ANTI-NUCLEAR NUTRITION:

BACKGROUND AND PRINCIPLES FOR REDUCING THE INTERNAL RADIATION DOSE AFTER NUCLEAR CONTAMINATION OR NUCLEAR DISASTER

by

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Preface to the electronic reprint of

Antinuclear Nutrition:
Background and Principles for Reducing the Internal Radiation Dose After Nuclear Contamination or Nuclear Disaster

by Karl Simanonok, Ph.D.

I wrote this book to satisfy thesis requirements for a Master's degree in nutrition (reference: Simanonok, K.E. Antinuclear Nutrition: Background and Principles for Reducing the Internal Radiation Dose After Nuclear Contamination or Nuclear Disaster. Thesis, Florida State University, Tallahassee, 1981). It explains basic radiation principles, the biological effects of radiation, and sources of radiation exposure. It then focuses on the specific radionuclides of concern to humans, pathways by which they can enter the body, and protection principles and methods by which the radionuclides of most concern can either be prevented from becoming deposited in the body or their removal from the body can be accelerated. It is therefore a book about short-term and long-term protection from **internal** sources of radiation (as opposed to radiation exposures from external sources) that would be of greatest concern after nuclear war or nuclear contamination event.

This information is valuable for those who wish to be prepared for the horrific aftermath of nuclear war or other nuclear disaster. It could make a large difference in your quality of life should it ever become necessary to apply its countermeasures in a radioactive environment. These countermeasures are not common knowledge and may not be readily accessible to most people after a nuclear war. After a nuclear war or other nuclear catastrophe you may not be able to access this document in its electronic form, so it is recommended that you print out a hard copy for yourself and make photocopies for friends and family. You can have its 201 pages bound at most copy shops.

Dedication

This book would not exist if it were not for the patience and encouragement of my major professor, Dr. Eleanor Noss Whitney. She inspired me with her gentle warmth and grace and example to want to bring something of value to the world, and my only regret is that this resulting book was not made available to the public earlier (it really required the Internet to do so, as no conventional publisher saw sufficient dollar signs in it). Ellie Whitney has mentored legions of students in one way or another, and in my case she literally saved me from dropping out of school. If you learn anything of value from this book, don't thank me, thank Ellie Whitney.

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Introduction

The purpose of this report is to present some practical measures for attaining a degree of protection from the radioactivity that might be encountered in a radiological emergency. Exposure to a spill of radioactive material may present a hazard due to radiation from outside the body or radioactive substances that may irradiate the body from inside. This report concerns internal emitters, those radioactive atoms which disintegrate within the body. Many radionuclides emit radiation that is virtually harmless as long as the atoms disintegrate external to the body; but when they deposit their energy in living tissues they are very destructive. Radioactive elements which enter the environment interact with a complex set of physical and chemical pathways that ultimately determine their transport and distribution characteristics. The same is true when they enter a human body or any other organism; they are then subject to the metabolism of the body, and may concentrate in certain organs and tissues. A radioactive element behaves in the body exactly like a stable element until it disintegrates and does its harm. The pathways by which radionuclides reach, enter, and become distributed in the body can sometimes be blocked or at least interfered with so that the internal dose received will be less.

This kind of information is available scattered throughout the scientific literature but barely mentioned in any Civil Defense or any other widely circulated publications. The need for the information is apparent in the light of many serious doubts about the safety of the nuclear fuel cycle and alarming forecasts of world nuclear weapons proliferation and even nuclear terrorism.

The sources of information cited in this report are books by authorities in their fields, research articles in refereed journals, and official governmental publications. There are a few personal communications from experts in their fields, and reference is made to newspaper articles in a few cases when it has been necessary to document events.

Because this information is meant to be of practical use, I have begun with the assumption that the reader has little or no knowledge of the subjects that are necessary to understand the nature of the problem, which is: What can be done to reduce an internal dose of radiation? Therefore, this report begins with a brief chapter about radiation principles. It is not meant to be a comprehensive survey of all that is known about radiation physics; it only supplies the general knowledge needed to understand the subject. Similarly, the following chapter on Biological Effects is a highly abbreviated survey of what is known about the effects of radiation in living cells and human beings. It provides a reference scale of biological effects which extends from small doses in excess of the low level of background radiation to all the effects seen in fatal doses. Included under Biological Effects are the radionuclide pathways and the specific radionuclides of concern. The following chapter, Sources of Exposure, discusses the potential sources of exposure and the magnitudes of the various hazards, especially as they relate to radionuclides of concern.

If you are already knowledgeable about these subjects, or involved in an emergency, you may save time by skipping to the Protection Principles. That is where the survival information begins.

Radiation Principles

Atomic Structure

The Rutherford model of the atom describes a very small but dense positively charged nucleus surrounded by orbiting negatively charged electrons (Miller, 1972, pp. 609-611). Nuclei are composed primarily of protons which are heavy particles with a positive charge of +1, and neutrons, which are about the same mass as protons but carry no charge. Together the protons and neutrons of an atom constitute almost all of its mass. The number of protons in an atom characterizes its elemental species; all atoms of hydrogen, the simplest element, have a single proton, all atoms of helium have two protons, lithium has three, and so on up the scale. The number of neutrons is somewhat variable, and the number of electrons is subject to change.

Some terminology. Atomic number refers to the number of protons and is constant in all atoms of a given element. Atomic weight refers to the number of protons plus neutrons, and varies with the isotopes. Each atom of an elemental species which is distinguished by its number of protons and neutrons is termed a nuclide. If there are additional neutrons or some neutrons lacking from a nuclide of a particular element, that atom is an isotope of the element. An isotope has an atomic weight that is slightly different from the nuclide, but they both contain the same number of protons.

For example, $^{235}_{92}U$ is a scientific convention for writing Uranium, mass number 235 (the number of protons plus neutrons), containing 92 protons. The number of protons is superfluous because all uranium isotopes have 92 protons, so

the notation ^{235}U serves just as well. It can also be written U-235, because that is how it is spoken, and it is easier to type as well. Even better for a report such as this is to write out the name of the element to avoid confusion: uranium-235. Since this report contains many elemental names, and it is not directed solely at those who would be expected to know all of the elemental abbreviations, the names and mass numbers are used, except in the cases of quotations and references.

The most common form of uranium is uranium-238, which contains a total of 238 protons plus neutrons. An isotope of uranium is uranium-235, which lacks three neutrons in comparison to the uranium-238 atom. Technically the uranium-238 atom should be called a radioactive nuclide or radionuclide, and the uranium-235 atom should be called a radioactive isotope or radioisotope. In practice, however, these four terms are used synonomously. The trend seems to favor the use of the word radionuclide when describing any radioactive elemental species, and that convention is used throughout this report unless one of the other terms is present in a quotation or reference.

Atomic nuclei are surrounded by electrons which orbit them at discrete energy levels called shells which may be further subdivided into orbitals. Each electron carries a negative charge of -1. A neutral atom has the same number of protons as electrons so that the charges sum to zero, but electrons are rather easily added or stripped away from atoms so their numbers are not constant with each elemental species.

Radioactive Decay

Atoms exist as a result of a balance of forces; radionuclides have unstable nuclei and may disintegrate, releasing energy in the process. The energy they

release is absorbed by matter and has the potential to harm living systems. Radionuclides occur naturally in small quantities all over the earth and in all organisms, and life has evolved with the capacity to repair most of the damage caused to cells by low levels of background radiation. Radionuclides may be produced in large quantities by the irradiation of stable elements and the fission (splitting) of nuclear fuel that occurs in nuclear reactors and in nuclear weapons detonations. Smaller quantities of radionuclides can also be produced by irradiation of stable elements in particle accelerators.

Some radionuclides are so unstable that they only exist for minutes, or even fractions of seconds, so they are not found in nature but can only be created for a short time or seen briefly in the decay chain of a heavier element. An example of a decay chain is seen in krypton-90, which has a half-life of 32 seconds, becoming rubidium-90 with a half-life of 153 seconds, becoming strontium-90 with a half-life of 28.8 years, which decays to yttrium-90 having a half-life of 64.1 hours before it becomes a stable element, zirconium-90 (Lederer & Shirley, 1978, p. 346). Other radionuclides are very stable, with such long half-lives that they have persisted in the environment since their creation billions of years ago.

Energy released from nuclear disintegrations can be either in the form of photons or as the kinetic energy of particles. Photons are called gamma rays if they originate in the nucleus of an atom, and x-rays if they are sufficiently energetic (short wavelength) and originate in the electron orbitals. Physicists have classified literally hundreds of types of subatomic particles (Lanutti, 1980), but in the vast majority of radioactive disintegrations there are only alpha particles, beta particles, or gamma photons emitted. Some radionuclides only emit a single kind of radiation; for example, strontium-90 is a pure beta emitter.

Others, such as radium-226, emit alpha particles, beta particles, and gamma rays.

Alpha particles are helium nuclei traveling at high speed; they are composed of two protons plus two neutrons. Beta particles are high energy electrons that are ejected from nuclei. Since both alpha and beta particles are electrically charged, they interact very rapidly with surrounding matter and do not penetrate very far. Gamma photons and neutrons, on the other hand, have no charge, and so may travel a great distance through matter without being stopped.

Some other nuclear disintegration products which can be lumped under the term of radioactivity are positrons (positively charged beta particles), and mesons (thought to be helpful in holding nuclei together), as well as protons and neutrons. The emitted particles besides alpha and beta particles are relatively harmless to living systems mainly because of their scarcity in most disintegration processes. Under certain circumstances they may present a hazard, such as if you accidentally stood in the beam of a particle accelerator. "Criticality" accidents have occurred when critical masses have been accidentally assembled, causing a flash of neutrons to be emitted and sometimes resulting in death to those exposed (Radiological Emergency Operations, no date, p. 221).

Ionizing Radiation

Radiation is a general term for the process of energy traveling across space. It includes all of the electromagnetic spectrum, from radio waves, infrared and visible light, to the ultraviolet and the higher energy x-rays and gamma photons which are the photons of higher energy that cause damage and are commonly considered to be "radiation." Even though the energy of a sound wave is a kind of radiation, the type of radiation of importance in the context of

this report is called ionizing radiation.

Ionizing radiation includes high energy photons (x-rays and gamma rays), subatomic or atomic particles in motion such as alpha and beta particles, and even heavy atomic nuclei such as occur in space and are called cosmic rays (which may penetrate the entire atmosphere and contribute to our background radiation; they are not emitted from radionuclides). Ionizing radiation causes ionizations in the matter that the radiation interacts with as electrons are stripped away from the stable atoms or molecules which absorb the energy or the radiation. Both positive and negative ions are usually formed. This causes them to become chemically reactive to an extent that is often greater than the reaction energies they normally possess; chemical reactions and molecular rearrangements may occur as equilibrium is regained. Large organic compounds may be cleaved, and reactions such as oxidation, halogenation, addition to double bonds, polymerization, carboxylation, nitration, and isomerization are just a few of the reactions that are known to occur in response to ionizing radiation (Chutny & Kucera, 1974). The biological effects of radiation are due to the absorption of the energy of radiation by living tissues.

In sum: the nuclear disintegrations of atomic nuclei result in the emission of radiation. The chief emissions from a disintegration are x-ray and gamma photons, and alpha and beta particles. Any of these may present a hazard; occasionally neutrons or other types of radiation may also cause harm if they also induce ionizations in living tissues.

Half-Life

Radioactive half-life. The radioactive half-life of any radionuclide is the time that it takes for one half of the starting material to undergo nuclear

rearrangement. Energy is emitted and the rearranged nucleus often (but not always) becomes transformed into another elemental species. With only one exception, irrelevant to this disucssion,[1] the rate of radioactive decay is not affected by the chemical state of the radionuclide. However, there are ways to accelerate the rates of nuclear reactions which are utilized in nuclear weapons, nuclear power plants, and particle accelerators. These altered rates of nuclear transformations are only attainable under drastic conditions which do not apply to radionuclides dispersed in the environment. Thus the half-life of elements in the environment will exhibit a characteristic exponential decay curve (see Figure 1).

Not all half-lives are the same length. Some radionuclides have half-lives of only fractions of seconds; plutonium-239 has a half-life of almost 25,000 years.

Biological half-life. Because there is a turnover of nutrients throughout the life of an organism, any particular element can be said to have a biological half-life which is a function of the rate of turnover for that element; an element like iron which is well retained has a long biological half-life, and an element like oxygen which is continuously being taken in and then excreted has a relatively short biological half-life.

Biological half-life is not to be confused with radioactive half-life. Radioactive half-life is a measure of a constant rate of decay in radionuclides regardless of where they are, and biological half-life is a means of describing

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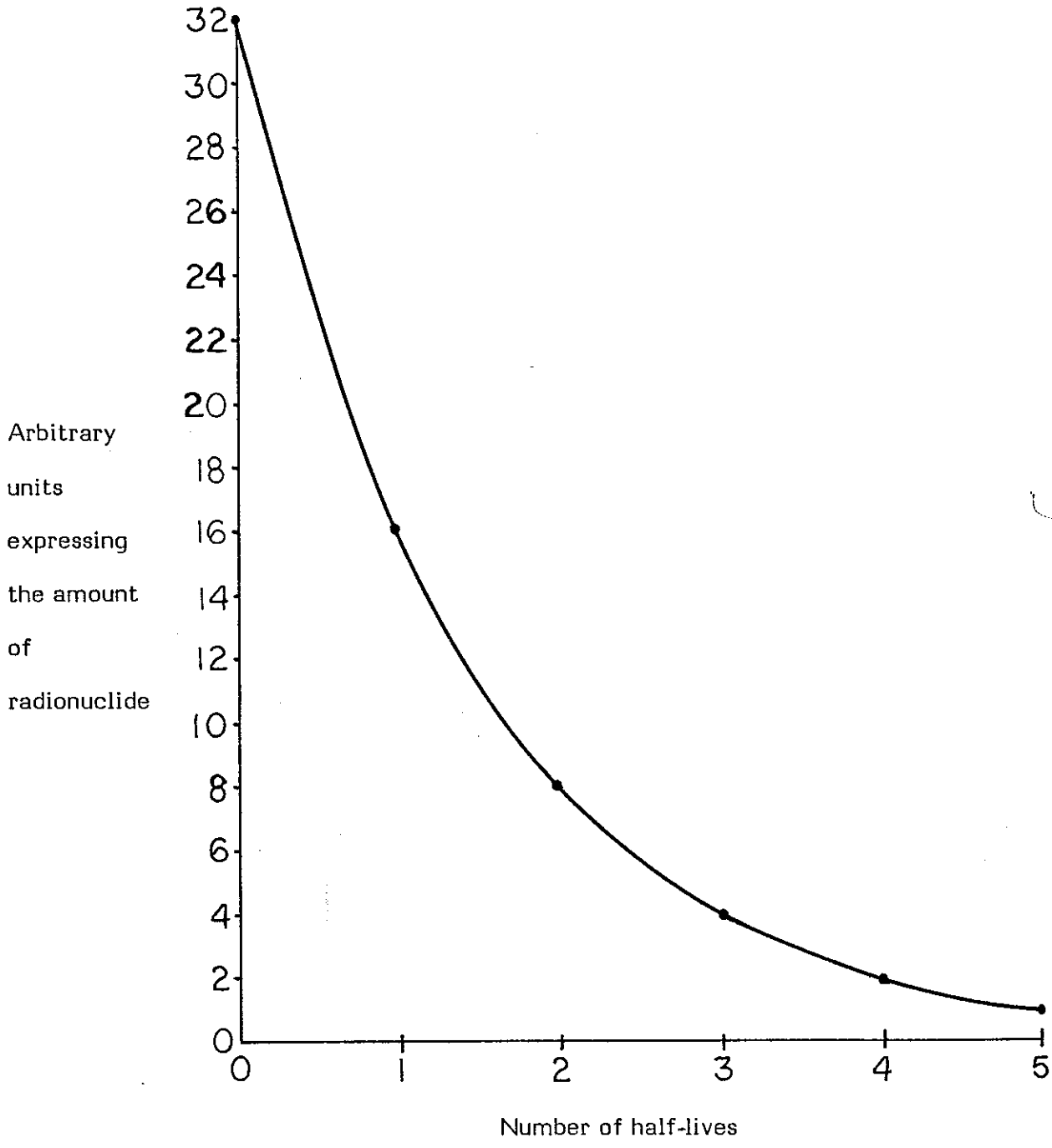
[1]The decay rate of Beryllium (atomic number 4, mass number 9) is slightly influenced by its chemical state.

Figure 1


Arbitrary units expressing the amount of radionuclide
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
Number of half-lives

how long a particular element (whether radioactive or not) is retained in the body.

The biological half-lives of many elements are not constant; they may vary with species, age, sex, genetic constitution, nutritional status, and other factors. Nutritional status can sometimes be modified to speed up the biological half-life of an incorporated radionuclide so that its hazard is diminished (see Protection Principles).

Effective half-life. The effective half-life of a radionuclide is dependent upon the combined factors of radioactive half-life and biological half-life. An ingested radionuclide with a very short radioactive half-life may all decay before any of it is excreted; the effective half-life would then be equal to its radioactive half-life. On the other hand, a long-lived radionuclide with a short transit time in the body will have an effective half-life that is nearly equal to its biological half-life. The effective half-life of any radionuclide can be described by the equation:

$$T_{eff} = \frac{(T_{\frac{1}{2}})\ (T_b)}{T_{\frac{1}{2}} + T_b}$$

where T_{eff} = effective half-life

$T_{\frac{1}{2}}$ = radioactive half-life

T_b = biological half-life (Wang, 1969 p. 194)

Decay Chains

Radioactive decay often proceeds through a number of stages and elemental species before a stable product is reached. This is especially true for the actinides, and other heavy elements such as radium, which undergo a series

of nuclear transformations before a stable element is formed. Differing half-lives for each transmutation step result in unequal environmental concentrations of each of the elements in the process. For example, the radium-226 present in uranium mill tailings has a half-life of 1,600 years. It emits an alpha particle and decays to radon-222, an inert gas with a half-life of 3.8 days (Lederer & Shirley, 1978, p. 1384). Therefore, the radon will only persist for a very short time relative to radium and will always be present in lower concentrations than the source of radium from which it is generated. Locked in rock in the earth, radium and radon will exist in equilibrium concentrations because the radon cannot readily move through rock. In mill tailings however, the radon produced can diffuse out of the pile, so that equilibrium conditions will not be the same in a mill tailings pile as in rock.

Radon-222 then forms polonium-218 when it decays, emitting an alpha particle (Lederer & Shirley, 1978, p. 1376). Polonium-218 has a half-life of only 3.05 minutes, and it then decays emitting another alpha particle and forming lead-214 with a half-life of 26.8 minutes. Lead-214 then undergoes beta decay to form bismuth-214, half-life 19.7 minutes, which decays by alpha or beta emission to form polonium-214 or thallium-210, more than 99% of the time forming polonium-214 (Lederer & Shirley, 1978, p. 1365). Polomium-214 has a half-life of only 164 microseconds before it emits an alpha particle and becomes lead-210; the thallium-210 takes a little longer to catch up, having a half-life of 1.3 minutes before it emits a beta particle and also becomes lead-210. Almost all of the lead-210 decays by beta emission to form bismuth-210 after a half-life of 22.3 years. Sometimes the decay is by alpha emission, and lead-210 becomes mercury-206. The bismuth-210 formed in this decay chain decays mostly by beta

emission (half-life 5.01 days) to become polonium-210 with a half-life of 138.38 days (Lederer & Shirley, 1978, p. 1348). Bismuth-210 may also decay by alpha emissions to an excited state of thallium-206. The mercury-206 also decays (half-life 8.1 minutes) to thallium-206 but by beta emission. Finally, thallium-206, with a half-life of 4.20 minutes, decays by beta emission to form stable lead-206, at last. Polonium-210 also forms stable lead-206, but by alpha emission (Lederer & Shirley, 1978, p. 1323).

This long cascade of disintegrations releases energy at each step in the process. Radon, as an inert gas, is the most mobile of the series. If a radon-222 nuclide is inhaled, it can irradiate the lung and bronchial epithelium; if it has been dissolved in the body it may irradiate the tissue that it is near. The daughter nuclides are not gaseous and are much more likely just to be retained within the body. Especially lead-210, with its 22.3 half-life, could be expected to accumulate in the body as a result of exposure to radon-222 or its parent nuclide, radium-226. I do not know that anyone has ever measured the lead-210 concentrations in the bodies of persons exposed to higher than normal levels of radon-222; it would make an interesting study.

Units of Measure

Various units are used to describe radiation; some are going out of style, others are coming in. The pioneering work done by Marie Curie with radium was recognized by adopting her name and her element as a standard of measure.

Curie. The curie (abbreviated Ci) is defined on the basis of the number of disintegrations per unit time in one gram of pure radium. It equals 3.7×10^{10} disintegrations per second, or 2.22×10^{12} disintegrations per minute. For other elements besides radium, one curie of that element is the amount of it that

undergoes 3.7×10^{10} disintegrations per second. The energy released need not be equivalent to the energy released from one curie of radium, for the reason that nuclear disintegration energies of different radionuclides vary.

Specific activity. Since each radionuclide has a characteristic rate of decay, the number of disintegrations per second in one gram of different radionuclides will vary. It will therefore take a smaller amount of a shortlived than of a longlived radionuclide to equal one curie. The unit of specific activity is measured in curies per gram (it can also be expressed in disintegrations per second per gram). A radionuclide with a short half-life will have a high specific activity (lots of curies per gram) for a short while. A radionuclide with a long half-life will have a lower specific activity for a longer period of time.

$$\text{Specific activity} = \underline{\lambda}\, N = \frac{.693\, N}{T_{\frac{1}{2}}} = \frac{\text{disintegrations per second}}{\text{gram}}$$

or

$$\text{Specific activity} = \frac{\underline{\lambda}\, N}{3.7 \times 10^{10}} = \frac{N\,(1.873 \times 10^{-11})}{T_{\frac{1}{2}}} = \frac{\text{curies}}{\text{gram}}$$

where $T_{\frac{1}{2}}$ = half-life in seconds

N = number of atoms per gram

$\underline{\lambda}$ = decay constant for particular radionuclide (Wang, 1969, p. 194)

Roentgen. Abbreviated R or r, a Roentgen is equal to the amount of radiation which delivers a flux of 10^9 photons per square centimeter (Brennan, 1956, pp. 127-133). Thus, a known quantity of a radionuclide is measured in curies, and the photon flux it emits will decrease with distance according to the

inverse square law: $R_1 d_1^2 = R_2 d_2^2$, where R_1 = dose rate at a distance d_1 from source and R_2 = dose rate at a distance d_2 from source (Radiological Emergency Operations, no date, p. 41). The closer you get to the source, the greater will be the dose in Roentgens.

Another way to define a Roentgen is the amount of x-ray or gamma radiation that produces 2.1×10^9 units of ionic electrical charge per cubic centimeter of air at standard temperature and pressure (Fessenden & Fessenden, 1976, pp. 265-266).

Rad. This stands for Radiation Absorbed Dose and corresponds to the absorption of .01 joule of energy per kilogram of the tissue concerned. This is equivalent to 100 ergs per gram of the absorbing material (Sources and Effects of Ionizing Radiation, 1977, p. 5). Since about 94 ergs of energy is deposited in tissue from an exposure of one R, one rad is nearly equivalent to one Roentgen (Glasstone & Dolan, 1977, p. 638).

Rem. The term is derived from the expression "Roentgen equivalent, man" (or mammal) and takes into account the Relative Biological Effectiveness (see below) of different kinds of radiation to compare different sources of radiation with a standard cobalt-60 usually gamma source. One rem of any radiation produces the biological effect that would be equivalent to absorbing one Roentgen of cobalt-60 gamma radiation (Fessenden & Fessenden, 1976, pp. 265-266). Rems are used when the type of radiation being measured by an instrument gives a reading that would not be very representative of the same dose to tissue received from a standard source. A correction factor for the biological effectiveness is applied to the instrument's reading (see RBE, below). In this way, for most practical purposes, one can consider Roentgens, rads, and rems to

be equivalent measures.

RBE. This is the abbreviation for Relative Biological Effectiveness, which relates the absorbed dose of a given kind of radiation to the amount of gamma radiation from a cobalt-60 gamma ray source that will produce the same effect biologically.

$$\text{RBE} = \frac{\text{absorbed dose of gamma radiation from a cobalt-60 source}}{\text{absorbed dose from another kind of radiation source}}$$

(Fessenden & Fessenden, 1976, pp. 265-266).

Radiosensitivity. The radiosensitivity of a cell varies with a number of factors, such as the degree of its hydration and oxygen tension, intracellular sulfhydryl groups, and the phase of the DNA synthetic cycle that a cell is in when it is irradiated. Radiation can stop or delay mitosis (cell division) as well as kill cells. In some tissues there is a constant cell turnover in which new, young cells are proliferating and replacing older cells which are being removed. Continuous replacement of cells is thus essential to the proper functioning of these types of tissues, such as in the gonads, bone marrow, lymph nodes, thymus, and intestinal mucosa. All of these tissues are particularly radiosensitive, since a depletion of the proliferating cell population by radiation may leave the tissue with insufficient numbers of cells to perform its function (Cohen, 1966, pp. 208-348).

Dose commitment. The total radiation dose to an individual or a population from a given source of radiation is known as the dose commitment. The radioactivity from incorporated radionuclides will continue to contribute to the dose commitment as long as they are in the body, so speeding up the removal of those internal emitters will reduce the dose commitment. The concept of dose commitment can even be extended to include a medical x-ray, in which the total

dose from a single x-ray is delivered in a short period of time (Goldman, personal communication, August 26, 1981).

Large doses of radiation which may be lethal when delivered in a short period of time can be tolerated when the dose is sufficiently spread out over time. In both cases the dose commitment would be the same, however.

Observed ratio (OR). This term was originated to describe the relative concentrations of strontium-90 in humans and in the foods consumed by humans (Comar, 1967, pp. 17-31). Since strontium is chemically similar to calcium and both move along the same metabolic pathways in food chains, the proportion of radiostrontium to calcium is important, and the ratios of Sr:Ca are used to calculate the OR (product/precursor). The OR, then, reflects the gain or loss of radiostrontium in proportion to calcium as both elements move up food chains toward humans. It happens that while most metabolic pathways for calcium will also transport strontium, calcium is favored, so that the OR is generally less than one. Also, since each step along the food chain consists of plants or animals with slightly differing metabolic preferences for strontium versus calcium, each OR is the product of the various physiological processes influencing the differential behavior of the two elements. Each physiological mechanism for handling strontium and calcium thus has a particular Discrimination Factor (DF = a ratio of fractional retentions), and the product of the DF's is equal to the OR. For further explanation, see Strategies for Protection under Radiostrontium.

Gray. This is the special name for the SI (Systeme Internationale) unit of absorbed dose, which is equivalent to one joule per kilogram, so 100 rads equal one Gray (Sources and Effects of Ionizing radiation, 1977, p. 27). Practically nobody uses this unit in the U.S., although it is in standard use in Europe.

SI prefixes. Since a whole curie of a radionuclide is very large in biological terms, the SI prefixes are commonly used in the scientific literature. They are given here for the benefit of those who are not familiar with them.

one curie (Ci) = 3.7×10^{10} disintegrations per second (dps)

one millicurie (mCi) = $\frac{1}{1000}$ Ci = 10^{-3}Ci = 3.7×10^{7} dps

one microcurie (μCi) = $\frac{1}{1000}$ mCi = 10^{-6}Ci = 3.7×10^{4} dps

one nanocurie (nCi) = $\frac{1}{1000}$ μCi = 10^{-9}Ci = 3.7×10^{1} dps = 37 dps

one picocurie (pCi) = $\frac{1}{1000}$ nCi = 10^{-12}Ci = 3.7×10^{-2}dps = .037 dps = 2.22 disintegrations per minute (dpm)

one femtocurie (fCi) = $\frac{1}{1000}$ pCi = 10^{-15}Ci = .002 dpm = .133 disintegrations per hour = 3.2 disintegrations per day.

Low doses of radiation are often measured in millirads or millirems. One thousand millirads = one rad. Very high doses can be expressed in Megarads (Mrad), units of a million rads.

Biological Effects

Internal Versus External Emitters

The energy released in a radioactive decay has the capacity to do damage if it interacts with living tissues. External emitters are those radionuclides which disintegrate outside the body. Internal emitters are those radionuclides which disintegrate after they have been ingested or absorbed into the body.

Most of the energy of radioactive decay is usually either in the form of a photon (a gamma ray or x-ray) or an energetic particle (such as alpha and beta particles). Photons are capable of penetrating tissue or intervening material to a depth that is dependent upon the density of the material being penetrated and the energy of the photon. Energetic particles, on the other hand, often carry electrical charges which cause them to interact very rapidly with the matter that they penetrate. This causes them to lose all of their energy of motion very soon after entering tissue, so that most alpha radiation, for example, cannot even penetrate the outermost dead layers of the skin. Alpha particles rarely have enough energy to penetrate tissues by more than .1 mm. The linear energy transfer (LET) is very high for alpha particles, which means that they produce very many ionizations per unit of distance traveled, compared to other types of radiation. The density of ionizations along the track of a beta particle is less (lower LET than for alpha particles), and they are a bit more penetrating than alpha particles. Beta particles are only occasionally able to penetrate any deeper than about 2 cm in tissue (Russell, 1966, p. 523).

A large number of beta particles striking the skin can cause reddening like a sunburn or even more serious burns, depending on the amount of exposure received. "Beta burns" were responsible for the skin burns due to nuclear weapons fallout on the Marshall Islanders in March of 1954. The islanders were unaware of the hazard of the white powdery material which fell on them. Wherever the fallout remained on the skin, itching and burning of the skin was experienced shortly afterward that disappeared within a day or two. After two or three weeks, epilation (hair falling out) and skin lesions became apparent on the scalp, neck, shoulders, forearm depressions, feet, limbs, and trunk--any exposed, moist areas unprotected by clothing. Heavily contaminated individuals developed lesions that became wet, weeping, and ulcerated. These areas developed scabs, and healing left depigmented areas that were slow to become pigmented again--it took about a year. Hair began growing again about nine weeks after exposure, and hair growth was complete after six months (Glasstone & Dolan, 1977, pp. 594-597).

The hazard from external sources of alpha and beta particles is almost negligible compared to the penetrating photons which may be emitted from fallout particles, although beta burns of the skin may result from visible quantities of fallout that are allowed to accumulate and remain.

When fallout is ingested, much more serious damage can result. It is not necessary that radionuclides actually be absorbed into the body to do a great deal of damage. Even though the esophagus, stomach, and intestines are topographically external to the body, the cells which line the gastrointestinal (GI) tract have no protective covering of skin to absorb some particle emissions. The cells lining the GI tract are also among the most sensitive to radiation, so that

radionuclides in transit along the GI tract can do much harm. The cells of the GI tract are rapidly dividing and dead cells are being sloughed away so that the epithelial lining of the GI tract is replaced every few days with new cells. Younger cells are generally more radiosensitive than are older cells, which is perhaps why cells of the GI tract, the bone marrow, and fetuses are highly radiosensitive (Grosch & Hopwood, 1979, p. 176, p. 200, p. 204).

If radionuclides are inhaled, alpha and beta particles can irradiate the lining of the lungs and some absorption of radionuclides is possible; if swallowed, besides irradiating the GI tract, if they are absorbed into the bloodstream where they can do damage all over the body. The Japanese crew of the Fukuryu Maru (Lucky Dragon) that also received fallout contamination from American nuclear testing was unaware of the fallout hazard; they all became ill, and one of the fishermen died. "A considerable proportion of the lethal dose of external radiation was received by individuals who barely exceeded, and only for a short period, the permissible internal burden" (The Biological Effects of Atomic Radiation, 1956, p. 39).

Radionuclides which are ingested are usually more damaging per disintegration than external sources because the energy of their alpha or beta particles can be absorbed by living tissues. Some radionuclides tend to concentrate in particular tissues or organs, where their damaging ability is also concentrated. For internal emitters, it is not only the energy of photons and particles released that can do damage. In addition, there may be an atomic recoil, like the "kick" of a gun when it fires a bullet, of the daughter nucleus (the nuclide remaining after radioactive decay) which can do damage; also, the daughter nucleus may be ionized as a result of its nuclear disintegration and cause damage by local charge

effects. Finally, when a radionuclide disintegrates, it most often is transmuted into a new elemental species, so if a radionuclide decays that has been incorporated into a molecular structure, when it disintegrates it will most likely not be the same element, and unable to perform the same function. For example, thyroid hormones have either three or four atoms of iodine attached to them which are necessary for the biological activity of the hormone. If one of the iodine atoms on a thyroid hormone molecule disintegrates the thyroid hormone molecule will lose its biological activity (see Radioiodine). If the radioiodine that disintegrates is an iodine-131 radionuclide, the daughter nuclide formed is xenon-131, an inert gas (Lederer & Shirley, 1978, p. 652).

Radionuclides incorporated into phage DNA can produce damage by valence changes, atomic excitation, and nuclear recoil of the daughter nucleus, all of which are capable of disrupting DNA molecules. A phage is a virus that infects bacteria, and a useful life form in which to study the effects of radiation on DNA. In particular, enhanced damage to DNA has been shown to occur from the incorporated radionuclides which disintegrate by the process of electron capture, in which an inner shell electron is captured by the nucleus of the atom. This results in vacancy cascades, a release of electrons, and a shower of localized ionizations called "Auger explosions." Those radionuclides that decay by this process were previously thought to be relatively harmless for therapeutic use because of their low emitted energies. Some of these radionuclides are chromium-51, gallium-67, selenium-75, mercury-197, strontium-85, and iodine-125 (Coquerelle & Hagan, 1978, pp. 261-279). The highly localized energy deposition, if it occurs in close proximity to DNA, results in an enhanced ratio of double strand breaks to single strand breaks, about 1:1 compared to only 1:20

after gamma irradiation (Coquerelle & Hagan, 1978, pp. 261-279). Double strand breaks in DNA are more lethal to cells than are single strand breaks (Schmidt & Hotz, 1973).

Radiation Damage to Biomolecules

The energy of a photon or particle of ionizing radiation is very much greater than the amount of energy which is normally exchanged in the reactions between biologically active molecules in a living organism. An atom or molecule that directly or indirectly absorbs some or all of the energy of ionizing radiation may become positively or negatively ionized. The reactions of such energetically ionized atoms and molecules within cells cannot be controlled or directed by the cells; they react rapidly with other cellular components, often with damaging effects.

Indirect action. Since human and animal tissues are composed mostly of water, the ionization of water by radiation has been extensively studied. The ions formed by irradiation of water are called free radicals from the less reactive ions formed by the dissociation of salts. Free radicals contain an uneven number of electrons, so that not all of the electrons are paired. The presence of an odd electron renders free radicals very reactive. In the radical formation sequence shown below, a dot symbolizes the odd electron; water is first ionized into a positive ion and a free electron if the absorbed energy is greater than the binding energy of the atom for that electron. The free electron may ionize another water molecule so that both ions formed may rapidly decompose into radicals:

$$\sim\!\!\sim\!\!\sim\!\!\rightarrow H_2O \longrightarrow H_2O^+ + e^-$$

$$H_2O + e^- \longrightarrow H_2O^-$$

$$H_2O^+ \longrightarrow H^+ + OH^\bullet$$

$$H_2O^- \longrightarrow OH^- + H^\bullet$$

The free radicals formed can undergo a number of reactions with other radicals, water, or organic substances such as enzymes and nucleic acids. If so, any damage that occurs is called indirect action because the damaging effect of radioactivity has been transmitted through the chemical reactivity produced in another molecule (Grosch & Hopwood, 1979, p. 18).

Direct action. Biologically active molecules such as enzymes may also be damaged by direct action of radiation when they absorb some or all of the energy of a photon or particle (Grosch & Hopwood, 1979, p. 19). The greatest damaging effects of ionizing radiation are seen when DNA is damaged (Sources and Effects of Ionizing Radiation, 1977, p. 5). Huttermann, Herak, and Weshof (1978, pp. 31-58) report that irradiation can cause radical formation in the constituents of nucleic acids. They describe additions and abstractions of hydrogen from purines and pyrimidines, the breakage of sugar-phosphate bonds and the formation of radical products. Sugar-phosphate bonds make up the DNA backbone, upon which the genetic code is arranged by the sequence of purines and pyrimidines that the backbone carries. Coquerelle and Hagen (1978, pp. 261-279) report that irradiation of dry DNA (the direct action of radiation being predominant) produces single strand and double strand breaks that increase linearly with dose up to 2 Megarads (M=Mega, that's two million rads). Irradiation of DNA in aqueous solution, however, causes single strand breaks to occur linearly with dose, but the frequency of double strand breaks increases with the square of the

dose.

DNA repair. Enzymes and other biomolecules can be replaced. It is only when DNA is irrevocably damaged that total recovery is impossible, unless the dose of radiation is so intense that "molecular death" occurs almost instantaneously, as a result of the nearly total inactivation of all biomolecules. Probably because the environment is naturallly somewhat radioactive, a variety of mechanisms have evolved that are capable of repairing different kinds of lesions induced in DNA by radiation.

Single strand breaks can be repaired by the excision of several bases on the damaged strands (there are specific enzymes for this purpose), and then replacement by copying the complementary base sequence of the intact strand. Corry and Cole (1973) produced double strand breaks in Chinese hamster DNA with cobalt-60 gamma radiation and found that at doses less than 50 krads (50,000 rads) "at least 80% and perhaps 'all' of these breaks are rejoined." Apparently the environment of the cell nucleus is such that the severed ends of a double strand break in DNA are not always lost, but the mechanism of excision repair, as for single strand breaks, seems unlikely to be effective for double strand breaks because no unbroken correct base sequence remains that can be copied. Schmidt and Hotz (1973) found that the double strand breaks they produced in phage DNA were always lethal--that means that no repair occurred. The reason was that the double strand breaks Schmidt and Hotz produced were made by Auger explosions from iodine-125 that was incorporated directly into the DNA base sequence on 5-^{125} iododeoxyuridine. An Auger explosion would deposit much more energy in the form of ionizations to the localized area of the DNA where it disintegrates than would be deposited there by a low LET gamma

ray. It is likely that the total lethality of double stranded breaks seen by Schmidt and Hotz was due to greater damage to the severed ends of the DNA chains; the double strand breaks produced in DNA as a result of the huge doses of gamma rays administered by Corry and Cole were perhaps "cleaner," resulting in less molecular damage to the severed ends (sort of like the difference between cutting a sausage with a knife or using a brick to bludgeon it into two pieces). Alternatively, an Auger explosion from within a DNA molecule may provide so much kinetic energy to the severed ends of the DNA chain that they are irretrievably separated.

Radiation Effects on Cells

Irradiation has been shown to have an effect on cell membrane permeability and on the permeability of intracellular membranes. Viscosity changes in protoplasm have been noted upon irradiation, as well as pathologic changes in the spindle apparatus during mitosis. Without any doubt, the most radiosensitive cellular target is the cell nucleus, because it contains the genetic material (Grosch & Hopwood, 1979, pp. 19-39).

> Disturbances at the molecular level, and even at the structural level are reparable under certain conditions; the extent of repair may vary depending on the hydration of the tissue, on its metabolic activity, on its oxygen content and on other factors. Much of the effect is apparently irreversible and may be lethal. "Lethal" effects can arise in two ways, either through the early death of the cell or through the frustration of the normal processes by which the cell is reproduced leading

> ultimately to its death. Alternatively, a cell may survive with an irreversible defect which, if it affects genetic characters, will be inherited by daughter cells. (Loutit & Russell, 1966, pp. 7-8)

The LD_{50} (the dose causing 50 percent mortality) for most mammalian cells is on the order of 100 rads (Loutit & Russell, 1966, p. 8). However, not all authors agree on this figure. Corry and Cole (1973) say "a radiation dose of 50-100 rad of gamma radiation has little effect (in terms of lethality) on mammalian cells."

Mutations. A mutation is an alteration in the genetic code of a cell which may result from as small a change as a single nucleotide in the base sequence of DNA. An altered base sequence results in the production of different proteins which is ordinarily deleterious to an organism. It is a rare mutation that is beneficial, perhaps one in a thousand. Proper proteins are necessary for structural and functional purposes in a cell, which ultimately determine the characteristics of the larger organism of which they are a part. Somatic mutations arise in body cells and only result in the incapacitation of a metabolic pathway, or no apparent change occur at all. A somatic mutation may also render a cell incapable of reproducing, or even kill it. Cancer or some other pathologic state is a possibility as a consequence of radiation exposure, and some aspects of aging can be attributed to radiation (Grosch & Hopwood, 1979, pp. 268-269).

In any event, a somatic mutation is only transmitted (copied) to daughters of the affected cell within one organism. It is not inherited by the organism's offspring. Studying the Japanese survivors of the nuclear bombs dropped on Japan, the investigators Bloom, Awa, et al. (cited in Jablon, 1973, p. 5) found

that "those survivors who received large radiation doses showed very significantly elevated numbers of complex chromosome aberrations"; 61% of those persons who were thirty years old or more at the time of the blasts that received 200 or more rads had significantly more chromosomal aberrations in their white blood cells, as compared with 16% of those who were not exposed. For those who had been less than thirty, 35% of the 200+ rad exposure group showed chromosomal aberrations while only 1% of the controls did. Children in utero at the time also showed a higher incidence of chromosomal aberrations if they had received 100 rads or more; 39% versus 4% in the controls. The offspring of exposed individuals that were conceived after the blasts showed no chromosomal abnormalities in their white blood cells. The chromosomal aberrations identified were fragments, rings, translocations, dicentrics, inversions, and deletions.

Genetic mutations affect the sperm or egg cells so that the offspring of an organism will carry that mutation in every cell of its body. Those rare mutations which are beneficial can contribute to the process of evolution of species; in a competitive world, any advantage that an organism has will contribute to its survival and the likelihood of successfully producing offspring. In such a case the mutation may eventually spread throughout the population. This is part of the mechanistic basis for Charles Darwin's theory of evolution. However, most genetic mutations are deleterious, and many are lethal.

There exists a large controversy over how much radiation actually results in a significant increase in the human mutation rate, which could be expected to be manifested as an increase in stillbirths and genetic defects. As long ago as 1956, the National Research Council of the National Academy of Sciences recognized that "any radiation dose, however small, can induce some mutations.

There is no minimum amount of radiation dose, that is, which must be exceeded before any harmful mutations occur" (The Biological Effects of Atomic Radiation, 1956, p. 15).

Studies of the Hiroshima and Nagasaki survivors have not found any significant differences at the 90% probability level between the children of bomb survivors and control groups in terms of stillbirths, infantile deaths, malformations, birthweights, and sex ratios, except for the children who were exposed in utero. The sample size of about 70,000 children born to the bomb survivors may not have been large enough to show a small proportionate increase in the number of mutations that would be normally expected to occur (Grosch & Hopwood, 1979, p. 146; Jablon, 1973, p. 5).

Applying studies of mouse mutation rates to humans, the doubling dose (that which produces a rate of mutations equal to the natural rate) is probably in the range of 30 to 80 Roentgens, about 40 R if given acutely, and up to 160 R if the dose is given over a long period of time (Grosch & Hopwood, 1979, p. 144). This range of radiation exposure that is considered to double the mutation rate is far more than the amount of radiation that most people normally receive. However, smaller doses will result in smaller increments of increased mutations, and some mutations will get into the human gene pool as a result of any excess radiation. A nuclear war or severe nuclear accident could very well expose large numbers of people to amounts of radiation greater than the estimated doubling dose, but of course doses which are lethal to whole organisms don't get a chance to result in heritable mutations.

Mutations which are not lethal or extremely disadvantageous may take a very long time to be eliminated from a population:

> The period required for elimination depends on the genetic nature of the mutant. With recessives the course of events will be slow, perhaps taking not less than thirty generations, and sometimes many more. Even when a short generation time of twenty years is considered, 20 x 30 = 600 years. What does the year 2580 mean to us? Or put another way, how would we regard ancestors in 1380 whose decisions could reflect on our health or how we live today? (Grosch & Hopwood, 1979, p. 41)

Large Doses of Radiation

The pathology of acute radiation injury has been studied in animals and in the human overexposures that have occurred. Since tolerances are very different for different species, this report will confine the subject as much as possible to human experience.

The Japanese survivors of Hiroshima and Nagasaki provided some of the first data on acute, whole-body exposure to ionizing radiation although the effects were often masked by other injuries and shock. About 250 Marshall Islanders were studied after their fallout exposure from a nuclear weapons test on March 1, 1954; they received doses up to 175 rems. Higher doses have not been so frequently encountered in humans that would provide good LD_{50} data, but animal studies allow some reliable extrapolation by following the severity of the observable effects. The LD_{50} dose for acute human irradiation is estimated to lie between 400 and 600 rads (Loutit & Russell, 1966, p. 9).

In general, radiation doses in excess of 600 rads are fatal. Survival is possible in the exposure range of 200 to 450 rads. Survival is probable at

exposures of around 100 to 200 rads; higher doses to parts of the body may occur and still permit survival. Below about 100 rads of exposure, survival is virtually certain, since none of the body's organ systems are seriously impaired (Bond, Fliedner, & Archambeau, 1965, pp. 115-158).

> Individuals receiving acute whole-body doses of ionizing radiation may show certain signs and symptoms of illness. The time interval to onset of these symptoms, their severity, and their duration generally depend upon the amount of radiation absorbed, although there may be significant variation among individuals. Within any given dose range the effects manifested can be divided into three time phases: initial, latent, and final.
>
> During the initial phase, exposed individuals may experience nausea, vomiting, headache, dizziness, and a generalized feeling of illness. The onset time decreases and the severity of these symptoms increases with increasing dose. During the latent phase exposed individuals will experience few, if any, symptoms and most likely will be able to perform useful tasks. The final phase is characterized by illness that requires hospitalization of people receiving the higher doses. In addition to the recurrence of the symptoms noted during the initial phase, skin hemorrhages, diarrhea, and loss of hair may appear, and, at higher doses, seizures and prostration may occur. The final phase is consummated by recovery or

death. (Glasstone & Dolan, 1977, p. 579) (see Table 1)

Radiation doses of 500 to 600 rads or above may produce death within a few days to about two weeks, depending on the dose received. Lower doses may produce death either due to the radiation effects or to infections brought on by a lowering of resistance. If the early stages of radiation sickness are very severe, death is likely. Those who survive to three or four months after exposure will almost certainly recover completely, and the length of the recovery period is proportional to the severity of the radiation sickness experienced.

The degree of radiation injury from internal emitters is not very likely to amount to a fatal dose or even immediate injury. Food and environmental contamination would have to be so large for that to happen that external sources would be massive and constitute the decisive factor in mortality long before a fatal internal burden could be accumulated. An exposure to internal emitters is more likely to result in the later development of delayed effects (Loutit & Russell, 1966, p. 9).

Late Effects

Those who survive an acute exposure to radiation may years later be more prone to developing cataracts, leukemia, various kinds of cancer, and nonspecific life shortening. Children exposed in utero, have a greater risk of stillbirth or early mortality. Some of those surviving may be mentally retarded or have other malformations (Glasstone & Dolan, 1977, pp. 593-594).

> Examinations done during 1966-68, more than 20 years after the [Japanese] bombings, showed that those who had been exposed to doses of 100 or more rads at ages

Table 1

SUMMARY OF CLINICAL EFFECTS OF ACUTE IONIZING RADIATION DOSES

Range	0 to 100 rems Subclinical range	100 to 1,000 rems Therapeutic range			Over 1,000 rems Lethal range	
		100 to 200 rems	200 to 600 rems	600 to 1,000 rems	1,000 to 5,000 rems	Over 5,000 rems
		Clinical surveillance	Therapy effective	Therapy promising	Therapy palliative	
Incidence of vomiting	None	100 rems: infrequent 200 rems: common	300 rems: 100%	100%	100%	
Initial Phase						
Onset	—	3 to 6 hours	½ to 6 hours	¼ to ½ hour	5 to 30 minutes	Almost immediately**
Duration	—	≤ 1 day	1 to 2 days	≤ 2 days	≤ 1 day	
Latent Phase						
Onset	—	≤ 1 day	1 to 2 days	≤ 2 days	≤ 1 day*	Almost immediately**
Duration	—	≤ 2 weeks	1 to 4 weeks	5 to 10 days	0 th 7 days*	
Final Phase						
Onset	—	10 to 14 days	1 to 4 weeks	5 to 10 days	0 to 10 days	Almost immediately**
Duration	—	4 weeks	1 to 8 weeks	1 to 4 weeks	2 to 10 days	
Leading organ	Hematopoietic tissue				Gastrointestinal tract	Central nervous system
Characteristic signs	None below 50 rems	Moderate leukopenia	Severe leukopenia; purpura; hemorrhage; infection. Epilation above 300 rems.		Diarrhea; fever; disturbance of electrolyte balance.	Convulsions; tremor; ataxia; lethargy.
Critical period post-exposure	—	—	1 to 6 weeks		2 to 14 days	1 to 48 hours
Therapy	Reassurance	Reassurance; hematologic surveillance.	Blood transfusion; antibiotics.	Consider bone marrow transplantation.	Maintenance of electrolyte balance.	Sedatives
Prognosis	Excellent	Excellent	Guarded	Guarded	Hopeless	
Convalescent period	None	Several weeks	1 to 12 months	Long	—	
Incidence of death	None	None	0 to 90%	90 to 100%	100%	
Death occurs within	—	—	2 to 12 weeks	1 to 6 weeks	2 to 14 days	< 1 day to 2 days
Cause of death	—	—	Hemorrhage; infection		Circulatory collapse	Respiratory failure; brain edema.

*At the higher doses within this range there may be no latent phase.

**Initial phase merges into final phase, death usually occurring from a few hours to about 2 days; this chronology is possibly interrupted by a very short latent phase.

Note: From Glasstone, S., and Dolan, P.J. The Effects of Nuclear Weapons, 1977, pp. 580-581.

under six years were about four centimeters, or an inch and a half shorter than the children who had lower doses or who were not exposed. For children exposed at aged 6 to 11 the effect was smaller, a diminution of about 2 and a half centimeters, or 1 inch, and in still older children no effect was found.

The fact that younger children were most sensitive leads immediately to a question about the youngest of all --that is, fetuses, offspring of women who were pregnant at the time of bombings. Such children were, in fact, greatly affected by large doses of radiation.

Beyond the general effect on size there was a specific effect on the heads of children irradiated prior to the 25th week of gestation and especially on those exposed prior to the 15th week . . . of 11 children who were in the 15th gestational week or earlier, and who had large radiation doses, 9 had distinctly small heads, and 8 of the 9 also manifested severe mental retardation--inability to perform simple tasks. Many of these retarded children have had to be placed in institutions. With increasing distance from the hypocenters and increasing gestational age the frequency of this head size-mental retardation syndrome decreases. It is thought now that the developing brain cells of the fetus are especially sensitive from about the 7th to the 15th week of gestation

> and at these ages many cells are killed by radiation and are not replaced. (Jablon, 1973, pp. 6-8)

Since radiation cataracts developed in some of the early radiation researchers, the Atomic Bomb Casualty Commission looked for and found that "among survivors who had doses of 90 rads or more the prevalence of so-called axial opacities is sharply increased." The kind of opacities noted were very small and did not interfere with vision; they were detected by ophthalmoscope and verified by a slit-lamp biomicroscope. In studying cancers in the survivors, the Commission found that:

> The most dramatic early finding was a sharply increased rate of leukemia. After a period of latency of two or three years the number of leukemias increased rapidly to a peak in 1950-1952. Since then the numbers diagnosed each year have slowly declined. However, among survivors with large doses, that is over 100 rads, the leukemia rate is still higher than normal more than 25 years after exposure. It appears that the frequency of leukemia has been about proportional to the radiation dose and among those with dose estimates of 200 rads or more the number of leukemia deaths has been about 30 times expectations at Japanese rates. This is over the whole 20-year period from 1950-1970. . . .
>
> The deaths from cancer over the 20 year period increased fairly regularly with the radiation dose. . . .
>
> For the survivors who had the largest doses, over

> 200 rads, cancer deaths have been about 60 percent higher than expectation. . . .
>
> The kinds of cancer that have occurred have been varied. To the extent that any concentration of the extra cancer deaths can be seen, the most important sites seem to be the lung, female breast, and digestive organs other than the stomach, primarily pancreas, liver, and colon-rectum. (Jablon, 1973, pp. 11-17)

"There is increasing evidence that in human beings . . . the induction of malignancies represents the most important effect produced at low doses in the exposed individual." (Sources and Effects of Ionizing Radiation, 1977, p. 362).

At the lower doses where survival is high but cancer induction is a risk, the effectiveness of the radiation in inducing cancer is less if it is spread out over time. As far as assigning numbers to the risks of radiation, although there is widespread disagreement, most radiation biologists have reached a consensus on the order of magnitude involved. Per rad of radiation, the risk is approximately one in ten thousand that an exposed individual will develop a cancer (Goldman, 1981). Another way to state it is that if a million people each get exposed to one rad (that's a million person-rads) it is likely that 100 people will get cancer as a result of the radiation. If ten thousand people each get 100 rads of radiation, that is also equal to a million person-rads, and the number of cancer victims is expected to be the same: one hundred.

No threshold has ever been found below which no effects of radiation occur. It is a theoretical possibility that a malignancy may arise from the action of a single radioactive decay on DNA. Increasing doses of radiation produce

increasing incidents of effects in all systems studied. At very high doses, the capacity for repair becomes a limiting factor in survivability or a secondary effect such as infection causes death.

Sources of Radiation Exposure

Natural Background Radiation

Life on earth has always existed in the presence of radioactivity, because natural sources of radioactivity are found in rocks and soils everywhere, and a nearly constant influx of cosmic and solar radiation is also present. Radionuclides with very long half-lives, such as the uranium and thorium series and potassium-40, have been here since the formation of the earth about four and a half billion years ago. Most cosmic rays do not reach the earth's surface; they are absorbed by the atmosphere and result in the formation of carbon-14 and tritium which account for a certain amount of natural radioactivity becoming cycled into the environment. According to Gustafson (1972) the background radiation from external sources for most of the world's population ranges from about 60 to 250 millirads of whole-body radiation exposure per year; the higher natural exposures occur at high altitudes such as Denver or in areas of higher than normal uranium and thorium deposits. There exist anomalous regions, such as parts of India, with natural dose rates as high as 1000 to 10,000 millirads per year (that is 1 to 10 rads per year) (Gustafson, 1972). The United Nations Scientific Committee on the Effects of Atomic Radiation has reported on the natural doses to some sensitive tissues (Sources and Effects of Ionizing Radiation, 1977, pp. 10-12) which is reproduced here in Table 2.

Table 2

Annual Per Capita Doses from Normal

Exposure to Natural Sources of Radiation

(millirads)*

	Gonads	Whole lung	Bone-lining cells	Red bone marrow
External irradiation:				
Cosmic rays	28 (28)	28	28 (28)	28 (28)
Terrestrial radiation	32 (44)	32	32 (44)	32 (44)
Internal irradiation:				
Potassium-40	15 (19)	17	15 (15)	27 (15)
Radon-222 (with daughters)	.2 (.07)	30	.3 (.08)	.3 (.08)
Other nuclides	2 (1.4)	55	9.1 (4.3)	4 (1.9)
TOTAL	78 (93)	110	84 (92)	92 (89)

* Figures in parentheses refer to estimates made in the 1972 report.

All values and the totals are rounded to two significant figures.

Note. From Sources and Effects of Ionizing Radiation, 1977, p.11.

> In all natural materials, ^{40}K, a primordial element, is now present as a constant percentage (0.0118 percent) of the total potassium. The ^{40}K contents of food and the relative contribution of various foods to dietary ^{40}K levels can thereby be estimated from data on total potassium. The ^{40}K intake for an adult male in the United States is estimated to be about 2300 pCi/day. The whole-body dose for the adult man from ^{40}K is estimated to be 20 mrad/yr. This radioisotope contributes, by far, the largest natural radiation exposure to man by way of his food. Because of its very long half-life (1.31×10^9 yr), it has been reduced little in intensity since the origin of man. It now probably exists at about one half to one fourth the levels that existed in Precambrian times when simple life first appeared on earth. (Radionuclides in Foods, 1973, p. 17)

Carbon-14, potassium-40, and tritium are ubiquitously distributed throughout the food chains of the world, and together contribute an average of 22 millirads per year to each person's internal dose of radiation. In addition to the twenty millirads that come from potassium-40, a little more than one millirad per year comes from carbon-14, and a little bit less than one millirad per year comes from natural tritium (Gustafson, 1972). By comparison, about 28 millirads per year is contributed by external irradiation from cosmic rays (Spiers, 1979); the rest comes from terrestrial sources. Tiny amounts of radioactivity in wood, brick, soil, and stones contribute to total external exposure. Radium in the diet

and in water provides a dose to bone that normally varies from five to 50 millirads per year. However, in a survey of the unusually high radium content of the drinking water of some North Carolina locales, the highest radium-226 content found was 19.5 picocuries per liter, which yields an estimated bone burden of 600 millirems per year to someone who consumes 2.2 liters of that water every day. The bone burden after fifty years of intake could be expected to be an order of magnitude higher (Lee, Watson, & Fong, 1979).

Lee et al. also measured the daughter nuclide of radium-226, the chemically inert radon-222. Radon-222 is a radioactive gas that also occurs dissolved in radium-containing drinking water. They found that over eighty percent of the water supplies they studied had radon-222 concentrations greater than 5000 picocuries per liter, which delivers a dose of 500 millirem per year to the stomach, the ICRP (International Commission on Radiological Protection) limit for the public. It is important to remember that a 500 millirem dose to a single organ is not the same thing as a 500 millirem whole-body dose.

Small amounts of higher than normal background radiation may be emitted from certain building materials, such as granite, and contribute somewhat to an increased natural radiation dose. Gaseous radon daughters from decay of the radium series of naturally occurring radionuclides may also be enhanced in some dwellings, especially if ventilation is low (Sources and Effects of Ionizing Radiation, 1977, p. 12). Aircraft passengers receive some extra radiation because they are above much of the protective layer of atmosphere which absorbs radiation. A typical San Francisco to Washington, D.C. flight in a conventional jet aircraft under average solar conditions delivers an estimated cosmic ray dose of about 3 millirads (Sources and Effects of Ionizing Radiation,

1977, p. 83).

The use of phosphate fertilizers and coal-fired power plants results in a technologically enhanced exposure to radium, the actinides, and their daughter products (see Actinides). The radon-222 which is present in most natural gas also supplies some radioactivity to homes that use it. The amounts of excess radioactivity from these sources are small, perhaps negligible when compared with the range of normal background radiation of 60 to 250 millirads. For example, an occupant of a typical household which uses natural gas might receive 1.5 to 3 millirads per year to the bronchial epithelium (Sources and Effects of Ionizing Radiation, 1977, p. 93).

Those who live at high altitudes receive some extra natural radiation from cosmic and solar sources, and airline pilots have an occupationally higher dose for this reason. Solar flares release radiation that can be a life-threatening hazard to astronauts, but O'Brien (1979) calculates that solar flares would only be likely to result in ground-level radiation doses of 100 rads about once in every two million years, and 500 rads once in every eight million years. She mentions that "such doses might be expected to leave their traces on the evolutionary record" because of the well-known mutagenic effect of radiation on life.

Indeed, natural radioactivity is responsible to some degree for natural mutations and thus evolution. It is a good thing that organisms possess repair mechanisms that allow them to alleviate most of the damage from low doses of radiation (see Biological Effects).

Minor Manmade Sources of Radiation

Medical and research uses. In this country, medical uses of radiation contribute almost as much exposure to the population as does the natural

background radiation (Gustafson, 1979; Spiers, 1979). Most of this constitutes an external dose from artifically generated x-rays. The use of radiation for medical purposes is a powerful tool for diagnosis and healing when it is properly used.

Relatively small quantities of radionuclides are used in research and medicine. Most research scientists use only microcurie quantities drawn from a stock of a few millicuries; medical uses are a little greater, sometimes with tens or even a couple of hundred millicuries being put into a single patient.

Radionuclides can be used for a wide variety of sophisticated diagnostic techniques such as radioimmunoassay and organ imaging. They are coming more and more into common use, so the hazard from accidents in hospitals and research facilities will very likely increase in proportion to the spread of the use of radionuclides. Even so, the quantities used are relatively small, so the extent of contamination in an accident is correspondingly minor, and is most likely to occur in an area of a hospital or research facility that can be readily sealed and decontaminated. In addition, the people who routinely work with radiation are usually knowledgeable about procedures to minimize contamination if there is an accident. However, cavalier attitudes in handling radioactive substances are easily developed, particularly if the quantities are small, because the danger is completely invisible and insensible.

In the early days of radiation research, the hazards of radiation were unknown or poorly understood, so that many unnecessary exposures to radiation resulted in lung and bone cancers, leukemia, burning and necrosis of the hands with atrophy of the muscles of the fingers, anemia, loss of hair, and fatigue (Rona, 1979). Marie Curie and her daughter, Irene Joliot-Curie, both died of leukemia, for example. They did not know that radium is a bone-seeking

radionuclide, and that the bone marrow is one of the most radiosensitive tissues of the body. Now that some of the hazards of radiation are more fully appreciated, those who work with it do so under conditions designed to minimize their exposure.

Careful attention to radiation protection at the Miriam Hospital in Providence, Rhode Island, has shown the kind of benefits that can result. The average personnel exposure to radiation has decreased even though the patient workload has increased. The average yearly exposure for the nuclear medicine personnel at Miriam Hospital dropped from 424 millirems of whole-body exposure in 1973 to 180 millirems in 1977. For perspective, the yearly permissible dose is 5,000 millirems. Every reduction of exposure reduces the occupational hazard, and increased safety consciousness also results in an improved preparedness to handle any major or minor spills of radioactive material (Gandsman, North, & Spraragen, 1980). Following are examples of some other minor sources of radiation exposure that the medical profession deals with more effectively of late. Each safety improvement that is implemented results in a small incremental dose reduction on the order of a few millirems.

Nishizawa, Ohara, Ohshima, Maekoshi, Orito, and Watanabe (1980) report that contamination can occur from hospital patients treated with iodine-131 for thyroid carcinoma and hyperthyroidism. Contamination of dishes, chopsticks, toothbrushes, linens, underwear, and the air was detected as a result of the volatilization of radioiodine in the breath, from perspiration, and from contact with saliva. They suggested that patients so treated should wear masks for the first few days after treatment and/or be isolated in a ward to themselves because a cough spray will contaminate a patient's surroundings, and physical

contact with a visitor will contaminate the visitor. Adequate ventilation of the room that a patient is in will reduce the air concentration. Van Middlesworth (1963) found that a single kiss from a patient so treated, eight days after treatment, can contaminate the recipient with 0.02 to 5 picocuries per microcurie of the original dose of iodine-131. This is not much radiation, but it all adds up, so any avoidable dose should be avoided.

Jalbert and Killian (1979) report that the inhalation dose from tritiated water can be substantially reduced by ventilation or containment rather than working with open containers on a bench.

Johnston, Minarcik, Rossi, and Pinsky (1979) describe a procedure designed for the autopsy of a radioactive cadaver, illustrating that the medical profession is adept at dealing with unusual sources of radiation.

Because the medical profession and most research uses of radionuclides are health oriented and quantities of radionuclides are relatively small, the hazard to the public from these sources is very minor. Even when a patient is deliberately given a dose of radioactivity, it is done for the benefit of the patient's health. Accidents which occur will almost always be localized within facilities containing personnel and equipment for rapid containment and decontamination of an area. The most likely people to become contaminated in a medical or research facility are the personnel who are trained in the handling of radioactive materials and are aware of the risks that they accept in the performance of their duties.

Industrial sources. Radiation is commonly employed in industry; x-ray pictures are often made of structural components for aircraft or power generation systems as part of quality control, for example. Small quantities of

short half-life radionuclides may be injected into an oil pipeline as a signal to the receiver at the other end; the list of industrial applications is very long. Radionuclides have found application in such areas as coal and metal mining, the petroleum industries, even in peat cutting. Radionuclides have been used in the food industry for such things as studying the biosynthesis of substances causing cloudiness in stored beer, and in studying the migration of antimony from solder pans into bread. Manufacturers of tobacco, textiles, wood and paper, rubber, detergent and soap, pharmaceuticals, paints and varnishes, fertilizers, cement, glass, and many other very common products have employed the use of radionuclides. Engineers use radionuclides for studying the wear in engines, gears, bearings, and machine tools (International Atomic Energy Agency, 1963).

The industrial uses of radioactivity provide another example of how radiation, properly and responsibly used, can provide a positive benefit to society. However, "it is generally recognized that industrial radiography gives rise to some of the highest average individual doses and to a large proportion of the overexposures." (Sources and Effects of Ionizing Radiation, 1977, p. 246) The estimated annual average dose to industrial workers in those industries with U.S. Atomic Energy Commission licenses was 190 millirads in 1969/70 (Sources and Effects of Ionizing Radiation, 1977, p. 248). Industrial users of radioactivity must meet government standards in the handling and disposition of radionuclides for safety's sake. Since quantities are small and the biological hazard may often be minimized by the choice of radionuclide, contamination events resulting from accidents or misuse of radionuclides in industry are not likely to result in widespread and intensely radioactive spills. There is no ingestion hazard from artificially generated x-rays.

Accelerators. Particle accelerators are used at various locales around the world, particularly by physicists seeking to explore subatomic structures. They are also used to produce certain desired radionuclides, especially for medical purposes. Undesired radionuclide production can constitute a hazard for researchers and staff, especially if ventilation is poor, the operating time and dose rate of the accelerator are high, and there are long treatment distances that involve a long path of air to become exposed to the beam. The radionuclides of concern around medical accelerators are nitrogen-13 and oxygen-15, produced from the stable nitrogen-14 and oxygen-16 in the air. Fortunately, they have half-lives of 10 minutes for nitrogen-13 and 122 seconds for oxygen-15 (Holloway & Cormack, 1980). The hazard is primarily from inhalation and whole-body irradiation, which can be reduced by good ventilation, periods between treatments that allow the short half-lived radionuclides to be reduced in concentration, lowering the energy beams (sometimes), and by reducing the path length of the beam through air.

Again, this hazard is not of appreciable magnitude ever to constitute a large danger to many people at once. The people who routinely work around radioactivity will tend to receive a cumulative dose that is greater than most people get who do not regularly encounter extra radiation.

Consumer products. Radionuclides are used in a wide variety of consumer products. They can be contained in paint or plastic and used in watches and other timepieces, aircraft instruments, compasses, various instrument dials, automobile shift quadrants, bell pushes, and many other devices so that they will be slightly luminous. They may be contained in sealed tubes and used for similar purposes as well as larger sources of illumination, such as EXIT signs for

buildings, step markers, public telephone dials, and mooring buoys (Sources and Effects of Ionizing Radiation, 1977, p. 95). The Arizona Atomic Energy Commission published an article in its newsletter about a traffic sign which is made luminous with krypton-85 and a phosphor; it was installed at a freeway intersection in Phoenix (Atom Powered Traffic Sign: A Unique Experiment, 1970, p. 1). Radionuclides are used in smoke detectors, various kinds of electronic and electrical devices, in ceramics and glassware containing uranium and thorium, and in many other devices and applications (Sources and Effects of Ionizing Radiation, pp. 96-97). Doses to consumers are minimal. For example, the tritium concentration in the body water of individuals wearing watches with hands made luminous with tritium may range from about .5 to 11 nanocuries per liter above background (averaging 3.2 uCi per liter) which gives an average annual dose of .3 millirads (Sources and Effects of Ionizing Radiation, 1977, p. 97).

The mantles used in gas lanterns contain mostly radioactive thorium, a naturally occuring radionuclide. If the first use of the mantle is in an enclosed space, some internal contamination via inhalation occurs.

The Nuclear Fuel Industry

The nuclear fuel cycle involves massive quantities of radionuclides at all of its stages. It begins with the mining of uranium ore, proceeds to the milling and enrichment of uranium, and then to fuel fabrication and the use of the fuel in a nuclear power plant or nuclear weapon. Then comes what is known as the "back end" of the nuclear fuel cycle, involving the reprocessing of used reactor fuel so that the valuable fissionable isotopes can be recovered and reused, the reprocessing of the nuclear weapons fuel which must be done every few years so

that it will be fresh and sure to explode when triggered, and the containment and storage of the radioactive wastes generated at all stages in the fuel cycle.

Mining. The hazards of mining are primarily to the miners, who are exposed to the radioactive radon gas that is released during mining.

> It does not appear that uranium mining activities result in significant increases in environmental radioactivity outside the immediate vicinity of mines. Measurements in mining communities and areas are in the same general range as non-mining areas. (Klement, Miller, Minx, & Shleien, 1972, p. 27)

In 1967, the Federal Radiation Council set standards for radon concentrations in mines, so adequate ventilation systems now protect uranium miners from most of the hazard.

Milling. Milling of the ore extracts the uranium and leaves behind radium and its radon daughters in the tons of the waste material called tailings. About 91% of the uranium is extracted from the ore, but this only accounts for 14% of the total radioactivity in the ore. Some of the thorium and radium are also removed from the ore, and the short-lived daughter nuclides of the material which is extracted from the ore no longer contribute to its radioactivity. In all, about 70% of the original activity in the ore is undissolved and is discharged in the mill tailings (Sources and Effects of Ionizing Radiation, 1977, p. 167). These tailings have been used for landfills, and in some cases homes and whole communities have been built on top of them. They increase the background radiation of an area to the detriment of the inhabitants. Once mined, the radium present in ore tailings will continue to disintegrate and thus release radioactive

radon-222 gas for thousands of years.

Radon-222 has a half-life of only 3.8 days; it decays by alpha emission to form polonium-218, which has a half-life of only 3.05 minutes, and also decays by alpha emission (Lederer & Shirley, 1978, pp. 1376-1384). Several more daughter nuclides are formed before a stable element is reached, but the total alpha emissions from the single radionuclide may be quite numerous; if the nuclide is retained within the body for the entire decay period, very much more radiation is received than that from a single alpha disintegration.

Air concentrations of radon-222 on top of the Salt Lake City tailings pile range from 1.6 to 22 picocuries per liter. This is just a representative figure; in Salt Lake City itself, for example, the radon-222 background concentrations average around .38 picocuries per liter. At distances greater than about one half mile downwind from the tailings pile, concentrations of radon-222 are not significantly increased above background levels (Evaluation of Radon-222 Near Uranium Tailings Piles, 1969, pp. 8-20).

According to a newspaper account of statements made by officials of the U.S. Nuclear Regulatory Commission, the worst nuclear accident in United States history occurred on July 16, 1979, when 100 million gallons of water containing uranium tailings was lost from a tailing pond into the Rio Puerco River in New Mexico ("Three Mile Island," 1980). Two hundred and fifty acres of land and about fifty miles of river were contaminated by the estimated 1,100 tons of tailings; some samples of river water contained 6,600 times the maximum permissible standard for radioactivity in drinking water. The radiation was detected up to 50 miles downstream of the spill. One ton of ore contains about 7.9 millicuries of total radioactivity (Sources and Effects of Ionizing Radiation,

1977, p. 167). If 70% remains in the tailings, then the 1,100 tons of tailings released 7.9 mCi/ton x .7 x 100 tons = 6,083 millicuries, or 6.083 curies of mostly radionuclides of uranium and radium; some thorium and lead-210 may also have been present. The Rio Puerco empties into the Little Colorado River, which flows into Lake Mead, which in turn supplies water to Los Angeles and much of southern California.

Enrichment. The uranium which is extracted from the ore in the milling process must then be enriched so that the concentration of the fissionable uranium-235 is increased in proportion to the more stable uranium-238. Normally the concentration of the lighter isotope is so small in a pure sample of uranium that it cannot serve as a fuel; the uranium-235 needs to be increased to a concentration of at least 3% for reactor fuel and at least 90% for nuclear weapons fuel. (This is what is meant by "bomb-grade uranium," that it is highly enriched in uranium-235.) The gaseous diffusion process of uranium enrichment relies on the slightly more rapid diffusion of uranium-235 through a thin porous membrane after the uranium has been converted to the gaseous uranium hexafluoride, UF_6. The gaseous diffusion enrichment plant is an enormously huge and complex structure, of which there are three in the United States: at Oak Ridge, Tennessee; Portsmouth, Ohio; and Paducah, Kentucky.

Fuel fabrication. The next stage of the nuclear fuel cycle, fuel fabrication, involves the solidification of the enriched uranium into pellets for reactors, which are encased in an alloy "cladding" (such as stainless steel or zircaloy) and then packed into long tubes, the fuel rods. The nuclear fuel for weapons is shaped into components for specific types of weapons. Plutonium-239 also serves well for both reactor fuel and nuclear weapons, so it may also be present at fuel

fabrication plants. Commercial uranium fuel fabrication is done at the Westinghouse plant in Columbia, South Carolina, and the Exxon plant in Richland, Washington. There is also a Nuclear Materials and Engineering Corporation plant near Pittsburgh that makes plutonium fuel rods.

Military facilities operate under a cloak of secrecy, such as the Erwin, Tennessee plant that is owned by Nuclear Fuel Services, Inc., a subsidiary of Getty Oil Co. An issue brought to bear by an environmentalist group concerning the Erwin, Tennessee facility, was over the charge that large quantities of bomb-grade uranium have been lost there. The military desire for secrecy has effectively blocked any inquiry ("Nuclear Agency Outlaws Inquiry," 1980). However, the military makes mistakes too. There is a large military facility at Hanford in Washington State which had an explosion that resulted in the contamination of a worker, H.R. McCluskey, with americium through cuts and acid burns he received in the explosion. The americium was being purified as a by-product stream from plutonium purification (King, 1976). The military way of doing things will almost always result in a warning to the public (if any warning is even given) about an accident long after it occurs.

The public hazard that exists from fuel fabrication facilities might take the form of a local contamination event, More likely, however, is the potential for exposure that might occur from diversion of bomb-grade nuclear material into the hands of criminals and terrorists (see Terrorism at the end of this chapter).

Nuclear power reactors. Nuclear power reactors in normal operation are designed to release no more radioactivity than is allowed by the Environmental Protection Agency. Currently, this is 5 millirems for the average dose to the population in the nuclear plant impact area, figured by elaborate dilution

calculations of releases to the environment, while adult nuclear workers are permitted 5,000 millirems (5 rem) per year as a lifetime average.

Since it has never been demonstrated that a threshold for radiation exists below which no biological damage occurs, public acceptance of low doses of radiation has always been predicated on cost-benefit analyses. Therefore, small doses of radiation to the general public are weighed against the cost (and impossibility) of removing all radioactive effluents from nuclear power generation. It is usually assumed that doses which comprise a small percentage of the natural background dose are acceptable because the risks associated with such low doses are considered to be very much lower than risks that many people nonchalantly accept, such as riding in automobiles and in aircraft. Also, the probability of severe accidents is considered to be (by the nuclear industry) so low that the risks are hardly worth worrying about.

The radioactivity that is released from nuclear reactors in normal operations may originate from two sources: leakage of nuclear fuel and/or fission products from the fuel cladding which is supposed to contain it, or from neutron-induced radioactivity of coolant, coolant additive, or structural materials surrounding the reactor.

> Although this metal cladding presents an impermeable barrier to the escape of fission products, it is likely that among the twenty to forty thousand of these individually clad fuel rods there will be a few defects through which fission products can escape. . . .
>
> Radioactivity also appears in the water coolant by (n,p) reactions in water to form N^{16}, proton-recoil,

> reactions with oxygen to form N_{13}, and neutron reactions with products of metallic corrosion... However, even though there are several sources of radioactivity in the reactor coolant, the coolant is contained in a closed loop of sealed high pressure vessels, piping, pumps, and heat exchangers. It is not easy for radioactivity to penetrate the third barrier presented by this enclosure. Although some leaks do occur, most of them are easily collected and the amount of associated radioactivity is extremely small. (Pigford, 1972)

Almost all of the radionuclides that are chemically reactive or nonvolatile are fairly easy to contain and are only released in very small amounts from a normally functioning reactor because of the system of traps and filters that contain them. However, some radioactive effluents may be discharged into the environment without ever having been filtered or controlled. Bruland et al. (1978, p. 107) explain that a pressurized water reactor that contains a leak in the heat exchanger between the primary and secondary cooling systems may release gaseous emissions from a low height, such that less dilution of the emissions occurs in the vicinity of the nuclear power plant.

Some radionuclides that are routinely released as gaseous effluents from nuclear reactors are various radionuclides of xenon and krypton. They are fission products that are inert gases that cannot be trapped on any kind of filter with very much efficiency. These radionuclides contribute to the whole-body dose from external exposure and from inhalation. Any system that could trap them all would be prohibitively expensive (Environmental Analysis of the Uranium Fuel

Cycle, 1973).

> Typically, about 7000 curies per year of Kr^{85} are discharged, and yearly average atmospheric mixing is calculated to result in a Kr^{85} concentration at the site boundary of only a few percent of the MPC [Maximum Permissible Concentration]. In some designs much of the PWR [Pressurized Water Reacter] off gas is compressed into cylindrical containers for permanent storage.
>
> The gaseous release problem is somewhat aggravated for boiling water reactors BWR because of the larger quantity of carrier gas to be handled. . . . In some recent BWR plants the condenser vent gas passes through a charcoal absorber which effectively delays the xenon isotopes for a period of about 14 days and the krypton by about 1 day. The gases, now containing a smaller concentration of the short-lived radioactive species, are released from the top of the building at a rate of about 30,000 curies per year. . . .
>
> Ultimately, the continued growth of fission power into the next century will require recovery of krypton and tritium. Technology is now available which could be applied to the recovery of these species, although the economics, particularly in the case of tritium recovery, may be uncertain. (Pigford, 1972)

Some reactors release a greater proportion of short-lived radioxenon

nuclides than krypton (Sources and Effects of Ionizing Radiation, 1977, pp. 176-177), presumably because they may lack the charcoal adsorption systems needed to delay their release.

Tritium is also released from nuclear power reactors, primarily as tritiated water, THO, in liquid radioactive waste effluents. Tritium is produced in the primary coolant of reactors by neutron reactions with deuterium, lithium, boron, and other minor reactions, and in the fuel by the "relatively rare (0.008%) ternary fission" (Pigford, 1972). Most tritium finds its way to the hydrosphere, being diluted in the oceans or other bodies of water. At present rates of increase, the production of nuclear reactor tritium will equal natural tritium production before the year 2000 (Koranda, Anspaugh, & Martin, 1972).

The type and quantity of radioactive materials released from reactors depends on the reactor type and on the specific waste processing systems utilized. Radionuclides may reach the environment through either the gaseous or liquid effluent streams. In the airborne effluents are found fission noble gases (krypton and xenon isotopes), activation gases (^{14}Ar, ^{14}C, ^{16}N, ^{35}S), tritium, radioactive halogens and particulates. In the liquid effluents are tritium, fission products, and activated corrosion products (Sources and Effects of Ionizing Radiation, 1977, p. 172).

Radionuclide production and releases vary to a large extent depending upon the generating capacity and type of reactor as well as many other factors (Koranda et al., 1972) such that exact predictions of routine releases can only be made for specific reactors, to some extent based on the empirical data gained from monitoring radioactive effluents.

When the public is assured by the nuclear power industry that nuclear

power plants emit very little radioactivity to the environment, that is true for normal operations and for that one particular stage of the nuclear fuel cycle.

> It is apparent that a unique- and unfortunate-characteristic of a nuclear power plant is that it produces enormous quantities of radioactivity, and most of these radionuclides will ultimately appear in the fuel cycle operations external to the reactor. (Pigford, 1972)

One must thus consider the other steps in the nuclear fuel cycle, especially reprocessing, and the possibility of improbable events occurring.

> Finally, it is important to point out that abnormal occurrences and major accidents at the reactor or the associated fuel cycle facilities can result in very significant releases of all the radionuclides in the reactor inventory. This is why it is essential that the impact of these events be considered in detail. (Tamplin & Cochran, 1975)

The hazards of radionuclides increase in direct proportion to the size of the radioactive mass. Obviously billions of curies of radiation in a reactor have the potential for harm that is many orders of magnitude greater than the picocuries and millicuries of naturally occurring, medical, or other minor concentrations of radioactivity. On the other hand, the hazard is nil if the radioactivity never escapes its confinement in the reactor reproducing plant, waste storage facility, or transport casks.

To fully understand the hazard that exists from nuclear reactors, it is first necessary to have an appreciation of the kind of radiation damage that does not

result in death or even immediate ill health: there is the possibility of cancer, leukemia, birth defects and stillbirths, growth and mental retardation and lowering of resistance to ordinary diseases and infections (see Biological Effects for details).

Secondly, it is necessary to gain some appreciation of the real likelihood of an accident at a nuclear power plant. This is an area of great controversy which cannot be resolved in this report, nor is it likely to be resolved anywhere or anytime in the near future. We simply do not have enough data to make very accurate predictions, and everybody who does make predictions seems to try to slant them toward their own point of view. The most recent government study, WASH-1400, also known as the Rasmussen Report or the Reactor Safety Study, sets accident hazards so low that they are apparently nonexistent. One of the reviewers of WASH-1400 was Dr. Daniel Kleitman, a mathematics professor at MIT who was asked to review the study's use of probability concepts and statistical methods. He found errors in procedure in the data analysis that predicted a very low probability for the worst case, "Class Nine," meltdown accident type. Using the same data but corrected statistical calculations, Dr. Kleitman calculated that with 150 reactors in operation for twenty years, we could expect four meltdowns, or an average of one every five years in that time (cited in Ford, 1977, p. 24).

Engineers have yet to design airplanes that cannot crash, dams that cannot break, and power systems immune to blackouts. It seems reasonable to suppose that unforeseen accidents will also occur in complicated and temperamental nuclear reactors. Consider this quotation by Orlandi (1977), a Metropolitan Edison Company official reporting on the problems encountered with the first

two years' operation of the Three Mile Island Nuclear Power station (reported before the well-known accident in March of 1979):

> We have learned something, but the lessons are subtile [sic], and sometimes conflicting. There are few absolutes. This is so because of the enormous complexity of the plant; so complex that it appears to have a personality. When I first heard our Supervisor of Operations say that, I thought he was feeling the strain of his job. But he was right, it does have a personality. It likes to run at 100%; take it to some other level and it fights back. Shut it down for an outage and when you try to "wake the sleeping giant" it responds with problem after problem. But coax it to 100%, and keep it there for a couple of days, and it seems happy again.

After a long list of some of the problems, Orlandi concludes:

> And on it goes. The lessons are there, but they are usually too subtile [sic] to help before the next problem occurs. Good people and good luck can help maintain the performance record, but there is a limit. One thing is certain: if you're planning on starting up a nuclear plant, you can be sure that it will be an interesting first two years.

The probability of a "worst case" meltdown accident, though small, is unknown. Even the Nuclear Regulatory Commission acknowledges that the possibility exists: "The NRC recognizes that accidents with more severe

potential consequences than design basis accidents can be hypothesized. However, the probability of such accidents is exceedingly low" (Collins, 1976).

Ultimately, each individual has to decide for himself or herself what the magnitude of the probability of such an accident will be, and this depends to a large extent upon the faith we put into the testimony of governmental and industry experts.

The power industries recognized the dangers inherent in nuclear power back in the 1950's; that is why they lobbied for and received an assurance before they would commit themselves to nuclear power, in a 1957 Federal law known as the Price-Anderson Amendment to the Atomic Energy Act, that they would only be liable for damages to a maximum of 60 million dollars if an accident happened. In the same amendment the government subsidized the fledgling nuclear power industry with a federally-insured maximum of another 500 million dollars, and limited by law the maximum liability per accident to 560 million dollars (Cavers, 1964, pp. 65-66).

Many authorities estimate that damage to life and property from a meltdown near a populated area would cause damage amounting to billions of dollars. This kind of liability would have clearly rendered the risks of nuclear power unacceptable to a profit-oriented power company.

> Early in the development of the atomic power industry, manufacturers and utilities began to worry about the risks of accidents which would create liabilities so huge that the firms held liable would be wiped out. The prospects of profit in the industry were then remote and speculative. The chance of a huge damage suit was not worth taking.

(Cavers, 1964, pp. 65-66)

The accident at Three Mile Island served to bring the hazards inherent in nuclear reactors into public view, although few people are aware of the other reactor accidents which occurred prior to the one at Three Mile Island and which involved much greater releases of radioactivity. The Windscale reactor accident in the United Kingdom was estimated to have released about 20,000 curies of iodine-131 into the environment, for example (NCRP Report No. 55, 1977).

Public protection in the event of nuclear reactor accidents was spelled out in a joint Nuclear Regulatory Commission and Environmental Protection Agency Task Force on Emergency Planning (Collins, Grimes, & Galpin, 1978). Public protection from a nuclear reactor accident is based on two phases: the "plume exposure pathway" of the volatile radionuclides released, and the "ingestion exposure pathway" for the longer term. The Task Force recommends the designation of "Emergency Planning Zones" (EPZs) surrounding nuclear power plants for which planning is recommended. The Task Force leaves the actual planning up to "responsible government officials," but makes the following recommendations on the kinds of planning which they consider pertinent for the EPZs:

(1) Identify responsible onsite and offsite emergency response organizations and the mechanisms for activating their services,

(2) Establish effective communication networks to promptly notify cognizant authorities and the public,

(3) Designate pre-determined actions as appropriate,

(4) Develop procedures for use by emergency workers,

(5) Identify applicable radiation measurement equipment,

(6) Identify emergency operations centers and alternate locations, assembly points, and radiation monitoring locations,

(7) Implement training programs for emergency workers as appropriate, and

(8) Develop test procedures for emergency response plans.

For the appropriate "pre-determined actions" (#3, above) the Task Force had this to say:

> For the plume exposure phase, shelter and/or evacuation would likely be the principal immediate protective actions to be recommended for the general public within the EPZ. . . .
>
> For the ingestion exposure Emergency Planning Zone, the planning effort involves the identification of major exposure pathways from contaminated food and water and the associated control points and mechanisms. The ingestion pathway exposures in general would represent a longer term problem, although some early protective actions to minimize subsequent contamination of milk or other supplies should be initiated (e.g., put cows on stored feed).

These recommendations offer some reassurance that the public's protection in a radiological emergency will be given some importance. However, further on in the report it becomes apparent that the actual public protection from a nuclear reactor accident is not a major concern.

The Task Force does not recommend that massive

emergency preparedness programs be established around all nuclear power stations. The following examples are given to further clarify the Task Force guidance on EPZs:

No special local decontamination provisions for the general public (e.g., blankets, changes of clothing, food, special showers)

No stockpiles of anti-contamination equipment for the general public

No construction of specially equipped fallout shelters

No special radiological medical provisions for the general public

No new construction of special public facilities for emergency use

No special stockpiles of emergency animal feed

No special decontamination equipment for property and equipment

No participation by the general public in test exercises of emergency plans

The Task Force goes on to mention that "Some capabilities in these areas, of course, already exist under the general emergency plans of Federal and State agencies." However it is clearly prudent for individuals to educate and prepare themselves as well for the eventuality of nuclear accidents.

Reprocessing. Reprocessing plants receive the spent nuclear fuel from nuclear reactors, or, in the case of military reprocessing, they receive the aged bomb components which have decayed in activity somewhat and need to be

replaced with fresher fissionable material so that they will be sure to explode when triggered. The expensive fissionable isotopes of uranium and plutonium can be recovered and recycled into more fresh fuel.

Fuel elements from reactors have undergone a great deal of fission, and, when freshly removed from a reactor, they are too intensely radioactive to be reprocessed right away because of the great quantity of short-lived fission products that they contain.

> After about three months storage, sufficient for radioactive decay of troublesome short-lived fission products which affect fuel reprocessing and for the decay of 6.75-day U^{237} which could affect subsequent isotopic re-enrichment of uranium, the fuel is shipped in massive shielded and cooled containers to a centralized reprocessing facility. There the solid fuel rods are dissolved in acid to begin the separation process which eventually results in essentially pure product streams of plutonium and uranium. As a result of dissolution the relatively immobile form of the fission products in solid fuel is converted to the relatively mobile forms of liquid solutions, liquid slurries, and gases. The dissolver off gas is processed to recover the remaining iodine, particularly I^{129}. Essentially all of the Kr^{85} formed in the reactor is released from the dissolved fuel and is discharged through a tall stack to the atmosphere. About one third of the tritium present in the fuel is released to the air along with

> the krypton, and the remainder is released as HTO to the surface water. (Pigford, 1972)

In a 1961 release incident at the Savannah River Plant in South Carolina, 153 curies of radioiodines were released to the environment because somebody accidentally dissolved some fuel elements that had only had a very short cooling time. That release of 153 curies of radioiodine from a Purex fuel reprocessing facility, most of which occurred May 30 through June 3, 1961, temporarily increased the level of I^{131} in the environment surrounding the Savannah River Plant. Prevailing southwest winds and atmospheric inversions dispersed the radioiodine mainly to the northeast of the Plant. Theoretical dispersion equations were verified by measurements of I^{131} in air at distances up to 25 miles from the Plant.

I^{131} on vegetation decayed with an apparent half-life of 5 days, as compared to the physical half-life of 8 days. This is attributed to dilution of the activity by new vegetative growth. The reduction of radioiodine in milk closely followed the apparent half-life in grass. Laboratory tests with iodine-contaminated vegetation showed that rainfall removed little or no iodine. Consumption of milk in the area of highest deposition could have resulted in a thyroid dose up to 1.2 rems for a child (Marter, 1963).

According to my calculations with data presented by Tadmor (1973), a hypothetical 10 ton per day reference reprocessing plant which would be needed by the year 2000 to service several nuclear reactors would release 1,440 curies per day, or over half a million curies per year of just krypton-85. Tritium releases would amount to about 39 curies per day, or just over 14,000 curies per year. Essentially all of these two radionuclides would circulate in the

atmosphere until washout by precipitation dissolved much of the tritium in the hydrosphere, but the krypton stays in the atmosphere and contributes to the whole-body dose. The exact amount of radiation released in reprocessing depends upon the amount of spent fuel being reprocessed and upon what source of information you believe; however, all estimates of radioactive releases are high. Pigford (1972) lists data illustrating that the production rate of fission products for a typical 1000 Megawatt (electric) power plant is 390,000 curies of krypton-85 and 16,000 curies of tritium, of which nearly all is released to the environment during reprocessing.

At the present time there are no commercial reprocessing plants in operation in the United States, and only two in the Western world are in operation: a large facility at La Hague in France and a small reprocessing plant at Windscale, England. The United States' commercial reprocessing plants have been closed (or never opened) because of high emissions, leaks, contamination events, and massive construction cost overruns, not to mention the opposition of local residents. Military reprocessing goes on in secrecy, however, ("Nuclear Agency Outlaws Inquiry," 1980) because it is necessary to reprocess fuel to extract the plutonium used in nuclear weapons (Radiological Emergency Operations, no date, p. 226).

Reprocessing plants have been observed on numerous occasions to deposit measurable amounts of radioactivity in the local fauna and flora. Small amounts of plutonium and particulate fission products escape the filters and are discharged to the environment, in addition to the large routine releases of krypton-85 and tritium.

Plutonium has been detected in the lungs of antelope near a U.S.

Department of Energy reprocessing plant in southeastern Idaho (Markham, Dickson, & Autenrieth, 1979), and in the bodies of arthropods (insects, spiders, bugs, and isopods) captured near the Rocky Flats nuclear weapons plant near Denver, Colorado. The mean arthropod concentrations of plutonium in the most contaminated area studied was 121 picocuries per gram of arthropods. This is about 500 times the mean concentration of .25 picocuries of plutonium per gram of arthropods that only received weapons fallout sources of plutonium (see Actinides) (Bly & Whicker, 1979). Strontium-90 has been detected in the bones of antelope near the Idaho plant at almost twice the levels of control antelopes (Markham, Halford, & Autenrieth, 1980).

Hazards to the public from reprocessing plants could arise from unusual meteorological conditions that might concentrate routine releases of radioactivity, from accidents that release large quantities of fission products or fissionable elements, and from diversion of bomb-grade material to illicit uses (see Terrorism at the end of this chapter).

Wastes. The end of the nuclear fuel cycle is the storage of the wastes generated at the various steps in the process. Wastes which contain plutonium-239 must be effectively isolated from the environment for many thousands of human generations because of its long half-life of nearly 25,000 years.

> The central scientific fact about radioactive material is that there is no method of altering the period of time in which a particular species remains radioactive, and thereby potentially toxic and hazardous without changing that species. Only with time will the material decay to a stable (non-radioactive) element. The pertinent decay

> times vary from hundreds of years for the bulk of the decay products to millions of years for certain of the actinide elements and long-lived fission products. Thus, if present and future generations are to be protected from potential biological damage, a way must be provided either to isolate waste from the biosphere for long periods of time, to remove it entirely from the earth, or to transform it into non-radioactive elements. (Report to the President, 1979, p. 9)

Cotton rats have been observed to accumulate and scatter radioactivity from radioactive waste ponds at the Oak Ridge National Laboratory in Tennessee (Garten, 1979), and coyote scats (feces) have been found to contain radioactivity when coyotes fed on jackrabbits that had burrowed into shallow waste burial sites on the Hanford Reservation in Washington (Springer, 1979). These are just two examples of transport vectors for poorly contained radioactive wastes. In addition, wastes may move in ground water, or even be blown about by the wind once they are released (Lassey, 1980).

If this country or any other country becomes committed to nuclear power production, the only economical path as uranium reserves dwindle will be a large scale production of plutonium in breeder reactors, according to Fortesque (1976). This will greatly magnify the present problems of waste disposal, and contribute to nuclear weapons proliferation since plutonium can be used in nuclear bombs.

As of March 1979, there were the following quantities of existing nuclear wastes:

High Level Waste (HLW), thousands of cubic feet
Commercial 80
Defense 9400

Transuranic Waste (TRU), contained TRU, kilograms
Commercial 123
Defense 1100

Spent Fuel Discharged from Commercial Reactors
2300 metric tons of heavy metal (MTHM)
(The spent fuel from military reactors is enriched in plutonium and gets reprocessed to recover plutonium and uranium for more fuel and bombs)

Low Level Waste (LLW), millions of cubic feet, buried
Commercial 15.8
Defense 50.8

Uranium Mill Tailings
140 million tons (Report to the President, 1979, p. 11)

President Carter stated in his April, 1977, National Energy Plan: "The waste generated by nuclear power must be managed so as to protect current and future generations" (cited in the above Report to the President, 1979, p. H-1).

Transportation. Transportation is integral to the nuclear fuel cycle for the shipment of ore, refined uranium, fresh and spent fuel, and wastes.

The hazard to the public from transportation accidents is probably less than the hazard that may ultimately result from hijackings of nuclear material in shipment (see Terrorism at the end of this chapter).

Two groups of people will receive radiation doses from the transportation of radioactive substances: transport workers and the members of the public along the path of the shipment. The drivers of a truck, for example, carrying unirradiated fuel on a typical average journey of 1600 km, would receive far more radiation than anyone that they passed. Figuring a travel time of 20 hours in transit and one hour spent at a distance of one meter outside the truck, the

average trucker would receive about .3 millirems per shipment (Sources and Effects of Ionizing Radiation, p. 240).

Nuclear Weapons

Unless they are detonated underground, nuclear weapons release all of their fission products to the atmosphere and/or hydrosphere. The explosive yield of a weapon and its design are large factors in the amount and kinds of radionuclides released. Fallout consists of fission products, unfissioned nuclear fuel, and activation products. Fusion detonations release about 20 kilocuries of tritium per kiloton of yield (Kenny, 1969, pp. 15-26), and fallout will vary in radionuclide composition depending upon the volume of matter encompassed by the fireball. In air bursts, neutron activation of nitrogen in the air produces carbon-14, which mostly becomes incorporated into carbon dioxide and can then enter the food chain through plants. Underwater or near-surface bursts produce tritium from neutron activation of some of the hydrogen in water molecules; the dirtiest weapons are those which are detonated on or near the earth's surface, such that large quantities of solid material are vaporized, much of it is neutron-activated, and all of it becomes fallout. Activation products from underground tests, for example, amount to about 2,000 curies per 100 kilotons of weapon yield (Kenny, 1969, pp. 15-26).

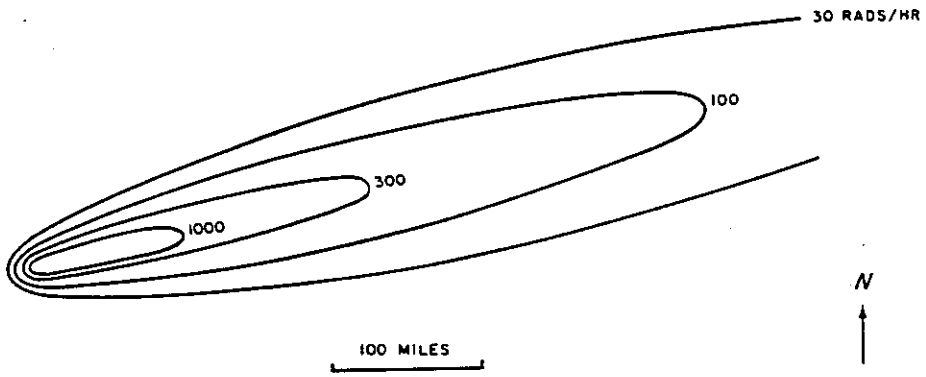
Some meteorological considerations play a role in the pattern of fallout deposition. Small bursts may produce only localized fallout, whereas the mushroom cloud from large detonations may penetrate the tropopause, the temperature barrier between the lower stratosphere and the overlying troposphere. If so, the weapon's fallout will be dispersed worldwide. Chinese nuclear tests have been monitored by collection of fallout in Britain, for example (Freke,

1979).

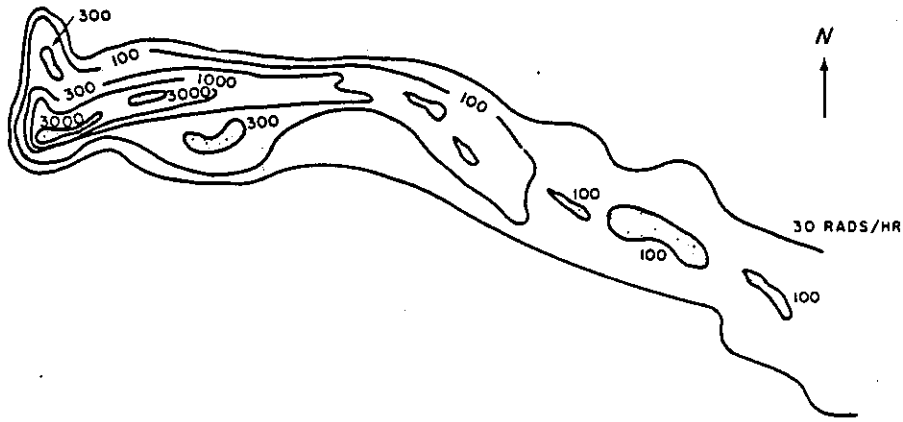
Weather conditions play a large role in the macro mechanisms of fallout transport and deposition. Machta (1963) reported on some meteorological processes that influenced the transport of iodine-131 produced by nuclear weapons. Low altitude releases of radioiodine just drifted along with prevailing winds near the surface, as one might expect. A subsiding anticyclonic (high pressure) system deposited fallout, which had arrived by way of the polar region, over the Mississippi Valley and the East Coast of the United States from tests in the Soviet Union. Most cases of radioiodine contamination of milk were determined to be caused by precipitation scavenging of fallout by snow and rain. Precipitation scavenging occurred mostly from stratospheric fallout, but some precipitation scavenging of the troposphere was noted when very intense thunderstorms extending to fifty or sixty thousand feet penetrated the tropopause.

Fractionation of fission products may occur, causing the depositions of different radionuclides to vary in relative composition with the distance downwind of the blast. Fallout condenses from whatever was vaporized or blown into the sky from a nuclear explosion, and some condensation of vapors may occur on the surface of particulates in the air. Lindberg and Larson (1956) found that the uptake of radioiodine from nuclear weapons tests was maximal in the thyroids of jackrabbits and kangaroo rats at a distance of 60 miles from Ground Zero, whereas strontium-90 was maximal in their bones at about 130 miles away. Not all weapons detonations will fractionate their fission products in this way; the megatonnage, altitude of explosion, prevailing winds and other meteorological considerations combine to make prediction of fallout deposition more of an art than a science (see Figure 2).

Figure 2



Idealized unit-time reference dose-rate contours for a 10-megaton, 50-percent fission, surface burst (30 mph effective wind speed).



Corresponding actual dose-rate contours (hypothetical).

Note: From Glasstone, S., and Dolan, P.J. The Effects of Nuclear Weapons, 1977. p.434.

Terrorism. The prospect of nuclear terrorism increases in proportion to the proliferation of reactors and weapons. Large quantities of nuclear material are unaccounted for (Inventory Difference, or ID, it's now called) in the inventories of nuclear facilities. For the first half of the 1977 fiscal year, for example, the ID for the Goodyear Atomic Co. enrichment plant at Piketown, Ohio was 120.3 kg. The Union Carbide enrichment plant at Oak Ridge, Tennessee, was missing 154.0 kg, and the Union Carbide enrichment plant at Paducah, Kentucky, had an ID of 321.2 kg (Semi-Annual Report on Strategic Special Nuclear Material Inventory Differences, 1978). These are just examples. It is not publicly known how much weapons grade nuclear material might be unaccounted for, because military facilities are not subject to public scrutiny. When an environmental group, the Natural Resources Defense Council, wanted to cross-examine witnesses and examine documents in a public hearing related to the losses of large amounts of bomb-grade uranium from the Irwin, Tennessee, Nuclear Fuel Services Plant, they were turned down by the Nuclear Regulatory Commission because of the military desire for secrecy (Nuclear Agency Outlaws Inquiry, 1980). Somebody detonated a nuclear weapon in September of 1979 over the South Atlantic, and apparently nobody knows who did it ("Blast caused flash," 1980).

Most of the information necessary for the construction of nuclear weapons is available in the unclassified literature, and the Nuclear Regulatory Commission is well aware that a dissident group with modest resources to steal the fissionable material could assemble a nuclear weapon (Willrich & Taylor, 1974, p. 80). This author has found manuals in the Florida State University's Strozier Library with titles such as Synthesis, Fabrication, and Chemical Reactivity of

Plutonium Mononitride (Pardue, Storhok, Smith, Bonnell, Gates, & Keller, 1964), as well as detailed descriptions of nuclear bomb development and construction (Seshagiri, 1975).

> Experts in government and industry have known of the security risks inherent in nuclear power for many years. They have worked long and hard to develop safeguards against the dangers of nuclear theft. However, many governmental policymakers and industrial leaders in the energy field are only vaguely aware of the problem, and most of the public does not know that it exists. (Willrich & Taylor, 1974, p. 1)
>
> On October 27, 1970, a nuclear bomb threat occurred in Orlando, Florida. The threat was made to blow up the city with an H-bomb unless $1 million was provided, and the threat was accompanied by a drawing of a device. Neither the AEC nor the FBI could assure the city government that the threat was unreal. City officials were seriously considering paying the ransom demand when conventional police methods and a slip-up by the would-be bomber cleared up the matter. The nuclear threat turned out to be a hoax perpetrated by a 14-year old boy who was an honor student in his high school science class. (Willrich & Taylor, 1974, p. 80)

Cooper (1978) maintains that certain vulnerable structures within a country (one of his examples is the Aswan Dam) present a hostage target for smaller

nations to attack. Nuclear power plants bombed with conventional weapons could be disabled so that a meltdown occurred; the consequential release of radioactivity would give those conventional bombs some of the fallout characteristics of nuclear weapons, and "if a bombing attack were timed to exploit adverse meteorological conditions, the release of radioactive aerosols could be a very serious matter."

In an analysis of catastrophic releases of radioactivity, Fetter and Tsipis (1981) conclude that "even a single nuclear weapon would contaminate a much greater area with radioactive fallout than the worst conceivable accident to a nuclear reactor," except for the worst-case situation: "Vaporizing the cores of nuclear reactors with nuclear weapons is clearly an efficient way to desolate large parts of a nation." Of course similar attacks on reprocessing plants, fuel fabrication plants, or even waste depositories would also similarly scatter radioactivity.

Nuclear terrorism may also take another form. A few dozen grams of plutonium, not nearly enough to make a bomb, could be used in a dispersal device to contaminate several square kilometers, requiring evacuation and extensive decontamination, because "the total weight of plutonium-239 which, if inhaled, would be very likely to cause death by lung cancer is not well known, but is probably between ten and 100 micrograms (millionths of a gram)," and "the total retained dose of plutonium that would be likely to cause death from fibrosis of the lung within a few days is about a dozen milligrams (thousandths of a gram)" (Willrich & Taylor, 1974, p.24).

Summary of Sources of Radiation Exposure

Naturally occurring radionuclides provide a radiation dose to everyone that

is usually in the range of 60 to 250 millirads per year. Medical and research applications, industry and consumer products provide some more radiation at about the same order of magnitude as background radiation. The nuclear fuel cycle adds small doses of radiation to the population by external and internal sources. Normally functioning nuclear reactors release large quantities of some radionuclides, primarily inert gases and tritium, but the quantities are diluted in air and water so that individual exposures from reactors are low. However, "in terms of normal environmental releases of radioactivity the fuel reprocessing plant contributes a far greater rate of radioactive release to the environment than does the nuclear power plant" (Pigford, 1972).

The present rate of atmospheric nuclear weapons testing provides global fallout that is very much less than the amount of fallout that was being deposited on the earth in the 1950's and early 1960's; tests since 1963, for example, have only added about an additional 10% of plutonium to the world inventory (Sources and Effects of Ionizing Radiation, 1977, p. 148).

To date, no serious reactor accident has resulted in civilian deaths. Three military men have died from the blast of an exploding military reactor, but they did not die from the radiation they received (Horan and Gammill, 1963). There have been a number of accidental discharges and spills from nuclear facilities, and near-disasters such as Three Mile Island.

Terrorists have yet to make their debut in the world of nuclear politics; the governments of the world still have a monopoly on nuclear war. Nobody knows, though, or if they do, they aren't saying, who tested a nuclear weapon in the South Atlantic Ocean in September of 1979 ("Blast caused flash," 1980).

Radionuclides of Concern

The radionuclides of greatest concern are those that:

1. Are most likely to be released in radiological emergencies, especially if large quantities are involved.

2. Have half-lives long enough to reach humans and result in significant exposures.

3. Are biologically mobile and may pass through food chains or otherwise enter the body.

These radionuclides are most likely to become internal emitters and so are the ones to be guarded against, if possible. Good protection can be obtained from some radionuclides, practically none from others (see Protection Principles).

Every elemental species will have a certain characteristic affinity for deposition within the body. For example, a radioactive atom of iodine will behave for all practical purposes exactly like a stable atom of iodine, physically and chemically, up to the time that it disintegrates. Then, it alters its nuclear structure and is transmuted into another kind of element with different physical and chemical properties. Until it disintegrates, however, it will follow the same biological pathways that already exist for stable iodine, with the result that most iodine in the body is found to be concentrated in the thyroid gland (see Radioiodines).

Some radionuclides enter biological pathways because they are so similar to other elements for which pathways exist. This is true for strontium-90, which

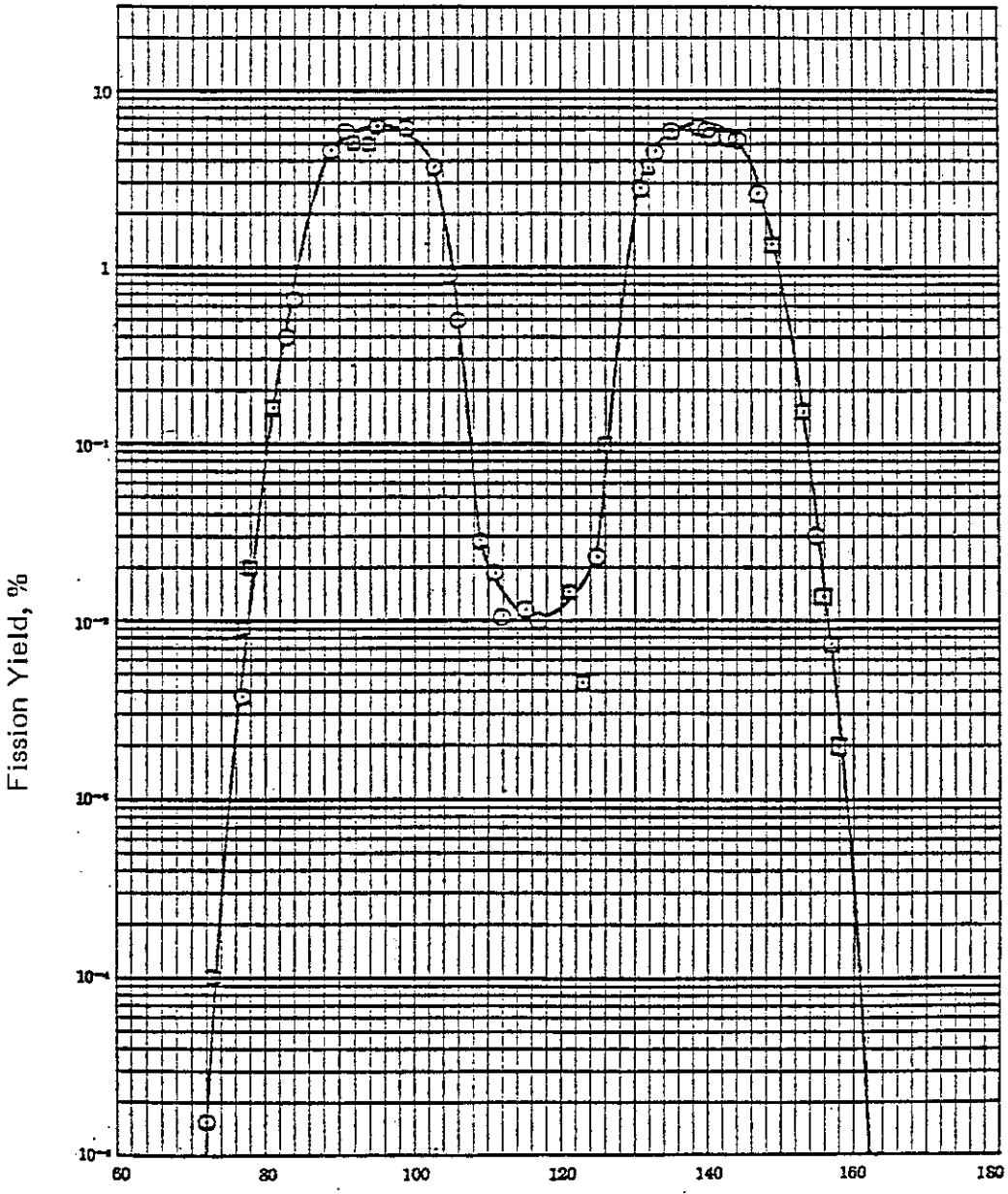
follows calcium into the body because the two elements are chemically similar. The same effect occurs with cesium-137, which is similar chemically to potassium, and follows potassium into the body almost as well as strontium follows calcium. The reason for the chemical similarities is that the outermost electron configurations of each pair of elements is the same. The number of electrons in the outermost electron shells of atoms determines to a large extent how they will behave chemically. This is reflected in the organization of the periodic table of the elements which arranges the elements in order of increasing atomic number and groups them in columns of chemical similarity. Calcium (Ca, atomic number 20) is located directly above strontium (Sr, atomic number 38). Both elements have identical outermost electron shells and thus very similar chemical characteristics. The periodic table helps to explain much of chemistry, and provides clues as to how radionuclides may contaminate biological systems.

The radionuclides shown in Figure 3 represent the end product yields of 42 chains of fission product decays as a function of mass number. In this case the figure represents the products of the fission of uranium-235. The curve for plutonium-239 or uranium-233 would be only slightly different. The curve is presented to illustrate the percentage distribution of fission products, but it does not represent the actual proportions of all radionuclides formed in fission, because the neutrons released in fission reactions can be absorbed by stable elements and induce radioactivity in them.

The spectrum of radionuclides released in a contamination event may vary in kind and quantity even from similar sources. For example, a core meltdown at a freshly fueled nuclear reactor would be less serious than the same accident at the same reactor but at a later time, because the quantity of fission products in

Figure 3

Yields of Uranium-235 fission product chains as a function of mass.



⊙ certain mass assignment ⊡ uncertain mass assignment

the fuel elements would be smaller. A nuclear bomb will cause some neutron activation of the stable elements which surround it, so an air burst produces carbon-14 by the neutron activation of nitrogen, a water burst produces tritium, and a detonation on land produces a mixture of assorted radionuclides and very heavy fallout. Even the types of bombs can make a difference, as Jablon (1973, p. 4) pointed out in his discussion of the bombs dropped on the Japanese:

> The two bombs were rather different. Not only did one use uranium and the other plutonium but the method of construction was different. The Nagasaki weapon was an implosion device, in which essentially a shell of plutonium was imploded to a critical mass at the center by a surrounding shell of high explosive. The Hiroshima device was essentially a gun in which one subcritical mass was fired against another within a tube. The explosive charge was at one end of the tube. The reason that these details of construction are of some importance is that nitrogen has a very high cross section for fission neutrons and the debris of high explosive is very high in nitrogen. Therefore, the Nagasaki weapon at the instant of criticality was entirely surrounded by a dense nitrogen shell which captured most of the escaping fission neutrons and became instead an intense source of gamma radiation produced by nitrogen capture reactions. In the Hiroshima weapon this did not happen. A large number of fission neutrons escaped from the bombs, reacting with nitrogen

> and oxygen in a large surrounding air mass. The result was that in Nagasaki the radiation of importance was almost exclusively gamma radiation, while in Hiroshima both gamma rays and high energy neutrons were of importance.

We can infer from this description that the Nagasaki weapon surrounded by its nitrogen shell formed a greater quantity of carbon-14 than did the Hiroshima weapon.

These examples serve to illustrate that it is impossible to predict exactly what radionuclides will be released in general cases of nuclear reactors and weapons, because there is no general case that is representative of all the possibilities that exist. Smaller contamination events, such as accidents at medical facilities, are more predictable because the radionuclide inventories are known.

Nonetheless, it is possible to identify radionuclides most likely to be released in the cases of nuclear reactors and weapons. If certain radionuclides are known to constitute a potential exposure hazard, preparation can be made beforehand. This is why stable iodine is stored at some nuclear power plants (Kohler, 1980), because iodine is a higly volatile and biologically available element, and radioiodines are present in large quantities in fresh fission products. Radioiodines, in fact, lead the list of Radionuclides of Concern because they are so prevalently used in research, are released in nuclear weapons detonations, and may be released in reactor accidents.

Glasstone and Dolan (1977, p. 442) list some radionuclides of concern in The Effects of Nuclear Weapons: "The delayed fallout, on the other hand, is almost

exclusively a potential internal hazard that would be due to the ingestion of iodine, strontium, and cesium isotopes present in food, especially milk." Russell (1966, p. 61) similarly concludes that:

> Both in the peaceful and military uses of atomic energy the following nuclides are of the most widespread importance as sources of dietary contamination:
>
> Iodine-131
>
> Strontium-90 (or strontium-89 in fresh fission products. . .)
>
> Caesium-137 [British spelling for cesium]

Russell also mentions some of the radionuclides formed by neutron activation and released in liquid discharges from nuclear reactors. He lists:

phosphorus-32 (half-life 14 days)

zinc-65 (half-life 245 days)

sodium-24 (half-life 15 hr)

cobalt-60 (half-life 5.3 yr)

iron-55 (half-life 2.9 yr)

iron-59 (half-life 45 days)

sulphur-35 (half-life 87 days)

tritium (H-3, half-life 12 yr)

This list is not exhaustive because reactor design and coolant modifications may cause other radionuclides to become important. "Nevertheless, there appear to be no grounds for believing that the biological significance of induced radioactive substances will approach that of fission products." (Russell, 1966, p. 60)

The radionuclides of concern for the case of seafoods may be slightly

different from the radionuclides which are normally considered to be the greatest hazard. For instance, strontium-90 is not a major contaminating radionuclide in the sea because the large amount of dissolved calcium and stable strontium serve to isotopically dilute it to a large extent. Also, it is not concentrated to any large extent by marine organisms (Chipman, 1966, pp. 436-437). Table 3, taken in part from Chipman (1966, p. 436) illustrates the concentration factors of some significant radionuclides which may be present in the marine environment.

To obtain some idea of the scale of the hazard, there is the Windscale, England, reactor accident that occurred in October of 1957. Although the reactor was an air-cooled, graphite-moderated, uncontained model that is not representative of nuclear power reactors, the magnitude of the radioiodine release is the greatest that is known to have occurred from any reactor to date. In that accident, an estimated 20,000 curies of iodine-131, 600 curies of cesium-137, 80 curies of strontium-89, and nine curies of strontium-90 were released to the atmosphere (Radiological Emergency Operations, no date, pp. 221-222). This release amounts to only a tiny fraction of the amount of radioiodines in an operating reactor in which radioiodine equilibrium has been reached; for a typical 1000 MWe (1000 Megawatts electrical output) power reactor the total radioiodine inventory is on the order of 7.2×10^8 curies. Some of the radioiodines are very short-lived; twelve hours after shutdown the total radioiodine inventory would be down to about 2.4×10^8 curies (Manual of Protective Action Guides, 1975, p. D-41).

A hypothetical case of a reactor accident that released a puff of 20,000 curies of radioiodines for a period of an hour beginning two hours after the

Table 3

Ranges of Probable Radionuclide Concentration Factors

in Edible Portions of Seafood Organisms Relative to Seawater Concentration

ISOTOPE	MOLLUSCS	CRUSTACEANS	FISH
Fission products			
Strontium-90	10^{-1}-1	10^{-1}-1	10^{-1}-1
Caesium-137	10-10^2	10-10^2	10-10^2
Cerium-144	10^2	10^2	10-10^2
Zirconium-95	10-10^2	10^2	1-10
Niobium-95	10^2	10^2	1-10
Ruthenium-106	1-10^3	1-10^3	1-10
Induced activities			
Zinc-65	10^3-10^5	10-10^4	10^3-10^4
Iron-55	10^2-10^4	10^2-10^4	10^2-10^4
Cobalt-60	10-10^3	10-10^3	10-10^2
Manganese-54	10^3-10^4	10^2-10^4	10^2-10^3
Chromium-51	10^3	10^3	10^2-10^3

The radionuclides of concern, then, in marine fish exposed to nuclear weapons fallout, are primarily the induced activities of zinc-65, iron-55, cobalt-60, and manganese-54 (Chipman, 1966, p. 447). Chromium-51, with a half-life of only 28 days, presents little hazard.

reactor had been shut down, and assuming an 8 mph wind, would deliver a projected dose of 5 rems to the thyroid of a child who was 5 miles downwind of the reactor (Manual of Protective Action Guides, 1975, pp. 5.23-5.24). This 5 rem dose to a child's thyroid is the Environmental Protection Agency's lower limit for a projected dose which warrants taking protective action (Manual of Protective Action Guides, 1975, p. 2.5).

Radionuclides of concern may show up in ways that would not ordinarily be expected. According to the United Nations Scientific Committee on the Effects of Atomic Radiation (Sources and Effects of Ionizing Radiation, 1977, pp. 176-177) there were 13.2 KCi (13,200 curies) of total xenon-137 released from four boiling water reactors in Germany and sixteen boiling water reactors in the United States as airborne effluents in 1974. Noble gases are ordinarily considered to be diluted in the air. Xenon-137, however, decays with a half-life of 3.82 minutes to cesium-137. Cesium is not a gas and therefore the effluents from boiling water reactors apparently add to the fallout of a very important radionuclide of concern. The same boiling water reactors also released 897,800 curies of xenon-138, which has a half-life of 14.1 minutes and decays by beta emission to cesium-138. Cesium-138 has two half-lives; there is a 2.9 minute internal transition 75% of the time which releases a gamma ray, and a 32.2 minute half-life beta decay process that occurs in all cases (Lederer & Shirley, 1978, p. 718). These short half-life processes probably would not result in much significant exposure to humans, at least internally, because the half-lives are far too short for them to enter biological pathways.

There are probably some other cases similar to this that remain to be pointed out.

Pathways to Humans

Routes of Uptake

The internal human contamination by radionuclides can occur through several routes:

1. Inhalation
2. Absorption across intact skin
3. Penetration through wounds
4. Ingestion

Inhalation. The physical and chemical state of the radionuclides will influence the degree of uptake of inhaled radionuclides. Insoluble particles may reside in the lungs for quite a while before they are excreted. Cool, Cool, Brodsky, and Eadie (1979) measured the clearance of an accidental inhalation of an aerosol of insoluble iridium-192 from the lungs of two workers. They found that the half-time of the lung clearance of the insoluble metal was in excess of 700 days.

More volatile radionuclides, such as those of iodine, may be appreciably accumulated through the inhalation pathway without becoming trapped in the lungs. Studying twenty beagle dogs downwind of a fallout cloud, Fountain (1963) found that the thyroid uptake of radioiodines via the inhalation pathway was very rapid, since thyroid uptake averaged 92 percent of the amount of radioiodine inhaled by animals which were sacrificed immediately after the passage of the radioactive cloud. In addition he noted that the maximum buildup of radioiodines in the thyroid glands occurred on the second or third day following exposure; he

attributed that to the radioactive decay of the fallout particles which had been trapped in the respiratory and digestive tracts of the beagles during the cloud passage. The decay chains of the trapped particulates resulted in the production of some radioiodines that were not present in the original radioactive cloud.

In evaluating the relative risks of ingestion versus inhalation of radioiodines, Wehmann (1963) measured air concentrations and milk concentrations of iodine-131 that were deliberately released to the environment in a test of the Aircraft Nuclear Propulsion program. He found that the thyroid dose to a standard man would have been 0.03 millirads from inhalation, compared to the 4 millirads which would have resulted from drinking one liter per day of the milk from the same farm. In Wehmann's words, "the ingestion dose was 133 times the inhalation dose."

Another factor to consider is that an accumulation of particulate fallout on the ground may become resuspended in air by the wind. While fallout is relatively fresh, this pathway is about as important as the inhalation hazard from the original fallout cloud, or perhaps even more unimportant (Lassey, 1980).

Absorption across intact skin. The passage of radioiodines across skin surfaces has been studied by Harrison (1963) who found that less than 1 percent of aqueous solutions of radioiodines, either as iodide or elemental iodine, crossed the skin surface. However, gaseous radioiodine was able to cross skin surfaces over the range of 1.2 to 78 percent of exposure dose, and this transport vector was facilitated by skin irritation. Burns, scrapes, or wounds would be likely to increase the intake of some radionuclides.

Penetration through wounds. Contamination of nuclear workers as a result of explosions or other accidents has occurred by penetration of the skin, but that

is not a hazard that most people might face in a radiological emergency. Radionuclides deposited on wounds, if they were open and moist so that skin, scabs, or a bandage would not provide a barrier, could enter the body through that route.

Ingestion. The release of radioactive materials into the environment results in the entry of radionuclides into food chains which then are available to humans via the ingestion pathway. Children in New England that were placed on restricted diets designed to eliminate fresh fission products (no fresh milk or dairy products or unpeeled fresh fruit or vegetables) showed levels of iodine-131 in their thyroids that remained usually below the detection level of 30 picocuries per thyroid. Untreated controls on regular diets had thyroid radioiodine contents that usually ranged from 90 to 170 picocuries per thyroid gland. This study demonstrated that "inhalation and water intake played only a negligible part in the uptake of fallout radioiodine under the conditions which prevailed in New England" (Visalli & Goldin, 1963).

Food Chains

It is difficult, if not impossible, to quantify in advance the dose that would be received by an individual exposed to radionuclides in food chains because of the many factors which act as variables. For example, the transfer of radioiodine from an oral dose to the milk of goats was studied at 33 degrees C and 5 degrees C. Of an oral dose of radioiodine, 16.8% was transferred to milk at 33 degrees C, whereas only 2.6% was transferred to milk at 5% C (Lengemann & Wentworth, 1979). However, it is possible to gain some idea of the magnitude of concentrations of the radionuclides which would most likely be concentrated in certain foods and food chains.

> All radioactive materials which are present in the environment may enter foodstuffs to some extent thus becoming sources of internal radiation. However, depending on their chemical and physical characteristics and on the sites at which they are introduced into the environment, the quantities which enter diet may vary by factors of many hundreds or thousands. The nuclides which reach foodstuffs to the greatest extent are those which are freely transferred through biological systems. (Russell, 1966, p. 47)

Terrestrial and aquatic food chains contrast very markedly in their transfer of radionuclides to man. Plants grown on dry land may accumulate radionuclides by direct deposition or by uptake through their roots. In aquatic systems, mixing with a large volume of water and other substances occurs before radionuclides are taken up by organisms.

> This causes marked differences both in the rapidity and in the extent to which radioactive materials can enter human food in the two environments. The process of transfer on dry land may be sufficiently rapid for relatively short-lived nuclides to reach diet in considerable quantity; this is unlikely in aquatic food chains. Furthermore, for a given deposition of radioactive materials, edible produce from water will show a lower degree of contamination. Both for these reasons and because the major part of man's diet is produced on dry

> land, the aquatic food chains are but a minor source of man's exposure to radiation when radioactive materials are released into the atmosphere so that they fall on land and water alike. This has been well illustrated in studies of the contamination of man's diet with world-wide fallout from nuclear weapons. (Russell, 1966, pp. 48-49)

Terrestrial food chains. Plants may take up radioactivity by the deposition of fallout onto their surfaces or through the root systems. Rough leafy surfaces and the tufts of grains can collect particulates, but vapors will be deposited by diffusion processes. Solutions of radionuclides in rain or fog may also deposit radioactivity. Heavy rains that provide a lot of flow of water over leaves may result in less retention of radioactivity than from light showers (Russell, 1966, pp. 90-91).

The roots of plants absorb only those substances which are soluble in water, and they enter plants as ions. The absorption of ionic radionuclides by plants will be primarily dependent on external ionic concentrations, the chemical characteristics of the radionuclide, the pH of the medium, and the rate of metabolic utilization of ions. For the fission products or other radionuclides that are normally unimportant in metabolic processes, the extent to which metabolism affects their uptake is minimal and "can usually be ignored" (Russell, 1966, p. 96).

There are complex interrelationships between ions that may influence plant uptakes. If a nutrient ion is supplied that increases the growth rate of a plant, other ions will be absorbed more rapidly. Ions may compete in antagonistic fashion, such that an excess of one cation results in the decreased absorption of another ion of the same charge (Russell, 1966, p. 99). This effect is of use in

reducing radionuclide uptake and is discussed at greater length under Protection Principles.

Aquatic food chains. Equal quantities of fallout deposited over land and water will result in less contamination of aquatic food chains because of the dilution of radionuclides in a large mass of water. There are many factors that influence radionuclide transport in aquatic food chains that vary largely from one environment to another and make predictions difficult. Concentrations of minerals may vary so much that some minerals in some fresh-water lakes may exceed ocean concentrations.

> The capacity of aquatic organisms to concentrate radionuclides is often expressed in terms of a concentration factor, i.e., the ratio of the concentration of a radionuclide in the organism to that present in the water. Concentration of a given radionuclide in a particular species is highly dependent upon a number of environmental and biological factors and, as a consequence, is subject to wide variation. Factors that affect the concentration of a radionuclide in an organism introduced into an aquatic environment include concentration of the corresponding stable element; concentration of chemically related and competing ions; chemical and physical state of the radionuclide in solution; rate of uptake and the nature of the metabolism of the radionuclide by the organism; temperature, pH, salinity, and degree of illumination of the aqueous medium; presence of binding or complexing

> agents in the system and organism; rate of radioactive decay and the dilution of the radioactive element; and probably others. (Radionuclides in Foods, 1973, pp. 41-42)

Radionuclides may be deposited in or on aquatic organisms by adsorption onto surfaces, absorption through surfaces (such as skin and gills of fish) and ingestion of food. Davis and Foster (1958) measured the radionuclide isotopes in the water and food chains of the Columbia River downstream of the Hanford military nuclear reactors. They found that the ingestion pathway was the major source of radioactivity in the organisms comprising the food chain. Each trophic level (each step up the food chain) acts as a reservoir for retaining some radionuclides before they are passed up to the next level. The greatest radioactivity was found in the plankton, a little less in the animals that eat plankton, and even less in the animals at the third trophic level, since some radioactive decay occurs while the radionuclides are held up for a time at each trophic level. This reduction of radioactivity at higher tropic levels is particularly applicable to those radionuclides with short half-lives, and for those organisms that do not consume a very large proportion of the total population of the trophic level on which they subsist. For example, when midge larvae contained four microcuries of phosphorus-32 (half-life 14.3 days) per gram of phosphorus, the minnows which fed on them contained only .5 microcuries of P-32 per gram of phosphorus. This works out to an average delay in the pass-through of radiophosphorus from one trophic level to another of about six weeks. For longer lived radionuclides, of course, this decrease in specific activity at higher trophic levels is not so pronounced.

The radionuclides of concern in a particular food are therefore dependent

in kind and quantity upon the kinetics of the physical and biological pathways of the sources of nourishment for that particular food organism.

Protection Principles

Planning Ahead

In a severe radiological emergency like a reactor meltdown, terrorist event, or nuclear war, there may be a need for quick action that becomes hindered by confusion and panic. Staying calm and using common sense may be the most important things that you can do. It will help tremendously if you have previously given some thought to the matter, in learning how to cope with radiation emergencies and by stocking up on some necessities.

Time Considerations

In radiological emergencies, particularly if they are reactor or weapons sources of radioactivity, a broad spectrum of radionuclides will be involved. Depending upon their various chemical and physical properties, their biological and physical mobilities will cause them to fractionate and be dispersed at different rates along different pathways. Their half-lives will also help to determine the time course of the hazard. Therefore, there will exist immediate, intermediate, and long term considerations concerning appropriate protective measures.

Immediate considerations (first things first). Decisions may have to be made in a very short time in the event of a radiological emergency. It is important to take immediate protective actions which are appropriate for the initial phase of a nuclear incident.

> The single most important pathway during the emergency phase is probably by air. The air pathway will be via

> inhalation of either gases or particulates and whole body exposure to the plume. Released gases will be either radioactive noble gases, organic iodides, inorganic iodides, or volatile inorganic materials. Particles will probably form by the condensation of vaporized material. (Manual of Protective Action Guides, 1975, p. 1.11)

Inhalation protection with a respirator or surgical mask will stop most particulates. Even a wet cloth over the nose and mouth to breathe through will provide some protection (Some Effects of Ionizing Radiation on Human BEings, 1956, p. 98).

Only evacuation, the use of SCUBA gear, or tightly sealed shelter will provide protection against the noble gases. Radioiodines are important radionuclides of concern in the early phase of reactor accidents or weapons detonations, and can be protected against by blocking the thyroid gland with stable iodine (see Radioiodines). Unless a large stable iodine supplement is taken before exposure or very soon afterward, the thyroid gland may accumulate a large percentage of the exposure dose of radioiodines. Luckily the radionuclides of iodine, save one, are short-lived so that the hazard diminishes rapidly and would be nearly gone after a couple of weeks following a single contamination event (see Radioiodines). For the ingestion pathway immediately after an accident, "with the possible exception of drinking water, milk, and contaminated leafy vegetables, entry of released materials into food and passage along this pathway is delayed" (Manual of Protective Action Guides, 1975, p. 1.12).

Remember that an internal accumulation of radionuclides is not likely to pose an immediate life-threatening danger; the effects on health will be manifest

later. If large amounts of radioactive materials are present, the immediate concern will probably be whole-body external irradiation. Any immediate hazard or priority should be taken care of even at the cost of some internal or external radiation exposure if the benefit to be derived is greater than the health benefit that would only be attained much later. For example, it may be necessary to be exposed to an ingestion hazard in order to evacuate. It also may be more important to eat a contaminated meal rather than starving oneself in order to avoid the possibility of leukemia years later. However, except for infants, small children, the elderly and sick, most people could survive for two or three weeks without food (Kearny, 1979, p. 65).

The initial decision in a nuclear disaster may be whether to evacuate or seek shelter. The correct choice will depend upon the kind of radiological emergency that occurs. For example, if the Dothan nuclear power plant melts down, Tallahassee residents may receive a couple of hours' warning that a radioactive cloud is headed in their direction. This hazard could be treated like an approaching tornado: move as quickly as possible out of its path at a right angle to its direction of travel.

Evacuation is an effective countermeasure at an early stage if it can be completed before the radiocactive cloud arrives. If there is a radioactive cloud present, then the dose received will be proportional to the time spent in the cloud. Traffic conditions in an emergency situation may be limiting:

> The capacity of a lane of traffic depends on the number of vehicles per hour and the capacity of each. Surveys during evacuations found 4 persons/car on the average indicating that at 2,500 cars/hr at 35 mph, the capacity of

> a lane is 10,000 person/hr. . . .
>
> The number of lanes of traffic is ordinarily sufficient for evacuation from the low population zone around fixed nuclear facilities. (Manual of Protective Action Guides, 1975, p. 134)

Each emergency situation will have to be individually evaluated as to the likelihood of evacuation serving as an effective protective action.

If shelter is chosen, a tightly sealed building will provide the best protection. An ordinary dwelling with windows and doors closed and ventilation turned off may provide good protection for a short period, up to an hour or so, but natural ventilation of most houses will likely render their shelter ineffective after about two hours (Manual of Protective Action Guides, 1975, p. 1.38).

Shelter is recommended by the Civil Defense people if there is a nuclear war, and it may also be recommended in some radiological accidents. There is a good booklet, In Time of Emergency: A Citizen's Handbook on Emergency Management (1980), available free from the Federal Emergency Management Agency, 1725 I Street N.W., Washington, D.C., 20472; or from most local Civil Defense offices, that provides a wealth of information on surviving a nuclear attack. An older version of the same book is Protection in the Nuclear Age (1977) which was published by the Defense Civil Preparedness Agency and may still be available at local Civil Defense offices. Civil Defense information deals almost entirely with protection from external radiation, that which irradiates the body from the outside. This report is only meant to deal with the means of protection from internal sources of radiation, but will briefly review some basic principles of protection from external radiation (see Protection from External

Radiation in this section).

Intermediate considerations. Fission product activity is greatest just after fission and declines with time, so the longer that one can avoid inhaling or ingesting any contaminated air, food, or water, the less will be the internal dose received. Existing supplies of stored food and water should be nearly exhausted before any contaminated supplies are eaten and drunk, for this reason. Priority for uncontaminated food should be given to children and the young who will be accumulating a body burden of radioactivity for the rest of their lives, and for pregnant and nursing mothers. Whatever planning and forethought is given to accumulating a store of emergency rations will help to get through the period of the most intense radioactivity with a minimum of internal exposure.

The retention of contamination on foliage decreases with a half-life of about two weeks (Lassey, 1979). However, root crops will only very slowly incorporate radionuclides as they are solubilized and penetrate the soil. Partial decontamination of food is possible by washing, scrubbing, soaking, rinsing, and some other preparative procedures (see Radiostrontium and Radiocesium).

Long term considerations. Health hazards from radiation in the long term center on cancer, leukemia, and liver accumulation of radionuclides, because some organs reach an early and relatively low concentration equilibrium of certain radionuclides, while other organs, especially liver and bone, progressively accumulate certain radionuclides over the course of a lifetime so that no equilibrium is reached. This is particularly true of the actinides, such as plutonium (Harley & Pasternak, 1979) (see Actinides). Strontium-90 also accumulates in bone, and may irradiate the radiosensitive bone marrow and osteoprogeniter cells. The bone seekers such as plutonium and other actinides,

strontium, and radium can be generally considered to be more hazardous than those radionuclides that are not deposited in bone, because of the great radiosensitivity of the hematopoietic tissue in bone marrow and the subsequent leukemia hazard.

After a nuclear war, the surviving population will slowly climb back to some semblance of civilization. Long-lived radionuclides that persist in the environment will continue to be a source of exposure for many generations. Soil treatments, farming techniques, food processing, and food consumption patterns may be altered to shift body burdens of radioactivity to lower levels than would be otherwise attained (see Radiostrontium and Radiocesium).

Food that is grown in areas that receive little or no fallout will of course be less contaminated than that food which is grown on contaminated soil. For small scale accidents like power plant meltdowns, it would be wise to avoid foods grown in the vicinity of the accident and for a long distance downwind of the prevailing winds. Dairy products, especially, should be avoided from these areas. If there is a nuclear war in the Northern Hemisphere, the areas of least fallout will most likely be some sections of the western United States, Canada, and Mexico because of the general west to east flow of the weather. Because of worldwide wind patterns, fallout which is generated in the Northern Hemisphere will largely stay there. What fallout does slip over the equator will not be evenly distributed in the Southern Hemisphere. The equatorial region will receive significantly less fallout than the mid latitudes of the Southern Hemisphere, and the southernmost section of the Southern Hemisphere will probably receive even less fallout than the Equator. The least contaminated continent will probably be Antarctica.

Protection from External Radiation

Briefly, protection from externally-emitting radionuclides may be obtained in these three ways:

1. **Shielding.** Put as much mass between yourself and the source(s) of radiation as possible.
2. **Distance.** Move away from the source(s) of radiation.
3. **Time.** Wait for the radioactivity to decay before getting near it. (Whitman, 1980, p. 60).

Surviving the radioactive fallout of a nuclear war will depend on one's dose from all exposure modes. Visible fallout as powder from dry deposition should be avoided, shielded against, and removed from one's surroundings and body as much as possible to reduce an external dose. Longer-term deposition of finer particles will be heaviest in wet deposition as the finest particles serve as condensation nuclei in cloud and fog formation. Therefore, it is reasonable to expect that wet environments should also be avoided; stay out of the rain and low-lying swampy areas. When sheltered, take all measures possible to prevent the entry of radioactive fallout which might then become ingested and be an internal emitter. Civil Defense manuals like the one previously mentioned give good advice on this point. Tightly sealed doors and windows will help to prevent particulates from entering the shelter. Since it may be possible for insects such as roaches and flies, as well as other vermin, to freely travel from the outdoors into your shelter when fallout is being deposited, keep them out as much as possible and don't let them get to your food. If they do, decontaminate the food if possible by washing or removing the skin or outer layer.

If it is essential to travel outdoors when fallout is being deposited, it will

be prudent to obtain as much protection from it as possible. In addition to a respirator or mask to prevent inhalation, a hat of some kind will keep the particulate fallout from lodging in the hair. A motorcycle helmet or anything similar that completely covers the head with a nonporous barrier will provide excellent protection, and can be decontaminated later by sponging or brushing off the fallout from the hard outer surface.

The Marshall Islanders who accidentally received nuclear weapons fallout accumulated fission products on their skin and in their hair that caused skin lesions and epilation (hair loss) primarily from beta radiation. The worst cases were those that had received a very heavy fallout deposition that was described as "snowlike"; their hair began falling out in about two weeks. For those who received less fallout (described as "mistlike"), the epilation began in about three weeks and was less extensive (Some Effects of Ionizing Radiation on Human Beings, 1956,

pp. 27-29).

If fallout contamination of the hair is visible, a good washing will probably get most of it out, depending on some factors such as hair length, oiliness, thickness, etc. Unless radiation monitoring equipment capable of detecting beta radiation is available, and if water is in short supply, then a safe bet is to shave the head (but carefully, because nicks are wounds providing possible paths of entry for soluble radionuclides).

A shaved head, or even just very closely cropped hair if well washed, could prevent a reoccurrence of the experience of the Marshall Island natives who suffered epilation as well as skin burns.

There is a possible protective measure from large external doses of

radiation for humans that this author has not found mentioned in Civil Defense types of publications, but which can be inferred from animal studies. That is protection by partial-body shielding. Rats, for example, have an $LD_{50/30}$ (Lethal Dose to 50% of them within 30 days) of about 714 rads, according to Bond et al. (1965, p. 107); according to tabular data compiled by Bond and co-workers of other researcher's data, the $LD_{50/30}$ for rats receiving only upper-body irradiation is in the range of 1450 to 1950 roentgens (the authors mix their units, rads and roentgens, in the same table, but they are roughly comparable; the radiation absorbed dose in rads is only a little less than the exposure dose in roentgens). For lower body (abdominal) irradiation the $LD_{50/30}$ dose for rats ranges from 851 to 1620 roentgens; for exteriorized intestines, the cited $LD_{50/30}$ dose for rats is 1550 roentgens (Bond et al., 1965, p. 111). Fatal doses of radiation, unless they are so high that they act upon the nervous system arise from early effects upon the GI tract if the doses are high enough, or from bone-marrow depression if the exposure is less, with GI complications also appearing (Bond et al., 1965, p. 219).

Some advantage in protection from external radiation could be attained by shielding just the most sensitive parts of the body. An improvised shield consisting of lead or other metal foil wrapped around the torso might attenuate sufficient radiation in a high radiation field to make the difference between life and death. According to this author's calculaitons, a one-centimeter thick breastplate and backplate made of lead would stop slightly more than 50% of even the very penetrating 1.173 MeV and 1.332 MeV cobalt-60 gamma rays. Together they would weigh, however, slightly more than 100 pounds. A more practical protective garment might be designed that shielded only the pelvis,

some vertebrae and the lower abdomen; any shielding of hematopoietic tissue and the GI tract is potentially helpful, especially the large amount of hematopoietic tissue in the pelvis and heads of the femurs, and the lower GI tract.

Protection from Internal Radiation

Protection from internally deposited radionuclides may be obtained by blocking the routes of uptake: inhalation, skin absorption, penetration via wounds, and ingestion. The pathways by which radionuclides may travel to humans are also sometimes amenable to manipulation so that the hazards from inhalation and ingestion are decreased. It is nutritionally axiomatic that consuming a wide variety of foods is likely to provide the optimum benefit of health to the consumer because of less likelihood of a shortfall of some mineral, vitamin, or some other nutrient which might develop into a deficiency state. In the event of large scale nuclear contamination, the opposite may become true; that health may be best optimized by restricting one's diet to those items which are known to be uncontaminated or less contaminated than other foods. If the extent of radioactive contamination of foods is not known, some application of general principles may provide some protection. This will be difficult to do if food is limited and hunger is a driving force. Even if that is not the case, some people already find it very difficult to modify their diets for the sake of their health, so it is likely that a potential hazard that cannot be seen, tasted, or sensed in any way will largely be ignored. Nonetheless, the following suggestions, if heeded, may help to enhance post-nuclear survival and health.

Reducing internal exposure via the inhalation pathway. Inhalation of radioiodines and particulates can best be prevented by the use of a respirator containing activated charcoal. The radioiodines are adsorbed onto the charcoal

and filtration stops particulates. Such respirators are readily available that are designed to be used by adult male workers in contaminated atmospheres, but respirators for women and children may not be available (Manual of Protective Action Guides, 1975, p. 1.40). Deposited fallout contamination on soil can provide a continuing inhalation hazard if it is resuspended. The resuspended fallout particles may also contaminate water and food pathways (Manual of Protective Action Guides, 1975, pp. 1.12-1.13; Lassey, 1980).

Inhaled radionuclides will either be soluble or insoluble in the body. The soluble radionuclides may be taken up and concentrated elsewhere in the body; insoluble radionuclides will reside largely in the lungs or bronchial airways and irradiate the sensitive epithelial tissues there. Drastic measures such as lung lavage may help to remove a lot of the insoluble, deposited radionuclides (see Actinides), but would only be recommended for an unusually large inhalation dose that would pose an immediate danger to the lung tissues. Less drastically, the removal of inhaled insoluble radionuclides can be somewhat accelerated by coughing (remember not to swallow, but spit instead).

Soluble radionuclides that enter the circulation across the lung surfaces can be dealt with isotopic dilution or hemodialysis (see these topics in this section).

Reducing internal exposure via skin absorption and wound contamination tion pathways. Very little skin penetration of radionuclides is likely if the skin is unbroken, unless there is an unusual immersion in contaminated water or air. Tight shelter and staying out of radioactive rain will probably be the best ways of insuring against radionuclide uptake by immersion.

Contaminated wounds should be rapidly cleaned; in accidents at nuclear facilities in which explosions or cuts inject radioactive material into the body,

surgical excision of the surrounding tissue is sometimes performed. Radionuclides contaminating open wounds may be dissolved in body fluids and enter the body through that pathway if wounds are open and moist. The conventional care of cleaning and dressing a wound to prevent infection is probably good protection from later exposure to radionuclides, if the bandage stays dry. Direct contamination of an open wound with radionuclides requires prompt cleaning, possible surgical excision of tissue, and preventive measures tailored to the radionuclides in the wound (See Actinides).

Reducing internal exposure via the ingestion pathway. The concentration of radionuclides that collects in a human body will represent a complex equilibrium that reflects many factors. The total quantities ingested, the effective half-lives of individual radionuclides, and such factors as age and nutritional status will have their effects on the dose received.

A key concept of protection from many kinds of internal emitters is that of isotopic dilution. If the contaminating radionuclide can be diluted with a stable nuclide, the radionuclide will be in competition with the stable form so that simple mass-action will accelerate the passage of a radionuclide from a system.

An excellent illustration of this principle is provided by Palmer (1976, p. 477).

> The use of liquid sodium as the primary coolant in fast-breeder reactors poses potential health concerns because of the chemical toxicity of sodium oxides and the radioactive toxicity of ^{24}Na and ^{22}Na. The paper describes some procedures which can significantly reduce the radiation dose to the body from ^{24}Na and ^{22}Na which

might be accidentally inhaled or ingested. Studies with rats indicate that the retention time of the sodium isotopes which have exchanged with the body sodium pool can be reduced by a factor of 10 by ingestion of high levels of stable sodium. In addition, the ingestion of a sodium salt at the time or immediately after the inhalation incident could result in at least 60% or more of the inhaled radioactive sodium being excreted before it exhanges with the body sodium pool. The combined effects of both immediate and sustained sodium ingestion in rats can result in a radiation dose from ^{22}Na of only 4% or less of that which would result if no additional salt is administered. The dose reduction for ^{24}Na would not be as much as that for ^{22}Na but would be significant.

Rats were first fed one microcurie of sodium-22 in a food pellet, then maintained on regular food for eight days to allow equilibration of the body burden. Whole-body counting of each rat on days 4, 5, and 8 was done to ensure that a normal excretion rate had been established. On the eighth day, two experimental and one control group of rats began their treatment regimen. One experimental group received stable sodium as sodium chloride in their food, the other received it as sodium bicarbonate. Each experimental group was further subdivided into dose levels of stable sodium. The sodium bicarbonate-treated rats received 1.5%, 2.6%, and 5.9% Na (this last group also had 10% sucrose added for palatability). The sodium-chloride treated rats received 1.0%, 4.3%, and 6.3% stable sodium in their diets. Control rats received .4% Na in their

normal diets. The rats were then whole-body counted every 2 or 3 days to determine their excretion rates of the sodium-22 that they had received. The rats on the 5.9% Na (from bicarbonate) and 10% sucrose diet consumed much less food than the other rats; apparently they did not find it very acceptable. The treated rats consumed much more water than did the controls, as would be expected. The sodium chloride proved to be more effective than the sodium bicarbonate; the effective half-life of sodium-22 in the 4.8% Na as sodium bicarbonate treated rats was 1 day. For the sodium chloride treated rats, both the 4.3% and 6.3% groups decreased the effective half-life of the sodium-22 in their bodies to .7 days, which resulted in a 99% removal of sodium-22 in just 5.4 days. In both groups, sodium-22 levels were reduced to about 1% of the amount ingested; that 1% had become incorporated into bone during the initial 8 days before stable sodium supplementation was begun and was non-exchangeable. Palmer concluded that increasing the sodium content of food above 3% was "not really effective in producing increased ^{22}Na excretion," because the excretion rate constant did not continue to increase after the sodium content exceeded this amount. Three percent Na in an average human diet of 1720 grams of food amounts to 52 grams of sodium (not sodium chloride, just sodium). Anyone with a heart or kidney problem, or hypertension, could not take this much sodium, and it is doubtful whether a normal person would tolerate it.

Palmer concludes that if a person could tolerate these high sodium levels, the radiation dose from ingested sodium-22 could be reduced to 4% or less of the dose that would occur from no treatment. The dose reduction from sodium-24 would not be as great because it only has a 15-hr. half-life, but a 50% reduction in dose should at least still be possible. Sodium-22 has a half-life of 2.6 years.

The principle of isotopic dilution should be applicable to two of the most important radionuclides of concern, radiostrontium and radiocesium. They are chemically similar to calcium and potassium, respectively, and enter biological pathways as a result. However, while radiostrontium can be competitively diluted out of the body by the stable nuclide of calcium, potassium has been found to be nearly useless in removing radiocesium from the body. (see Radiostrontium and Radiocesium).

> Because strontium-90 and caesium-137 are the two long-lived fission products of greatest concern from the viewpoint of the contamination of human diet, their interaction with calcium and potassium have received particular attention. However, interactions between chemically dissimilar ions can also be of importance. The majority of fission products are present in the soil as cations; thus in addition to its particular effect on the absorption of strontium-90, a high level of calcium is likely to reduce the absorption of other fission products also. (Russell, 1966, p. 100)

Hemodialysis. The technology of hemodialysis is in widespread use in hospitals and clinics. Portable units exist, and the components which are most likely to become contaminated are disposable.

However, in a widespread contamination event, the use of these machines would be impractical because of limitations in facilities and personnel. For a small contamination event involving only a few people, the use of dialysis machines could quite effectively remove internal radionuclides and reduce the

internal dose if the contingency protocol had been worked out beforehand and the appropriate fluids against which to dialyse were kept in stock (discussion by Williams, Smith, Bair, and Rundo after the seminar presentation by Palmer, 1976, pp. 477-483).

Carbon-14 and tritium. There are some radionuclides of concern for which there is no practical method of reducing the equilibrium concentration in the body. Particularly important in this category are carbon-14 and tritium. Once they are dispersed into the environment, they behave exactly like their stable counterparts and will therefore enter food chains. Carbon and hydrogen are components of nearly all the major nutrients: carbohydrates, fats, proteins, vitamins, even fiber. Only minerals and trace elements remain, and these are the ones which can best be manipulated if their radionuclides present a problem.

The only way to reduce human exposure to carbon-14 and tritium is to have a deep well or lots of stored water and to grow food in an environment that contains little or none of those radionuclides. This could be accomplished by growing food in a tightly sealed greenhouse (Hofer, personal communication, 1980). It would be necessary to have a deep well or stored supply of water for watering the plants to minimize the uptake of tritium, and a device to generate carbon dioxide from fossil fuels (or stored wood, say) to supply stable carbon to the plants. It would also be necessary to keep the greenhouse at a positive air pressure to prevent the entry of radionuclides from a contaminated environment; the air would have to be dehumidified and cleaned of its carbon dioxide first. This would be a very expensive method for reducing internally deposited radionuclides, and then there would be the problem of defending it.

This method of internal protection for incorporated radionuclides is

probably only possible for the very rich who would desire fresh, uncontaminated produce. Otherwise a large supply of stored food is more practical.

Greenhouse cultivation might become a popular commercial method of food production in the years following a recovery from nuclear war.

Surviving a nuclear war. Rarely in war is the objective to totally obliterate the civilian population of one's enemy. A nuclear strike could be expected to have as a prime objective the destruction of the enemy's capability to respond in kind: the air bases, harbors, and weapons launchers of all kinds. Then the secondary objective might be to obliterate the means for launching an immediate opposition or later rataliation: military bases, industries, power generation facilities, airports, communications centers, state and federal governments. In military calculation of such events, only military deaths are considered significant. Therefore, you are not the target unless you are wearing a uniform, but you can be killed if you are accidentally too close to a target.

Assuming that one has survived the initial blast and fires without immediate fatality, it is possible that close proximity to a nuclear burst has resulted in a dose of gamma rays and neutrons produced during a period of about one minute after the explosion (Glasstone & Dolan, 1977, p. 324) sufficient to cause death in days or weeks. People farther removed from the bursts may only have to deal with the fires and wind damage until the arrival of fallout.

Nuclear weapons detonations, especially high-altitude ones, emit such a large amount of energy even as radio waves that many electrical and electronic systems will be incapacitated as the electromagnetic pulse (EMP) sweeps over them. This means that there may be no power, no radio transmitters operating, no Walter Cronkite to tell people how they may save themselves.

Survival may depend mostly upon keeping one's head. Depending upon the distance of the nearest blast, several hours may elapse before fallout begins arriving. This would be the time to collect one's family and seek shelter or distance for protection from the immediate hazard of the strongest fallout radioactivity. The radioactivity decreases rapidly at first, then less rapidly with time. An approximate measure of predicting future exposure rates is known as the 7:10 Rule of Thumb, which states:

> For every 7-fold increase in time after detonation, there is a ten-fold decrease in the exposure rate. . . .
>
> Suppose the exposure rate at H+1 [time plus one hour] is 1000 R/hr. You can apply the 7:10 rule like this: Multiply the time by 7, which gives H+7. At that future time, the exposure rate will be about 10% of the H+1 exposure rate. So the exposure rate at H+7 will be about 100 R/h. . . . The approximate H+49 exposure rate will be 10 R/hr. . . . An exposure rate at H+343 of 1 R/hr. (Introduction to Radiological Monitoring, 1974, pp. 131-132)

Before taking shelter, if possible, get plenty of food and water, a radio and batteries (just in case somebody's transmitting), the potassium iodide, bone meal, and Prussian Blue that you've stocked up on after reading this report, perhaps some face masks to avoid inhaling particulates if the shelter is minimal, and rags, plastic bags, and extra water for decontamination when needed. You might want a gun and plenty of bullets. . . survival may become rather barbaric.

Some of the best shelters will be deep basements in areas not too close to

blasts. Home basements will have to suffice for many, because "Under the most favorable conditions only about half the population could find space in public shelters" (Gant & Haaland, 1979).

Every city of any size, any town that contains a strategic industry, every power plant, military base, airport, and harbor is a potential target in a nuclear war. Certainly every state capitol is targeted by Soviet missiles.

If they really want to do us dirty they will bomb our nuclear power reactors, reprocessing plants, fuel fabrication plants, et cetera. The fallout from these targets would be devastating in severity. According to data presented by Gant and Haaland (1979) these are likely targets.

There is an excellent book by Cresson Kearny entitled Nuclear War Survival Skills (1979) that is available for $20.00 from:

National Technical Information Service

U.S. Department of Commerce

5285 Port Royal Road

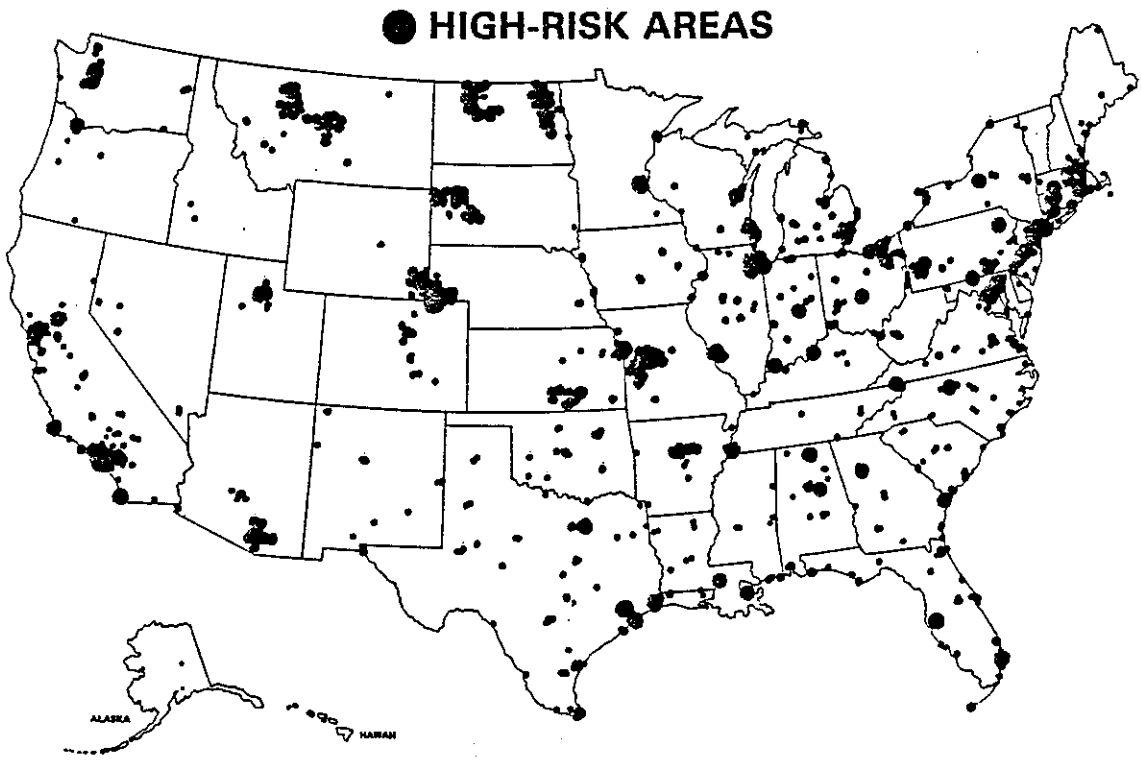
Springfield, Virginia 22161

Kearny discusses emergency fallout shelter construction, how to build a hand-powered shelter ventilation system, how to construct a homemade fallout meter, and many other important survival skills that are beyond the scope of this report.

The reader may be interested to know what areas are potential nuclear targets; see Figure 4: High-Risk Areas.

The best advice for survival is the Boy Scout Motto: **Be Prepared.**

Figure 4



Note: From High Risk Areas, (1-104), a map published by the Federal Emergency Management Agency, April 1980.

Radioiodine

Sources

Radioactive iodines are very commonly used in research and medicine. Laboratory research usually involves microcurie or millicurie quantities of radioactive substances. A little more is used in medicine, usually millicurie quantities. Contaminating events from these sources are relatively localized and affect a small number of people. In addition, only a single radionuclide would usually be released into an area; it could be contained, and decontamination procedures could readily be performed by trained personnel.

The potential exists for very large quantities of radioiodines to be released into the environment because radioactive isotopes of iodine are formed from the fission of the elements uranium and plutonium which are used as fuel in nuclear power reactors, research reactors, and nuclear weapons.

The fission products formed in reactors are supposed to be retained within the fuel element cladding, with only a small percentage of leaks in normal operation. Filtering systems ensure that routine releases of radioiodines from nuclear reactors are very small.

Accidents can happen, however, that involve the release of large quantities of radioiodines. An estimated 70 curies of iodine-131 were released from the accident at the SL-1 Reactor in Idaho, in January of 1961 (Horan and Gammill, 1963). It has been estimated that 20,000 curies of radioiodines were released from the Windscale reactor in the United Kingdom during a 1957 accident (NCRP Report No. 55, 1977, p. 4). Only about 14 curies of radioiodine was released from

the Three Mile Island reactor accident (Book, personal communication, 1981).

Reactors contain a very large inventory of radioiodines. Pigrod (1972) has estimated that a hypothetical reactor accident releasing 25% of the radioiodine inventory in a 24 hour period would result in the release of 2.4×10^8 (240 million) curies of radioiodines in that time.

Reprocessing plants take the spent fuel elements from reactors, dissolve them in acid, and chemically recover the expensive uranium and plutonium which can be recycled into more fuel for reactors or weapons. They are relatively "dirty" in normal operation when compared to nuclear power plants because the gaseous fission products are released from their containment within the fuel elements, and much of the radioactivity is exhausted through tall stacks to the atmosphere (Pigford, 1972). Much of the radioactivity in the spent fuel elements is first reduced by allowing the used nuclear fuel to "cool down" for a long time so that the short-lived fission products will decay; most of the radioiodines have short half lives and are very substantially reduced in this way.

> At equilibrium in a nuclear reactor, the I^{134} would be the most abundant . . . in terms of radioactivity. After 1 day's decay, the I^{132} is the most abundant iodine activity, but its importance in the environment would clearly depend upon whether tellurium was released [tellurium-132 is the decay chain precursor to iodine-132 and has a half-life of 78 hours. The half-life of iodine-132 is 2.3 hours]. After two days, I^{131} is the dominant radioisotope. (Holland, 1963)

In a 1961 accident at the Savannah River fuel reprocessing facility, 153

curies of I-131 were released to the environment because of someone's mistake; fuel elements were dissolved that had only had a very short cooling time and so contained a large amount of short-lived radioactivity. Consumption of milk from cows grazing in the area of highest deposition was estimated to have had the potential of delivering a radiation dose of 1.2 rems to a child's thyroid gland (Marter, 1963).

Nuclear weapons detonations release large quantities of radioiodines, all of which go into the environment except in the case of well-contained underground tests. Dispersal of the radioiodines as fallout depends on many factors (see Sources of Exposure); the radioactivity from various fission products is not evenly distributed downwind in the fallout "footprint." Lindberg and Larson (1956) studied the uptake of radioiodines and radiostrontium by kangaroo rats and jackrabbits that were captured on a line downwind of nuclear weapons tests in Nevada. Fractionation of the elements in fallout occurred such that the greatest uptake of radioiodines occurred in animals that were 60 miles downwind of Ground Zero, whereas the radiostrontium increased to a maximum in the bones of the animals at 130 miles from Ground Zero. So many variables act on fallout deposition that these numbers should not be taken as representative of any other weapons detonations than the ones that were set off in Nevada in 1956. The distances given serve only to illustrate that fractionation of fission products occurs. Machta (1963) studied the fate of the iodine released from nuclear weapons tests, and found that the greatest deposition of radioiodines on the earth was due to precipitation scavenging of the fallout cloud.

There are fourteen radionuclides of iodine formed from the thermal neutron fission of uranium-235. The radionuclide usually considered to be of

greatest concern is iodine-131, which has a half-life of 8.05 days, accounts for 2.9% of fission products, and is formed in decay chains. Another important radionuclide of iodine is iodine-129, with a half-life of 16 million years; it is formed in decay chains and accounts for .8% of the fission yield (Holland, 1963).

Also variable are the chemical and physical characteristics of the fallout released from nuclear weapons detonations. For example, Perkins (1963), studying the physical and chemical states of I-131 as fallout from the Soviet nuclear weapons tests of late 1961 and the American and Soviet tests of 1962, found that the gaseous form of I-131 varied from 10 to 90 percent of the total fallout I-131.

Chemistry

Iodine is an element in Group VIIA of the Periodic Table that is composed (in descending order) of fluorine, chlorine, bromine, iodine, and astatine. This group is referred to as the halogens, meaning salt formers. They all have outer electron shells composed of seven electrons, and thus they have a tendency to react with other atoms or molecules to add an electron and complete their outer shells. This means they have an affinity for electrons; they are electrophilic (electron-loving), and potent oxidizing agents due to their high electron affinities (Fessenden & Fessenden, 1976, p. 234). Iodine is less reactive than fluorine, chlorine, and bromine but more reactive than astatine (de la Mare, 1976, p. 20).

Elemental iodine, I_2, will be converted to iodide, I^-, when it is absorbed into the body (Ganong, 1977, p. 237). Salts of iodine such as potassium iodide or sodium iodide will dissociate in solution, the iodide ion then becoming biologically available if it is ingested, or if the salt is dissolved within the GI tract, for example.

Oxyanions of iodine may occur, the common ones being iodate (IO_3^-) and periodate (IO_4^-) (Dove & Sowerby, 1967, pp. 41-132). The British use potassium iodate instead of potassium iodide for thyroid blocking in radiological emergencies because of its greater shelf life (NCRP No. 55, 1977, p. 23).

Since iodine is a reactive halogen, it has the potential for incorporation into an organic molecule that would then have absorption and deposition characteristics of its own (Hofer, 1980). Ingestion of organic compounds (food) that contain radioactive iodine covalently bonded to them will result in a distribution pattern of the radioactivity in the body that would be expected to be very different than the distribution pattern of radioactivity resulting from ingestion of the elemental or ionic forms of the radioactive iodine. This would probably not present much of a hazard under most circumstances, but it should be remembered that the effect of nuclear disintegrations which deposit their energy in close proximity to cell nuclei carry a potential for damage which is many times greater than cytoplasmic or extracellular disintegrations (Hofer, 1980).

Critical Organ: The Thyroid Gland

Iodine's role in the thyroid gland and thyroid hormones is well known. The concern with radioactive iodine is that it is avidly concentrated in the thyroid gland, where a concentration gradient of 30 to 40X over serum iodide is achieved. In an iodine-deficient state, the thyroid's iodine concentrating ability may increase to 850X (Lissitzky, 1979, pp. 15-45). Regulation of the hormone output of the thyroid gland is controlled by the release of TSH (Thyroid Stimulating Hormone) by the anterior pituitary gland which lies at the base of the brain.

Essential functions such as energy metabolism and protein synthesis are dependent upon sufficient quantities of thyroid hormones in the circulation. Thyroid hormones are metered out in response to physiological needs at rates which are normally independent of iodine intake. If there is a deficiency of iodine, however, the stored hormones may be depleted and production of new thyroid hormones may be insufficient to meet the body's needs.

The minimun daily iodine intake considered to be necessary to maintain normal thyroid function is 100 to 150 micrograms for adults. The RDA for infants is 35 to 45 micrograms, and for children one to three years of age, 60 micrograms, for children 4 to 6, 80 micrograms. The average daily intake in the United States is estimated to be about 500 micrograms (Ganong, 1977, p. 237). A dietary intake of iodine that is less than ten micrograms per day will not provide enough iodine for thyroid hormone synthesis, so hormone secretion will decline (Ganong, 1977, p. 248). A decrease in circulating thyroid hormone causes a feedback control to act on the pituitary so that more TSH is released. The thyroid gland hypertrophies (enlarges) in response to the TSH stimulation, which ultimately results in goiter unless iodine is supplied in the diet. Damage to or disease of the thyroid gland can result in partial or complete hypothyroidism (not enough thyroid hormone being secreted), slowing down metabolism (Ganong, 1977, p. 246).

In the adult, the symptoms of hypothyroidism are referred to as myxedema. Hair becomes coarse and sparse, skin turns dry and yellowish, and cold is not well tolerated. Thought processes are slowed, memory impaired, and the voice becomes slow and husky. Severe mental states ("myxedema madness") can develop. Children who are hypothyroid from birth are retarded both mentally

and physically, with enlarged tongues and pot bellies; this condition is called cretinism (Ganong, 1977, p. 246).

Radioactive iodine will behave just like stable iodine in the body until it disintegrates. Following exposure (such as by inhalation), it will be avidly absorbed, taken up and concentrated by the thyroid gland, and then incorporated into thyroid hormones.

Damage to the thyroid gland from the disintegration of radioiodines will be dependent upon a number of factors. The absolute amount of radioiodine that one is exposed to is of primary importance; this constitutes the potential dose to the thyroid. The nutritional status for stable iodine prior to and during exposure will influence the avidity with which the thyroid gland will absorb and concentrate a dose of radioactive iodine. Age and the exposure pathway are important factors, especially for the young (See Table 4).

In the 1961 accident at the Savannah River Plant where 153 curies of radioiodines were released, the maximum concentration of iodine-131 in milk was found to be 5.4 nanocuries of iodine-131 per liter, about fifteen or twenty miles north of the plant. According to Marter (1963) the effective half-life of the iodine-131 in milk was four to five days and the same effective half-life was also representative of the decrease in radioiodine concentration in vegetation.

> If a child regularly consumed 1 l. milk/day containing 5.4 nc/l. initially, his total integrated thyroid dose would be 1.3 rems. This was calculated assuming a thyroid mass of 2g. An adult consuming 1 l./day would receive a thyroid dose of 140 mrems. The average concentration in milk collected June 5 and 6 from forty-eight farms and dairies

Table 4

Age, Pathway, and Isotopic Relationships in Radioiodine Doses to the Thyroid Gland

	Age			
	6 months	4 years	14 years	Adult
Thyroid mass (grams)	2.0	4.0	14	20
Percentage uptake by the thyroid				
Ingestion	40	35	35	35
Inhalation	30	26	26	26
Iodine-131 effective half-life in the thyroid (days)	6.0	6.3	6.9	7.6
Iodine-131 dose per unit intake (rads per microcurie)				
Ingestion	16	7.3	2.4	1.9
Inhalation	12	5.5	1.8	1.4
Iodine-129 effective half-life in the thyroid (days)	23	28	48	1.36
Iodine-129 dose per unit intake (rads per microcurie)				
Ingestion	20	11	5.6	1.1
Inhalation	15	8.3	4.2	8.4

Note. From Sources and Effects of Ionizing Radiation; 1977, p. 195.

> was 890 pc/l. This could result in a total integrated thyroid dose of 205 mrems to a child and 23 mrems to an adult. These are pessimistic calculations because decrease of I^{131} in milk was based on an 8-day half-life. Over 98 per cent of this dose would be received in the first 2 months. The Federal Radiation Council (FRC) recommends as a Radiation Protective Guide for thyroid dose for individuals 1500 mrems/year and for a suitable sample of exposed population groups 500 mrems/year. (Marter, 1963)

The most common effect of radioiodines upon the thyroid gland is hypothyroidism (NCRP No. 55, 1977, p. 5). Ablation of thyroid tissue by radiation causes a decreased output of thyroid hormone (hypothyroidism) which lowers metabolism--in short, the person so affected becomes relatively slow and stupid. Because thyroid ablation with radioactive iodine has been performed on humans in the treatment of various diseases, information on doses and effects is available. The time of onset and the degree of hypothyroidism produced by ablation of the thyroid gland is dependent upon the dose received (See Table 5).

Goolden and Davy (1963) performed thyroid ablations by administering radioactive iodine to patients suffering from angina pectoris and in some cases of congestive heart failure; relief of some symptoms was thus obtained by the resultant lowering of the basal metabolic rate. The antithyroid drugs carbimazole and thiouracil were given prior to the radioactive iodine to enhance thyroid uptake of the iodine-131. Their experience suggests that 30,000 to 40,000 rads delivered to the thyroid results in total ablation. A dose of about

Table 5

Probability of Hypothyroidism in Adults After Exposure to Iodine-131

Estimated thyroidal concentration of I-131 (microcuries per gram)	Estimated Dose to thyroid (rad)	Estimated probability of hypothyroidism within 1 year	Estimated probability of hypothyroidism within 5 years
26-50	3,400	.06	.13
51-75	5,750	.09	.17
76-100	8,000	.14	.20
101-125	10,000	.16	.24
126-150	12,600	.17	.28
151-175	14,900	.20	.31
176-200	17,150	.20	.24
201-224	19,400	.19	.45

Note. From NCRP No. 55, 1977, p. 6.

50,000 rads will be delivered to the thyroid if it absorbs one millicurie of iodine-131 per gram of tissue, and if the rate of iodine turnover is not too high.

Lower doses of radiation can produce hypothyroidism without total thyroid ablation. The threshold for induction of hypothyroidism is probably about 20 rads (NCRP No. 55, 1977, p. 7). This dose might be expected to take many years to produce an observable effect.

Goolden and Davy noted that thyroiditis, characterized by thyroidal pain and tenderness, usually developed after a single large dose of iodine-131 that was large enough to cause total or near total ablation of the thyroid gland, from 24 to 100 millicuries of iodine-131. Since the authors stated "failure to develop thyroiditis suggests that the radiation dose may be inadequate" (to cause ablation of the thyroid), then the reverse should be true, and thyroidal pain after an accidental exposure to radioiodines may be taken as a warning sign of having ingested a large dose of radioactive iodine, sufficient to ablate the thyroid gland at least to some extent. Two of Goolden and Davy's patients still possessed some thyroid function after ablation, each showing 6% uptake of a test dose of stable iodine after ablation, as compared to 36% and 40% uptakes in a 24-hr. period of the doses of iodine-131 that they received. The onset of thyroiditis took about four days, but ranged from two to eight days after exposure. Severe symptoms of thyroiditis were relieved by steroid treatment.

Fetal exposure. Fetal exposure to radioiodines can occur if the mother is exposed because iodine readily crosses the placenta. Beginning at 12 weeks of gestation, fetal uptake of iodine is maximal at term, although the percent radioiodine per gram of thyroid tissue was found by Evans et al. (1967) to be greatest at the five to six month period of fetal age. Newborns show about 70%

uptake of ingested radioiodines (compare with Table 4) (Shleien, Schmidt, & Chiacchierini, 1978, Appendix B-2).

Since normal thyroid functioning is essential for growth and development, the hazard of radioactive iodine is particularly severe for children and fetuses. Green et al. (1971) recommend that termination of pregnancy may be justified when a pregnant woman is given radioiodine in early pregnancy because "It is well-documented that congenital hypothyroidism may be a consequence of maternally administered radioactive iodine." They studied a woman who was given about 12 millicuries of iodine-131 in early pregnancy. Even though she was later administered thyroid hormones in an effort to protect the fetus from the effects of hypothyroidism, her daughter was still born a cretin.

The child of a mother who was given 14.5 millicuries of iodine-131 toward the end of her first trimester of pregnancy was retarded but responded well to thyroid extract therapy (Fisher, Voorhees, & Gardner, 1963).

Neoplasms. Benign nodules or cancer may arise in thyroid tissue after radioiodine exposure. Of the 86 Marshall Island natives who received the highest absorbed doses (estimated at 1100 rads to the thyroid) after nuclear weapons fallout was accidentally deposited on them in 1954, 37 have developed thyroid neoplasms and two cases of clinical hypothyroidism have been reported (NCRP No. 55, 1977, p. 4). However, in a study of 1378 Utah children who were exposed to an estimated mean dose of 46 rads from radioiodines (maximum 120 rads) from 1950's weapons testing, no significant difference in the occurrence of thyroid neoplasms was found between the irradiated group and a group of 3453 non-irradiated children (Rallison, Dobyns, Keating, Rall, & Tyler, 1974).

Other organs. Although the thyroid gland is the critical organ for exposure to radioiodines, other organs and tissues have the capacity to concentrate iodine. These include salivary and mammary glands, ciliary body, choroid plexus, stomach, some portions of the small intestine, and the placenta (Lissitzky, 1979, pp. 15-45). The incidence of salivary gland tumors is greater in the Japanese survivors of Hiroshima and Nagasaki nuclear explosions that in the unexposed Japanese population (Glasstone & Dolan, 1977, p. 593). In addition, the kidneys concentrate iodine so that it may be excreted in the urine. (Ganong, 1977, p. 237).

Strategies for Protection

Evacuation from the area downwind of a contaminating event may be a viable method of protection if it is possible under the circumstances involved (NCRP No. 55, 1977, pp. 30-31).

Taking shelter indoors in a tightly closed area and/or the use of an activated charcoal gas mask could reduce the inhalation dose, and would be very effective in the case of a contaminating event that was relatively small and if the radioactive cloud passed quickly (Manual of Protective Action Guides, 1975, pp. 1.38-1.40). SCUBA gear could also be useful in this case.

Evacuation and shelter could serve to reduce exposure to radioiodines not only from inhalation and ingestion, but also from absorption across the skin surface. Harrison (1963) demonstrated that aqueous and gaseous forms of iodine-131 can penetrate the skin. Aqueous absorption was lower than the skin's absorption of the gaseous form of iodine, and chemical irritation of the skin with stable iodine caused the absorbed dose of I-131 to be greater. This study was performed under conditions designed to simulate the possible exposure from

nuclear reactor accidents; the skin surfaces were not pretreated in any way, and the skin was washed within two hours after exposure. Radioactive potassium iodide in aqueous solution was absorbed in three subjects to the extent of .13, .15, and .19 percent of the total exposure dose. Elemental iodine (I_2) in aqueous solution was absorbed in two subjects to the extent of .057 and .12 percent of the exposure dose. The seven subjects whose skin was exposed to gaseous I_2-131 along with variable amounts of stable I_2-127 absorbed from 1.2 to 78 percent of the total exposure dose. Despite the wide range of variability, this study demonstrated that radioactive iodine can cross the skin surface, and that the absorption is facilitated by chemical irritation of the skin caused by stable iodine. In a real-life disaster situation, it can be expected that absorption of radioiodine across the skin surface, although a minor exposure pathway, will be highly variable from one person to another, and will probably be facilitated by skin irritations such as abrasions and burns. Iodine solutions for skin and wound sterilization should not be used by emergency medical personnel in first aid to radiological disaster victims, since the stable iodine irritates the skin and facilitates the skin absorption of radioiodines.

Fallout radioiodine is deposited onto plants, which appear to take it in through the stomata of the leaves (Barry & Chamberlain, 1963). More radioiodine is absorbed by plants in humid air and in light when the stomata are open, than when they are closed, such as in dry air and darkness.

Vigorous washing, scrubbing, and boiling will remove most of the deposited radioiodines from plants. Washing of radish, lettuce, and geranium leaves exposed to I-131 gas was an effective method of decontamination (Hungate, Cline, Uhler, & Selders, 1963). Even a brief five second washing in water

removed nearly half of the absorbed I-131, and five minutes' shaking in distilled water removed 60 to 70 percent of the contamination. The best results were obtained by shaking the leaves for five minutes in a .1 percent solution of Tide; this removed about 90 percent of the radioactive iodine. One experiment was run using a reactor fuel element being melted as a source of I-131; it also released many other radionuclides. It is interesting that the foliar washing was effective in reducing those other radioactive contaminants to near background levels.

Aqueous I-131 applied to leafy plants was also removed by washing in a study by Thompson and Howe (1973). They found the best results were obtained by washing, scrubbing, and rinsing the plants, then boiling them and throwing away the cooking water. Seventy-five to 90 percent of the I-131 contamination could be removed this way, and was most effective if done as soon as possible after the contamination occurred.

In a real-life situation it would be preferable to use canned, uncontaminated foods as much as possible. Root crops could be expected to be least contaminated by radioiodines; leafy vegetables grown in a humid environment and contaminated in daylight the most.

Iodine can move up the food chain to humans; the most significant route is the plant to cow to human (via milk) pathway (Eisenbud & Wrenn, 1963). Hull (1963), monitoring the passage of I-131 emitted from the reactor at Brookhaven National Laboratory in New York, found that the I-131 deposited on grass showed up in the milk of cows in the ratio of one microcurie per kg. of grass to .07 microcurie per liter of milk, which is close to the value obtained from measurements at Windscale of one microcure per kg. of grass to .1 microcurie

per liter of milk.

Some countermeasures suggested by Straub and Fooks (1963) to reduce radioiodine uptake by cows are to take the animals off pasture and put them on stored hay or feed, or to heavily fertilize the contaminated pastures so that a cow eats grass from a smaller surface area of pasture, thus reducing the radionuclide concentration in her diet. According to data presented by Straub and Fooks, the average concentration of I-131 per kg. of grass can be cut in half by fertilization of the pasture.

Using stored feed for cows was promoted by the states of Utah and Minnesota in 1962 in response to heavy weapons testing by the Soviet Union (Lengemann & Thompson, 1963). This recommendation was shown to be an effective way of reducing bovine uptake of radioiodines by Kahn, Straub, and Jones (1962) who measured up to 270 picocuries of iodine-131 per liter of milk from pastured cows at the Oregon State University School of Agriculture, versus the maximum of 20 picocuries per liter of iodine-131 in the milk of sheltered cows on stored feed at the same school.

Milk containing radioactive iodine could be processed to cheese or dried so that storage would allow most of the radioactivity to dissipate. The chief radioiodine hazard is usually from I-131, with a half-life of only eight days, so storing contaminated milk products for a few months will reduce the radioactive contamination to near zero level. In the meantime, stored milk could best be utilized by rationing to the most critical segments of the population (Lengemann & Thompson, 1963).

Iodine-131 can also be removed from milk by the use of ion exchange resins, but this would require the production of a milk processing capability that

is not in current use and would probably be considered a low priority action after a radiological disaster, considering that it might only be useful for a short time. Pilot studies have demonstrated that radioiodines can be removed from milk with over 99% efficiency (Easterly, Brooks, & Hasuike, 1971, pp. 18-19).

Protection of the thyroid gland from radioactive iodine can be achieved by "blocking" the thyroid, either with drugs or with a large quantity of stable iodide. Drugs such as propylthiouracil or methimazole prevent the synthesis of organic forms of iodide and have some clinical uses, but they also have some serious side effects and are not as effective as ionic blocking. Anions such as thiocyanate, tetrafluoroborate, perrhenate, and perchlorate can be used to block the thyroid uptake of radioiodines, but are too toxic, risky, or expensive to use (NCRP No. 55, 1977, p. 20).

A good countermeasure to protect the thyroid gland is a large dose of stable iodine. The National Council on Radiation Protection and Measurements recommends (NCRP No. 55, 1977, p. 33) 100 milligrams of iodide, present in 130 milligrams of potassium iodide, as an oral daily supplement to block the uptake of radioactive iodine by the thyroid gland. Half this dose can be given to children, but even the full amount is safe. Pregnant women can safely take the adult dose of 130 milligrams of potassium iodide for at least three to seven days without danger, to protect themselves and the fetus.

The National Council on Radiation Protection and Measurements considers that in a nuclear reactor accident, the need for thyroid blocking might last as long as ten days, with three to seven days being more likely, and they recommend that "instructions of public health officials should be followed carefully" (NCRP No. 55, 1977, p. 33).

In the event of nuclear war, survivors may be without the advise of public health officials, and thyroid blocking might be of value for months, particularly if there are second and third strikes by surviving nuclear forces.

Breastfeeding should stop after a mother's exposure to radioiodines because iodine is concentrated in human milk. An unweaned child should be put on formula, but if that isn't possible, then potassium iodide (at half the adult dose) can be given to a child to reduce the uptake of radioiodines from its mother's milk, and the nursing mother should also take the iodide supplementation, at the adult dose of 130 mg of potassium iodide (NCRP No. 55, 1977, p. 33).

Large doses of stable iodine given to normal individuals can result in a temporary decrease in the rate of thyroid hormone synthesis called the Wolff-Chaikoff effect (Nagataki, 1979, pp. 453-464). This results from an inhibition of the organic binding of iodide. Extremely large doses of iodine can even result in goiter or myxedema in certain susceptible individuals, but this is rare and only occurs after weeks or months of high iodide administration (NCRP No. 55, 1977, p. 25).

Long term supplementation of large doses of iodine during pregnancy are not recommended because "goiter of the newborn has been found when iodide was used for as little as the last four months of pregnancy" (Wolff, 1969). An infant born with an enlarged, goitrous thyroid gland may have difficulty in breathing.

It should be noted that not all experts recommend thyroid blocking by potassium iodide as a preventive measure. Yalow (cited in Iodide: Yes or no after nuclear accident?, 1980) cites problems with occasional severe reactions to potassium iodide, the possibility of hyperthyroidism in older patients with heart conditions, and skin eruptions. She also maintains that "the short and long term

consequences are far less than the possible injury from the mass panic arising from the effort to get the blocking agent." The National Council on Radiation Protection and Measurements (NCRP No. 55, 1977, pp. 23-26) calculates the risk of side effects of higher doses, 300 milligrams of potassium iodide, to constitute only a 7th order risk: between 1×10^{-7} and 10×10^{-7}.

Some removal of ingested radioiodines may also be facilitated by spitting out one's saliva, since iodide is concentrated in the saliva some 14 to 130 X over plasma levels, according to Schiff et al. (1947). Tobacco chewers have been known to develop iodine deficiencies in this way. However, this is not recommended as a preventive measure because of the possibility of potassium depletion resulting from the loss of saliva.

Potassium iodide is available at drugstores with a doctor's prescription in 300 milligram tablets. If these can be obtained, only half a tablet per day is necessary to block the thyroid gland. Iodine may be obtained without prescription in the form of kelp tablets which commonly contain .225 milligrams each of iodine. At this concentration, one would need to consume 444 kelp tablets per day to obtain the 100 milligrams of iodine needed to block the thyroid gland. Potassium iodide is also available without prescription from chemical supply firms and is in many laboratories. A saturated solution (one in which some crystals remain) can be made with water, or also obtained at a pharmacy with a doctor's prescription. It should be stored in a dark bottle, sealed with a non-metallic cap. Using a dropper, the adult dose is 4 drops per day; children less than one year take 2 drops per day. Since it tastes bad, the drops may be diluted in a beverage or dropped onto a piece of bread and made into a pill.

Do not use tincture of iodine as a blocking agent because the iodine in it is

in elemental form that is poisonous in large quantities (Kearney, 1979, pp. 101-103).

Radiostrontium

Sources

Radiostrontium nuclides are fission products, formed as daughter nuclides from the fission of uranium and plutonium in the operation of reactors and nuclear weapons.

Routine releases from nuclear reactors and reprocessing plants are small. For example, about 1.71 microcuries of strontium-90, and 41.4 microcuries of strontium-89 are typical liquid effluent releases per year to the environment from the Florida Power and Light reactor number 2 at St. Lucie (Rodger, 1975, p. 43). Releases of strontium-90 from a nuclear fuel reprocessing plant in southeastern Idaho, according to Markham et al. (1980) account for the approximate doubling of the strontium-90 content of the bones of antelope collected near the site, compared to off-site animals. Since the average dose due to strontium-90 to the bone marrow of the antelope near the site was 20 millirads per year, with a maximum of 85 millirads per year, the authors conclude that that level of increased dose poses no health hazard to the antelope in light of the 500 millirem per year maximum permissible dose to bone marrow from strontium-90 that has been set as a standard for humans by the National Council on Radiation Protection and Measurements.

Fission products such as strontium-90 are present in the nuclear wastes generated in fuel burnup. A serious accidental spill of nuclear fuel wastes or an event such as a terrorist bombing of a nuclear waste storage facility could result in large releases of radiostrontium to the environment.

Nuclear weapons detonations, unless they are underground, release all of their fission products into the environment. According to Comar (1966), a one megaton fission yield equivalent produces about 100,000 curies of strontium-90. It is distributed worldwide as fallout, some of it remaining in the atmosphere for years.

Chemistry

Strontium is an alkaline earth element in Group IIA of the Periodic Chart of the Elements. Group IIA elements all have low ionization potentials and therefore tend to easily lose two electrons from their outermost energy levels and exist as ions in a +2 oxidation state (Fessenden and Fessenden, 1976, p. 215). Strontium is just below calcium (and above barium and radium) in the periodic table, and it tends to follow calcium in biological systems, as does radium.

Critical Organ: Bone

> It is estimated that 1 megaton fission yield equivalent produces about 0.1 megacurie of strontium-90 (1 megacurie is one million curies). Thus, about 19.3 megacuries of ^{90}Sr were produced from the 193 megatons of fission yield equivalent produced in tests through 1962.
>
> The amount of ^{90}Sr settling to earth is expressed in terms of millicuries per square mile (1 millicurie is one-thousandth of a curie). Under the conditions of testing through 1962, the 19.3 megacuries of ^{90}Sr that were produced resulted in an average level of about 140 millicuries of ^{90}Sr per square mile in the United States in 1965.

> The amount of ^{90}Sr appearing in food and human bone is usually expressed in terms of picocuries per gram of calcium (one picocurie, pc, also known as a micro-microcurie, is one million-millionth of a curie; 10^{-12} curie). The amount of ^{90}Sr produced in tests through 1962 gave rise to about 25 picocuries of ^{90}Sr per gram of calcium in total diet and about 6.0 picocuries of ^{90}Sr per gram of calcium in bones of children in the United States in 1965. (Comar, 1966, pp. 13-14)

Now that some of the strontium-90 has had a chance to decay, and mix in with soil so that it is not transferred quite so much into food chains to humans, and because atmospheric testing of nuclear weapons has practically ceased, bone concentrations of strontium-90 have decreased. Typical values in 1975 for strontium-90 in the bones of children less than one year old, in New York were about 1.4 picocuries per gram of calcium. Children aged two had 1.6 pc/g Ca, children aged 5-19 had 1.4 pc/g Ca. Children in San Francisco in 1975 had less strontium-90 in their bones; children there less than one year old had only .5 picocuries per gram of calcium, those 5-19 years old had .8 picocuries/g Ca. Theirs was lower because of the unequal distribution of fallout due to latitude; a weapons detonation deposits most of its fallout in a narrow band of latitude around the world, depending on where it is detonated. For example, the human dose commitment to bone tissues from strontium-90 produced in all the nuclear detonations up to the end of 1975 amounts to 85 millirads to bone marrow and 116 millirads to endosteal (bone lining) cells in the temperate zone of the Northern Hemisphere; and 24 millirads to bone marrow, 33 millirads to endosteal

cells of those people who live in the temperate zone of the Southern Hemisphere. This is because most of the nuclear testing goes on in the Northern Hemisphere (Sources and Effects of Ionizing Radiation, 1977, pp. 132-137).

From June of 1946 to August of 1958, the United States conducted at least 65 unclassified nuclear weapons tests at Bikini and Eniwetok atolls in the Pacific (Announced United States Nuclear Tests, 1980, pp. 5-12). The resident native inhabitants were first removed from the islands; after a period of about ten years after the end of testing a restoration program was begun, and some of the native inhabitants were repatriated. The population of the area increased to about 140 by 1978. During the maturation period for the tree crops planted (which was five to seven years), the local population subsisted mainly on imported foods. A garden development program encouraged the growing of squash, papayas, bananas, and other nonindigenous crops, and "the diet became less restricted to imported foods so that by 1978, the diet contained substantial quantities of locally grown items" (Greenhouse, Miltenberger, & Lessard, 1980).

Whole-body field measurements of gamma emitting radionuclides was done to measure body burdens of radionuclides, from which future dose commitments could be calculated. In 1978, the inhabitants were again removed out of concern for the chronic exposure to fallout radionuclides that became evident.

During mean residence intervals of less than five years, seventeen adult males whose body burdens were measured had received an estimated average 1,100 millirems whole-body dose and had a dose commitment of 110 millirems at that time. Sixteen adult females had received an average of 830 millirems, and were committed to 85 millirems more. Twelve children (aged five to 14 years) had received an average of 1,200 millirems and were committed by their body

burdens to 140 millirems in the future.

Measurements of strontium-90 by urine bioassay of the activity of Sr-90 and its daughter nuclide, yttrium-90, allowed bone dosimetric calculations for these radionuclides to be performed. Nineteen adult males with a mean residence interval of 4.2 years had a mean dose equivalent of 28 millirems to their bones during that interval. The range, however, was very large, from 120 to .59 millirems. These men were committed to a future bone dose of 68 millirems average, ranging from 230 to 7.3 millirems. Fifteen adult females, mean residence time 4.1 years, received 15 millirems to their bones, ranging from 42 to .35 millirems. Their dose commitment was 42 millirems average, ranging from 110 to 5.8 millirems. Three male children with a mean residence time of 5.3 years had received an average dose to their bones of 47 millirems, ranging from 120 to 13 millirems; their dose commitment averaged 130 millirems, ranging from 310 to 29 millirems (Greenhouse et al., 1980).

Strategies for Protection. Since strontium is chemically similar but physically a bit larger and heavier than calcium, it is usually discriminated against in its travels along calcium pathways to humans.

Comar (1967, pp. 17-31) reports on the Observed Ratio (OR):

$$\text{OR product/precursor} = \frac{\text{Sr:Ca of product}}{\text{Sr:Ca of precursor}}$$

for example, an OR of .1 is obtained when a cow fed 100 picocuries of strontium-90 per gram of calcium yields milk containing 10 picocuries of strontium-90 per gram of calcium. The Observed Ratio can result from a constant intake, but it doesn't have to; it can also arise from a short-term intake. It is the product of various factors that may discriminate between two elements. These factors are called Discrimination Factors.

DF = Discrimination Factor = Ratio of fractional retentions

OR = (DF_1) (DF_2) . . . (DF_n) where the discrimination factors are the ratios of fractional radionuclide retentions that result from various processes.

Example: For a single-step process such as intestinal absorption, the retention of Sr is equal to

$$\frac{Sr_0 - Sr_F}{Sr_0}$$

and the retention of Ca is equal to

$$\frac{Ca_0 - Ca_F}{Ca_0}$$

where Sr_0 and Ca_0 refer to elemental intakes and F refers to fecal excretion.

The ratio of the two values obtained is the discrimination factor, DF, so, for this example

$$\frac{\frac{Sr_0 - Sr_F}{Sr_0}}{\frac{Ca_0 - Ca_F}{Ca_0}} -= DF_{absorptive}$$

For a single-step process such as this, the $OR_{body/intake} = DF_{absorptive}$.

The Discrimination Factors are expressions of the relative efficiency with which Sr and Ca are transported across physiological barriers. Treatments which alter Discrimination Factors may do so by altering the transport of both elements simultaneously or by changing the relative rate constants of the transport of each element.

For example, Comar (1967, pp. 17-31) presents data that illustrate an age-dependency on the Discrimination Factors, which result in the $OR_{body/diet}$ for

children in the first month of life being in the range of .9 to 1. By about 24 months of age, the $OR_{body/diet}$ has fallen to the adult value of .25. This means that very young children will take up much more radiostrontium than older children or adults.

Comar's Observed Ratios are customarily calculated with strontium:calcium quotients in units of picocuries of strontium per gram of calcium. Because of the cow's biological discrimination against strontium in preference to calcium, it usually contains less radiostrontium per gram of calcium than other foods. There are no other foods, however, which approach milk or milk products in calcium concentration, so the greatest absolute quantities (per gram of milk, say, versus per gram of greens) of radiostrontium are in the milk. If one is to obtain sufficient calcium in the diet, it is usually necessary to consume a dairy product that is higher than other foods in absolute radiostrontium content; but since it is the ratios of strontium to calcium that are important, milk will supply less radiostrontium per gram of calcium than almost any other foods (Sources and Effects of Ionizing Radiation, 1977, p. 126). If no supplemental source of calcium is available, then, and no uncontaminated foods such as dried milk, cheese, or canned greens are available to supply sufficient calcium in the diet, the preferential source of calcium would be milk. It should be mentioned that enough time should pass to allow most of the radioiodine in milk to decay. If no radioactivity measuring equipment is available, ten half-lives should be safe. For iodine-131, the radioiodine of greatest concern, that would be 80 days.

The kinetics of strontium movement in soil and of the rates of plant uptake are dependent upon a lot of factors. Most strontium-90 in fallout is water-soluble, but it takes some time for precipitation to solubilize it, and its

penetration into soil is slow. Plants absorb cations from solution in soil, but not all the soluble cations in soil are in solution. Some cations are adsorbed to clay particles, for example, and replenish the soil solution of cations as they are depleted by plants, so that "the solution is replenished by cation exchange reaction with the solid phase" (Roberts & Menzel, 1965, pp. 20-19). The chemical characteristics of different soils results in a variability of available calcium and strontium. Whereas plants grown in water extracts of soils and in nutrient solutions of strontium and calcium show no discrimination factor in their absorption of strontium (DF=1), "the availability of exchangeable strontium in some soils is less than that of exchangeable calcium" (Roberts & Menzel, 1965, pp. 20-29), and results in a variable discrimination factor against strontium transfer to plants between 1 (no discrimination) and 4.

The solubilization and downward movement into soil of strontium-90 are greatest when rainfall is heavy and in soils with a high exchangeable calcium content (Garner, 1972, p. 36). The availability of strontium-90 for plant uptake is increased if the amount of calcium in solution is increased by adding basic fertilizer. The application of ammonium nitrate, for example, has been shown to increase the rate of movement in soil and the uptake of strontium-90 into rye grass, barley, and tomato plants (Garner, 1972, p. 36).

When strontium-90 is absorbed into plants, the highest concentrations are found in the foliage and the lowest in the reproductive organs, such that little or no discrimination may occur in the uptake of strontium-90 to plants, but there may be a discrimination factor of .3 or more in the passage of strontium-90 to the ear of cereals (Garner, 1965, pp. 36-37).

Of course plants that absorb more calcium from the soil, such as legumes,

will also absorb more strontium-90, as a general rule (Garner, 1965, p. 36).

Direct fallout deposition results in far more strontium-90 contamination of the above-ground parts of plants than does the contamination arising from root uptake. An example cited by Garner (1965, p. 37) is .09% of the strontium-90 fallout being taken up by the roots of bluegrass, but 12% being retained by the above-ground parts, but those figures are not representative of all plants or all soils.

When soluble strontium-90 in soil is the only source of strontium-90, roots show the highest uptakes. Root crops such as beets, carrots, and potatoes accumulate a higher concentration of strontium-90 than do the above-ground parts (Russell & Newbould, 1966, pp. 213-245).

Suggestions for reducing the internal dose due to strontium-90 based on these factors are time-dependent. When fallout is being deposited the above-ground parts of plants will contain most of the radioactivity, particularly leaves and grains that trap particulates.

Root crops in the ground when fallout is deposited will remain relatively free of radioactivity until the fallout is solubilized and penetrates the soil, so they should be acceptable as food as soon as it safe to leave shelter unless rainfall has been very heavy and/or frequent.

Early in the period of fallout deposition, the fallout particles containing strontium will not penetrate the soil nor become significantly soluble to cause much root uptake of radiostrontium for a period of a few months after deposition (Lassey, 1979). Foliage will be highly contaminated, but is washed away naturally with a half-life of around two weeks (Lassey, 1979).

After fallout deposition has decreased to low levels (days, weeks, or months, depending on the severity of the release), plants which are grown on contaminated soil will contain most of the absorbed strontium in their roots, least in the reproductive organs. Potatoes, beets, and carrots will thus be higher in strontium-90 content than grains, for example.

It would seem that strontium-90 in soil could be isotopically diluted by excess calcium, but this seems not to be the case. Since the calcium content of soil is far more than the strontium content (even under fallout conditions), the rate of absorption of strontium and calcium into plants is governed by the total concentration of both (Russell & Newbould, 1966, pp. 213-245). An increase in one nuclide results in the increase of plant uptake of both.

As precipitation leaches strontium-90 more deeply into the soil, and strontium-90 very slowly is bound into the nonexchangeable soil fraction, and removal of strontium-90 by plants occurs, the uptake of strontium-90 into plants will decrease. Garner (1972, p. 37) cites soil studies in Italy and the United Kingdom that indicate that the annual uptake of strontium-90 by plants in those regions decreases by about 13% and 14%, respectively.

Cows grazing on pastures which contain freshly deposited strontium-90 can be expected to secrete a lot of strontium-90 in their milk. If they can be sheltered and kept on stored feed, this problem will be minimized. After fallout deposition has ceased, pasture grass grown on contaminated soil will reflect the soil concentrations of strontium-90, but the discrimination factor of the cow (diet/milk) will result in less transfer of radiostrontium to humans. Isotopic dilution is a possible mechanism for reducing the strontium-90:calcium ratio even further in the milk of cows. Comar, Wasserman, and Lengemann (1966) report

that Holstein dairy cows fed 121 grams of calcium (as dicalcium phosphate) per day, versus 54 grams of calcium fed to the controls, had strontium-90 concentrations in their milk that were half those of the controls. Both groups of cows received about 6,000 picocuries per day of strontium-90 in their diets from fallout. The calcium-supplemented animals secreted strontium-90 at the rate of 4.5 ± .5 picocuries per liter of milk, whereas the control group secreted 8.4 ± 1 picocurie per liter of milk. As picocuries of strontium-90 per gram of calcium, the high calcium group secreted 4.1 ± .4 pCi/g Ca, the control group secreted 8.0 ± 1 pCi/g Ca.

Goldman and Della Rosa (1967, pp. 181-194) have studied strontium kinetics in beagle dogs and found that the discrimination against strontium by the mammary glands provides some protection to pups so that the pups only contain 20% of the strontium in their mother's diets ($OR_{body/mother's\ diet} = .2$). Plasma levels of strontium-90 in the mothers were about 40% of the dietary ratio of strontium-90:calcium ($OR_{plasma/diet} = .4$). The placenta provides even more protection to fetal pups, such that the $OR_{fetal\ bone/maternal\ diet} = .1$, or 10% of the strontium-90 to calcium ratio in the mother's diet. Upon weaning, the pups fed the same strontium-90 supplemented diet as their mothers also rapidly equilibrated to the same OR of about .4, or 40%.

Kostial, Gruden, Durakovic, and Simonovic (1970) reported that a diet including supplementation with calcium, phosphate, and alginate fed to suckling, pregnant, and lactating rats was successful in reducing the absorption of radioactive strontium-85 without interfering with the increased absorption of calcium under conditions of increased nutritional need for calcium and its absorption from the digestive tract.

In another rat study, Kostial, Maljkovic, Kadić, Manitaševic, and Harrison (1967) found that dietary supplementation of barium and sodium sulfates (5.7g of an equimolar mixture of barium and sodium sulfates per 100g of diet) was effective in halving the percentage of strontium-85 absorbed in the GI tract and retained in the body. Calcium, alginate, and phosphate supplementation was even more effective, with the best results obtained with a mixture of the three. Dietary analysis was 2.5 grams calcium, 2.4 grams phosphorus, and 10 grams alginate per 100 grams of food. Only 1.5% of the oral dose of strontium-85 was retained by the animals who received this diet, as compared to the 11.5% retention of strontium-85 observed in the carcasses of the control rats.

In humans, the absorption of strontium was found by Warren and Spencer (1978) to range from 12 to 20% in patients on a low calcium diet containing about 200mg calcium and 750mg phosphorus per day. It is likely, then, that these are near maximal uptake values considering that the U.S. Recommended Daily Allowances for these minerals are 1,000mg each, per day. Many people probably consume more than the RDA values; Harland, Johnson, Blendermann, Prosky, Vanderveen, Reed, Forbes and Roberts (1980) recently reported on a food consumption survey that indicates the average adult American receives 1,616 grams of calcium and 2,412 grams of phosphorus per day.

Strontium-90 from fallout deposition is now ubiquitous in foods all over the world, so everyone maintains an equilibrium in their body that reflects their average intake. Because strontium follows calcium in food chains, the total amount of strontium-90 ingested is more or less proportional to the calcium intake.

Typical fallout ingestion of strontium-90 in food was found to range from

3.1 to 7.7 picocuries per day when calcium intake was 179 to 247 mg/day. When milk supplementation increased daily calcium to the range of 820 to 1257 mg/day, strontium-90 intakes ranged from 7.8 to 19.2 picocuries per day. Most of the strontium-90 that is ingested is excreted in stool, and urinary excretions account for only a sixth to a fourth of fecal excretion (Spencer, Kramer, Samachson, Hardy, & Rivera, 1973).

Spencer (1975) studied hormonal factors influencing strontium metabolism and concluded that "the intestinal absorption and excretion of ^{85}Sr in man is altered by those hormones which induce changes in calcium metabolism." Interestingly, she studied the effects of the functional state of the thyroid gland in connection with strontium-85 metabolism, and found that hyperthyroid individuals absorbed strontium-85 in the low normal range which was increased markedly after the hyperthyroidism was corrected, and a similar result was seen in an individual who had been rendered hypermetabolic by the administration of a thyroid extract.

If a decrease in thyroid hormone output results in an increase in absorption of strontium-90, then those individuals most at risk from strontium-90 after global contamination by nuclear war would be those who had also suffered thyroid ablation as a result of exposure to radioiodines.

Dietary supplements which reduce the absorption or retention of radio-strontium have been experimented with a great deal in animals and humans. Interest and effectiveness generally center on those agents which will bind to strontium in the gut or isotopically dilute it so that its retention half-time is decreased.

In an experiment by workers at the United Kingdom Atomic Energy

Authority, the inhibition of radiostrontium uptake by man was studied following reports of its effectiveness in rats. A healthy male volunteer was given orally, 10 grams of a low viscosity form of sodium alginate twenty minutes before an oral dose of .36 microcuries of strontium-85. After 23 days the strontium-85 had dropped below detection limits in the volunteer, and the volunteer was then given .48 microcuries of strontium-85 under conditions identical to the first administration except that no sodium alginate was given. Results of retention measurements showed that after five days, the amount of strontium-85 was lower by a factor of 8 when the sodium alginate was administered. The experimenters concluded that the administration of sodium alginate was effective in selectively inhibiting the GI uptake of radiostrontium without significantly interfering with the calcium uptake, and that sodium alginate would be of potential value to a victim of a contamination event which included radiostrontium (Hesp & Ramsbottom, 1965).

The presence of food in the GI tract has an influence on strontium absorption. Spencer, Norris, and Kramer (1973) found that an acutely administered oral dose of strontium-85 is absorbed by a factor of 2 to 3 times greater when it is given without food, compared to when it is given with breakfast, which was probably due to a large extent to the 45mg Ca and 120mg phosphorus contained in the breakfast meal. Twice these amounts of calcium and phosphorus, given alone with the oral dose of strontium-85, were equally as effective as the breakfast in reducing the absorption of strontium-85. A large (one gram) dose of calcium, given with the food just prior to administering strontium-85, decreased the absorption of the radionuclide by 40 to 60%.

According to Soviet Union investigators cited in the Journal of the

American Medical Association, pectin offers some protection against strontium-90, since pectin precipitates with ions of polyvalent metals, forming insoluble salts. The report lists no dose levels, but quotes the Soviet conclusion that pectin "binds radioactive strontium in the gastrointestinal tracts of rats and reduces the absorption and deposition of the isotope in the skeleton" (Soviets say sunflower extract may protect against strontium 90, 1961).

Aluminum phosphate gel ($AlPO_4$) in a single dose of 100-300 ml given immediately prior to an oral dose of strontium-85 has been shown to decrease the absorption of radiostrontium in humans by an average of 87%. When given at half an hour and one hour after the oral administration of the radionuclide, the absorption of strontium-85 was decreased by 58% and 37%, respectively. If the same dose of aluminum phosphate was given with radioactive calcium-47, it decreased the absorption of that radionuclide by only 37% compared to the 87% reduction of absorption of strontium-85. Thus the use of aluminum phosphate gel resulted in a high discrimination factor acting against strontium-90 absorption, and had only a slight effect on calcium balance (Spencer, Lewin, Belcher, & Samachson, 1968). However, in a later paper by Spencer (1979) some long-term adverse effects of the use of aluminum hydroxide (such as Maalox) included hypophosphatemia, osteomalacia, hypercalcemia, and bone demineralization. She expressed a concern over the use of any aluminum compound as an oral supplement because of the potential for intestinal absorption of aluminum and its deposition in varius organs. High aluminum levels have been reported in patients with chronic renal failure, and aluminum deposition in the brain has been implicated as an etiologic factor of neurologic disorders seen in patients with chronic renal failure and with Alzheimer's disease.

In a human balance study, Spencer, Kramer, and Hardy (1977) determined the effect of calcium and phosphorus on excretion and retention of the strontium-90 contained in food from fallout. Control levels of phosphorus were 800 mg/day, versus 2000 mg/day for experimentals. Effects on strontium-90 balance were determined at low calcium intakes of about 200 mg/day and high calcium intakes of 2000 mg/day. The experiments were carried out on five male patients in the Metabolic Research Unit of the VA Hospital in Hines, Illinois. Constant, analyzed daily diets contained 237 mg Ca and 800 mg phosphorus, and the patients received this constant diet under controlled conditions for several weeks prior to the start of the study. Complete collections of urine and stools were made for analysis. Phosphorus supplementation was given as glycerophosphate in the high-phosphorus portions of the study, and calcium supplementation was given as calcium gluconate. Strontium-90 was present in food averaging 4.9 picocuries/day during the low calcium intake and 4.3 picocuries per day during the high calcium intake. They found that the addition of calcium alone to the diet resulted in a net loss of strontium-90 from the body (negative balance), whereas raising only the phosphorus intake had very little effect. The best results, however, were obtained when both calcium and phosphorus in the diet were high (each 2000 mg); the mean balance of strontium-90 was -21.4%, indicating that more strontium-90 was being removed from the body than was being ingested. This compares with mean balances of -4.9% with only the high calcium supplementation, +7.5% with high phosphorus only, and +13.7% with both low calcium and low phosphorus. The authors conclude that a high calcium and phosphorus supplementation results in a decreased absorption of the strontium-90 which is present in small amounts in the diet, but mention that definitive data

are not available for the case of acute exposure to strontium-90. They conclude:

> However, one may assume that acutely ingested ^{90}Sr would be more readily available for the inhibition of radiostrontium absorption than the ^{90}Sr which enters the body chronically due to the long term intake of small amounts of dietary ^{90}Sr. The potential usefulness of the combined dietary regimen of a high calcium and a high phosphorus intake to decrease the intestinal absorption of ^{90}Sr in case of accidental exposure is suggested.

According to the information presented in this report, a recommended protection against strontium-90 uptake via food is the oral supplementation of 2000 mg (2g) each of calcium and phosphorus per day. Bone meal is one good source of both elements.

However, mineral supplementations that do not take into consideration the disruptions of mineral balance within the body that may result have the potential for doing more harm than good. Drastic measures to facilitate removal of small quantities of radionuclides should not be undertaken lightly. For example, some people are prone to the formation of kidney stones and should not take a calcium supplement that might result in stone formation.

Some removal of strontium-90 from food is also possible prior to ingestion. Vigorous washing, scrubbing, and soaking of food can remove a large portion of the radioactivity. For example, Ralls, Maagdenberg, Guckeen, and Mercer (1971) found that washing externally contaminated pea pods before podding resulted in a more than 90% reduction in the strontium-89 content of the peas.

Weaver (1978) found that internally deposited strontium-90 in vegetables

could be removed to a large extent in sweet potatoes by peeling the outer skins. This would probably be applicable to other root crops such as carrots, beets, and regular potatoes. Weaver also found that much of the internally deposited strontium-90 in kidney beans could be removed by washing, blanching and canning. She had similar success with kale, and she found that cucumbers could be very well decontaminated by pickling and canning.

Radiocesium

Sources

Radiocesium is a fission product which is generated in reactors and in nuclear weapons detonations. The yield of cesium-137 is about six atoms per hundred fissions, and about 34 megacuries of cesium-137 were produced in atmospheric nuclear weapons tests up to 1971 (NCRP No. 52, p. 3), much of which has been distributed worldwide in fallout. "Other actual or potential sources of ^{137}Cs release include the routine operation of nuclear reactors, fuel reprocessing facilities, the use of nuclear devices for earth-moving and cavitation operations, and accidental releases" (NCRP No. 52, p. 3).

Because of its relatively long half-life of 30.2 years, cesium-137 is considered to be the major cesium radionuclide of concern. Cesium-134 has a half-life of 2.06 years, and cesium-136 has a half-life of only 13 days (Lassey, 1979; Sources and Effects of Ionizing Radiation, 1977, p. 146).

The movement of fallout cesium-137 into food chains and humans is well documented. Soil types affect plant uptakes of cesium-137, with cesium-137 readily adsorbed onto clay particles which renders it less available for plant uptake. Sandy soils, and soils with a high organic content, bind cesium-137 less readily (Fredricksson, Garner, and Russell, 1966, p. 317). This may account for the relatively higher levels of cesium-137 found in foods grown in Florida, and in the bodies of Florida residents. Roessler, Dunavant, and Roessler (1969), who studied the body burdens of cesium-137 in Florida residents with a whole-body gamma counter at the Miller Health Center at the University of Florida in

Gainesville from 1965 to 1968, discovered that the body burdens of cesium-137 in Floridians were elevated two to three times over reported values for residents of other sites in the United States, ranging from California to Massachusetts, and from Washington State to New Mexico. The average Floridian's body burden of cesium-137 was determined to be 130 $\pm$ 7.5 picocuries per gram of potassium, which results in an average dose of 2.6 millirads/year. Roessler et al. also had the opportunity to periodically measure the increasing burdens of cesium-137 in three new arrivals to Florida. Two of them reached typical Floridian cesium-137 body burdens after only eight weeks; the third was a tourist from Minnesota whose body burden was increased in cesium-137 content by about 60% in one month. Floridians, then, can be considered particularly at risk from nuclear accidents and weapons fallout, in terms of radionuclides of cesium.

Radionuclides of cesium may enter the body by inhalation of aerosols, in which case the amount absorbed into circulation is dependent upon the amount of soluble fraction in the quantity inhaled (Richmond, 1968).

Skin absorption of radiocesium is possible. Pendic and Milivojevic (1966) found that up to 3% of the dose placed on skin (as radiocesium chloride in aqueous solution) could be absorbed after six hours. Furthermore, percutaneous transport was increased by usual decontamination agents, such as detergents and MO 8.385, a special decontaminant.

The movement of radiocesium through food chains constitutes the largest vector for human exposure, particularly for flesh-eaters. This is because cesium accumulates in tissues, and even establishes a higher concentration gradient in tissues than does potassium (Relman, 1956, p. 256). Food chains vary in how much they concentrate cesium radionuclides. Brungs (1967) found that bottom-

feeding freshwater carp contained five times as much cesium-137 per gram of dry weight as did bluegills, which are fish that never eat food from the bottom. The radionuclides had been added in totally soluble form to a pond containing the fish; apparently much of the cesium-137 became bound to inorganic materials on the pond bottom. Freshwater Lamsilis clams accumulated cesium-137 at an even greater rate than the carp. They are filter feeders, and Brungs hypothesizes that some of the cesium-137 probably was also bound to suspended organic solids. The clams reached a concentration of cesium-137 that was over twice the concentrations in the bottom-feeding carp.

A food chain that has received quite a bit of attention in regard to cesium-137 is the lichen to caribou to Eskimo food chain, which results in Alaskan Eskimos' maintaining very high body burdens of cesium-137 that are 50 to 100 times the body burdens of people who are on a temperate zone diet. This is because the Eskimos may obtain half their food form caribou meat, and caribou may subsist primarily on lichens. Lichens are dependent upon precipitation for nourishment, and the long-lived plants have a tenacious hold capacity for the cesium-137 they receive from fallout. The biological half-time of cesium-137 in lichen is estimated to be 13 years, as compared to three to five weeks in caribou and 65 days in Eskimos. Since wolf flesh contains twice the concentration of cesium-137 as is present in caribou, and because the Eskimos who consume half of their diet as caribou flesh have cesium-137 concentrations in them that are about equal to the caribou body burdens, "it is reasonable to assign a concentration factor of two to the caribou-carnivore (including man) link of the Alaskan food chain" (Hanson, 1967).

The high body burdens of cesium-137 that Eskimos have are due to their

particular carnivorous diet of caribou, which in turn are high in cesium-137 because of the characteristics of the lichen which make up the caribou diet. Most other plants do not derive all of their nutrients from precipitation, and their concentrations of radiocesium are therefore much lower. In comparison with strontium, cesium moves into plants from the soil more slowly by a factor of 10 to 100, due to the fixation of cesium in the soil minerals which renders it insoluble for root uptake. The amount of binding of cesium in the soil is much more variable than is the binding of strontium between different soil types (Lassey, 1979).

The radiocesium that does enter food chains is increased in concentration at each trophic level, due to the more tenacious retention of cesium by cells as compared to potassium. At present levels of worldwide fallout contamination and in most food chains, there is only a small increment in radiation dose due to radiocesium compared to background levels. Pendleton, Mays, Lloyd, and Church (1965), in a study of trophic level concentrations of cesium-137, said: "It appears for many animals that the cesium/potassium ratio in their bodies will be about two to three times that in their diet. This finding would be of particular importance for animals in the higher trophic levels after massive ^{137}Cs contamination."

Chemistry

Cesium is a member of the Group I alkali metal series on the periodic chart of the elements. In descending order, the Group I elements are lithium, sodium, potassium, rubidium, cesium, and francium. They are all monovalent positive ions and are qualitatively similar in their electrical, chemical, and physical properties. The similarity of these monovalent ions explains why rubidium and

cesium can move into biological systems along potassium pathways. Potassium is an abundant element making up about 2.5% of the earth's crust by weight, and is vital to life processes. Rubidium is present at about 1/2500 the concentration of potassium, and naturally occurring cesium is present at about 1/10 the concentration of rubidium. Therefore there is a certain amount of naturally occurring nonradioactive rubidium and cesium in virtually all animal tissues, each on the order of 2×10^{-3} to 6×10^{-3} percent of dry weight (Reiman, 1956).

Although rubidium radionuclides are formed as products of nuclear fission, they are considered to be much less of a hazard to humans because of their short half-lives. Rubidium-86 has a half-life of only 18 days, for example.

The radiochemistry of cesium-137 is significant, because each disintegration initially results in a beta particle emission. Ninety-three and one-half percent of cesium-137 disintegrations are to the metastable barium-137, which has a half-life of only 2.55 minutes, and decays with the emission of a .662 MeV gamma ray that is commonly attributed to sources of cesium-137. In the other 6.5% of the cesium-137 disintegrations, there is radioactive decay directly to the ground state of barium-137 with only the emission of an energetic 1.176 MeV beta particle (Bailey, Clarke, Ferris, Krause, & Strong, 1978, p. 469). Therefore, the radiation from internally deposited cesium-137 involves both a beta particle and a gamma ray, and usually both.

Critical Organ: Whole Body

Cesium is a biologically mobile element, and is rapidly deposited in the body throughout all soft tissues, with about 80% being deposited in muscle. Some is more slowly deposited in bone, about 8% (Sources and Effects of Ionizing Radiation, 1977, p. 144).

Most excretion of cesium occurs through the urine, via the kidneys, as is also true of potassium. However, some is lost in the feces, and there is a constant secretion and reabsorption of both elements going on in the gut, which circulates a large portion of the body burden of radiocesium (Richmond, 1968). This fact becomes useful for reducing the internal burden of radiocesium nuclides.

The preferential retention of cesium over potassium in the body is expressed by the experimentally derived ratio:

$$\frac{\left(\frac{\text{Cs-137}}{\text{g K}}\right)_{\text{body}}}{\left(\frac{\text{Cs-137}}{\text{g K}}\right)_{\text{urine}}}$$

If cesium and potassium were both metabolized in the same manner, one would expect this ratio to be equal to one. However, actual values measured in humans range from 1.6 (Boni, 1966) or 2 (Langham and Anderson, 1959) to 3 (McNeill and Trojan, 1960; Morgan and Arkell, 1961). Richmond (1968, p. 316) describes the retention of cesium in human beings as being represented as the linear sum of two exponential functions. One component, representing up to 20% of the initial body burden, has a biological half-life of only one day. The second component, which is much more important in terms of radiation dose, has a biological half-life ranging from 50 to 150 days in adult humans. This large range reflects the interaction of many factors, the entire process being incompletely understood.

Boni (1966) noted that the biological half-life of cesium-137 in children is about one-half that of adults. In a study of maternal and infantile metabolism of

cesium, Bengtsson, Naversten, and Svensson (1964, pp. 21-32) found that the biological half-lives of radiocesium in pregnant women was only about 30 days, and the placenta appeared to discriminate against desium somewhat, since the specific activities of the newborn infants in the study were slightly less than in their mothers, ranging from 85 to 96%. The biological half-time of the radiocesium in the newborns was only 25 days.

Strategies for Protection

Apparently the metabolism of potassium and cesium are dissimilar enough that potassium supplementation does not appreciably affect the body's cesium content; "the metabolic relation between potassium and cesium is less exact than that between calcium and strontium" (Richmond, 1968).

Protection against incorporating radionuclides of cesium begins with preventing ingestion of fallout through inhalation, wounds, and in food and water, as for other radionuclides (see Protection Principles).

Many attempts have focused on the problem of removing radiocesium from man and animals. Isotopic dilution with stable potassium and cesium are ineffective. Diuretics, thyroid hormones, ion exchange resins, chelating agents, and natural food products have all been tried and found to be insignificant for the purpose in human subjects.

One compound has been found to be effective in accelerating the turnover of internally deposited radiocesium. This is Prussian Blue, which is non-toxic and well tolerated as a dietary additive. It is also known as Berlin Blue, and more technically called ferric ferrocyanide or ferric cyanoferrate (II). Some commercial supplies of Prussian Blue or Berlin Blue may contain contaminants or not be composed of ferric ferrocyanide, but it is easily made. Mix together 0.5

molar solutions of $FeCl_3$ and $K_4[Fe(CN)_6]$ in a 4 to 3 ratio. The precipitate is then washed three times with distilled water to remove the KCl, and dried at 100 degrees C (Richmond, 1968), although Strömme (1968) claims that Prussian Blue is most effective in reducing the body burdens of radiocesium in rats when it has been allowed to dry at room temperature.

Oral administration of Prussian Blue is believed to interrupt the circulation of radiocesium in the gut, and therefore result in an increased fecal excretion of radiocesium. According to Nigrović (cited in Strömme, 1968) Prussian Blue is insoluble and not absorbed from the gut. It is thought that Prussian Blue acts by binding cesium to it, perhaps by an ion exchange process whereby potassium ions in the Prussian Blue are exchanged for cesium. However, there is disagreement as to whether Prussian Blue must contain an excess of potassium ions to be effective, or whether any potassium ions need to be present at all, and the exact structure of Prussian Blue remains unknown. Strömme (1968) has also observed that there is no prophylactic effect of Prussian Blue, because a large dose in humans, three grams per day, preceeding the ingestion of cesium-137 which was then taken with one gram of Prussian Blue, did not significantly reduce the absorption of the cesium-137 into the body from the gut.

Richmond (1968) gave two grams per day of Prussian Blue to a human volunteer who had previously ingested some cesium-137. They estimated that the biological half-life was shortened from 140 days prior to treatment to about 50 days during the treatment with Prussian Blue. In this case the Prussian Blue was divided into ten 200 milligram doses taken at intervals during the day for two separate five-day treatment periods. Between treatment periods, the rate of loss of the cesium-137 was decreased, and the biological half-life consequently

increased.

Madshus, Strömme, Bohne, and Nigrović (1966) experimented upon themselves and found that three grams of Prussian Blue could be tolerated daily, taken as three one-gram oral doses per day. There was some slight constipation reported at that dosage, but no other side-effects were seen, and no loss of potassium was observed. They were successful at reducing the biological half-time of the radiocesium from about 110 or 115 days to about 40 days by this treatment, significantly speeding the diminution of their radiocesium body burdens.

Ferrocyanide salts are reported to be relatively nontoxic, not being decomposed to cyanide even when given intravenously (Gosselin, Hodge, Smith, & Gleason, 1976).

Strömme (1968) reports that storage of the compound for a year did not reduce its efficacy.

Actinides

The Actinides include the natural radionuclides thorium, protactinium, uranium, and the man-made transuranics--neptunium, plutonium, americium, curium, berkelium, californium, einsteinium, fermium, mendelevium, nobelium, and lawrencium. They are included in this report because of their extreme toxicity and because large quantities of some of them may be released into the environment.

Although radium is not classed as an actinide element, and also is not an important radionuclide of concern in nuclear reactor accidents or nuclear war, it is present in uranium ore and shares some of the chief characteristics of the actinides: high molecular weight and a series of alpha-emitting nuclear disintegrations. Therefore some mention is made of radium in this section.

Sources.

Naturally occurring exposure to the actinides has been estimated by the United Nations Scientific Committee on the Effects of Atomic Radiation (Sources and Effects of Ionizing Radiation, 1977, pp. 57-63) to result in a United States dietary intake of uranium-238 of about .44 picocuries per day, the contribution from drinking water being very small, on the order of less than .03 picocuries per liter. About 1.4×10^{-3} picocuries per day comes from an inhalation dose based on an assumed dust loading of 100 micrograms per cubic meter in surface air, and an average uranium-238 activity concentration in soil of .7 picocuries per gram. This results in a yearly absorbed dose to the cells lining the bones of .3 millirads from alpha radiation and .04 millirads due to beta

and gamma radiation. Similar calculations for thorium give the results of .8 millirads to the bone lining cells from thorium-230 and .7 millirads from thorium-232. (These are the principal actinides. For radium, which is not an actinide, the figures given are .7 millirads due to alpha radiation plus .03 millirads due to beta and gamma radiation from radium-226, and 1.08 millirads from alpha radiation plus .04 millirads from beta and gamma radiation from radium-228 per year.)

The soil concentration values for uranium and thorium were both considered for purposes of calculation to be .7 picocuries per gram in the United Nations report. McNabb, Kirk, and Thompson (1979) report that the activity of sieved soil samples near a phosphate ore processing plant in the vicinity of Pocatello, Idaho, were as great as 26 picocuries of uranium per gram of soil, and 10 picocuries of thorium per gram of soil, measured in surface samples taken downwind of the plant.

Some products of the Florida phosphate industry were studied by Roessler, Smith, Bolch, and Prince (1979) to determine their uranium-238 and radium-226 contents. The ore from Central Florida contained an average of 37.6 picocuries of radium-226 per gram and 38.5 picocuries of uranium-238 per gram. The ammoniated phosphate fertilizer produced from the ore had 4.1 picocuries of radium-226 and 70.2 picocuries of uranium-238 per gram. The triple superphosphate fertilizer contained 19.7 picocuries of radium-226 and 56.5 picocuries of uranium-238 per gram. The radioactivity measured in north Florida phosphate fertilizer products was less, ranging from about one tenth to one half the Central Florida concentrations.

Bailey, Clarke, Ferris, Krause, and Strong (1978, p. 489) mention that one of the by-products of the fertilizer production is gypsum, which may contain

about 25 picocuries of radium-226 per gram, and "because gypsum is used in the fabrication of wallboard, concern has been expressed that the contaminated gypsum might find its way into buildings."

Combustion of fossil fuels, especially coal, adds to some natural actinides to the environment. Harley and Pasternak (1979) indicate that a local enhancement factor of about two can be measured around coal-fired power plants, but add: "we suspect that more general widespread sources, such as industrial pollution and space heating, have contributed to pollution for the past 50 yr. They may have made a more significant contribution to the total population than power production."

Fallout from nuclear weapons will contain actinides. A very serious reactor accident or accident at a nuclear fuel processing facility might release a large amount of actinides as well. Terrorists might build a dispersal device solely for this purpose. Accidents with nuclear weapons have contaminated large areas with plutonium. In one case an aircraft that was carrying nuclear weapons crashed and burned, contaminating a military base and involving a large spread of contamination before it was learned that the contamination had occurred (Radiological Emergency Operations, no date, p. 226).

Nuclear reactors can use several radionuclides of uranium, plutonium, or thorium for fuel. Breeder reactors are designed to convert some actinide radionuclides that are impractical to use for fuel into radionuclides that will serve as fuel that can be used in other reactors or to make bombs. Some of the heavier actinides are also formed in nuclear reactors, such as americium and curium (Harley & Pasternak, 1979). This also happens when nuclear weapons are detonated; in fact, elements 99 and 100, einsteinium and fermium, were first

discovered as a result of the study of the unknown heavy elements that were formed in thermonuclear weapons tests (Hyde, 1964, p. 18).

Special research reactors have been designed specifically to produce the heavier actinides:

> In a high neutron flux Pu^{239} captures successively several neutrons forming in turn Pu^{240}, Pu^{241}, Pu^{242}, and Pu^{243}. In the early steps of this capture chain, there is a high depletion of the plutonium by nuclear fission and only a small percent is ultimately converted to Pu^{243}. When Pu^{243} is produced, it undergoes beta decay to form Am^{243} before it can capture another neutron. Americium-243 then captures a neutron to form Am^{244} which is beta unstable and decays to form Cm^{244}. Curium in turn captures several neutrons until Cm^{249} is produced; this is transformed by radioactive decay to the heavier element, berkelium. In this way the heavier elements are built up from the lighter. (Hyde, 1964, p. 33)

Of course the reprocessing, transportation, and waste handling facilities of the nuclear fuel cycle will all involve the actinides. In normal operation, nuclear facilities only release small quantities of actinides to the environment. For example, Markham, Dickson, and Autenrieth (1979) found detectable amounts of plutonium in the lungs of 50% of the pronghorn antelope sampled within 10 km of the Idaho National Engineering Laboratory's nuclear fuel reprocessing plant. Since antelope are large animals with lungs that are similar in size to a human's, a valid comparison can be made between the two species. The quantities of

ingested plutonium in the lungs of the antelope collected were so small that they constituted only ".5% of the average radiation dose equivalent to human lungs from natural back-ground radiation." According to Volchok, Schonberg, and Toonkel (1977), plutonium concentrations in air downwind of the Rocky Flats Plant, where accidental contamination of the soil has occurred, decreases with an effective half-life of one to two years. This may result from the plutonium becoming mixed into the soil and perhaps from a change in effective particle size.

Accumulated nuclear wastes as of 1979 amounted to only 123 kilograms of transuranic wastes from commercial operations and 1100 kilograms from defense-related activities. Since the reprocessing of spent fuel discharged from commercial reactors in this country has stopped, about 2300 metric tons of heavy metal has accumulated as waste (Report to the President, 1979, p. 11). This spent fuel contains actinides as well as fission products.

Another potential source of actinides is from reentering satellites which use radionuclide power supplies. Plutonium-238, curium-242, and curium-244 have been used for this purpose in very small and lightweight power packs (Hyde, 1964, p. 32). Satellite reentries are not a trivial source of actinides in the environment. While all nuclear tests as of 1974 had contributed about 9 kilocuries of plutonium-238 to the worldwide global fallout, a single nuclear-powered satellite in 1964 which reentered the atmosphere in 1964 contributed about 17 kilocuries, of which about 70% was deposited on the Southern Hemisphere (Sources and Effects of Ionizing Radiation, 1977, p. 148).

Chemistry

The actinide elements are all elements which occur in their own group in

the Periodic Table and thus share very similar chemical characteristics. They are the heaviest elements that exist, have low solubility and consequently are not very biologically mobile. Since their biological availability is very low, their most important pathway to humans is through the physical deposition route of inhalation (Harley & Pasternak, 1979). Their physical chemistry is not comparable to that of any of the elements for which biological pathways exist. They are trace contaminants that do not readily enter food chains, and in this context their chemistry is best described by their biological interactions.

Only a very small percentage of transuranics is absorbed from the GI tract, about 10^{-4} to 10^{-5} percent of those ingested (Harley & Pasternak, 1979), and the variations seen in all routes of absorption in experiments may be due to species differences, physiological and dietary factors, as well as the physical and chemical forms of the ingested compounds (Bair, 1976, pp. 51-83). For example, larger aerosol particles of plutonium-239 were eliminated from the lungs of beagle dogs with a retention half-time of 500 days, versus 250 days for smaller aerosol particles (Mewhinney, Muggenburg, McClellan, & Miglio, 1976, pp. 87-97). Even the depth of inhalation is important. In a review by Bair (1976, pp. 51-83), he cites data of lung clearance rates of about .5 to .8 days half-time in humans when plutonium is deposited in the upper respiratory tract, and from 300 to 566 days half-time residence in the lungs of humans when the plutonium is deposited in the alveoli of the lower respiratory tract. The retention half-times of the long term whole-body content of actinides are very much longer, on the order of more than 100 years (Toohey & Essling, 1980). Reviewing the data on intestinal absorption in rats of different actinides in some different chemical states, Bair found that about one percent of neptunium-237 nitrate was absorbed and about

.0001 percent of plutonium-239 oxide was absorbed, but that the absorption in newborn rats was one or two orders of magnitude higher. Plutonium citrate was absorbed to a five times greater extent (.12%) in iron deficient mice than in iron replete mice (.024%). Absorption across intact skin is negligible. Plutonium compounds as a general rule tend to be ten times less readily absorbed in the GI tracts of rats than americium, curium, berkelium, and einsteinium compounds.

> These translocation patterns apply when the transuranics are inhaled individually; they may not apply when transuranics are inhaled in mixed oxides with uranium, a likely form in the developing breeder reactor program, or in any of the other exotic fuel forms. Biological studies of mixed transuranium oxides and possibly of other fuel forms are urgently needed to determine this. (Bair, 1976, pp. 51-83)

Critical Organs: Lungs and Bones

As previously mentioned, the residence time of actinides in the lungs is variable, but can be on the order of 500 days' effective half-life or more. Since the actinides are all alpha emitters (as well as also emitting some gamma and beta radiation), they deliver a large dose over a short distance (high LET) to the cells they are in close proximity to. According to data and calculations by Harley and Pasternak (1979), the average annual dose to the basal cells of the bronchial epithelium from the natural actinides uranium and thorium amounts to 2.3×10^{-3} millirads per year; the average dose from the reactor produced actinides of plutonium, americium, and curium is 7.7×10^{-3} millirads per year.

Although some small solubility differences between the actinides exists,

particularly when their chemical forms are optimal for absorption, once they are absorbed into the bloodstream their relative distribution within the body is the same. Quantitatively, their distribution depends to a large degree upon the chemical and physical characteristics of the inhaled material (Bair, 1976, pp. 51-83).

Organ burdens of actinides reach equilibrium levels in organs such as lungs and lymph nodes if exposure is continuous, but increase as a function of age in organs such as liver and bone (Harley & Pasternak, 1979). Typical values taken from a table by Bair (1976, pp. 51-83) of the organ burdens of plutonium (as citrate--a soluble compound) in dogs, as a percentage of the initial lung burden, are 29% in the lungs, 16% in the liver, and 38% in the skeleton. Other animals, other actinides and other chemical compounds, even other experimenters might well be expected to show different distribution patterns of incorporated actinides, but these are typical proportions.

Actinides which are deposited on bone first bind to glycoproteins on the surfaces of resting bone. Since the human bone turnover rate is about 10% per year, the processes of resorption and deposition will serve to redistribute incorporated actinides into the entire mass of bone. The greatest doses to the radiosensitive cells which are in close proximity to bone surfaces will thus occur in the early stages of bone contamination by actinides, and decrease as they become uniformly mixed in bone in about ten years. The range of an alpha particle in bone (for example, the 5.48 MeV alpha particle of americium-241 only penetrates about 35 micrometers) causes the dose to the target cells on bone surfaces to decrease with time as the actinides become redistributed (Harley & Pasternak, 1979).

Harley and Pasternak (1979) have calculated the fifty-year dose to cells on bone surfaces from actinides. Naturally occurring thorium-230 and thorium-232 account for .8 millirads over fifty years to the bone surfaces. The man-made actinides plutonium, americium and curium, for continuous exposure, account for 1.82 millirads to bone surfaces. A fifty year dose to the bone surfaces from man-made actinides, assuming that atmospheric levels will diminish with a 2 year half-life (meaning that no more actinides than at present will be released to the environment in fifty years), would amount to .15 millirads.

Strategies for Protection

When actinides are known or suspected to be released to the environment, any method that reduces the inhalation of fine particulates and dust can help to reduce the likelihood of depositing actinides in the lungs. Even if the contamination is later found to be confined to a known area, wind can resuspend actinide particles and redistribute the hazard.

> In the particular application of assessing the consequences of hypothetical reactor accidents, it is shown that pessimistic assumptions about the short-term resuspension can easily lead to the inhalation-via-resuspension exposure pathway during the first few weeks being at least as important as the inhalation directly from the cloud from which deposition took place. (Lassey, 1980)

Airborne actinide concentrations downwind of a contaminated area can be expected to decrease with an effective half-life of one to two years (Harley & Pasternak, 1979).

Coughing (which can be induced by the administration of 10% nebulized saline) can help to speed up the clearance of actinides from the upper respiratory tract. Nasal passages may be irrigated with saline, eyes flushed with water, and skin contamination removed with mild soaps, progressing to stronger reagents if necessary (Jech, Heid, & Larson, 1969).

> Following an accidental exposure of ^{239}Pu the physician should obtain the best possible predicted estimate of the deposition without treatment. He should then consider the possible consequences of the deposition, the effectiveness of available treatment, the risk of treatment, and then balance risk versus gain to the patient in deciding whether or not to treat. (Norwood & Fuqua, 1969)

A large quantity of inhaled actinides may be decreased to a large extent by lung lavage. Snipes, Runkle, and Muggenburg (1979) removed 29 to 42% of the lung burden of radiolabelled particulates in dogs with a single lavage treatment. They found that particles were removed from all regions of the dog's lungs, and were not redistributed in a way that might cause a greater hazard. This kind of drastic treatment would only be recommended for a patient who somehow received a large inhalation dose of actinides.

For contamination involving skin breaks, the first thing is to determine the extent of contamination. A survey of contamination can be conducted on exposed skin surfaces, on the object causing the wound, on gloves, dried blood, et cetera, if suitable equipment such as a Plutonium Wound counter (a thin sodium iodide detector and analyzer used in facilities handling plutonium) if such equipment is available (Jech et al. 1969).

For superficial wound contamination, surgery to excise the contaminated tissue is recommended. If the deposition is deep in tissue, the physician must weigh the hazard of excision versus the hazard of potential bone deposition (permissible bone deposition .04 microcuries) (Norwood and Fuqua, 1969). DTPA (Diethylene Amine Penta Acetic Acid) is usually administered prior to excision, and if some contamination remains after excision the wound can be flushed with DTPA, so that any plutonium that is solubilized by the DTPA will be excreted in urine (Jech et al., 1969). DTPA is a chelating agent that binds with heavy metals such as actinides and renders them soluble so they can be excreted in the urine.

Actinide contamination of the bloodstream can lead to bone deposition and significant hazard to the victim. For inhalation and skin break exposures, DTPA therapy is recommended. Chelating agents such as DTPA should not be given orally in cases of gastrointestinal exposure because the absorption of actinides in the gut is low, and the administration of chelating agents which are absorbed to a greater extent than the relatively insoluble actinides may result in a greater absorption than if no treatment had been administered. For example, the absorbed fraction of plutonium oxide absorbed from the gut may be about 10^{-4}%, whereas a plutonium-DTPA chelate may be absorbed from the GI tract in quantities as great as 2% of the amount administered. Chelation of americium, neptunium, plutonium and thorium also increases their absorption, as does the presence of citrate ion and fasting (The Metabolism of Compounds of Plutonium and Other Actinides, 1972, pp. 10-13). However, the oral administration of DTPA may reduce body burdens of incorporated actinides. Taylor and Volf (1980) studied the effect of orally administered DTPA and some other chelating agents on injected plutonium-239 and americium-241 in rats. Even though less than 5%

of oral DTPA is absorbed, when it was given at double the injected dose level, it reduced the total body retention of plutonium-239 to one fifth that of control rats. To equal the effect of an injected dose of DTPA, the oral DTPA had to be given at about 30 times the dose of the injected DTPA. Also, the oral DTPA was given as the zinc salt (Zn-DTPA) because of its lesser toxicity. At lower oral doses, Zn-DTPA and the more commonly used Ca-DTPA were equally effective at reducing the internal body burdens of plutonium and americium.

Norwood and Fuqua (1969) recommend that one gram of DTPA administered intravenously presents little hazard and should be done promptly after an inhalation accident because it allows for favorable mobilization of the soluble actinides while a more complete assessment is being made. For long term DTPA therapy, they recommend this regimen:

Time following deposition	Dose	Frequency
1st week	1 gram	Daily for 5 days or 1, 2, or 3 times/wk
Next 6 weeks	1 gram	2 or 3 times/wk
Next 6 weeks	No therapy	
After 13 weeks if indicated	1 gram	3 weeks of therapy, 2 or 3 times/wk alternated with 3 weeks of no therapy.*

*Therapy should be altered depending upon effectiveness under given conditions and as effectiveness decreases.

Therapy is contraindicated in patients with kidney disease. Therapy should be withheld if there is albumin or blood in urine or if any other sign of kidney irritation becomes evident. Therapy may be resumed when urine is normal. Chelation therapy in humans who have been internally contaminated with

plutonium in various accidents has resulted in increases in the urinary excretion rate of plutonium by factors of 20 to 130, even when years have gone by between the contamination and the treatment (Schofield & Lynn, 1973).

DTPA is the most efficient chelating agent for removing internally deposited actinides that has yet been found (Bulman, Griffin, and Russell, 1979). Its most common use has been in the form of its calcium salt, which is somewhat toxic. It is contraindicated for minors, pregnant women, nephrotics, and persons with bone marrow depression, because it can deplete other essential trace metals and interfere with important mitotic cellular processes (Lushbaugh & Washburn, 1979). Lushbaugh and Washburn also reported that the use of the zinc salt of DTPA has been approved by the Food and Drug Administration as an Investigative New drug for clinical use. Although Ca-DTPA is more efficient for early treatment, especially within two hours after contamination, Zn-DTPA is just as effective for long term therapy, and is much less toxic, so it can be administered to those for whom the calcium salt of DTPA is contraindicated.

Work with rats, dogs, and calves reveals that some pathological changes of the kidneys and small intestines can occur from chelate administration which can alter permeability and retention patterns of normally nonpermeable solutes and of minerals. Reductions of Mn, Zn, Mg, Ca, Na, and K may occur as a result of chelation, and thus leave a patient in an enhanced absorptive state after the chelating agent is discontinued (Levine, 1979, p. 119). Because of this and the increased intestinal permeability due to chelating agents, they should only be given as a remedial measure for radionuclide contamination when the contamination event does not involve the release of mixed fission products. The absorption of radiostrontium, radiocesium, or other fission products could otherwise be

enhanced. However, if it were known that these fission products were only present in very small amounts, the decision might be made to chelate the abundance of heavier radionuclides.

Thus chelation therapy could best be applied to those contamination events resulting from release of only fissionable material or other heavy radionuclides. This would be most likely in accidents involving nuclear weapons or reactor fuel manufacture, transportation, or storage, or the accidental detonation of the chemical explosive triggers of nuclear weapons which can disperse fissionable material over a wide area.

Conclusion

The world we live in is now abundant in radioactive hazards, and fast becoming more so. For the person who wishes to be prepared for personal protection against reactor accidents or nuclear war, there is ample Civil Defense (now known as the Federal Emergency Preparedness Agency) literature available on sheltering oneself from external radiation and on other survival techniques. This report is concerned with protection from internal emitters, particularly those that are biologically mobile and most likely to be encountered: radioiodines, radiostrontium, and radiocesium. Actinides are also discussed.

The uptake of radioiodines by the thyroid gland can be blocked by large doses of stable iodide, 130 milligrams of potassium iodide per day for as long as the hazard is present: probably about three months after nuclear war if there is only one wave of nuclear missiles exchanged before both sides lose.

Protection from radiostrontium depends upon large daily doses of calcium and phosphorus, two grams per day of each for an adult, for at least the surviving generation.

Radiocesium will also concern the survivors of a nuclear war for the rest of their lives. Prussian Blue will help to reduce body burdens of this radionuclide. Commercial sources are unreliable as to composition, and nuclear survivors will, at least in the beginning, have to manufacture their own according to the directions described in the chapter on Radiocesium. However, the long term effects of ingesting this substance in the desired 2 to 3 gram oral dose are unknown.

Actinide elements, though not very biologically mobile, are included here because they are very likely to be present in large-scale nuclear disasters or in various scenarious involving terrorism. It is unlikely that anyone but a pharmacist or physician will have access to the diethylene amine penta acetic acid (DTPA) to administer intravenously for reducing actinide body burdens. DTPA is not recommended for use when there are mixed fission products also in the gut as might be likely in most nuclear disaster events, since DTPA chelation therapy can result in an enhanced uptake of other radionuclides.

It is because of the reality of modern society that this report has been written, to counter the sense of helplessness that arises from the contemplation of our apparent rush to self-destruction. It would be a far better world to live in if there was no nuclear threat, but until that day comes, let us hope that the threat never materializes and that this report will remain an intellectual exercise of no practical value whatsoever.

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