameco	ISL	597	1.7
Western world total from top ten mines				25225	70.7

Source: Uranium Institute, http://www.uilondon.org/utopmin.htm. A list of leading uranium mining companies can be found at http://www.uilondon.org/utopco.htm.

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. 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 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 US 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 [see main article, *The Uranium Burden*, on page 1].

Studies of survivors of the atomic bombings of Hiroshima and Nagasaki 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—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).[3] Thus, assuming a constant quality factor, as is common

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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:[4] 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."[5] 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:[6] 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:[7] 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 US Environmental Protection Agency uses a cancer incidence risk factor of 0.06 per person-sievert.[8] 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.[9]

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." Also, this article appeared in IEER's global newsletter *Energy & Security*, no. 4 (1997).

2 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.

3 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.

4 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.

5 Ibid, p. 17.

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

7 ICRP 1991, pp. 69–70.

8 US 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.

9 National Research Council 1990, p. 8.

WHY IS THERE NO ATOMIC PUZZLER IN THIS ISSUE?

Dr. Egghead and his puzzle-hunting dog Gamma weren't kidding when they said IEER would award $108 to the person who submits the most accurate answer to the *Special Atomic Puzzler* which appeared in the last issue of SDA (volume 8 number 3, May 2000).

So far, we've received only one response to the *Special Atomic Puzzler*, and Gamma is still puzzled!

If you haven't tried already, consider helping Gamma figure out this nuclear waste numbers conundrum. Find the *Special Atomic Puzzler* on page 19 of the last issue of SDA or on IEER's Web site at http://www.ieer.org/sdafiles/vol_8/8-3/puzzler.html.

To give our readers more time to figure out this challenging problem, we have decided to skip a new Atomic Puzzler for this issue, and instead extend the deadline for answers to last issue's *Special Atomic Puzzler*. The new deadline is November 1, 2000. We will publish our findings shortly thereafter.

Happy problem-solving!

Measuring Radiation: Terminology and Units

BY DAVID CLOSE AND LISA LEDWIDGE

Ionizing radiation is emitted when radioactive substances decay. Radioactive decay occurs when the nucleus of an atom spontaneously decays by emitting a particle (an alpha particle, an electron, or one or more neutrons).

The four forms of ionizing radiation are alpha particles, beta particles, gamma rays, and, indirectly, neutrons. All have enough energy to ionize atoms, in other words, remove one or more of the atom's electrons.

An **alpha particle** (α-particle) consists of two protons and two neutrons, the equivalent of the nucleus of a helium atom. Alpha particles readily ionize material they contact and transfer energy to that material's electrons. An alpha particle can travel several millimeters in air, but in general its range decreases with increasing density of the medium. For example, alpha particles do not penetrate the outer layer of human skin, but if inhaled, alpha particles can damage lung tissue.

A **beta particle** (β-particle) is an electron or a positron and is much lighter than an alpha particle. Thus, it takes beta particles a longer distance than alpha particles to lose energy. A medium-energy beta particle travels about one meter in air and one millimeter in body tissue.

Gamma rays (γ-rays) are electromagnetic radiation. A radioactive element may emit gamma rays (in discrete bundles, or quanta, called **photons**) if the nucleus remaining after alpha or beta decay is in an excited state. Gamma rays can penetrate much more deeply than alpha or beta particles; a high-energy gamma ray photon may pass through a person without interacting with tissue at all. When gamma rays interact with tissue, they ionize atoms. The term "X rays" is also sometimes used for the gamma rays emitted in the process of radioactive decay that are at the lower end of the energy spectrum of electromagnetic radiation resulting from radioactive decay.

Neutrons are neutral particles that have no electric charge. Unlike alpha and beta particles, they do not interact with electrons or cause ionization directly. Neutrons can, however, ionize indirectly in a variety of ways: elastic collisions, inelastic scattering, nonelastic scattering, capture reactions, or spallation processes. These processes variously result in the emission of gamma rays, beta radiation, and, in the case of spallation, more neutrons. For a more detailed explanation, see *Health Effects of Exposure to Low Levels of Ionizing Radiation (BEIR V report)*, National Academy Press, 1990, pp. 15–17.

Measuring Radioactivity

Ionizing radiation can be measured using units of electron volts, ergs, and joules. The **electron-volt** (abbreviated eV) is a unit of energy associated with moving electrons around. An electron is "tightly bound" in a hydrogen atom (one proton and one electron). It takes energy to move this electron away from the proton. It takes 13.6 electron-volts of energy to move this electron completely away from the proton. We say then that the atom is "ionized." In the jargon, the "ionization energy" of the tightly bound electron in hydrogen is 13.6 electron volts.

Electrons are very light objects, so we don't expect an electron-volt to represent very much energy. One electron-volt is only 1.6×10^{-19} joules of energy, in other words, 0.16 billion-billionth of a joule. One **joule** (abbreviated J) is equivalent to the amount of energy used by a one-watt light bulb lit for one second. The energy associated with the radioactive decay ranges from thousands to millions of electron-volts per nucleus, which is why the decay of a single nucleus typically leads to a large number of ionizations.

The radioactivity of a substance is measured in the number of nuclei that decay per unit time. The standard international unit or radioactivity is called a **becquerel** (abbreviated Bq), which is equal to one disintegration per second (dps). Radioactivity is also measured in curies, a historical unit based on the number of disintegration per second in one gram of radium-226 (37 billion). Hence 1 curie = 37 billion Bq. One picocurie (a trillionth of a curie) = 0.037 Bq, and 1 Bq = 27 picocuries. Radioactivity is also measured in disintegration per minute (dpm). One dpm = 1/60 Bq.

Specific activity measures the radioactivity of a unit weight of substance. The units are curies per gram or becquerels per gram. This allows us to compare whether a substance is more or less radioactive than another. The specific activity of a radionuclide is inversely proportional to its atomic weight and its half-life.

Environmental and biological measurements of radioactivity are generally expressed as concentrations of radioactivity in soil, water, air, or tissue. Examples of units include picocuries per liter, becquerels per cubic meter, picocuries per gram, and disintegrations per minute per 100 square centimeters. One picocurie (abbreviated pCi) is 10^{-12} (or 0.000000000001) curie. Sometimes, the weight of a radioactive material per unit of soil or tissue might be given and expressed in parts per million, or ppm, can be expressed in terms of mass. This can be converted into radioactivity units, since we know the specific activities of

various radionuclides. Disintegrations per minute per 100 square centimeters (dpm/100 cm^2) is a unit commonly used to measure the surface contamination of an object, such as concrete or metal.

Measuring Dose

Placing your body near a radioactive source results in exposure. To evaluate the hazard from this exposure one must compute the **absorbed dose**. This is defined as the energy imparted to a defined mass of tissue. Dose is generally not uniform over the body. A radioactive substance can be selectively taken up by different organs or tissue.

Radiation doses are often calculated in the units of **rad** (short for radiation absorbed dose). One rad is 100 ergs/gram, in other words, 100 ergs of energy absorbed by one gram of a given body tissue. An erg is one-ten-millionth of a joule. One hundred rad equals one Joule/kilogram (J/kg), which also equals one **Gray** (Gy), the standard international unit for measuring radiation dose. Suppose time is involved? Then we are talking about dose rate (or dose per unit time). An example of the units for dose rate is millirad/hour. In everyday terms, a joule (and even more so, an erg) is a rather small amount of energy. But in terms of ionization potential of molecules or elements, a joule is a huge amount of energy. One joule of ionizing radiation can cause tens of thousands of trillions of ionizations.

The **roentgen** measures the amount of ionization in the air caused by radioactive decay of nuclei. In non-bony biological tissue, one roentgen is the equivalent of about 0.93 rad. In air, one roentgen equals 0.87 rad. Dials that show calibration in mR/hr are reading milliroentgen per hour.

Physically speaking, the most elementary way to measure the effect of radiation is to measure the amount of energy deposited in a given weight of material. However, the deposition of energy is only one aspect of the potential of radiation to cause biological damage. The damage caused per unit of deposited energy is greater when it is deposited over a shorter distance. Hence an alpha particle, which would deposit

SOME UNITS USED IN MEASURING IONIZING RADIATION AND RADIATION DOSE

UNIT	DESCRIPTION	EQUIVALENT
Rem (roentgen equivalent man)	A unit of equivalent absorbed dose of radiation which takes into account the relative biological effectiveness of different forms of ionizing radiation, or the varying ways in which they transfer their energy to human tissue. The dose in rem equals the dose in rad multiplied by the quality factor (Q). For beta and gamma radiation, the quality factor is taken as one, that is, rem equals rad. For alpha radiation, the quality factor is taken as 20, that is, rems equal 20 times rads. Rem is essentially a measure of biological damage. For neutrons, Q is typically taken as 10.	rem = rad x Q
Sievert (Sv)	A unit of equivalent absorbed dose equal to 100 rem.	1 Sv = 100 rem Sv = Gy x Q
Rad (radiation absorbed dose)	A unit of absorbed dose of radiation. Rad is a measure of the amount of energy deposited in tissue.	1 rad = 100 erg/gram
Gray (Gy)	A unit of absorbed radiation dose equal to 100 rad. Gray is a measure of deposition of energy in tissue.	1 Gy = 100 rad
Curie (Ci)	The traditional unit of radioactivity, equal to the radioactivity of one gram of pure radium-226.	1 Ci = 37 billion dps = 37 billion Bq
Becquerels (Bq)	The standard international unit of radioactivity equal to one disintegration per second.	1 Bq = 27 pCi
Disintegrations per second (dps)	The number of subatomic particles (e.g. alpha particles) or photons (gamma rays) released from the nucleus of a given atom over one second. One dps = 60 dpm (disintegrations per minute).	1 dps = 1 Bq

Sources: *Nuclear Wastelands*, Makhijani et al., eds., Cambridge: MIT Press, 1995; *Science for Democratic Action*, volume 6 number 2, November 1997; *Radiation Protection: A Guide for Scientists and Physicians*, 3rd Ed., Jacob Shapiro, Cambridge: Harvard University Press, 1990.

its entire energy over a very short distance, causes far more damage per unit of energy than a gamma ray, which deposits its energy over a longer track. The weight of biological matter in which the energy is deposited is also important. The sensitivities of different organs also vary. The concept of relative biological effectiveness (RBE) has been created to try to capture the relative efficiency of various kinds of radiation in producing biological damage.

The RBE varies according to the organ exposed, the age of exposure, and other factors. A single factor, called the quality factor, for converting deposited energy in rad is used for regulatory purposes, even though this represents a considerable simplification of real life risks. For beta and gamma radiation, the quality factor used is 1, that is 1 rad = 1 rem. Alpha radiation is far more damaging per unit of energy deposited in living tissue. Currently, the quality factor for alpha is 20 (multiply rad of alpha radiation by 20 to get rem). We say "currently" because the quality factor for alpha radiation has changed over the years. The current quality factor generally used for neutrons is 10.

Dose conversion factors (DCFs) are used to convert an amount of radioactivity (expressed in curies or becquerels) breathed or ingested by a person into a dose (expressed in rems and sieverts). The DCFs used for regulatory purposes are derived from a combination of a variety of experimental data and mathematical models.

GLOSSARY

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

Alpha radiation: Radiation consisting of helium nuclei that are discharged by radioactive disintegration of some heavy elements, including uranium-238, radium-226, and plutonium-239. Alpha, the first letter of the Greek alphabet, is written as α.

Beta radiation: Radiation consisting of beta particles, which are electrons or positrons (positively charged electrons), emitted by certain elements in the course of radioactive decay, at high speeds. Beta, the second letter of the Greek alphabet, is written as β.

Effective dose equivalent (EDE): An equivalent dose to the whole body, calculated by multiplying the dose to a particular organ (or collection of organs) by a factor that allows a rough representation of equivalent whole body dose and hence the risk of radiogenic cancer.

Electron: An elementary particle carrying one unit of negative electric charge. Its mass is 1/1836th that of a proton.

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 relatively superficial tissues.

Gamma radiation: High energy electromagnetic waves, such as those released during radioactive decay of some nuclei. Gamma, the third letter of the Greek alphabet, is written as γ.

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, and gamma radiation caused by incorporated radioactive material. Internal dose also includes indirect ionization cause by neutrons traversing the body.

Ionize: To strip one or more electrons from an atom or to break up a neutral molecule, thus leaving the parts as electrically charged particles.

Neutral atoms: Atoms that bear no net electrical charge because their negative and positive charges (electrons and protons, respectively) are exactly balanced. At temperatures such as those occurring on Earth, atoms of elements are neutral.

Neutron: An elementary particle slightly heavier than a proton, with no electric charge. Free neutrons are unstable, decaying into protons and electrons with a half-life of about 12 minutes.

Positron: An elementary particle with a positive electric charge, but in other respects identical with an electron.

Proton: An elementary particle with a positive electric charge and a mass that is given the value 1 on the scale of atomic weights.

Relative biological effectiveness (RBE): A factor that is used to express the relative amount of biological change caused by a unit of energy deposited by a particular type of ionizing radiation into a specific part of the body. The RBE is complex and organ-specific. Due to its complexity, a simple parameter, called the quality factor, is applied to different types of radiation as a matter of regulatory practice for the purpose of estimating biological damage and the resulting cancer risk.

Measuring Radiation: Devices and Methods

BY DAVID CLOSE AND LISA LEDWIDGE

Devices and methods used to measure external exposure to ionizing radiation can be grouped into four categories: dosimeters, beta and gamma radiation detectors, alpha radiation detectors, and neutron detection methods. Though less straightforward, there are also methods of detecting internal exposure to radiation. We will also discuss measurement of radionuclides in air, water, vegetation, and soil.

Dosimeters

Dosimeters are devices that monitor an individual's external radiation dose. The two most commonly used dosimeters are **thermoluminescent dosimeters (TLDs)** and **film badges**. Both devices measure the dose accumulated over a given period of time. For example, film badges might be worn for a month. When they are collected and analyzed, the total exposure for that month can be determined.

One widely used type of thermoluminescent dosimeter uses a crystal of lithium fluoride. When radiation is absorbed by the lithium fluoride, it raises electrons in the crystal to higher energy levels. Some of these electrons are trapped by impurities in the crystal where they remain in their excited states until the crystals are heated. When the crystal is heated, the electrons are released from these trapping sites and give off light. The light emitted can be measured and is proportional to the amount of radiation to which the TLD crystal, and presumably the individual, were exposed. Once the crystal is heated to a sufficiently high temperature, all the trapped electrons are released, and the dosimeter may be reused. Some TLDs are sensitive enough to measure a dose of beta or gamma radiation of a few tens of microrads. Some TLDs can also detect neutrons.

ICN BIOMEDICALS, INC.

Film badge

BIODEX MEDICAL SYSTEMS

Pocket dosimeters

Film badges are used to monitor personal exposure to beta and gamma radiation. To assess various radiations simultaneously, a strip of film is covered with absorbers. By varying the type and thickness of the absorbers, one can determine skin dose, dose to the lens of the eye, and whole-body dose. Some film badges have a small window shielded by a sheet of mylar which can detect beta radiation, and one or more sections shielded by metal foils for detecting gamma radiation. The radiation exposure of the film is determined by the degree of darkening of the film after the film is developed. Film badges look like badges and can be clipped onto a pocket or a belt.

While film badges and TLDs measure a workers dose over an extended period of time, **pocket dosimeters** measure a worker's radiation dose each day. Rather than waiting weeks, pocket dosimeters can detect whether a worker might have received a dangerous dose during a given workshift. In principle, one should wear a film badge or TLD and a pocket dosimeter at the same time. Pocket dosimeters can measure gamma radiation with energies up to two MeV. They are basically devices that can store an electric charge. They consist of an exterior wall, which is essentially a plastic tube coated with a conducting material, and an interior central wire which is insulated from the outer wall. An additional device, called the charger-reader, is used to place a positive charge on the central wire. When exposed to radiation, some of this positive charge is neutralized by ions created by the radiation. The dosimeters are read directly or by being placed in the charger-reader to determine the actual radiation dose received. Pocket dosimeters look like pens, and are clipped onto a shirt pocket.

Beta and Gamma Radiation Detectors

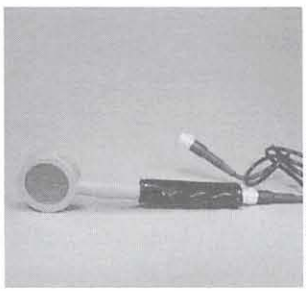
Radiation detectors are devices used to detect beta and gamma radiation in air. They differ from dosimeters in that they can measure radiation directly, in real time. Most radiation detectors detect the interaction of radiation with gas molecules. As radiation slows down in a gas, it ionizes gas atoms by ejecting electrons from them and leaving behind positive ions. In a Geiger-Müller detector, or **Geiger counter** as it is more commonly known, the result of this ionization produces a constant output electrical pulse, regardless of the amount of energy deposited in the detector or the nature of the ionizing radiation. On the other hand, the output of scintillation counters and gas flow proportional counters is proportional to the amount of energy deposited in the detector.

A Geiger counter can count beta particles and gamma rays. If equipped with a window thin enough (as in, for example, a "pancake" detector), a Geiger counter can also detect alpha particles. The entire

instrument is actually made up of two components: a Geiger-Müller tube (the detector in which the ionizations are produced) and an electronic amplifier (which activates a device that counts the ionizations). The Geiger-Müller (GM) tube consists of a cylindrical chamber with a metal wire stretched along its center which is insulated from the outer wall. The tube contains an inert gas such as helium or neon. The positive lead of the high voltage supply is connected to the central wire; the negative lead is connected to the outer shell of the tube.

The process of measuring a source of radiation begins by holding the Geiger counter near the source. An incident beta particle or gamma ray will then ionize

Survey meter (used with scintillation probe [not shown] or pancake GM probe [right])



BIODEX MEDICAL SYSTEMS

Pancake Geiger-Müller probe (also called a "frisker")

atoms of the gas. The resulting electrons are strongly attracted to the positive wire. In the path of the electrons are other gas molecules which will also be ionized. These new electrons will produce further ionizations, resulting is a cascade of ionizations. One initial ionization results in billions of ionizations which are collected on the central positive wire. An electronic amplifier is then used to activate a counting device.

Beta particles that reach the gas in the detector and cause ionizations will register a count. Many gamma rays, however, will pass through the entire gas without any interaction, and thus will not be recorded (unless thicker absorbers are used to capture the high-energy gamma rays). While a GM tube is more efficient at detecting beta particles than gamma rays, the tube must be designed so that the window is thin enough to allow the beta particles to penetrate. Its output signal cannot be used to provide information on the type of incident particle that produces the count. To distinguish between beta particles or gamma rays, absorbers can be used. For instance, a thin absorber between the radiation source and the GM tube will stop all the beta particles, allowing the gamma rays to enter the detector. The counting rate with and without the absorber can be used to distinguish between beta particles and gamma rays.

Whereas Geiger counters count the ionizations resulting from the incident radiation's interaction with gas atoms, **scintillation counters** are sensitive to the energy of the incident radiation itself. A scintillation counter is made with a material which glows (a scintillator) when it is struck by radiation, and a light amplifier. When a beta particle slows down in a scintillator, a fraction of the energy it imparts to the atoms in the scintillator is converted to light. When gamma rays pass through the scintillator, they produce electrons which in turn behave just like beta particles and convert some of their energy into light.

Scintillators come in all shapes and sizes. Some are plastic, and some are dense sodium iodide crystals. Large, dense scintillators are necessary to detect gamma rays since energetic gamma rays can pass through moderate thicknesses of ordinary matter (human tissue, concrete walls, water, etc.) with little interaction. The amount of light produced in the scintillator can be measured with a light amplifier, called a photomultiplier. The amount of each pulse of light represents a measure of the energy deposited in the scintillator. The ability to measure this energy means that radiation from various sources can be identified and at the same time one can evaluate the magnitude of the source. The other devices discussed above do not enable us to discern the amount of energy of the photons (that is, the type of gamma rays). Determining the type of gamma rays allow us to infer the type of radionuclide that emitted them.

BIODEX MEDICAL SYSTEMS

Portable survey meter (measures alpha, beta and gamma radiation)

Geiger counters can be made as small hand held instruments. They are easy to use as portable radiation monitors. Scintillation counters are generally large laboratory instruments.

Alpha Radiation Detectors

Detecting alpha particles is technically more difficult than detecting beta particles and gamma rays. Like beta and gamma radiation, alpha particles can produce ionizations, but they are not as penetrating.

In principle, alpha particles could be detected with an ordinary GM tube. GM counters equipped with a detector made with a very thin mylar window (e.g. pancake GM probe) can be used to detect alpha as well as gamma and beta radiation. However, alpha particles are best measured by what are called **gas flow proportional counters.**

In some proportional counters, the radioactive source that is to be measured, or the sample, is placed directly inside the detector. In these "windowless" tubes, the

sample is in direct contact with the counter gas (the gas in the detector). As in Geiger counters, the signal produced by a proportional counter results from the electric charge, which in turn is produced by the ionization of the gas by the incident radiation. The gas in the detector is usually 90% argon and 10% methane and flows through the chamber at atmospheric pressure.

Hand-held instruments that measure alpha, beta and gamma radiation combined (in terms of the amount of ionization they produce) with readings in counts per minute or milliroentgens per hour are commercially available (see photo of portable survey meter, page 12). Alpha counters are used in, for example, places where workers are handling plutonium (an alpha-emitter).

Neutron Detection

Gamma rays are classified as ionizing radiation. They are electromagnetic rays (just like light), and have no charge associated with them. They remove electrons from neutral atoms, leaving behind a positive ion. Alpha and beta particles are ions; in other words, they carry a net charge. Alpha particles have a net +2 charge and beta particles have a single negative or positive charge. Various schemes, discussed above, have been employed to turn ions, or the products of ionizations, into measurable events (counts).

Neutrons, on the other hand, are neutral particles. They carry no electric charge and cause no direct ionization. Neutrons can be detected indirectly through the charged particles they produce in a nuclear reaction or by gamma rays produced by indirect ionization. For instance, a typical capture reaction would involve a neutron being captured by the isotope boron-10. This would initiate a nuclear reaction that would produce a characteristic gamma ray which could be detected by one of the gamma radiation detection methods described above. However, the gamma detector must be able to discriminate between the gamma rays produced in the nuclear reaction and the gamma rays arising from other sources.

Doing this is not so easy, but if one has a way of detecting the energy associated with the radiation (see scintillation counters, above), then one can be on the look out for energies of certain ranges that might be associated with the source of radiation (for example, gamma rays that are known to be decay products). It is possible to build electronic circuits that discriminate the characteristic gamma rays from all others.

Environmental Measurements

Radionuclides can be measured in air, water, vegetation, and soil using the instruments described above in conjunction with air monitoring stations, water sampling with lab analysis, soil sampling, and other equipment and methods. To detect the amount of radiation in the workspace air, a certain quantity of the air would be drawn through a paper filter which would then be measured with one of the detectors described above.

Radioactivity in liquids is measured with a liquid scintillation counter. If the liquid is water, this is a fairly routine procedure. For example, facilities using radioactive materials have to measure the radioactivity in liquid waste to determine if it is below the standards set for disposal as waste water. Determining the level of radioactivity in other liquids, particularly unknown liquids, is more difficult.

Measuring the concentration of a gamma-emitting radionuclide in soil can be done in the field with a simple hand-held Geiger counter. However, to detect specific alpha- or beta-emitting radionuclides, a soil sample would be analyzed with a scintillation or gas flow proportional counter, usually in a laboratory.

Many laboratories that perform radionuclide measurements submit themselves to testing protocols. The Department of Energy's Environmental Measurements Laboratory (EML) evaluates participating laboratories through its Quality Assessment Program. This program compares the analytical performance of participating laboratories. The EML publishes their evaluations roughly twice a year and makes them available on its Web site, http://www.eml.doe.gov/qap/.

Internal Dose[1]

External monitoring devices, such as TLDs, can measure how much external radiation a worker has been exposed to, but not the radiation dose due to radionuclides taken into the body through inhalation,

DEVICES USED TO MEASURE IONIZING RADIATION

DEVICE	CAN MEASURE
Film badge	beta particles gamma rays
Thermoluminescent dosimeter (TLD)	beta particles gamma rays neutrons
Pocket dosimeter	gamma rays
Geiger-Müller counter (Geiger counter)	alpha particles (if using appropriate detector) beta particles gamma rays
Scintillation counter	beta particles gamma rays
Gas flow proportional counter	alpha particles very low energy gamma rays and beta particles

ingestion, or other means. It is generally much harder to estimate doses from substances inside the body. The size of an internal 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 (called biological half-life), among other factors. Since metabolic factors vary considerably from one person to the next, the internal dose that any individual gets from a particular radionuclide may be considerably different from the dose calculated using its average biological half-life.

Internal doses can be monitored in various ways. One common way is to measure radionuclide concentrations in urine. If one knows the rates of excretion corresponding to various body burdens, then it is possible to calculate these body burdens and thereby infer the radiation dose.

Another method is to measure the gamma radiation being emitted by the radionuclide inside the body. Since a portion of gamma radiation penetrates the body, a fraction of the gamma rays emitted by radionuclides inside the body escape outside it. This is measured by putting the worker or part of his or her body into a "counter," which is a chamber that measures gamma radiation. Thus, we have "whole body counters," "lung counters," and so on. Care must be taken to exclude or adjust for other sources of environmental radioactivity in the measurement of internal body burdens, notably radon and its decay products.

Internal doses to workers can also be assessed indirectly by measuring the concentrations of radionuclides in the air in the workplace. In areas where exposure is more likely, workers can wear portable air monitoring devices to measure concentrations of radionuclides in the "breathing zone" — that is, in the air very close to their faces. Internal worker doses can be estimated if breathing rates, efficiencies of protective devices worn by workers (if any), and other factors are known.

It is essential that radiation monitoring be carried out accurately and in sufficient detail. For instance, film badges and TLDs must be stored properly when not in use, so that they are not contaminated between worker exposure times. Also, workers at risk of internal exposures must be monitored frequently enough to accurately determine internal body burdens of radionuclides.

In the nuclear weapons industry, worker dosimetry and exposure records are seriously deficient. In 1994, the Department of Energy admitted that its records for worker exposure to external radiation are incomplete, unreliable, and misleading, and that this was partly due to poor calibration of measuring devices, issuance of multiple badges, and poor placement of dosimeters.[2] More recently, a study that evaluated the performance of approximately 1,000 personal monitoring devices in Europe found that 25% of the external doses recorded by the beta and neutron dose monitors were significant underestimates.[3]

[1] Excerpted from *Science for Democratic Action*, vol. 6 no. 2, November 1997.

[2] For more information on this point, see *Science for Democratic Action*, volume 6 number 2, November 1997, and *Nuclear Wastelands*, Makhijani, Hu, and Yih, eds., Cambridge: MIT Press, 1995.

[3] J.M. Bordy, et al. "Performance Test of Dosimetric Services in the EU Member States and Switzerland for the Routine Assessment of Individual Doses (Photon, Beta and Neutron)," Radiation Protection Dosimetry 89(1–2), pp 107–154 (2000), as reported in *New Scientist*, 26 August 2000.

ERRATA

In the article "Waste Transmutation: The Nuclear Alchemy Gamble," which appeared in the last issue of *Science for Democratic Action* (vol. 8 no. 3, May 2000), we misplaced two electrons and left out another. The following three equations are the *corrected* versions of those that appeared in the section The Physics of Transmutation on page 5, at the bottom of the first and second columns. The article has been updated on IEER's Web site, http://www.ieer.org. A full list of errata in IEER publications can also be found there.

I-129 (1.6×10^7 years) + n → I-130m (9 minutes) → I-130 (12 hours) → Xe-130 (stable) + e

Cs-135 (2.3×10^6 years) + n → Cs-136m (19 seconds) → Cs-136 (13 days) → Ba-136m (0.3 seconds) + e → Ba-136 (stable)

Pu-239 + n → Pu-240 →

Te-135 (19 seconds) → I-135 (6.6 hours) + e → Xe-135 m (15 minutes) + e → Xe-135 (9.1 hours) → Cs-135m (53 minutes) + e → Cs-135 (2.3×10^6 years)

+

Mo-102 (11 minutes) + 3 n → Tc-102m (4.4 minutes) + e → Tc-102 (5.3 seconds) → Ru-102 (stable) + e

DEAR ARJUN

Dear Arjun,
What exactly is Accelerator Transmutation of Waste? Some of the news articles and other materials seem to say that an accelerator is all that is required in order to transmute spent nuclear fuel into a more benign form of waste. Is this true?

—Awash in Plutonium, Cap de la Hague, France

Dear Awash,
The term "accelerator transmutation of waste" actually comes from the ancient alchemists. Most people know of their quest to turn lead into gold. A small group of them were also concerned that their growing cities were producing too much garbage. While exploring ways of getting rid of it, they hit upon the idea of "accelerator transmutation of waste." This involved using catapults to throw the garbage long distances so that when it hit the ground it would break up, or "transmute," into pieces so small nobody would notice or care. In the end, they built one pilot garbage catapult, or "waste accelerator," but quickly discovered that it merely spread the mess around a big area without getting rid of it. And that was the end of *that* kind of accelerator transmutation of waste.

Accelerator Transmutation of Waste now refers to a proposed set of nuclear technologies for the treatment of the highly radioactive spent fuel from current nuclear reactors. The short answer to your question is that ATW requires a lot more than just accelerators. Each accelerator would supply neutrons to a nuclear reactor (or sometimes multiple nuclear reactors). Associated with these accelerator/reactor stations would be facilities for nuclear fuel reprocessing, fuel fabrication, and waste management. In addition, in the end, a repository would still be necessary to handle the residual waste from ATW as well as all the radionuclides that ATW cannot transmute. See the diagram below for a map of a generic ATW system.

For a more detailed response to your question, please see an expanded version of this "Dear Arjun" on our website.

For more information on transmutation and ATW, see *Science for Democratic Action* vol. 8 no. 3 (May 2000) or *The Nuclear Alchemy Gamble: An Assessment of Transmutation as a Nuclear Waste Management Strategy*. The newsletter and portions of the report are available on IEER's Web site (http://www.ieer.org), or can be ordered by contacting IEER.

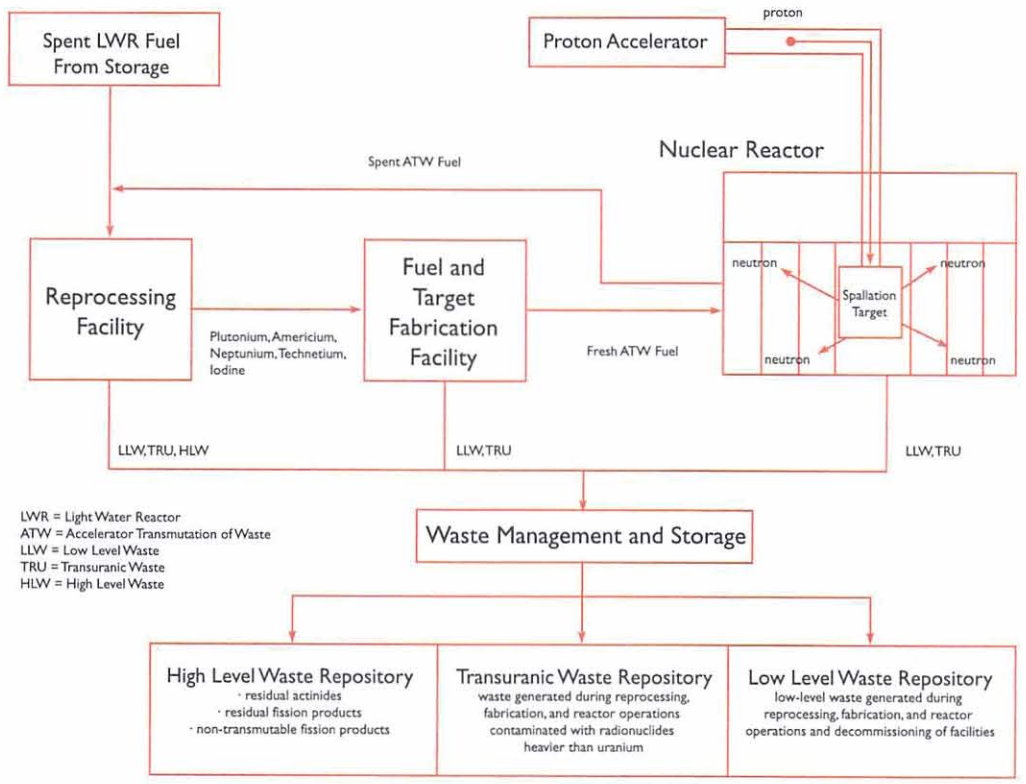


Diagram of generic ATW system. Not shown are emissions of radioactive and non-radioactive toxic substances to air and water, the highest proportion of which likely would come from reprocessing.

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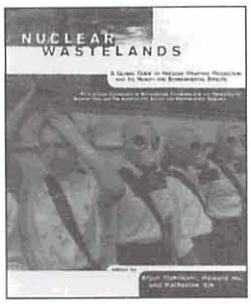

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