Radiation Protection and the Human Radiation Experiments

On the cover are the images of ten men who have worked with plutonium and now carry measurable body burdens of this radioactive element. Some of those individuals were at Los Alamos during the days of the Manhattan Project, and some of them are here today. In this volume on radiation protection and the human radiation experiments, these men share their experiences with plutonium, the stories of their accidents, and their perspectives on the human plutonium injection experiments.   We thank them for their generosity. No doubt their stories will help others who come into similar circumstances.

As much as the plutonium injection experiments were flawed from an ethical standpoint, they did provide the bulk of the data that are now used to estimate the seriousness of an accidental intake of plutonium. Those data relate the amount of plutonium excreted in the urine to the amount retained in the body. The graph (above right) shows data points for the amount of plutonium in the urine versus time for one individual. The fit to that data made using the maximum-entropy method is shown in red. Fifty-year committed doses in rem are calculated from the urine results using biokinetic models of the time-dependent distribution of plutonium in the body. Those models are based on data gathered from the plutonium injectees as well as from the tissues of deceased plutonium workers.

Because plutonium is an ongoing responsibility of this Laboratory, the protection of those who handle that dangerous material is also our ongo-ing responsibility. This volume is dedicated to openness and to the proper handling of our role in plutonium work.

Radiation Protection and the Human Radiation Experiments

Los Alamos
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Los Alamos Science

Comments from

It is with pleasure that I introduce this volume of *Los Alamos Science*. The volume culminates a two-year effort by our Laboratory's Human Studies Project Team. The team was formed to address questions concerning the ethics and conduct of human radiation experiments that were carried out by Los Alamos researchers from the Manhattan Project days through the 1960s. The credibility and forthrightness of the team's effort has a very special meaning in the context of today's mission and tomorrow's challenges. This Laboratory continues to be the steward of nuclear weapons technology. As the world tries to roll back the number of nuclear weapons and reduce their impact on the community of nations, it is our job to help make that possible by maintaining a credible nuclear weapons technology base in the absence of testing and by developing the specific technologies needed to safeguard nuclear materials and retire them permanently. Working with plutonium and other radioactive materials while limiting radiation exposures thus remains at the heart of our mission just as it was during the Manhattan Project. Concurrently, maintaining public trust regarding environmental, health, and safety issues has become ever more important to the success of our mission. The Human Studies Project Team's review of past work on radiation protection and the human experiments as well as their examination of the current state of knowledge regarding radiation and risk are presented in this volume and represent a major effort by our Laboratory toward achieving public trust through the sharing of experiences and information.

The need for the team became evident in late 1993, when our credibility and integrity were put in question by the widespread publicity regarding the plutonium injection experiments and other human radiation experiments. Challenged by Department of Energy Secretary Hazel O'Leary's openness initiative and encouraged by Dr. Tara O'Toole, the DOE Assistant Secretary for Environment, Safety, and Health, we decided to try to turn the negativity that gripped the media, the public, and many of the Laboratory's employees into a positive force. In my editorial of January 28, 1994, I encouraged all employees to keep open minds because I was certain that the Laboratory and the nation would gain perspective from a thorough review of both the science and the ethics of the human radiation experiments.

Our initial responsibility was to participate in the Department of Energy's openness initiative by gathering information for the agency and for President Clinton's Advisory Committee on Human Radiation Experiments. To that end the Human Studies Project Team, sponsored by the Laboratory's Environment, Safety, and Health Division, was charged with combing the archives and other sources for anything and everything related to human radiation experiments. The team includ-

the Director

Siegfried S. Hecker

ed scientists, physicians, lawyers, ethicists, archivists, and others, some from the Laboratory, some from local universities, and a few representatives from state government. At the beginning there was tension between the retiree experts on the team, who had participated in the radioactive tracer studies done at Los Alamos during the 1950s and were outraged that their mentors Wright Langham and Louis Hempelmann were being maligned by the public, and the younger generation on the team, who had less reverence for the past. But everyone wanted the truth to surface and the team soon became a smoothly functioning body. The documents that were found were reviewed on a weekly basis, decisions were made about removing material that was confidential under the privacy act, and the material was released to the public. That process continued for over 15 months until the entire team was satisfied that all existing documents had come to light. Over 500,000 pages of historical documents were reviewed, and the relevant ones were released with no editing and no editorial comment. It was for the public and President Clinton's Advisory Committee to decide the value and judge the ethics of what had been done. In total, the team released over 1,600 documents. The members also responded to hundreds of specific requests for information from the President's Advisory Committee and from individuals who were concerned about their own exposures. All in all it was an extraordinary accomplishment.

However, there remains a second ongoing job. It concerns our own evaluation of what happened in the past and our efforts to learn from that past. This volume, written by members of Human Studies Project Team in collaboration with the *Los Alamos Science* staff, is dedicated to educating ourselves and the public about radiation, about the human experiments, and about the real consequences of exposure to plutonium. It's also dedicated to saying things as they are. Some of the facts about the plutonium injection experiments are difficult to accept, especially for those of us who take pride in the accomplishments of our Laboratory. We know in retrospect that hospitalized patients were injected with plutonium, and there is no documented evidence that any of them fully comprehended what was being done to them. Most of the eighteen subjects received five micrograms of plutonium, a tracer amount, but nevertheless five times greater than the limit set for workers in the Manhattan Project immediately following the results from the first three injectees and about ten times the amount that we allow today. In general, the health of the injected patients was not followed after the main study was complete even though it was apparent from the experiments that most of the plutonium would remain in their bodies for the rest of their lives. Also, even after the subject of plutonium became declassified, the injectees were apparently never told what was done to them even though a few were called back so additional plutonium excretion data could be gathered. That is not a pretty picture. The President's Advisory Committee came to the conclusion that the injectees and their families had been ethically wronged. We don't believe there are many among us who would disagree with that conclusion, and certainly today, those experiments could not and would not be done in that manner.

But there are mitigating facts. The pressure to gather data for interpreting the results of accidental intakes of plutonium was enormous and immediate. The choice

of the five-microgram injection dose was not an arbitrary one; it was at the limit of detection for the analytical techniques then available. Before the experiments were done, careful work with animals had shown that the injected dose would not be acutely toxic. Also the risk of delayed effects, in particular cancer, were expected to be quite small: The experiences, for example, of the radium-dial painters (many of whom had ingested large quantities of radium, another alpha-emitting radioactive element like plutonium) had shown that only when very large internal doses of radium were present would bone cancers be induced. Thus the researchers at Los Alamos who planned and analyzed the experiments at Oak Ridge and the University of Rochester did not expect the injectees to suffer from their intakes although they admitted to some uncertainty. Fortunately, there is no evidence that plutonium caused harm to any of the patients.

That's an important finding. The press often wrongly states that the tiniest amount of plutonium can kill you. To the contrary, we know from our own plutonium workers that individuals carrying accidental intakes comparable to the amount given to the injectees have lived healthy, vital, and productive lives, some for over 50 years from the time of intake. As part of the effort to educate ourselves, and especially for this volume, the Human Studies Project Team sponsored an informal workshop with ten of those folks and some of our experts in health physics. "On the Front Lines" presents the rather remarkable stories and comments that were shared at the workshop. What may not come across in the telling is the talent and ability of those individuals—many are said to have "golden hands"—and we, and our nation, owe them a debt of gratitude for their skill, their courage, and their dedication in handling very difficult work in the safest and most expeditious fashion. We also hope that their stories will increase our awareness and our respect for each other and for the jobs that we do.

At the end of the workshop, some of the Laboratory experts summarized the safety record in the area of plutonium work as well as the present understanding of the dangers of plutonium exposure. As far as we know, among the thousands of individuals who have worked with plutonium, there are only about 50 people in the United States who have plutonium body burdens greater than the maximum permissible level. Of those, there is only one case in which plutonium may have been implicated in the cause of death. That death involved a bone sarcoma in the sacrum, an unusual place to get bone cancer but an area that tends to concentrate plutonium. The exposure records are admittedly incomplete. Nevertheless, it appears that the worker protection standards and the adherence to them have served us well. Remarkably, those standards and the means to implement them were and still are based on the information gathered from the early plutonium injection studies. Those data are used both to calibrate the techniques for monitoring workers and to interpret the amount of accidental intake so that an individual can be taken off the job before the internal body burden becomes dangerous. The article entitled "The Human Plutonium Injection Experiments" presents a definitive review of the motivations, implementation, aftermath, and scientific impact of those experiments. The set of raw data gathered from the injectees, although a rather meager set, constitutes the main source of information on plutonium metabolism in humans. Because it is so important, it has been analyzed and re-analyzed over the years. The article reviews that work and then presents a brand new analysis performed by one of the authors. The new analysis puts to rest many of the ambiguities that have plagued the interpretation of the original data and is yet another accomplishment to emerge from the Human Studies Project.

"Tracer Studies at Los Alamos and the Birth of Nuclear Medicine" adds another

dimension to this story—one for which we can be very proud. The doses involved in the tracer studies were extremely small, the volunteers were appropriately informed, and the studies were important both for radiation protection and nuclear medicine. A most exciting spinoff from the radiotracer work was the invention of a new type of radiation detector made from a liquid scintillator. The device was developed in Wright Langham's Radiobiology Group for the detection of low-energy beta particles from tritium so that the metabolism of tritium in the body could be studied. But word got out, and Fred Reines and Clyde Cowan, Jr., then at our Laboratory, came to the Radiobiology Group for help in designing and building a very large liquid-scintillation detector for neutrinos. Naturally, they got the help they needed from the very talented scientists whom Langham had recruited, and the resulting detector was used to make the first observation of the neutrino. Fred Reines was awarded the 1995 Nobel Prize in Physics for that discovery. In a totally different vein, that large detector became the forerunner of the whole-body counter for *in vivo* monitoring of radioactive fallout from nuclear testing.

This volume is filled with history. It also surveys our present understanding of radiation and the risks associated with radiation exposure. When the story of the human radiation experiments reached the media in the fall of 1993, all kinds of numbers were being quoted to describe the events—picocuries of radioactive iron, 100-millirem doses of iodine-131, microgram quantities of plutonium. Only the experts knew what those numbers meant, and everyone else was baffled. Were those numbers big or small? What radiation exposures are considered acceptable, and how are they measured? What are the known risks from radiation exposures, and how do they depend on the level of exposure? Perhaps the most valuable contribution of the present volume is a three-part primer summarizing what we know about radiation and risk. The first part, "Ionizing Radiation—It's Everywhere!," introduces the physical properties of radiation in a way that should be engaging even to young students and describes various sources of natural background radiation, of which many of us are mostly unaware. The second part, "Radiation, Cell Cycle, and Cancer," presents the latest knowledge regarding the molecular mechanisms of cancer, the mechanisms of radiation-induced cancer, and the body's natural molecular and cellular defenses against radiation damage and cancer induction. That area of research is evolving very rapidly, and the story researched and written especially for this volume has not been told anywhere else at the same level of accessibility. The last part of the primer is a review of all the epidemiological data on radiation effects in humans. The article is entitled "Radiation and Risk—A Hard Look at the Data," and it is just that. We see data for the Japanese atomic-bomb survivors that form the basis for estimating the risk of radiation-induced cancer, we learn the hypothetical risks derived by extrapolating the high-dose risk factors to low doses, and we learn about the epidemiological data that have been gathered at low doses. The data are clearly presented so that anyone can make their own judgement about what is known and where the uncertainties lie concerning the effects of low-level exposures. We hope this volume will take its place on the shelf beside two important reports on the human radiation experiments: the Department of Energy's "Roadmap to the Story and the Records" and the "Final Report" of the President's Advisory Committee on Human Radiation Experiments.

Tara O'Toole helped us to get on this path. Despite considerable discomfort, the Human Studies Project Team took on the task of assessing the science and the ethics of the human radiation experiments. Their openness and commitment can serve as an example for all of us in the Laboratory and elsewhere. It is now up to us to continue. ∎

Ionizing Radiation

DISCOVER RADIOACTIVITY

REPEATING BECQUEREL'S EXPERIMENT
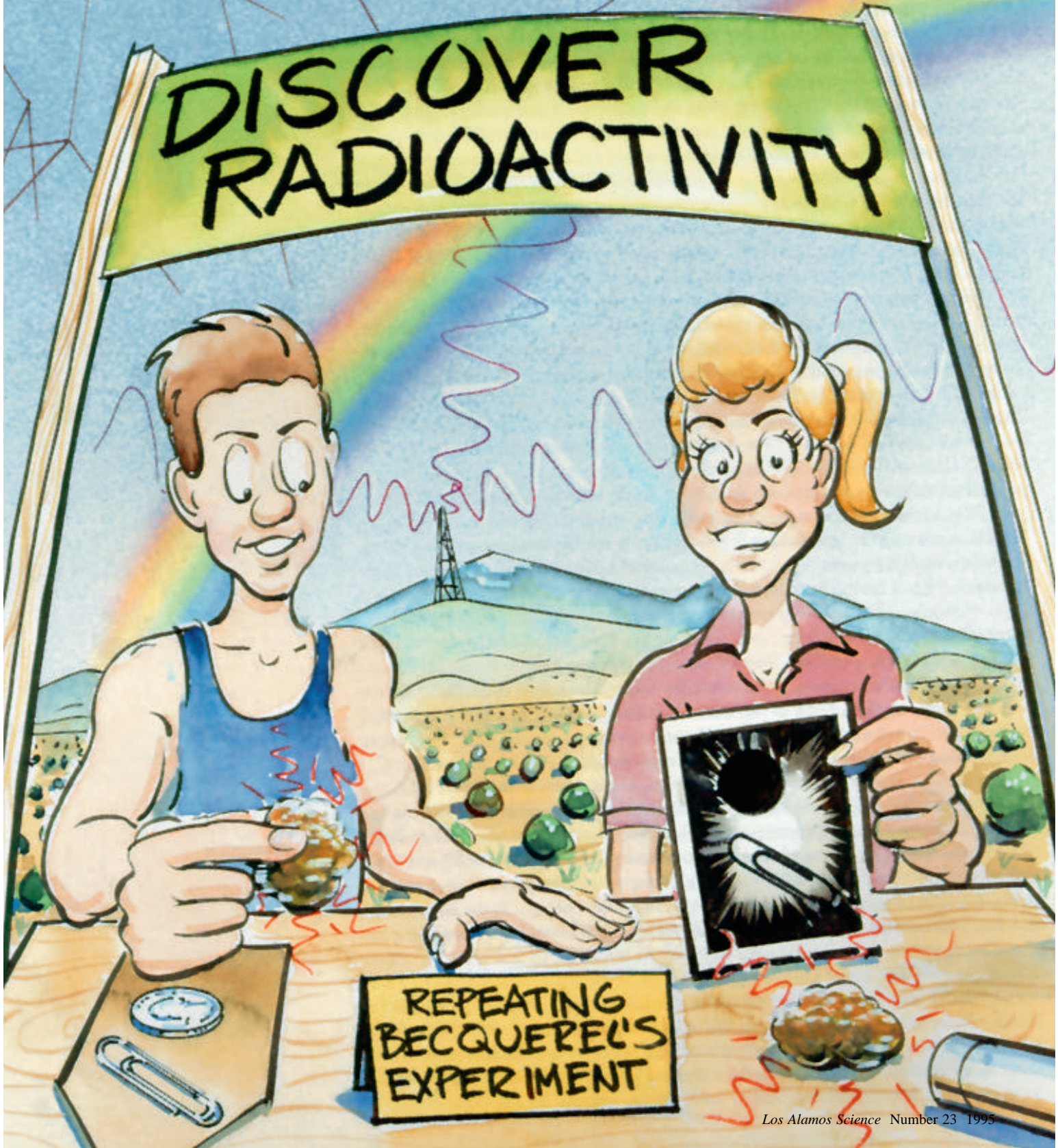
It's Everywhere!

Roger Eckhardt

We are surrounded and permeated by radiation—sunlight, radio and television waves, medical x rays, infrared radiation, and the vibrant colors of the rainbow, to name a few. Sunlight drives the wind and ocean currents and sustains life. Radio and television broadcasts inform and entertain us. X rays produce the images needed for medical diagnosis. Infrared radiation warms us and radiates back into space not only the energy brought to the Earth by sunlight but also the entropy produced by life and other processes on Earth. All societies, from the most primitive to the most technological, depend on these various fluxes of natural and artificial radiation.

The dictionary defines radiation as "the emission and propagation of waves or particles," or as "the propagating waves or particles themselves, such as light, sound, radiant heat, or the particles emitted by radioactivity." Such definitions neglect one of the most important characteristics of radiation, its energy. Ultimately, the energy carried by radiation is what makes it so useful to life and civilization.

Because much of the radiation we encounter has relatively low energy, its effect on our bodies is benign. For example, radio waves pass through us with no perceptible effects to our health. However, for many people, the word radiation has a negative connotation—it's linked strongly with danger to life. This association comes from focusing on the so-called nuclear radiations, which are highly energetic, and especially on those generated by the radioactive materials of nuclear weapons and nuclear power plants. It's not always remembered that similarly energetic radiation is generated within the x-ray tubes at hospitals and at particle accelerators in physics laboratories. These radiations are used for medical diagnostics and as a primary therapy for the treatment of cancer. They are thus responsible for helping save many lives every year. The dual nature of energetic radiation, as both a killing and a healing agent, is sometimes difficult to keep in mind.
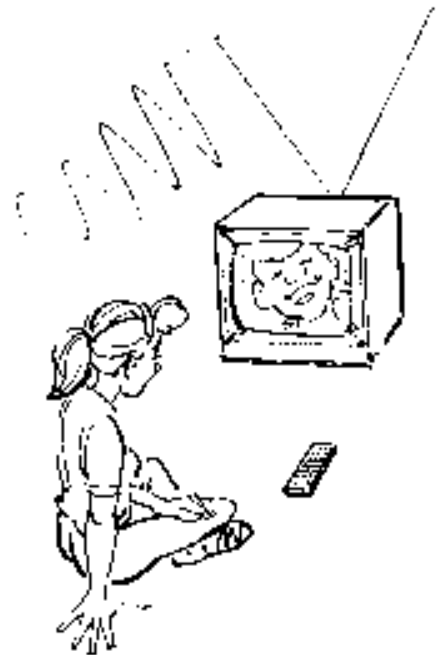
In this article, we'll attempt to sort through much of the confusion about radiation. We'll use two radiation experts, Irene and Carl, to introduce many of the topics, and they'll illustrate some of the ideas with imaginary experiments. In fact, here are Carl and Irene now. "What are you two up to?" you ask.
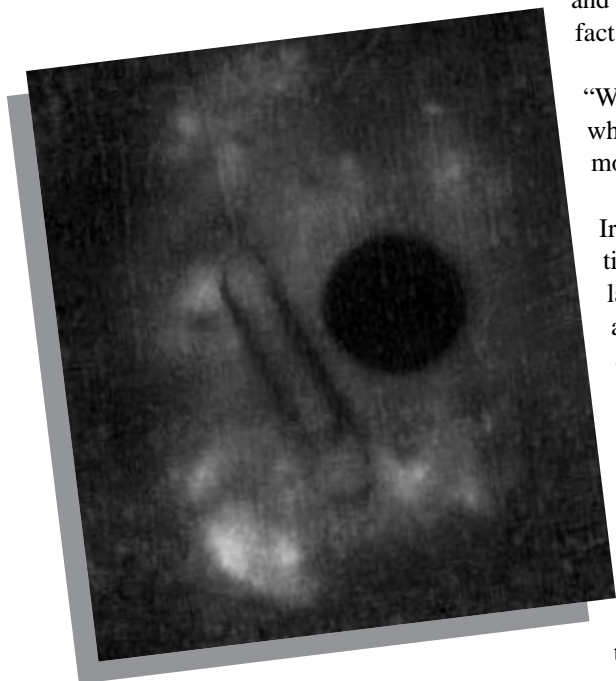
"We're repeating Becquerel's experiment with uranium minerals in which he discovered radioactivity," Carl answers. "Except we're using modern film—high-speed Polaroid™."

Irene removes the film from under the uranium ore, where it's been sitting overnight, and pulls it through a roller to develop it. A minute later, we see the "picture"—a fuzzy white area with about the same diameter as the lump of ore. There's a blurry outline of a paper clip and a dark, round circle in the middle.

"It worked!" exclaims Carl. "The radiation from the uranium passed into the film except where it was partly blocked by the metal paper clip and the nickel we'd put between the lump of ore and the film."

"Do you know where the radiation is coming from?" asks Irene.

"From atomic nuclei!" Carl answers before you can reply. "From the tiny centers of lots of the uranium atoms."

Radiation emitted by radioactive materials is born deep within atoms—in unstable nuclei undergoing changes that involve strong nuclear forces. As a result, the radiation has very high energies, thousands or millions of times higher than radiation produced by typical atomic processes. Such energetic radiation can create many thousands of ions and molecular fragments by tearing loose electrons from neutral atoms or molecules. Hence, the name, ionizing radiation. In Carl and Irene's experiment, ionizing damage to the film emulsion created the "exposure."
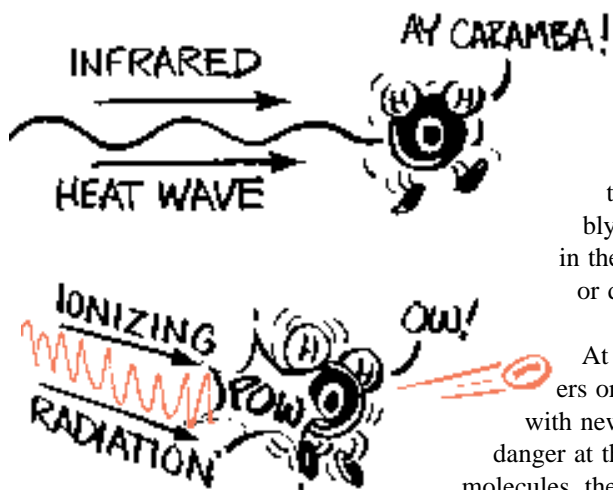
When ionizing radiation traverses living cells, it leaves behind a trail of ions and uncharged molecular fragments, called free radicals, which are highly reactive and can damage other molecules in the vicinity. Such damage disrupts cellular mechanisms and can lead to the death of cells. If the exposure is very high, it will destroy the cells of the immune system and lead to illness and possibly death by infection. Even more massive exposures kill cells in the central nervous system and can cause death within hours or days.

At the lower exposures typically encountered by radiation workers or the general public, the body is able to replace the dead cells with new ones without degradation of bodily functions. The potential danger at those lower levels is mutation, which is damage to the DNA molecules, the genetic material of the cell. Usually the damage is kept to a minimum through DNA repair mechanisms or self-checks that direct the cell to die. However, if the mutation has occurred in the regulatory genes, the cell may survive the self-checks and develop the runaway growth we know as cancer. Finally, a mutation may occur in a germ cell and be passed on to future generations, but the probability of a successful passage is so small that the inheritance of such mutations has not been observed in human populations.

Because of the very specific effects of ionizing radiation, it's helpful to split the subject of radiation into two broad categories—ionizing and non-ionizing. In both cases, the radiation interacts with matter by transferring its energy to molecules and atoms, thrusting them into excited states. However, ionizing radiation breaks chemical bonds; non-ionizing radiation usually only heats the molecules—a more benign process.

In addition to being either ionizing or non-ionizing, radiation has other properties that we should know about. For example, most of the radiation we encounter in everyday life, such as visible light and radio waves, consists of electromagnetic waves traveling at the speed of light. Other radiation consists of massive particles with a variety of masses, charges, and energies. We need to be clear about these differences if a whole range of misunderstandings is to be avoided.

The Electron Volt and Ion Pairs

One of the most important defining characteristics of radiation is energy, so we need a convenient measure of energy to facilitate comparisons. For ionizing radiation, a common unit is the electron volt—the kinetic energy a free electron acquires when it's accelerated across an electric potential of one volt. (If you're familiar with mks units, an electron volt is 1.60×10^{-19} joules.)

When ionizing radiation ejects an electron from a neutral molecule, a fragment with a plus charge is left behind and the electron with its negative charge speeds off, eventually to add its charge to another molecule. The two charged entities are called an *ion pair*. On the average, it takes about 25 electron volts (25 eV) to create an ion pair in water, although the minimum energy needed is only 12.6 eV. Thus, the electron volt is a very appropriate unit of energy for ionizing radiation.

Visible light has energies of the order of only an electron volt, and so it is non-ionizing. On the other hand, the radiation emitted by radioactive materials has energies of the order of thousands of electron volts (keV, or kilo-electron volts) or millions of electron volts (MeV, or mega-electron volts). Such radiation is capable of generating thousands of ion pairs.

As you can see, the term "radiation" encompasses a variety of emissions, all of which carry energy. The main purpose of this article is to discuss the ionizing radiations emitted by radioactive materials and to explain the physical properties that determine their effects on the body. We'll also explain how radiation doses are calculated, and then survey the ordinary sources that we're all exposed to. Finally, you'll find a guide to help you estimate your own annual dose. But before we tackle ionizing radiation, we'll begin with the more familiar, lower-energy radiations and gradually move to those of higher energies.

Electromagnetic Radiation

The most illuminating of radiation—light!—is a tiny portion of what's called the *electromagnetic spectrum*. The rest of this spectrum consists of a broad range of similar, but invisible, radiations—from radio waves through infrared and ultraviolet to gamma radiation. All these radiations are waves of fluctuating electric and magnetic fields that travel through space at the speed of light and that can be classified solely in terms of a single parameter, such as the frequency of the wave or its wavelength. The arrangement of the different types of electromagnetic radiation along a frequency (or wavelength or energy) scale is called the electromagnetic spectrum.
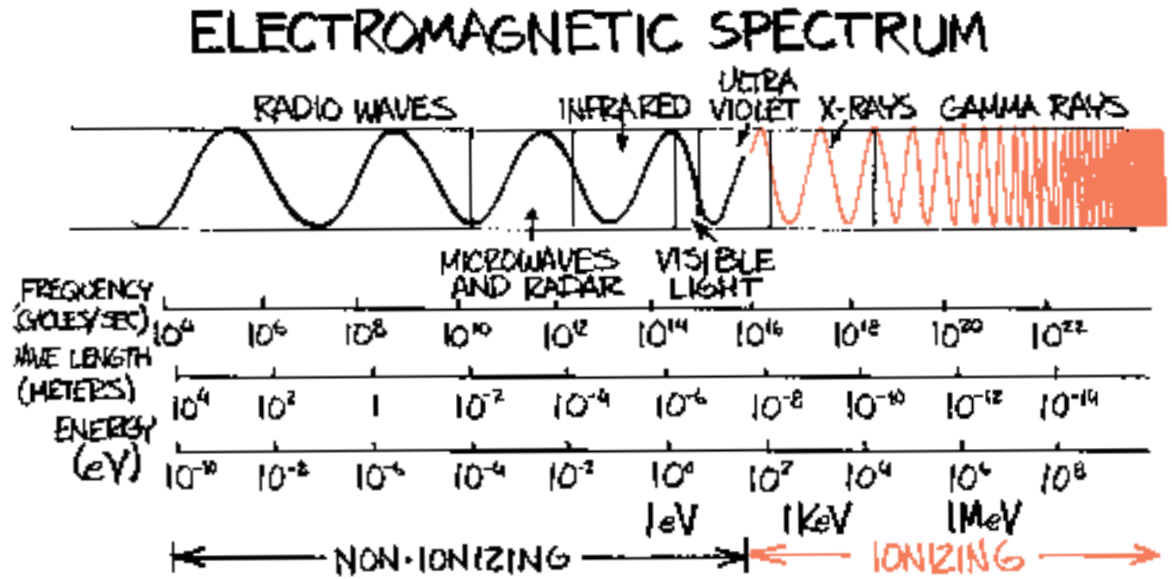
ELECTROMAGNETIC SPECTRUM

Einstein established that light actually has a dual nature—it behaves both as an electromagnetic wave and as particles, or *quanta,* called photons. The wave parti-cle-duality is captured in the equation:

$$E = h\nu,$$

where E is the quantum energy of the photon, ν is the frequency of the corre-sponding wave, and h is called Planck's constant. Because energy is directly pro-portional to frequency, the electromagnetic spectrum becomes a visual guide to the relative quantum energies of the various types of electromagnetic radiation. The energy per photon can be anywhere between zero and infinity. In terms of our unit of energy, the electron volt (eV), some examples are 10^{-10} eV for a photon in the AM broadcast band, 2 eV for a photon of visible light, and on the order of MeVs for a nuclear gamma-ray photon.

Non-Ionizing Radiation. What happens when electromagnetic radiation interacts with matter? It can be absorbed, reflected, or transmitted—usually a combination of all three. The extent of these interactions depends on the type of material and the frequency of the radiation. For example, glass is transparent to visible fre-quencies; these photons mainly pass through unaffected, although some are reflect-ed at the surface and a few are absorbed or scattered. On the other hand, glass ab-sorbs ultraviolet wavelengths heavily so that very few of these higher-energy photons penetrate appreciable thicknesses of glass.
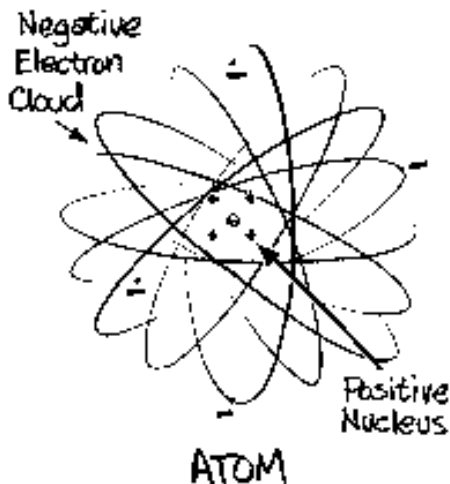
What causes such behavior? The wave nature of light helps explain many features of the interaction between electromagnetic radiation and matter. Atoms are made up of a tiny, inner nucleus that's heavy and positively charged and an extended, outer cloud of very light, negatively charged electrons. The total charge of the electrons is exactly the negative of the charge on the nucleus, so the atom as a whole is un-charged. However, the electrons are in constant motion and create fluctuations in the electric charge and localized currents. The electric and magnetic fields of the ra-diation can interact with these fluctuations and transfer energy to the atom. If the electromagnetic waves happen to be oscillating in resonance with the atom, that is, if their frequency is close to a natural frequency of the atom, they'll transfer energy more efficiently. We see the same thing pushing a child on a swing—you transfer energy most efficiently if you match the natural rhythm of the swing.

Wavelength, Frequency, or Energy?

In vacuum, all electromagnetic radiation travels at the speed of light. As a result, there is a one-to-one relationship between the frequency and the wavelength of the electromagnetic waves:

$$\lambda\nu = c,$$

where λ is the wavelength of the oscillation, ν is the frequency, and c is the speed of light ($c = 3.0 \times 10^8$ meters per second).

The choice of parameter characterizing electromagnetic radiation can, thus, as easily be wavelength as frequency. In fact, because radio waves have wavelengths of the order of meters and microwaves have wavelengths of the order of millimeters (milli = 10^{-3}), these radiations are often identified with their wavelengths rather than their frequencies. Similarly, visible light may be characterized by its wavelength, generally in nanometers (nano = 10^{-9}).

At the upper end of the spectrum, very short wavelengths and very high frequencies make both frequency and wavelength cumbersome. It's easier to identify the radiation with the quantum energy of its photons.

This wave description of radiation is useful for explaining a variety of macroscopic interactions between radiation and matter. For example, waves can help us understand how a metal antenna picks up a radio broadcast. Some of the electrons in metals move easily—after all, metals are good conductors—and the electrons oscillate with the incoming radio waves. The resulting current flow through the radio is detected, amplified, and finally converted by the speaker into the sounds we hear.

What about the dual nature of light? What does it mean for a photon, which is a particle, to be in resonance with an atom or molecule? Electrons bound in an atom or molecule occupy a set of discrete energy levels, which means they can't have energies in between the allowed levels. When a photon collides with the atom or molecule, it can be absorbed if its quantum energy matches the energy difference needed to excite an electron from one level to a higher one. If the photon energy doesn't match any of the energy transitions and is not high enough to cause ionization, then the photon will continue through the material unimpeded.

The frequency dependence of the interaction of photons with matter is responsible for a variety of things. For example, microwave ovens operate at a frequency chosen to be in resonance with an energy transition of the water molecule. Thus, microwave energy is effectively absorbed by most foods. If the radiation were "out of sync," it would simply pass through without losing intensity or heating the food. Certain regions of the spectrum are absorbed by the atmosphere, whereas other regions penetrate to the surface of the earth. The sky is blue because blue light is more effectively scattered out of the direct path from the sun than other colors. Plants appear green because chlorophyll selectively absorbs in the red and blue portions of the spectrum, leaving the green light to be scattered. The energy of the absorbed light is used by the plant in photosynthesis, thereby converting electromagnetic energy to stored chemical energy.
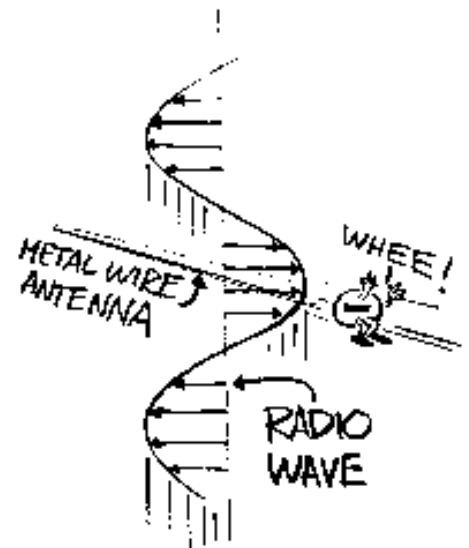
Some Health Effects of Common Radiations

Characterizing radiation by the quantum energy it carries can help make its potential effects less mysterious. We'll illustrate with examples of common forms of electromagnetic radiation.
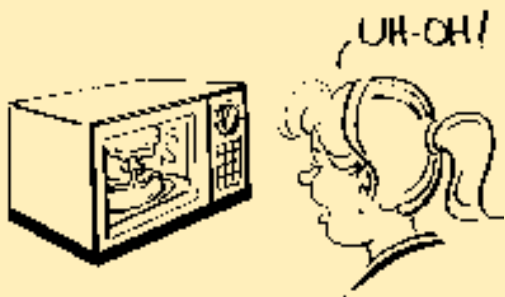
Much of the public is apprehensive about the harmful effects of microwaves. In fact, many people say "Let's nuke it!" when they put food in the microwave. Although colorful and expressive, the phrase is misleading because the energy of microwave photons (about 0.001 eV) is even lower than those of infrared heat radiation or visible light. Thus, microwaves are non-ionizing and have nothing to do with the radiation of nuclear weapons. The occasional explosion of hot-dogs in a microwave oven from trapped steam may have something to do with the genesis of the phrase.
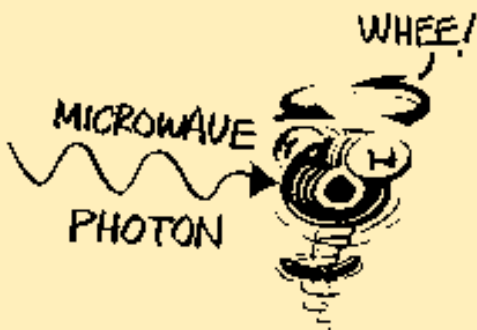
The real danger of microwave radiation lies in its efficient heating of tissue. The frequencies generated by microwave ovens match the rotational frequencies of water molecules, spinning them up like little tops. Because water is the most common substance in cells, the microwave energy is quickly absorbed and converted to heat energy as spinning molecules collide randomly with their neighbors. Possible health effects of direct exposure to microwave radiation range from "cooking" of tissue to changes in cardiac rhythm, damage to nervous systems, and cataracts. Microwave ovens are generally well shielded, and proper use results in minimal exposures. However, each of us should take mental note of the real dangers when we "nuke" our next meal.

Most people are much better informed about ultraviolet radiation (3 to 124 eV). The widespread use of sun block to prevent skin cancer is a rational response to the danger of the damaging effects of ultraviolet radiation. Such protection is even more important now that there's evidence of a thinning ozone layer in the upper atmosphere. The ozone layer serves as "nature's sun block," absorbing much of the ultraviolet radiation before it reaches the surface of the Earth.

The public's concern about the number and extent of medical x-ray exposures is also well-founded. X rays are of higher energy (tenths to hundreds of keV) than ultraviolet, and are definitely ionizing. They quite readily penetrate soft tissue, which is made mostly of light atoms, but are absorbed more efficiently by material containing heavier elements, such as the calcium in bone or most metals. This property makes x rays useful for examining the human skeleton or luggage in airports. There is also more absorption in denser soft tissue, making x rays useful for detecting tumors and tuberculosis. The danger, of course, is the possibility that the ionizing properties of the x rays can damage the exposed cellular material.

The health dangers of x rays are very real and well documented. Early scientists in the field quickly seized on obvious clinical and scientific applications of x rays but only gradually understood the full health implications of x-ray exposures. Researchers were carried away by the excitement of what the rays could reveal and frequently ignored warning signs from high exposures, including loss of hair, inflammation, and skin burns. Although these visible effects were usually only temporary, the massive ionization damage of frequent exposures overwhelmed normal cellular repair mechanisms. The long-term effects of the practice were numerous cases of cancer and radiation-induced diseases among the researchers. Several hundred people died before safety practices became prevalent.

These early experiences taught us that the more frequent and intense the exposures, the higher the probability of lasting damage. Also, cells undergoing rapid growth—such as those in the fetus—are more susceptible to permanent damage. Modern guidelines for the safe use of x rays stress the lowest practical dose per exposure, exposures administered infrequently and only when needed, and avoidance of exposures for pregnant women. Damage under such circumstances is minimal and usually is repaired easily by the cells. Our society has decided that, in most cases, the benefits from such use of ionizing radiation outweigh the hazards. (See the next two articles, "Radiation and Risk" and "Radiation, The Cell Cycle, and Cancer," for detailed discussions of the risks and biological effects of ionizing radiation.) ■

Ionizing Radiation. "But now," you ask, "where in the spectrum does electromagnetic radiation first become ionizing?"

"Well, the dividing point is a bit fuzzy, but we can use what we know about the spectrum to sort it out," Carl suggests.

As we move up the frequency scale, we reach a point at which the energy per photon is sufficient to break molecular bonds—a few electron volts. Ultraviolet light of this energy is responsible for skin aging and cancers, for example. Farther up the scale near 10 eV, an ultraviolet photon has enough energy to eject an electron from a molecule and leave behind a positively charged ion. It takes an energy of at least 12 eV to ionize water or oxygen molecules, or 15 eV to ionize nitrogen. Thus, radio waves, microwaves, infra-red radiation, visible light, and low-energy ultraviolet light are all non-ionizing. High-energy ultraviolet, x-rays, and gamma-rays and beyond are ionizing.

At photon energies of thousands of electron volts (kilovolts, or keV) and higher, the ejected electron itself may have enough kinetic energy to damage molecular bonds along its track by colliding and knocking free additional electrons. When this happens, a *region* of ionization damage is created, not just a single ion pair.

What happens to the photon in this process? When the photon has just enough energy to eject an electron, it's almost always completely absorbed. At higher quantum energies, such as the hundreds of eVs for x-rays, the photon is more likely to lose only part of its energy to the ejected electron and then continue on as a lower-energy photon until it collides again. Each such collision creates another region of ionization until either the photon passes out of the material of interest or approaches the threshold energy, ejects one last electron, and is completely absorbed. Because usually not all the energy of the photon is lost in a single scattering, the pattern of energy deposition is more complicated than for non-ionizing radiation. The number of unscattered photons drops off exponentially (as for non-ionizing radiation), but because the photons continue with reduced energy, energy deposition by ionizing photons must be treated as an exponential drop-off times a "build up factor," which, typically, has a value of one to ten.
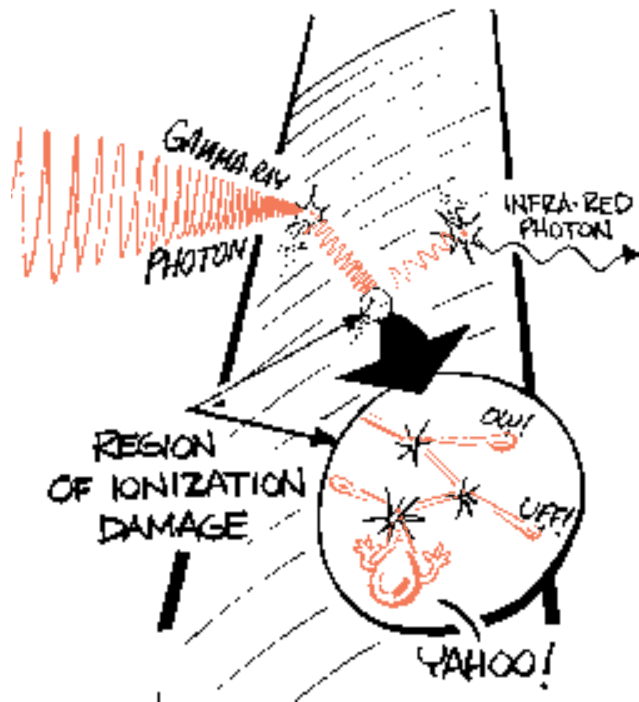
What is the source of the high quantum energy of ionizing radiation? At the turn of the century, when Becquerel discovered that uranium ores were radioactive—that they emitted ionizing radiation in the absence of any external energy source—this question was the great mystery. How could radioactive materials, such as uranium and radium, continually emit quantities of energetic radiation with no apparent diminishment? Why didn't they "burn up?" Was radioactivity a violation of the conservation of energy? Well, as we'll see, they do in fact burn up. Becquerel just happened to be dealing with materials that took such a long time to do so that he could not detect the gradual decrease in radiation being emitted by the source.

Radioactivity—What Is It?

Now, imagine yourself in a room with your new friend and radiation expert, Irene. Also, imagine very relaxed safety standards. The two of you are standing next to a table that holds a round lump of silver-gray metal, a small beaker of colorless solution, and a large, clear glass bottle closed at the top with a valve. The only thing that alerts you to the fact that these are not ordinary materials is the standard magenta and yellow trefoil symbol for radiation.
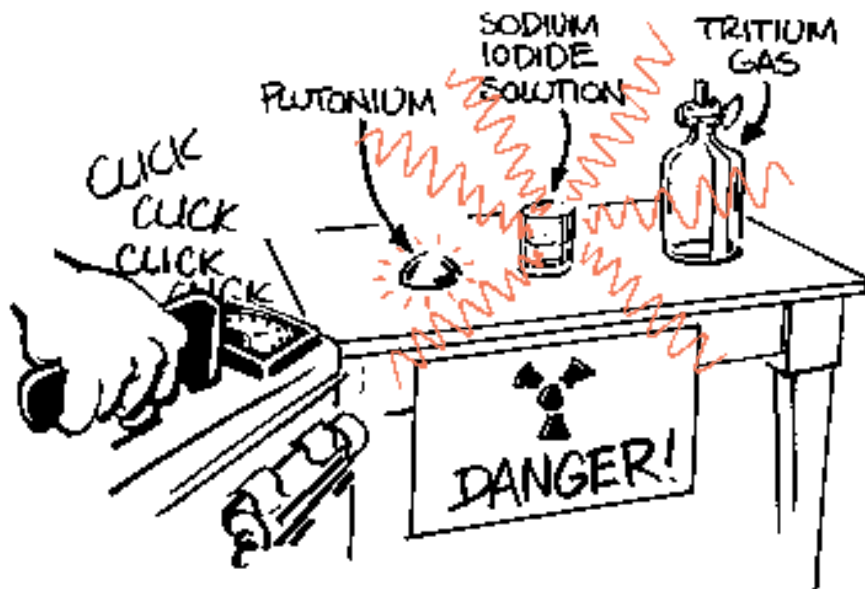
Irene tells you that the metal is plutonium, a heavy, radioactive element and one of the last in the periodic table. More specifically, Irene says the metal is called plutonium-239—the same kind used to power two of the first three nuclear explosions in 1945—the one at Trinity Site and the Nagasaki bomb.

Next, Irene explains that the glass jar contains a special form of hydrogen, called tritium, or hydrogen-3. Hydrogen is a colorless gas, and a very light element—in

Plutonium Metal

Plutonium is a soft, silvery metal that's highly reactive. It oxidizes so easily that a fine powder of the pure metal will burn in air spontaneously. Such high chemical reactivity is one of the reasons plutonium is difficult to work with.

In real life, the lump of plutonium you're looking at would probably have been coated with something, perhaps a thin layer of platinum-rhodium alloy. This coating would seal out oxygen and allow you to handle the plutonium without getting radioactive particles of the metal on your skin. The coating would also absorb most of the radiation.

fact, it's the first, or lightest element. The tritium form of hydrogen is radioactive and is one of the important ingredients of the hydrogen bomb.

The liquid in the beaker is a dilute solution of sodium iodide. In this case, the iodine, called iodine-131, is radioactive. This type of iodine can be used for thyroid treatments. It's also of concern as a radiation hazard in nuclear power plant accidents or with fallout from atmospheric weapons testing.

Irene apologizes about the glassware—for safety purposes, she should be using unbreakable metal containers. You remind her that this is only a thought experiment, so it doesn't matter. She grumbles anyway, figuring she'll have to fill out a sheaf of imaginary safety report forms later.

Now, what physical evidence is there that these radioactive elements are emitting continuous streams of highly energetic ionizing radiation? Is there anything that you can see, hear, smell, or feel? After much inspection, you find no evidence. Then you pick up the plutonium—it's warm! This warmth is the only thing that seems unusual, but when you feel the jar of tritium and the beaker of solution, they're at room temperature.

Irene brings out a radiation detector, which immediately starts flashing and clicking, demonstrating that ionizing radiation is present. Presumably, the radiation has been present all this time, and the only hint was the warmth of the plutonium.

The invisibility of ionizing radiation is one of the reasons people fear it so much. You cannot sense ionizing radiation directly. You need instruments to detect it. Even the warmth you feel in the plutonium is an effect—the metal is being heated by its own radiation.
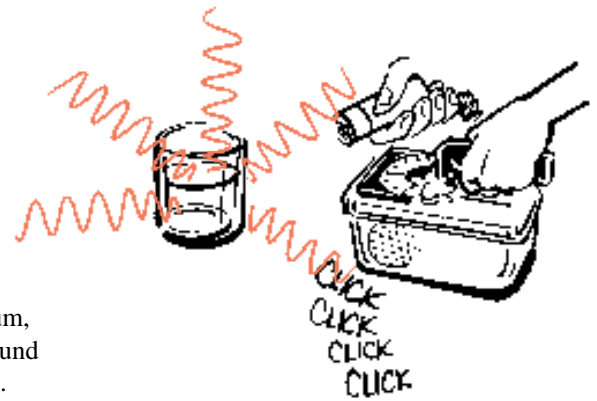
To assure yourself about the source of the radiation, you move around the room with the detector. The readings increase as you approach the iodine solution and drop off as you move away. Is it the only source? Why doesn't the same thing happen when you move toward the glass jar of tritium or the lump of metal?

Then you happen to move the window of the detector right next to the plutonium, and the counts skyrocket! As you pull the counter back slowly, the buzzing sound holds steady until, just a few inches from the surface, the counts suddenly drop. There seems to be a limit to how far the radiation from plutonium can go. But up close it's very active.

You bring the detector back next to the plutonium, and Irene slips a piece of paper between the metal and the detector window. Again the counts drop precipitously. Most of the radiation from plutonium is stopped by paper!
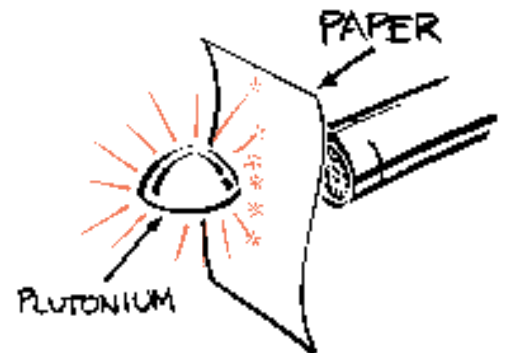
You now realize that the glass jar may be blocking radiation from the tritium. Irene brings out a special detector called a tritium sniffer, similar to a Geiger-Müller counter except gas can flow directly through it. She releases some of the tritium gas into the counter, and this time there's a strong response.

Apparently, these three materials emit different types of radiation because the emanations behave so differently. To understand what's happening we need to look more closely at the structure of the three radioactive atoms. We'll start with the plutonium.

RADIOACTIVE NUCLEUS

Alpha Particle
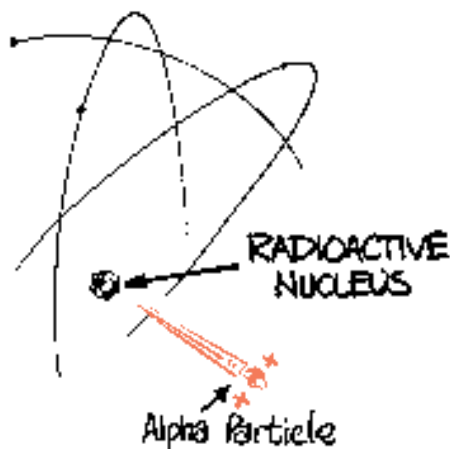
The Alpha Emitters. As we pointed out earlier, atoms consist of a positively charged nucleus surrounded by a cloud of negatively charged electrons. One of the implications of this structure is a neat division between chemistry and nuclear physics. All chemistry is a direct consequence of the electrons on the outside. These light, speedy particles are the "hooks" that enable atoms to bind together and form molecules.

Radioactivity, on the other hand, comes from deep within the atom—it's the emission of radiation due to changes in the nucleus. Radioactive properties are nearly independent of chemical properties.

Many of the atoms that are radioactive—uranium, plutonium, thorium, radium, radon—are located at the bottom end of the periodic table. These are all heavy atoms. In fact, all the elements heavier than bismuth are radioactive. Have the nuclei of these atoms grown too big for their own good?

PERIODIC TABLE
Radium / Uranium Plutonium
Thorium

The Geiger-Müller Counter

A common radiation detector is the Geiger-Müller counter, which has a long, narrow tube containing a gas that's easily ionized. The tube has a wire down its center, and a voltage drop is created between the wire and the sides of the tube. Whenever radiation penetrates the tube and ionizes some of the gas, the voltage causes positive ions to be pulled toward the walls and negative electrons to accelerate toward the wire, creating an electrical discharge—a miniature lightning bolt. The resulting current pulse in the circuit is registered by the counter.

IONIZING RADIATION
Electrical Discharge
GEIGER-MUELLER TUBE
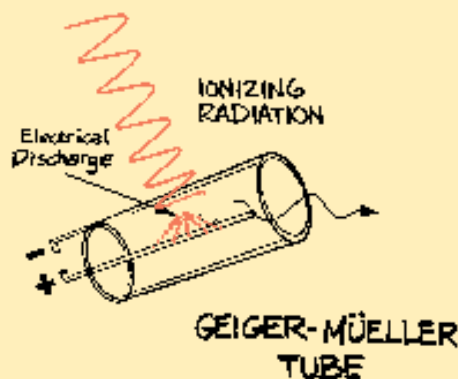
Sometimes radiation may not be counted by the detector because it's blocked by the wall of the tube or it passes through the tube without ionizing any of the gas. So to understand your measurements fully, you need to know the type of radiation you're trying to measure and the efficiency of the counter for detecting that radiation.

Still, a Geiger-Müller counter with a thin mica window on one end of the tube (to let some of the weakly penetrating radiations into the gas) is a good all-around tool for detecting most types of ionizing radiation. You can learn a lot about your environment and your own exposures taking measurements with a simple hand-held Geiger-Müller counter. There are several such counters available today in the $250 to $350 price range.

One of the favorite ways for these atoms to decay is by ejecting a charged particle from the nucleus called an *alpha particle*. Why do they do this? We'll need to examine nuclei and their forces before we can understand this type of radioactive decay.

If we start by looking closely at a plutonium atom, we'd see that it has 94 negatively charged electrons on the outside, balancing 94 positively charged protons in the small volume of the nucleus. The number of electrons in an atom is called the *atomic number* because it determines the atom's chemical properties and its place in the periodic table. Plutonium is the 94th element.
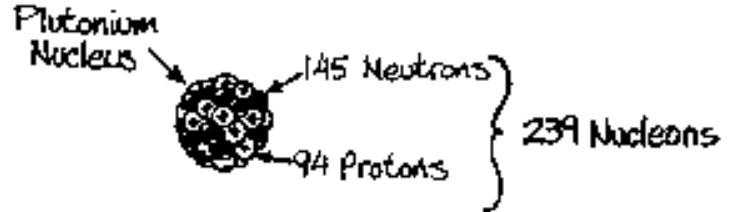
But that's not all. Besides the 94 protons in the nucleus, there's many of a second particle, called the *neutron*, squeezed in as well. The mass of the neutron is about the same as a proton (an atomic mass unit), and the proton and the neutron (called *nucleons*) constitute more than 99.95 per cent of the mass of any given atom. Looking again at the plutonium atom, we see that it has 145 neutrons, giving it a total of 239 nucleons (94 protons plus 145 neutrons). Thus, 239 is both the approximate atomic mass of plutonium and its *nucleon number*. We now know why the lump of metal is called plutonium-239.
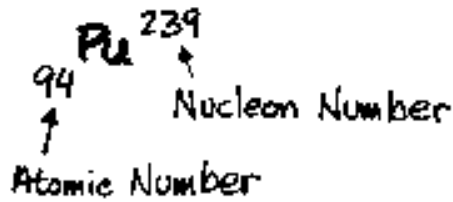
Isotopes

If two atoms have the same number of protons, they have the same number of electrons, making them chemically identical, or the same element. But chemically identical atoms can have different numbers of neutrons. Changing the number of neutrons changes the nucleon number and the nuclear properties. Such atoms (with the same number of protons but different numbers of neutrons) are called *isotopes* of that element.

We identify different isotopes by appending the total number of nucleons to the name of the element, as we did when we called the metal plutonium-239. There is, in fact, a whole series of plutonium isotopes, ranging from plutonium-232 to plutonium-246. Each of these isotopes has 94 protons but different numbers of neutrons, ranging from 138 to 152. The isotope used in the atomic bombs, plutonium-239, was chosen because its particular mix of neutrons and protons give it nuclear properties suitable for a rapid and efficient—explosive!—release of its nuclear energy.
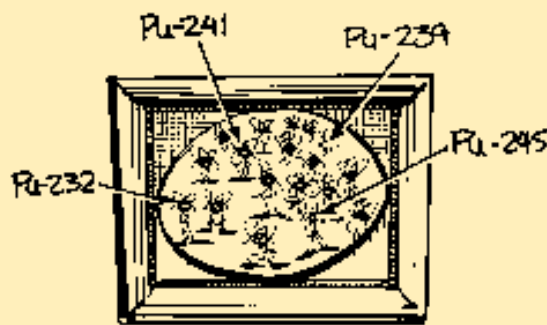
PLUTONIUM FAMILY PORTRAIT

To understand how the neutrons and protons are held together in the nucleus, we need to examine the forces between the particles. First, there are the electrical forces. We can experiment with these, for example, by rubbing a balloon against our hair—creating a slight imbalance of charge on the two materials—and then noticing that the balloon attracts our hair. Because of electrical forces, particles with opposite charge are attracted to each other, whereas those with the same charge are repelled from each other. Thus, a proton and an electron attract each other, whereas two protons or two electrons repel each other. Neutrons, with no charge, are unaffected by electrical forces. In fact, we can picture them helping to mediate the electrical forces trying to push the charged protons apart.

If there were only electrical forces, the protons would separate, each would attract an electron, there would be only one kind of atom, and chemistry would be very dull. Too dull in fact to sustain life. Nuclei as we know them are formed because of very strong nuclear forces that attract nucleons to one another.
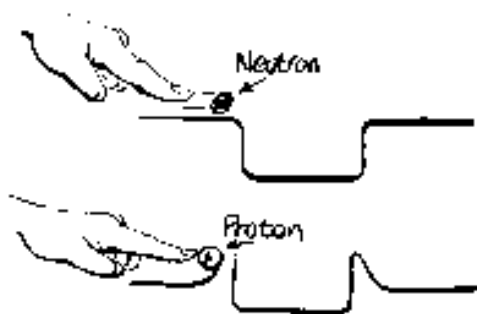
The nuclear forces have a very short range. If you were able to push a neutron toward a nucleus you'd feel no force until you were very close to the nuclear surface, at which point strong nuclear forces would suck the neutron into the nucleus. The sensation would resemble pushing a marble along a level surface until it suddenly rolled into a deep basin.

If you were to do the same experiment with a proton, there'd be a major difference. This time the sensation would be more like pushing a marble up an incline that grew steadily steeper until the top where, once again, the marble would suddenly roll into a deep basin. In other words, you'd begin to feel electrical repulsion at very long range and the repulsion would increase in strength, making it more and more difficult to get the proton next to the nucleus. But once you did manage to get it there, attractive forces like those the neutron experienced, forces stronger than the electrical repulsion, would also suck the proton into the nucleus.

Such are the forces that hold nuclei together. Now we need to look at what makes the nuclei of large atoms fall apart, or decay. To do that requires an idea from quantum mechanics—the idea of tunneling. In our macroscopic world, an object rolling back and forth in a basin can't get out unless it has enough energy to roll up over the top edge. In the atomic world of quantum mechanics, a particle that doesn't have enough energy to get over the barrier can occasionally "tunnel" out through the sides, especially if the walls aren't too thick.

A nucleus resembles a basin with finite walls in the sense that the dominant force inside is attractive (the nuclear force holding the energetic nucleons together), but just outside the dominant force is repulsive (the electrical force that will expel particles that manage to break free). As discussed in more detail in "Alpha Decay of Heavy Nuclei," the heaviest nuclei have the thinnest barriers, making it more likely that particles can escape by tunneling.

Even so, individual nucleons can't escape because they have too little energy. But when a group of four nucleons, two protons and two neutrons, come together, the energy they gain from binding allows them to make it. This group of nucleons, called the alpha particle, is the most likely particle to tunnel out of a heavy nucleus. If we look at the periodic table, we see that an alpha particle is identical to the nucleus of a helium atom (atomic number 2), the lightest of the rare gases (or more exactly, it's the nucleus of helium-4, the most comon isotope of helium).

Alpha Decay of Heavy Nuclei

To understand in more detail why heavy nuclei undergo alpha decay in which an alpha particle "tunnels out," we need to discuss the characteristics of the forces inside nuclei. To start with, the volume of a nucleus is proportional to the number of nucleons it contains, just as a water drop has a volume proportional to the amount of water it contains. Although two nucleons attract one another very strongly when they get very close, at even shorter distances they repel even more strongly. This "repulsive core" keeps the density of nucleons from rising indefinitely. The repulsive core and the short range of nuclear forces means that a nucleon in the center of any but the smallest nuclei is attracted by about the same amount.
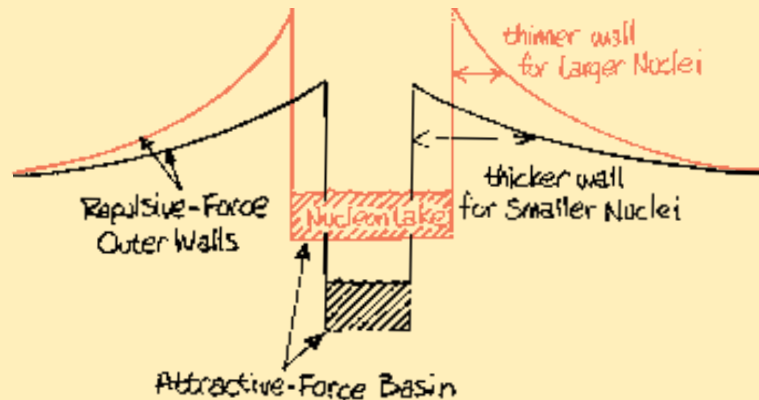
A useful analogy here is to think of the nucleus as the crater of a volcano with the basin and inner walls being the attractive potential of these nuclear forces and the outer walls being the repulsive potential of the electrical forces between protons. What happens to the shape of the volcano as we go to heavier atoms? Increasing the total number of nucleons makes the nucleus bigger and increases the diameter of the basin. Increasing the number of protons increases the charge, making the slope of the repulsive potential steeper—the flanks of the volcano are steeper and higher at a given radius. These effects combine to increase the height of the caldera rim and to make the walls thinner as you move below the rim. Also, the attractive force between nucleons is constant, so the drop from the rim to the crater floor stays constant.

Inside the crater, we may imagine a lava lake, representing the range of kinetic energies of the nucleons. In general, the top of the lava lake is *below* the level of the far away "plane," making tunneling impossible, or forbidden, for nucleons. However, every now and then, as the nucleons move about in the nucleus, they come together to form an alpha particle. The shape of the potential-energy volcano for an alpha particle is qualitatively the same as for individual nucleons. The major difference is that the binding energy gained in forming the alpha particle puts it at a level *above* the outside plane, and tunneling can take place.

As we already pointed out, the walls of heavy nuclei are thinner (for a given height above the floor) than the walls of light nuclei. Thinner walls makes tunneling more probable, so heavy nuclei decay frequently by ejection of an alpha particle, whereas light nuclei do not. When tunneling does occur and the alpha particle finds itself outside the walls, the repulsive electrical forces push it away from the nucleus (in our analogy, it careens down the side of the volcano). The released particles achieve high velocities and kinetic energies of several MeV. ■
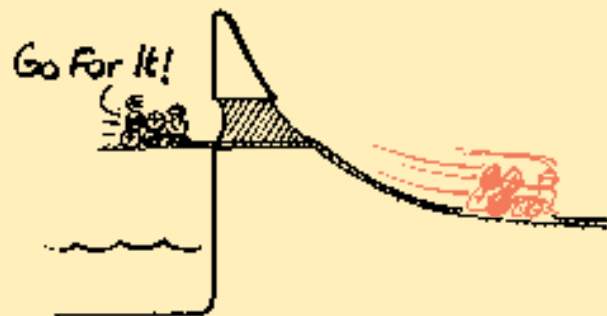
The alpha particles emitted by plutonium-239 all have essentially 5 MeV of kinetic energy, a typical energy for alpha decay. But as particles, they're relatively heavy, relatively slow, and possess a double charge, so they expend their energy quickly by creating a short, very dense trail of ion pairs. In air, they travel only an inch or two. This is why the detector in our experiment registered counts only when it was close to the lump of plutonium metal.

When alpha particles hit denser matter they stop almost dead in their tracks. They have such weak penetration abilities they can be blocked by a piece of paper or the dead, outer layers of our skin. While they are losing their energy, they each pick up two electrons, become neutral helium atoms, and float away.

Essentially all the radiation from our lump of plutonium consists of alpha particles. Each particle removes two protons from a nucleus, which means the atomic number of the atom is reduced to 92. Likewise, the alpha particle removes four nucleons, reducing the nucleon number to 235. Thus, when a plutonium atom emits an alpha particle, it becomes uranium-235, an isotope of the 92nd element in the periodic table.
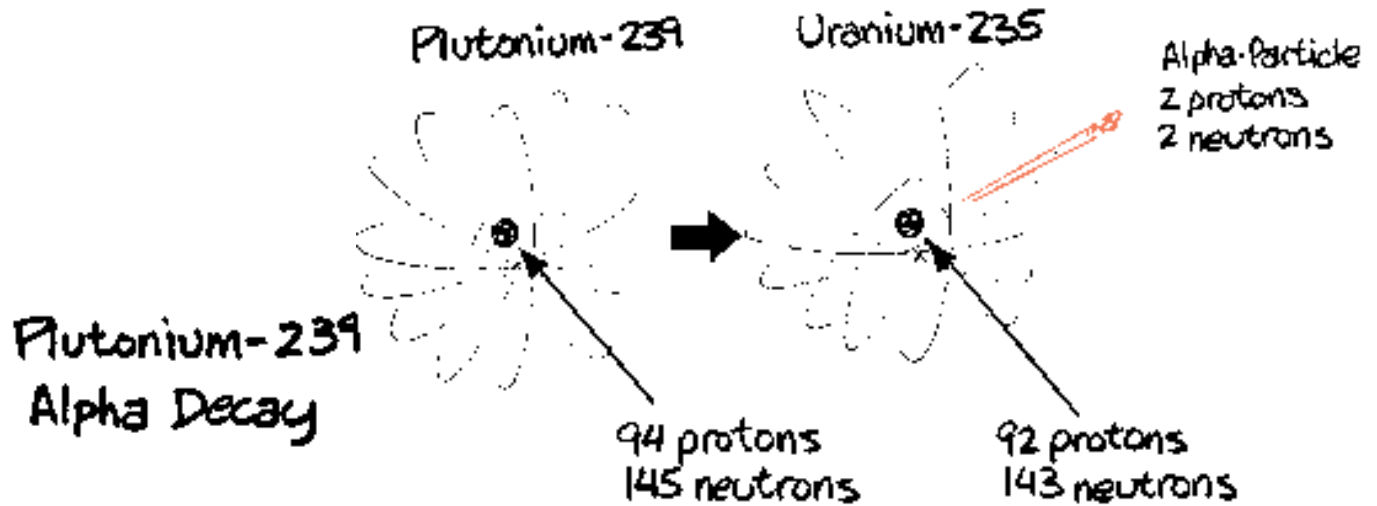
Alpha particles, or alpha rays, are one of the primary types of radiation associated with radioactivity. They are the least penetrating but create dense ionization trails. As a result, the prime danger of an alpha emitter, such as plutonium, comes from having it inside your body. If you inhale or ingest plutonium, or have it pass into your blood stream through a puncture wound, much of the element can end up lodged in various organs, especially the lung, liver, and bones. The plutonium atoms, and their daughters, sit there, emitting alpha radiation and damaging the immediate surrounding tissue.

Of course, other alpha emitters, such as uranium and radium, are already peppering your insides. You take in these substances in the food you eat or the dust you inhale, but the amounts are small and minimal damage is done. In this vein, limits have been established, called *permissible body burdens*, for the people who work with plutonium and other radioactive materials. The idea is to remove people from such work before they've ingested amounts of these materials that have been shown to be dangerous.

The Plutonium Alpha Particle

Initially, the alpha particles emitted by plutonium-239 have about 5 MeV of kinetic energy and are moving at a speed of about 1.5×10^7 meters per second (5 per cent of the speed of light). This relatively slow speed and the particle's double charge create a characteristic ionization trail that's short and thick. Usually, most of the alpha particles from a given radioactive material have about the same energy, so all the trails are essentially the same length.

In air, the 5-MeV alpha particles from plutonium-239 generate about 44,000 ion pairs per centimeter (centi = 10^{-2}). As a result, they travel 3.5 centimeters (1.4 inches) before their 5 MeV of energy is depleted, and they generate a total of about 150,000 ion pairs.

In denser matter, such as human tissue or paper, the path length of the 5-MeV alpha particles will only be 32 micrometers (micro = 10^{-6}). This distance is less than the thinnest part of the epidermis, the dead layer of external skin cells, and less than the 100-micrometer thickness of an average piece of paper.

With the shorter path length in dense matter, the density of ions pairs increases to 62,000,000 per centimeter, which is what makes alpha emitters dangerous when present in sufficient quantity. The damage is more of a shotgun blast than a rifle shot. ∎
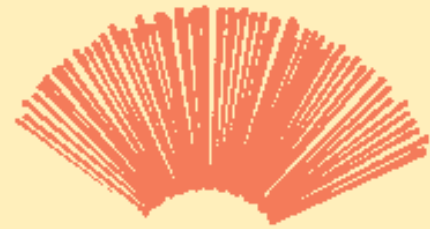
ALPHA PARTICLE TRACKS FROM A SINGLE SOURCE
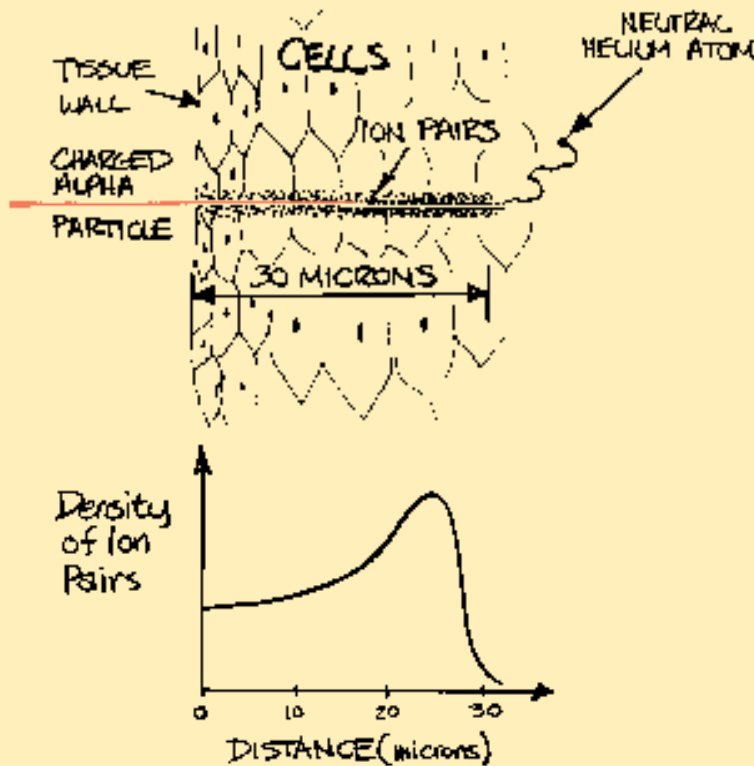
Beta Emitters.   Now let's look at the tritium gas to see what's going on there. We're at the opposite end of the periodic table—the smallest atom—so it isn't radioactive because of its size! As it turns out, there's another reason—the ratio of neutrons to protons in the nucleus of particular isotopes can be out of balance.

Balance in the nucleus is determined by three things. First, the proton is more stable than the neutron. On that account, stable nuclei would have more protons than neutrons. Second, there's a quantum mechanical principle—called the exclusion principle—that requires identical particles to be in different states. Consequently, if you have more of one kind of nucleon than of the other, the excess of the more common kind end up in higher energy states. On that account, the most stable nuclei would have equal numbers of neutrons and protons. Third, the electrical forces repel protons and not neutrons, which favors neutrons over protons. The nucleus that's actually the most stable for a given element depends on a competition between these three effects.

Now let's examine hydrogen, which has three isotopes—hydrogen-1, hydrogen-2 (deuterium), and hydrogen-3 (tritium). The first two isotopes are stable (hydrogen-1 with a single proton and hydrogen-2 with a proton and a neutron), but the third isotope is radioactive. Why?
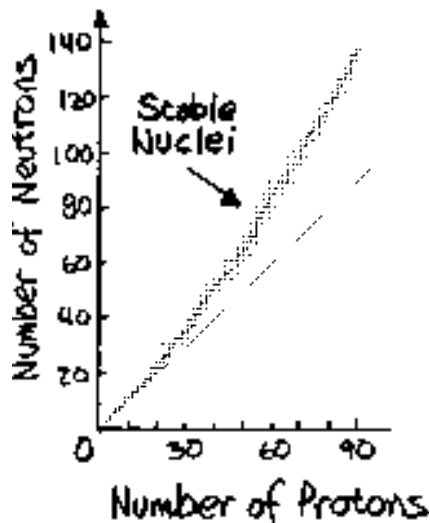
For nuclei with three nucleons, the fact that protons are more stable than neutrons is the key factor. Thus, tritium (2 neutrons and a proton) is not stable and is radioactive, whereas helium-3 (2 protons and a neutron) is stable. Hydrogen-1 and helium-3 are the only two nuclei where stability favors more protons than neutrons. All other stable isotopes have as many or more neutrons than protons because of the second and third effects. As the size of the nucleus grows, proportionately more neutrons are required as the third effect (electrical repulsion between protons) becomes dominant.

Nature has provided a way for nuclei such as tritium to change their charge without changing the number of nucleons, that is, without a large change in their mass. This process, called beta decay, can happen in two ways. In the case of tritium and other nuclei that have too many neutrons to be stable, a neutron decays to a proton while emitting an electron and another particle, called a neutrino.

The neutrino has no charge, negligible mass, and interacts with matter only through what's called the weak force, the force responsible for beta decay. In fact, the force is so weak that a neutrino passes through our radiation detector or our bodies with almost no chance of causing any ionization. Only the electron, or

Mass, Energy, and Stability

Why does the neutron decay into a proton rather than something else? First, the neutron is a bit heavier than the proton. Einstein's equivalence of mass and energy (E 5 mc^2) says that a heavier particle has more energy. Systems with higher energy tend to be unstable and decay to lower energy states by emitting photons or other particles that carry off the extra energy. However, such decays must still conserve energy, charge, and a few other things that remain constant in isolated systems. One of those things is a nuclear quantity called *baryon number*—which is one for nucleons but zero for lighter particles, such as electrons, photons, and neutrinos. Thus, ejection of a negative electron in beta decay means a plus charge must remain behind. In addition, the neutron decays into a proton rather than into gamma rays or neutrinos alone because the baryron number must be conserved.

beta ray, creates significant ionization in matter. Thus, when radioactive nuclei undergo beta decay, only the electron is detected and only the electron generates biological effects in our bodies.

In another type of beta decay, a proton changes to a neutron while emitting a positron and a neutrino. The positron is the anti-particle of the electron and is just the same except that its charge is positive rather than negative. Beta decay with emission of an electron increases the atomic number by one; beta decay with emission of a positron *decreases* the atomic number by one.

In both types of beta decay, two particles are emitted, the electron (or positron) and the neutrino, and the available energy can be shared between them in a somewhat arbitrary way. As a result, beta particles emitted from a single source have a continuous distribution of energies rather than all the particles having essentially the same energy, as is the case for alpha rays.

Typical energies for beta particles are hundreds of keVs (a factor of ten lower than for alpha particles), although some radioisotopes emit beta particles with energies (several MeV) that range higher than alpha particles. However, the fact that electrons are almost 8000 times lighter than alpha particles means that the beta particles travel much faster.

Electron Capture

Another process that reduces the number of protons in the nucleus is one in which a proton captures one of the electrons surrounding the nucleus, turns into a neutron, and emits a neutrino. This process is called electron capture and is related to beta decay because it involves the weak force and the same four particles, the electron, neutron, proton, and neutrino.

TRITIUM   HELIUM-3 ION

1 PROTON
2 NEUTRONS

BETA PARTICLE

2 PROTONS
1 NEUTRON

NEUTRINO
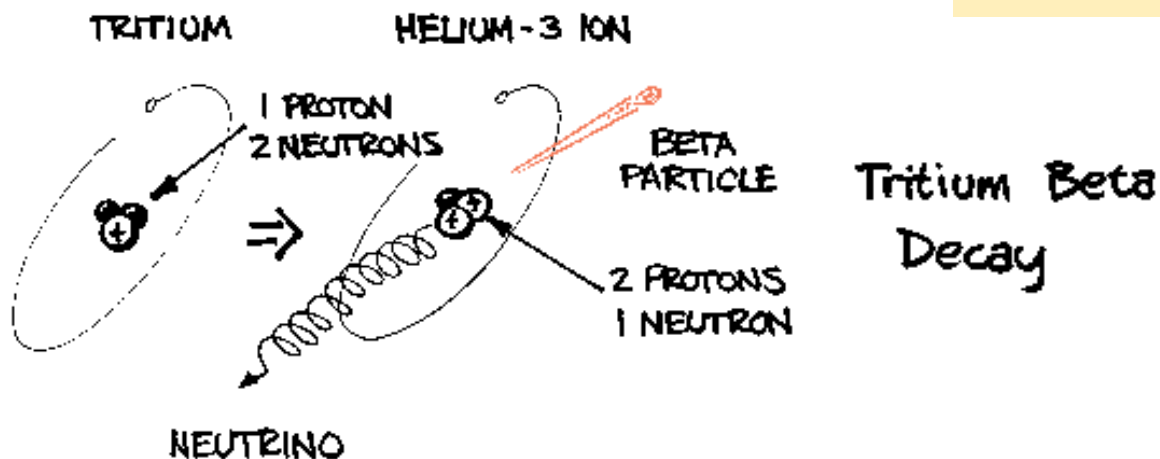
Tritium Beta Decay

The beta particles ejected in the tritium decay have the lowest energy (an average of 5 keV) of any beta decay. This low energy is why the beta rays from the tritium gas did not even penetrate the glass walls of our container. On the average, the tritium beta particle travels a shorter distance in water or tissue than the plutonium-239 alpha particle. We'll meet stronger beta rays in our next example.

The Tritium Beta Particle

The beta particle emitted by tritium atoms has an average energy of 5 keV (and a maximum of 18 keV), a thousand times less energy than the 5 MeV for the plutonium alpha particle. In fact, this beta particle is so low in energy it travels much less than half a centimeter in air, and it won't penetrate mylar, glass, or the thin window on the Geiger-Müller counter. It takes a special detector—the tritium sniffer—just to record its presence.

The tritium beta is neither a shotgun blast nor a rifle shot; rather it's a bee-bee from an air gun. An average beta particle from tritium would, at the most, generate around 150 ion pairs in water. Of course, as with all radiation sources, tritium can be dangerous in the right place and at high enough concentrations. If tritium gets in the body, it can go everywhere (after all, it's hydrogen). Sufficient concentrations can then do immense damage throughout all the cells of the body.

Decay Chains. Now that we know about both alpha and beta decay and before we discuss the sodium-iodide solution that Irene put out for us, let's return briefly to the decay of heavy elements, such as plutonium. The isotope that results from a decay, called a *daughter*, does not necessarily have a stable nucleus. It may undergo a whole series of further decays, called a *decay chain*. The chain for plutonium, illustrated here, begins with two alpha decays but then includes a beta decay, another alpha decay, a beta decay, and so forth. The end result for plutonium, as well as for other heavy radioactive elements, is a stable isotope, usually of lead. But it can take billions of years for a radioactive atom at the top of a decay chain to undergo all the decays and reach its final stable configuration.
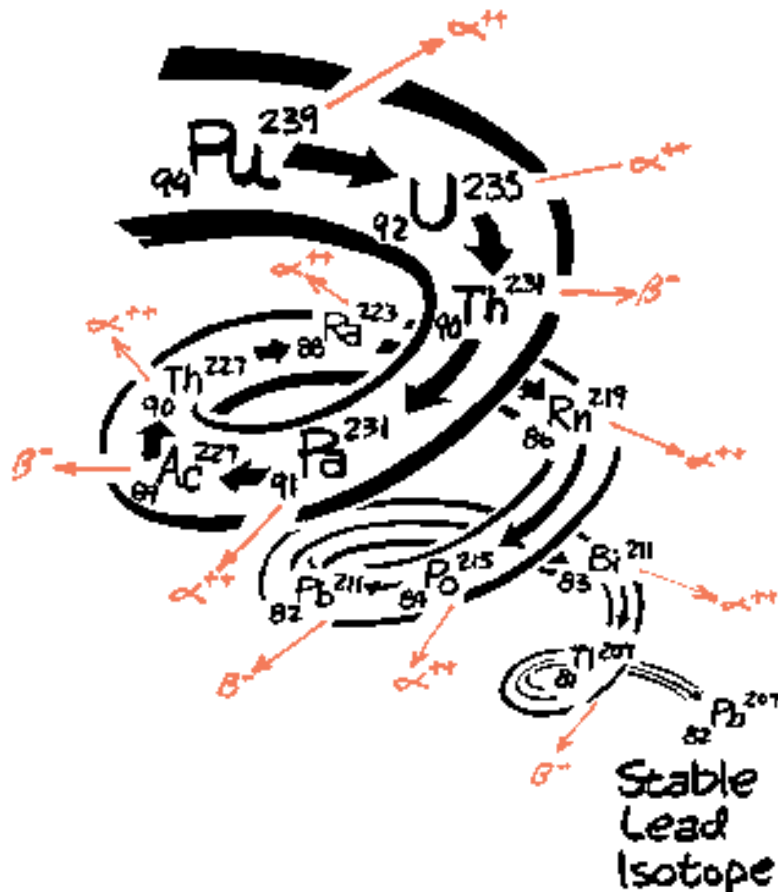
Radioisotopes. What can we say about the beaker of sodium-iodide solution? The solution was actually the most interesting because our detector was registering significant counts from the beaker even several feet away. What sort of radiation is the iodine giving off?

Every element in the periodic table can have a range of isotopes, some stable, others unstable and radioactive. The latter are called radioisotopes. Many of these radioisotopes emit more than one kind of radiation. Such is the case with iodine-131. In the periodic table, iodine is roughly halfway between plutonium and hydrogen—it's the 53rd element. All the natural iodine found in nature is iodine-127, which is stable and non-radioactive. The iodine-131 radioisotope has 4 more neutrons than iodine-127, and this excess makes it unstable. It has to be produced artificially—in nuclear reactors, in the explosions of nuclear weapons, or at accelerators.

With its extra neutrons, iodine-131 gains stability by emitting a beta particle. Once again, the decay converts a neutron to a proton, increasing the atomic number by one—the isotope changes to xenon-131. So far, this is similar to tritium, except the betas are more energetic and leave longer ionization tracks.
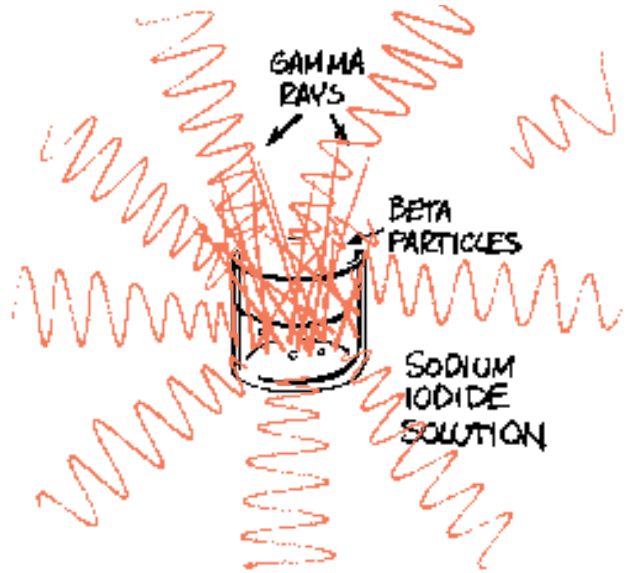
The Iodine-131 Beta Particle

Iodine-131 emits beta particles with energies up to 810 keV and an average energy of 180 keV, considerably more than the energy of the beta particles from tritium. The average iodine-131 beta particle is traveling very fast—67 per cent of the speed of light!—which is much more typical of beta particles.

In air, the single charge and high speed of the average beta result in a sparse ionization track—about 250 ion pairs per centimeter (compared to 50,000 or so for an alpha particle), and the track is much straighter and longer (about 30 centimeters) than that from a tritium beta particle. In water or tissue, the density of ion pairs rises to 180,000 per centimeter, and the range drops to 0.04 centimeter, or 400 micrometers.

Thus, despite the higher energies, most of the betas never get out of the iodine solution or through the glass walls of the beaker. Some of the betas emitted at the water surface escape, traveling up to ten feet through the air. But placing an aluminum sheet that's 2 millimeters thick over the beaker will easily block all of them, even the most energetic.
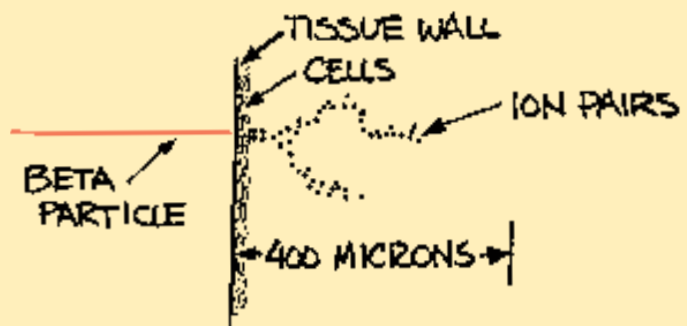
The main threat from beta radiation occurs, once again, from ingestion. In fact, since iodine likes to concentrate in the thyroid, iodine-131 can be used to help kill cells in a hyperactive thyroid. With the beta particles traveling from 0.01 to 0.3 centimeter, the radiation is confined primarily to the thyroid, resulting in an efficient treatment of hyperthyroid disorder.

Another major difference between iodine-131 and tritium is that the beta decay of iodine-131 leaves the nucleus in an excited state. The newly formed xenon-131 atom has a balance of nucleons that make it stable, but the nucleus needs to rid itself of extra energy. Most of the time it does this by quickly emitting one or more gamma-ray photons. Photons have no charge and no mass, so after the gamma-ray emission, the xenon-131 remains just that—xenon-131. Except now it's happy and relaxed. In fact, xenon is one of the rare gases, so it diffuses out of the solution and floats away.

Radioactive Decay of Iodine 131
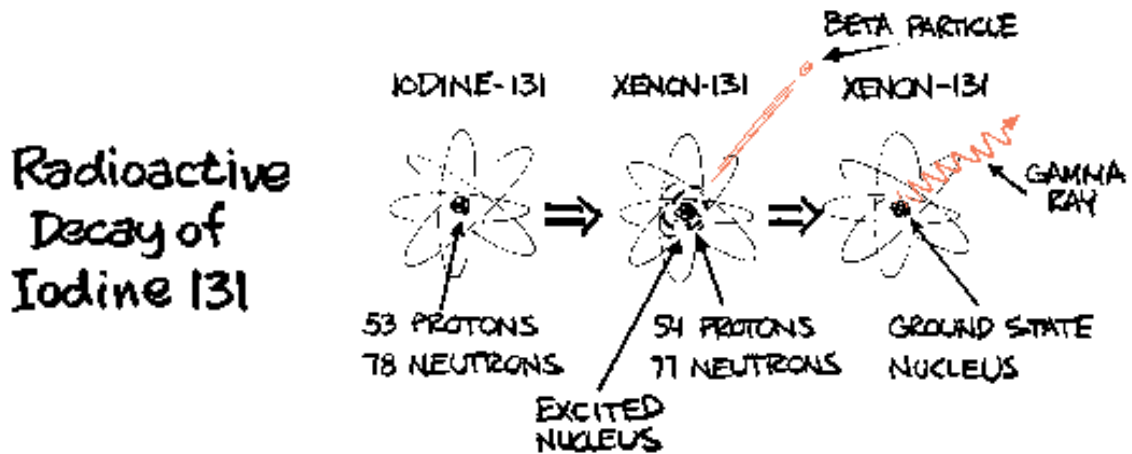
Almost all the radiation we measured in our thought experiment with the Geiger-Müller counter was gamma radiation from the iodine. Gamma rays are electromagnetic rather than charged-particle radiation, so they are highly penetrating. They pass through the solution, the glass beaker, the air, and our bodies.

Gamma rays are penetrating because, as we described earlier, photons lose energy randomly in "collisions" with atoms, knocking electrons free to create local regions of ionization. For a given thickness of material, only a fraction of the photons, and a smaller fraction of the energy, are absorbed. For example, a centimeter of water will scatter about 10 per cent of the incident photons from iodine-131, and in the process, absorb about 3 per cent of the incident energy. Doubling the thickness of water will scatter another 10 per cent of the remaining unscattered photons, but to calculate the absorbed energy, we'd have to take into account that 7 per cent of the incident energy is traveling through the water in the form of reduced-energy photons. In general, alpha and beta radiation have finite ranges; gamma radiation falls off continuously, never quite reaching zero.

The Gamma Rays of Iodine-131

We speak of the gamma rays of iodine-131 even though the real source of the gamma rays is the daughter nucleus, xenon-131. One or more gamma rays with energies ranging from 80 keV to 723 keV follow each beta decay. By far the most common gamma ray, accompanying 81 per cent of the decays, has an energy of 364 keV. Furthermore, the total gamma ray energy emitted (sometimes in the form of several gamma rays) is 364 keV in 89 per cent of the cases. To simplify our discussions, we will always speak as if all the decays of iodine-131 emit a single 364-keV photon.

In water or tissue, it takes 6.4 centimeters (2.5 inches) to reduce the intensity of 364-keV photons in half. Thus, although the beta radiation from iodine-131 in hyperthyroid treatments is limited to the thyroid, the gamma radiation deposits energy more diffusely throughout the body.

The following table summarizes information about the interaction with water of the three primary forms of ionizing radiation emitted by radioactive sources. We use

Alpha, Beta, and Gamma Radiation			
Radioisotope	**Radiation**	**Energy (MeV)**	**Range or Mean-Free Path in water or tissue (millimeters)**
Uranium-238	Alpha	4.2	Range: 0.027
Polonium-210	Alpha	5.3	Range: 0.037
Carbon-14	Beta	0.154 maximum	Maximum range: 0.29
Phosphorous-32	Beta	1.71 maximum	Maximum range: 8
Iodine-125	Gamma	0.035	Average distance to collision: 33
Colbalt-60	Gamma	1.33	Average distance to collision: 164

other examples than the ones we've already discussed. In particular, alpha radiation produces short, dense ionization tracks; beta radiation produces sparse tracks that are longer; and the highly penetrating gamma radiation leaves scattered, local regions of ionization where the photons have knocked electrons free of their atoms. These local regions have the same type of ion density as the tracks from beta particles.

If the radiation source is external to the body, then only gamma radiation poses a threat. Alpha and beta radiation do not penetrate far enough to be very dangerous. However, if the alpha and beta sources have somehow been deposited in the body to become internal sources, they may be very dangerous.

Radiation Doses

Now you turn to your friend, Irene, and say, "This is more complicated than I thought. I'm beginning to realize why health physicists always seem to hedge when they're asked to explain how they calculate radiation doses. They *can't* give a simple answer."

"Exactly," Irene answers. "There are many factors that go into the calculation including the type of radiation emitted by the source and the circumstances of the exposure. Let's discuss these for our three radioactive materials."

The most important thing to know, of course, is how much energy carried by the ionizing radiation is actually deposited in your body, because biological damage increases with the energy absorbed by the cells. Thus, absorbed energy is the basis for several quantities that health physicists call *dose*.

When the tritium gas is inside the bottle, figuring the dose is easy—there's none! Likewise, as long as you keep the plutonium a few inches away, your dose from it is zero. (Actually, the plutonium is emitting a small amount of gamma and x radiation, but we'll ignore this.) The energy of the beta particles from the tritium is absorbed in the glass jar and the energy of the alpha particles from the plutonium is absorbed in air immediately surrounding the metal. (In both cases, much of the energy is absorbed in the materials themselves, and the radiation never escapes.)

If you hold the lump of plutonium in your hand, your body absorbs energy from the alphas—but the energy is deposited in dead skin tissue, where it's relatively harmless. If you kept the plutonium against your skin for a length of time, it would eventually lead to skin burns.

WEAK BETAS

GLASS

NO DOSE

Now, say you lean over the beaker of sodium-iodide solution. What sort of exposure are you getting? Beta radiation would hit your face, but it only penetrates a short ways (about ten times farther than the plutonium alpha particles). And if you happen to be wearing glasses, the lenses would block the betas and none of the radiation would reach your eyes. At the same time, however, the gamma radiation is passing through the beaker, the table, your glasses, and exposing your entire body.

Of course, all this changes if the sources are internal. If you made water using tritium gas rather than hydrogen and then drank it, there'd be a beta dose everywhere, in all your organs and cells. In that case, it's the source that would have penetrated the body, not the radiation.

If you drank the sodium iodide solution, you'd need to calculate two doses. The first is a concentrated dose to the thyroid, because that's where the iodine ends up and deposits its beta rays. The second is a diffuse dose of gamma rays that travel out from the thyroid and deposit energy throughout the body (to be accurate, you should also add in doses from the small fraction of iodine outside the thyroid).

If you breathed plutonium dust, the particles would initially be deposited in your lungs. You would then need to know the eventual distribution of the plutonium, that is, what fraction ends up in each organ or tissue type and what fraction works its way out of your body. A significant fraction, for example, can be coughed up, swallowed, and passed on though the gastrointestinal tract. On the other hand, if the plutonium is in a soluble form, say a plutonium salt, it can move quickly to various organs, such as the bones, and be deposited there. Only with such information could you calculate an accurate dose.

Calculating the Dose. So far we've been talking qualitatively about whether the radiation ever reaches you and where it deposits its energy. But to calculate the size of the dose we first need to know the amount of energy emanating from the source. The amount of energy depends on two factors: the *activity* of the source, that is, the number of radiation particles being emitted each second, and the energy per particle. The product of these two factors is the power of the source, or the total energy being emitted per second.

How much of the emitted energy is finally deposited in your body depends on your distance from the source, the amount of time you're exposed to it, the attenuation of the radiation on its way to you by the air or by shielding, and the
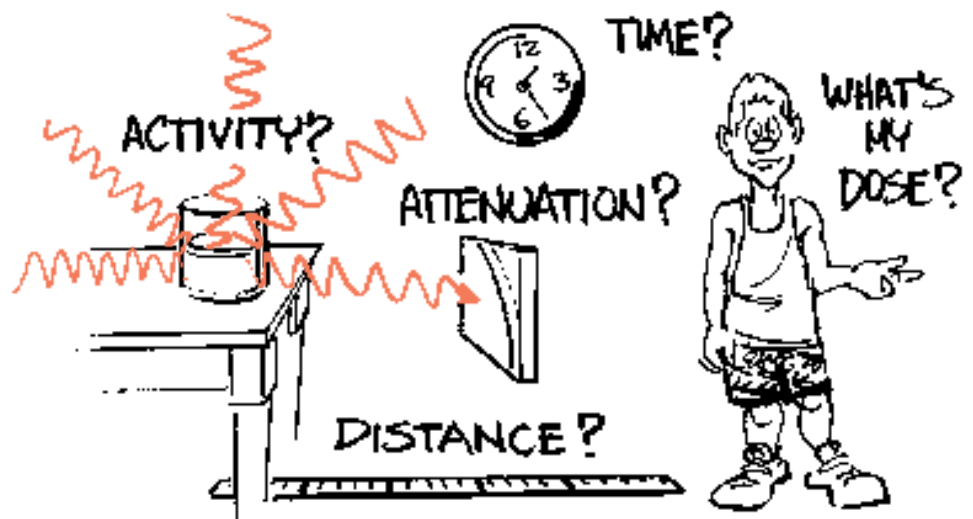
penetrating power of the radiation once it reaches you. For example, if you double how long you stand beside an external source with constant activity, you double your dose because twice as much energy gets deposited. Many of these factors can easily be overlooked in discussions of radiation exposures.

What about distance? Radiation from a localized source spreads outward as it travels. For example, the intensity of gamma or x radiation falls off with the inverse square of the distance. Absorption in air reduces the intensity still further, so doubling your distance from a gamma-ray source reduces your dose by a factor of more than four.

In the case of alpha and beta radiation, the range is what's important. Staying beyond this distance keeps the dose from those charged particles at zero. If you're within the range, you still need to subtract the energy lost to the air before the particles reach you as well as to account for any spreading of the beam.

Common Radiation Units. Irene suggests that to understand dose calculations you need to become familiar with several radiation units. The three most important are *activity*, *absorbed dose*, and *dose-equivalent*. We've already explained that activity, A, is a measure of the number of decays per second. The typical unit for activity is curies. The quantity that health physicists call the absorbed dose, D, is the energy absorbed per gram of tissue in the body, which is frequently given in a unit called the rad. Finally, the dose-equivalent, H, is the absorbed dose multiplied by a biological effectiveness factor and is typically expressed in rem. The most relevant quantity for determining an individual's risk from a radiation exposure is the dose-equivalent, H, but its calculation requires knowledge of the other two. We'll now explore these units more fully.

Activity. The activity, A, of a radioactive source is equal to the number of atoms decaying every second in the material. The more material that's present, the higher the activity because there are more atoms to decay and emit radiation. The higher the activity, the higher the dose you receive in a given amount of time.

A common unit of activity is the curie, which is 3.7×10^{10} disintegrations, or radioactive decays, per second. The curie was originally defined in terms of radium, the second radioactive element discovered and isolated by Marie and Pierre Curie (the first was polonium). One gram of radium-226, the isotope the Curies had found, has an activity of 1 curie, that is, 3.7×10^{10} atoms decay per second. Since there are 2.7×10^{21} atoms of radium per gram, it takes a long time for the radium to disappear (11,000 years for more than 99 per cent to decay).

The *specific activity* is the number of curies *per gram* of material and measures the rate of decay in one material relative to rate of decay in radium (1 curie per gram). The specific activity of plutonium-239 is 0.06. In other words, plutonium-239 has 6 per cent as many decays per unit time as an equal mass of radium-226. We can thus calculate that one gram of plutonium-239 emits 2.2×10^{9} alpha particles per second.

Two radioactive substances can have considerably different specific activities. An isotope with a very high specific activity, such as iodine-131, has a significant fraction of its atoms decaying every second. As a result, such isotopes don't hang around very long. We say they have short *half lives*.

Many of the radioactive sources discovered at the turn of the century—such as uranium and radium—have low specific activities and long half lives. Only a

I CURIE

I gram Radium

3.7×10^{10} DECAYS PER SECOND
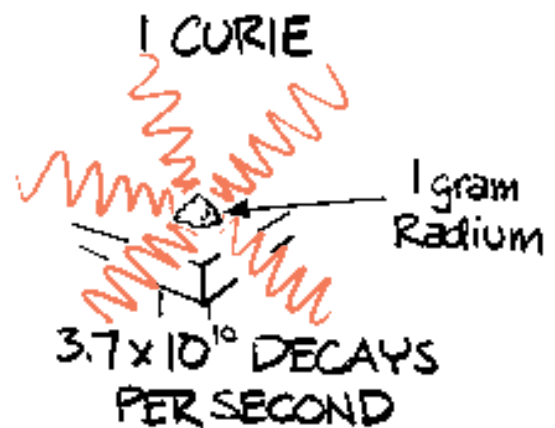
The Radioactive Half-Life
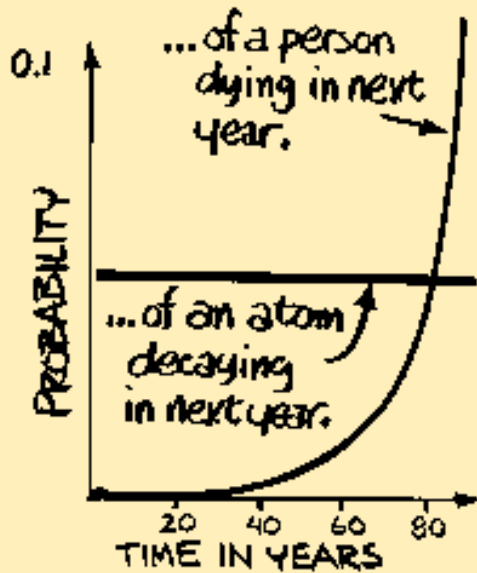
Biological life is a series of progressive stages from birth through aging to death. When you met Irene, you knew without asking that she wasn't two or even ten years old, and you probably could make a pretty good guess as to whether she was closer to 30 or 60. The life expectancy at birth in the U.S. is around 75 years, at age 75 it is around 11 more years, and hardly anyone lives to 150 years. The probability of death per year generally increases with age. Radioactivity is very different. There's no way to tell how long ago a radioactive atom was created. A nucleus of uranium-235 created yesterday by the decay of plutonium-239 is identical to one that has been on Earth since the planet was formed. One aspect of this indistinguishability is that the "life expectancies" are the same. So, if half of a set of identical nuclei decays in a set time, half of the remainder will decay in the next equal time interval, etc.

The time interval needed for half the atoms to decay is a commonly used parameter, called the half-life. For example, iodine-131 has a half-life of 8 days. If we start with, say, 10^{23} atoms of iodine-131, one-half (5×10^{22} atoms) will remain after 8 days, one-fourth (2.5×10^{22} atoms) after sixteen days, one-eighth (1.25×10^{22} atoms) after 24 days, and so forth. An important rule of thumb in radiation protection is that after seven half lives less than one per cent of the radioisotope will remain ($(1/2)^7 = 1/128$). Radioactive decay thus follows an exponential decay law:

$$N = N_o e^{-0.693\ t/T}$$

small fraction of the atoms actually decay every second, so those sources appear to have a constant activity. This is why the materials appeared to have been sources of endless energy and to have violated the conservation of energy laws.

Absorbed Dose. The absorbed dose, *D*, is the energy deposited in an organ or a mass of tissue *per unit mass* of irradiated tissue. A common unit for absorbed dose is the rad, which is 100 ergs per gram of material.

Note that absorbed dose is not the *total* energy deposited in an organism, organ, or mass of tissue. However, to calculate absorbed dose you usually calculate the total absorbed energy first. You use the activity of the source and the energy of the radiation to calculate the total amount of energy that arrives at the surface of your body (by taking into account such factors as the fraction of the radiation from the source that's moving in the right direction, the distance between the source and your body, the length of time for the exposure, and attenuation from any shielding or the air). You then use tissue absorption coefficients or particle ranges to calculate the total energy absorbed in the body.
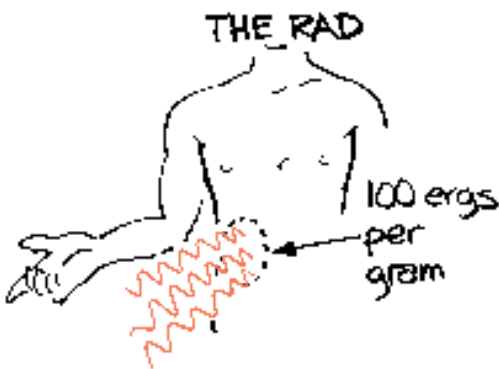
where N_o is the initial number of atoms at time $t = 0$, N is the remaining number of atoms at time t, and T is the half-life expressed in the same units as t.

We can use this formula to show, for example, that the fraction of plutonium-239 (with a half-life of 2.4×10^4 years) that remains after 8 days is $N/N_o = 0.9999994$—only 6 atoms out of ten million have decayed! Quite a few less than the five million out of ten million for iodine-131.

As these examples illustrate, the half-life of a radioisotope is an important indicator of the material's radiological activity—the shorter the half-life, the more atoms disintegrate per unit time. The specific activity (curies per gram) of a particular radioisotope is inversely proportionately to the isotope's half-life and its atomic weight. The half-life of iodine-131 is about 10^6 times shorter than that of plutonium-239, and each atom weighs about half as much. As a result, iodine-131 is 2×10^6 times more radioactive per gram. Let's hope our solution of radioactive sodium iodide was pretty dilute!
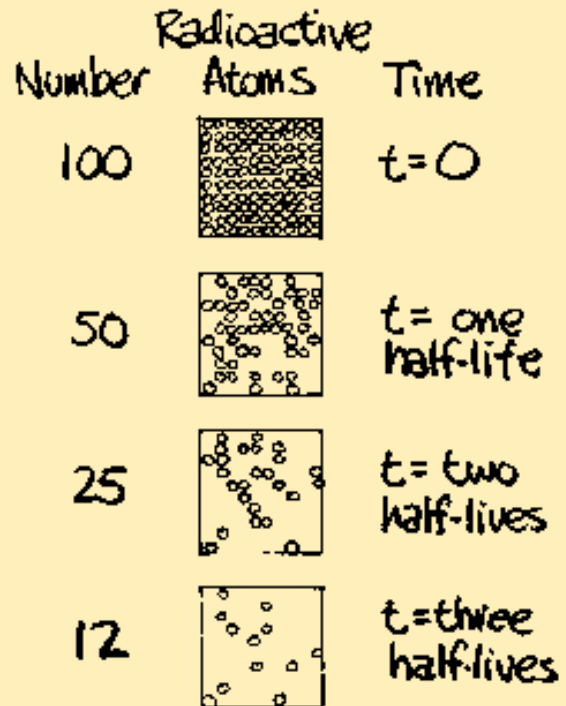
The first measurement of radioactive half-life was made by Rutherford in 1900, about four years after Becquerel discovered radioactivity. Rutherford measured the half-life of radon-220, or "thorium emanation," which is 55 seconds. With such a short half-life, the substance is quite active but also obviously disappears rapidly, in contrast to its original parent in the decay chain, thorium-232, with a half-life of 1.4×10^{14} years. ■

Radioactive

Number	Atoms	Time
100		$t = 0$
50		$t =$ one half-life
25		$t =$ two half-lives
12		$t =$ three half-lives

The last step is to calculate the absorbed energy per unit mass, which requires a decision on what mass of tissue to use—the mass of the whole body or just the mass of the irradiated tissue. When energy is deposited primarily in a single organ (such as the beta radiation of iodine-131 in the thyroid), one usually calculates the actual dose to that organ—after all, that's where the damage occurs. When energy is deposited throughout the body (such as from an external gamma-ray source), the mass of the whole body is obviously appropriate.

$$\text{Whole Body Dose} = \frac{\text{Energy Absorbed}}{\text{Mass of Body}}$$

$$\text{Organ Dose (rads)} = \frac{\text{Energy Absorbed}}{\text{Mass of Organ}}$$

However, comparisons between different kinds of exposures are facilitated if the doses are all put on the same basis. To do this, organ-specific doses can be recalculated using the mass of the entire body to yield the *whole-body dose*. This dose is much lower than the organ-specific dose and, in one sense, is a rather artificial contrivance. In effect, we've spread the energy over the entire body. However, the adjusted value is more suitable as a measure of risk to the entire organism, and it can be added or compared to other whole-body doses.
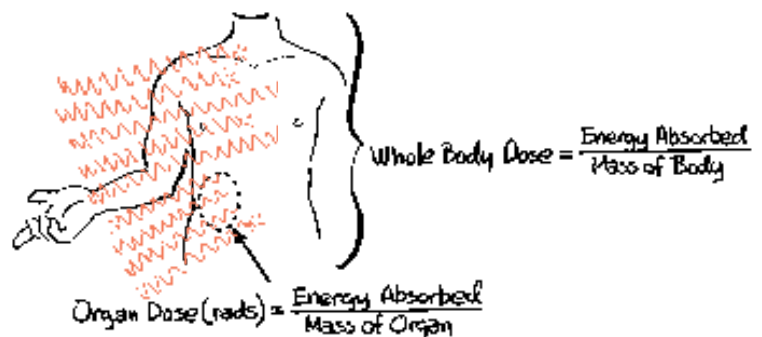
Dose-equivalent. A key factor that the absorbed dose doesn't take into account is the density of the ionization created by the radiation. For example, alpha radiation leaves an ion track that's several hundred times more dense than that of a beta particle. This means that if an alpha particle and a beta particle penetrate tissue, the deposition of energy for the alpha particle is several hundred times more focused. The alpha won't cross through as many cells (possibly only one or two), but the effectiveness at creating lasting damage in the cells it does hit is higher per unit energy deposited. Generally, one rad of alpha radiation is about twenty times more effective at causing cellular damage—and thus cancer—than one rad of gamma or beta radiation.

Health physicists account for these differences using a *radiation-weighting factor*, *Q*, that represents the effectiveness of each type of radiation to cause biological damage. The factors are determined by measuring the occurrence of various biological effects for equal absorbed doses of different radiations.

The product of the radiation weighting factor and the dose ($Q \times D$) is a more direct measure of the biological risk and is called the dose-equivalent, *H*. The idea is that equal dose-equivalents generate equivalent amounts of biological damage. The common unit for dose-equivalent is the rem.

Looking at the table, you ask, "Why does gamma radiation have the same weighting factor as beta particles? After all, gamma radiation deposits its energy in a very diffuse manner."

What you say is correct. For example, less than half the energy of 5-MeV gamma-ray photons is absorbed as they pass horizontally through your torso. However, the energy that's deposited is from electrons that have been knocked loose. The ionization tracks generated at these points by the ejected electrons have the same ion density as beta particles, despite the fact the regions are scattered throughout the material. Thus, beta and gamma radiation delivering the same dose-equivalent create the same density of ionization in the cells per gram of tissue.

Irene shows you some calculations about possible doses a person might receive from the radioactive materials on the table. For example, a tenth of a microgram of plutonium-239 spread in a thin coating on your skin over an area about 5 centimeters in diameter would give a localized dose-equivalent to the skin tissue of about 3 millirem per second. After an hour, the total dose-equivalent would be 11 rem. It takes about 4000 rem of alpha radiation to the skin before you start to see hair falling out and more than 6000 rem before a skin burn appears.

If the same mass of iodine-131 (a tenth of a microgram) were present in the beaker (a very dilute solution) and you were standing so that your midsection was about a foot away, you'd receive a much smaller dose—an average of about 1.3 microrem per second—except now the entire body is exposed, not just a small amount of tissue in the palm of your hand. Your head and feet, which are furthermost from the beaker, will, of course, receive less than 1.3 microrem per second; your midsection will receive more. On the average, however, every gram of tissue in your body receives 1.3 microrem per second, not just a small amount of tissue in your hand as was the case for the plutonium.

These examples can help emphasize that the doses are based on energy per unit mass! The iodine-131 delivers a total energy to the body that's ten-thousand times more than the total energy from the plutonium-239. But the energy of the gamma

Dose Equivalent (rems)

$$H = Q \times D$$

Radiation Weighting Factor · Absorbed Dose (rads)

Radiation-Weighting Factors

Type of Radiation	Q
Alpha particles	20
Beta particles	1
Gamma radiation	1
Protons, Fast neutrons	20
Slow (thermal) neutrons	5

Important Units of Radiation and Dose

Basic Units

Type of Unit	Explanation	Older Unit	Newer SI Unit	Conversion
Activity, A	The number of radio-active decays per unit time occurring in a given source.	**curie (Ci)** 3.7×10^{10} decays per second	**becquerel (Bq)** 1 decay per second	$1 \text{ Ci} = 3.7 \times 10^{10}$ Bq
Absorbed Dose, D	The energy absorbed from the radiation per unit mass of exposed tissue.	**rad** 100 ergs per gram	**gray (Gy)** 1 joule per kilogram	1 Gy = 100 rad
Dose-Equivalent, H	Absorbed dose weighted for the effectivness of the radiation for causing biological damage.	**rem** H (rems) = Q 3 D (rads) (Q = radiation-weighting factor)	**sievert (Sv)** H (Sv) = Q 3 D (Gy) (Q = radiation-weighting factor)	1 Sv = 100 rem

Other Derived Units

Type of Unit	Explanation	Equation
Effective Dose, H_E	A dose calculated for the whole body in which the dose-equivalents for various organs are weighted to account for different sensitivities of the organs to the radiation.	H_E 5 S $w_T H$, where w_T is the tissue-weighting factor and the summation is over all organs.
Whole-Body Dose, H_W	Dose-equivalent, H, for an exposure that irrad-iates the entire body uniformly, or the effective dose, H_E, when the exposure irradiates the body non-uniformly and different organs experience different doses.	H_W 5 H (for uniform dose to body) H_W 5 H_E (for non-uniform dose)
Collective Effective Dose, CED	A measure of total risk to an exposed population based on the average effective dose, $<H_E>$, and the number of people being exposed.	CED = $<H_E>$ N, where N = number of people in the exposed population.

radiation is dispersed, and no one cell receives a large amount. The energy of the alpha radiation is concentrated, and each gram of irradiated tissue receives 100 times more energy from the plutonium than from the iodine-131. This fact, com-bined with the radiation-weighting factor of 20 for alpha particles, makes the dose-equivalent 2000 times larger for the alpha particles than for the gamma radiation.

It's the difference between focused and diffuse energy deposition. But that's an important difference when it comes to the effects of radiation damage on tissue and cells!

Irene's Calculations

Say you have 0.1 microgram of plutonium-239 coating the palm of your hand in a 5-centimeter diameter area. What dose do you receive from the 5-MeV alpha particles?

As a rough estimate, we assume that half the alpha radiation penetrates your hand and the other half goes into the air. Earlier, we'd shown that the activity of plutonium-239 is such that one gram of plutonium emits 2.2×10^9 alpha particles per second. Thus, from 10^{-7} gram, the skin would absorb the energy of 110 alpha particles per second, or (since there are 1.6×10^{-6} erg per MeV and 5 MeV per particle) about 0.0009 erg per second.

The alpha particles penetrate 30 micrometers into the skin, so the energy is deposited in a disc of tissue with a volume of about 0.06 cubic centimeter. Using a density for tissue of approximately 1 gram per cubic centimeter, we find that 0.015 erg per second are being absorbed by each gram of exposed skin tissue, which gives an absorbed dose rate of 1.5×10^{-4} rad per second in the skin tissue.

If we apply the radiation weighting factor for alpha particles of 20, we get a dose-equivalent rate of 3 millirem per second. If you go an hour before scrubbing off the plutonium, the dose-equivalent to the irradiated skin is 11 rem, not enough to cause observable skin damage.

What about the dose from the gamma rays of iodine-131? The activity of iodine-131 is 1.24×10^5 curies per gram, about two million times larger than that of plutonium. If there is 0.1 microgram of radioactive iodine in the solution, it will be emitting about 4.6×10^8 gamma rays in all directions every second. As we discussed earlier in the main article, we'll simplify by assuming each decay leads to a single 364-keV gamma-ray photon and calculate that there are 270 ergs per second of gamma-ray energy being emitted in all directions.

How much of this energy is absorbed in the body, say, of a six-foot, 180-pound person standing so his or her midsection is about one foot away? A bit of simplified geometry indicates that the body is intercepting about 6 per cent of the rays. A 364-keV gamma ray is attenuated, that is scatters, with a mean free path of about 10 centimeters in water, but only about a third of its energy is lost in this scatter. This begs for the use of the build-up factor defined earlier. However, for absorption in water at these energies, it's not too bad an approximation to assume that energy deposition is constant, 1/30th of the initial energy in each centimeter, or about 2/3rds of the energy in the 20-centimeter thickness of an average torso. Combining these numbers, we calculate that 11 ergs are being absorbed by the entire body every second.

Next, we divide by the mass of the body—180 pounds or 8.2×10^4 grams to arrive at about 1.3×10^{-4} erg per second per gram, or 1.3×10^{-6} rad per second. With a radiation-weighting factor of 1 for gamma rays, the body is receiving 1.3×10^{-6} rem per second as well. Standing next to the solution for an hour gives a whole-body dose equivalent of 5 millirem.

If we compare the two examples, the body receives about ten thousand times more total energy from iodine-131 than from plutonium. However, each *gram of skin tissue* irradiated by the plutonium absorbs about a hundred times more energy (0.015 erg per second) than that

$$\text{Absorbed Dose (rads)} = (\text{Activity}) \times \left(\begin{array}{c}\text{Average Energy}\\\text{per Particle}\end{array}\right) \times \left(\begin{array}{c}\text{Time of}\\\text{Exposure}\end{array}\right) \times \left(\begin{array}{c}\text{Fraction of}\\\text{Energy}\\\text{Absorbed}\end{array}\right)$$

$$\text{Dose Equivalent (rems)} = \left(\begin{array}{c}\text{Absorbed Dose}\\\text{(rads)}\end{array}\right) \times \left(\begin{array}{c}\text{Radiation Weighting}\\\text{Factor, Q}\end{array}\right)$$

absorbed by each *gram of body tissue* from the iodine-131 (0.00013 erg per second). When the radiation-weighting factor of 20 for alpha particles (versus 1 for gamma rays) is included, the dose-equivalent rate to skin tissue from plutonium is about 2000 times higher than the dose-equivalent rate for the iodine-131. ∎

Sources of Natural Background Radiation

"These numbers are all very nice," you say, "but I've nothing to compare them with."

Just then, Carl enters the room. "What you need is a tour of natural sources of ionizing radiation. If we look at the types of doses everyone is receiving every day, you'll have a much better feeling for what we're talking about."

"To give you a reference point," says Irene, "the average person in the United States receives about 360 millirem of ionizing radiation every year. Eighty-two per cent of that—about 300 millirem per year—is from natural sources."
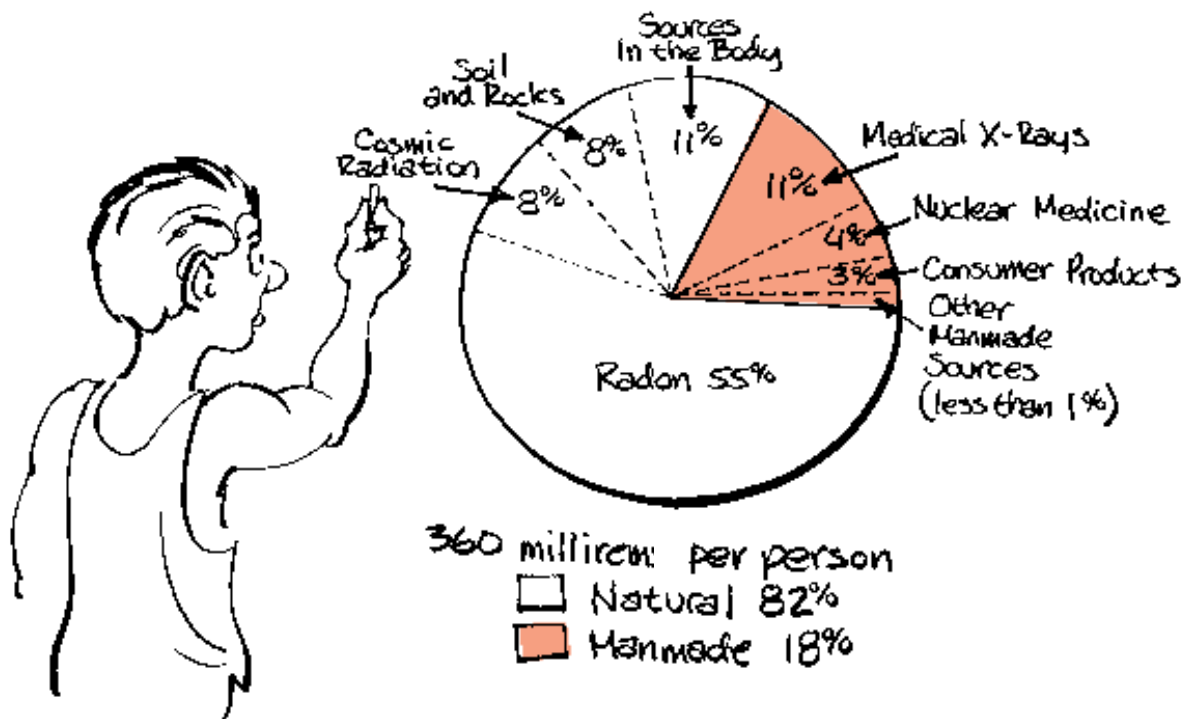
So the three of you grab radiation detectors and head outside to start measuring. Along the way, Carl and Irene discuss the major sources of natural background radiation. They explain that most people are not aware they're constantly being bombarded with ionizing radiation. This radiation is directed at us from the soil beneath our feet, from the heavens above our heads, and even from within our own bodies. Carl suggests we start with the star matter at our feet, and picks up a piece of granite rock to measure its activity.

The Soil.   Our planet was formed from a cloud of dust containing all the natural elements. Many of these, including a variety of radioisotopes, were trapped in the Earth's crust. Where did this cloud of debris come from?

Astronomers believe that the first stars were formed when only very light elements were present. In stars, many of the lighter elements are fused from hydrogen. Some of these fiery crucibles will become unstable and explode as supernovas, forming many of the other elements and spewing their material outward. New

INTERSTELLAR VOYAGERS

stars eventually form from these clouds and from additional hydrogen, but they now include the heavier elements produced by the previous generation of stars. As the stars form, they may leave behind some matter which coalesces into planets, which have all the elements necessary for life. We are the stuff of stars.

Initially, the ejected clouds of matter contain a broad distribution of stable and unstable isotopes, but the short-lived isotopes decay to stable daughters long before the matter condenses into a solar system. The isotopes with very long half lives, such as uranium-238 (4.5 3 10^9 years) and thorium-232 (1.4 3 10^{10} years), remain to become part of the Earth's crust. Uranium, thorium, and their daughters are especially plentiful in igneous rock, such as granite (about 4 parts per million uranium), as well as in bituminous shale (50 to 80 parts per million) and phosphate rock (20 to 30 parts per million). In Florida, the phosphate rock has uranium concentrations of about 120 parts per million! Thus, we breathe radioactive dust, we fertilize our gardens with radioactive materials, and we pour thousands of tons of radioactive atoms into the air every year from the smokestacks of coal-fired power plants.

HERE'S OUR BACKGROUND!

20 counts per minute

CLICK CLICK CLICK

SOIL AND ROCKS 8%
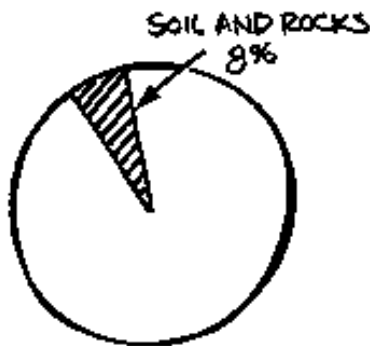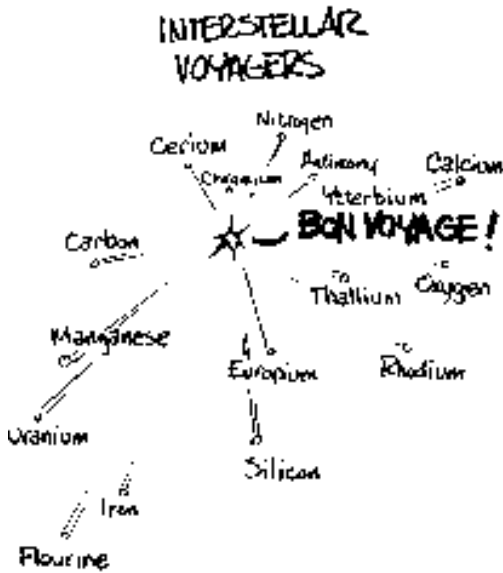
The average person receives an dose-equivalent of about 46 millirem per year from terrestrial gamma rays. This is only about 1.5 nanorem (nano = 10^{-9}) per second, 1000 times less per second than what we were receiving standing next to the iodine-131 solution. But we only stood next to the solution, say, for an hour (6 millirem total), whereas we receive the dose from the soil every second for most of our life. We can get away from it only on boats (although sea water is slightly radioactive also) or in airplanes (but then we get more cosmic rays) or in specially shielded rooms! The yearly accumulative dose-equivalent from the soil (46 millirem) is about nine times more than our one-hour exposure (6 millirem) from the iodine-131 solution.

Radon. Uranium and thorium both undergo a long chain of radioactive decays—the daughters are themselves unstable and continue releasing additional alpha, beta, and gamma radiation until a stable isotope of lead is finally reached. Uranium-238 undergoes eight alpha decays and six beta decays before it reaches the

RADON 222
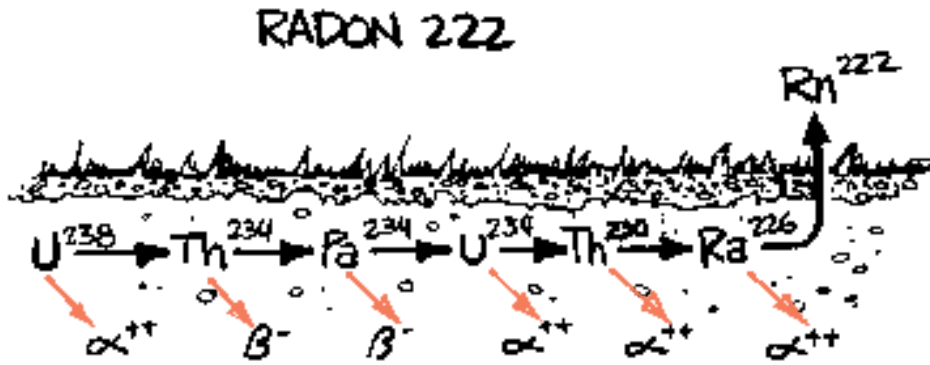
stable lead-206 isotope. Thorium-232 undergoes six alpha decays and four beta decays before it reaches the stable lead-208 isotope.

Midway through the decay chains for uranium and thorium, radon isotopes are formed. Because this element is one of the rare gases, the type of radiation exposure changes from an external dose to a significant internal dose. Isotopes before radon on the decay chain remain in the soil. Radon, however, can diffuse out of the soil and accumulate in the air we breathe. The most common radon isotope—radon-222—is a member of the uranium-238 decay chain and has a half-life of 3.8 days. The radon isotopes in the other decay chains (thorium-232 and uranium-235) have short half-lives (55 and 4 seconds, respectively), so these radon isotopes typically decay before they can percolate out of the soil.
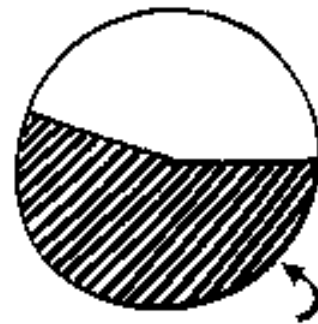
On the average, more than half of your total exposure to ionizing radiation is due to radon and its daughters (200 millirem per year). Radon itself is not the main culprit—if you breathe the gas in, you mostly just breathe it back out again. However, when the radon decays, the daughter atoms are charged and so stick to dust particles. These daughters can then be breathed in and deposited on the lungs. Once in the lungs, they continue down the decay chain, releasing alpha, beta, and gamma radiation to the tissue.

RADON 55%

Water is another major source of radon. This source wasn't accounted for until recently, so the estimates of our average exposure to radon have increased. Water obtained from surface sources, such as lakes and reservoirs, is low in radon because very little of the gas remains dissolved. However, water pumped from wells can have relatively high concentrations of the gas that are released after the water comes from the tap. Your highest exposure to radon may actually come while you're taking a shower!

It's estimated that five to ten thousand cases of lung cancer annually are due to radon (6 to 12 per cent of the total number of cases). Many uncertainties make

Effective Dose, H_E: Weighting the Sensitivity of Organs

The average annual dose from radon is usually cited as 200 millirem (55 per cent of a person's average total dose) even though the actual dose-equivalent to lung tissue is estimated to be 2,400 millirem per year. What's going on here?

The 2,400-millirem dose-equivalent is a direct measure of potential damage to lung tissue. But what is the potential risk to the entire body? To calculate that type of dose, we need to account for the different sensitivities of organs or tissue types and we need to change the basis from an organ-specific dose to a whole-body dose.

A new factor, called the *tissue weighting factor* is applied. For lung tissue exposed to the radiation of radon daughters, this factor is estimated to be 0.08, a combination of the radiation sensitivity of lung tissue and the fraction of total body weight for lungs. Our new dose is then 2,400 x 0.08, or 200 millirem. When tissue weighting factors have been applied, the dose is called the *effective dose*, H_E, and it still has units of rem.
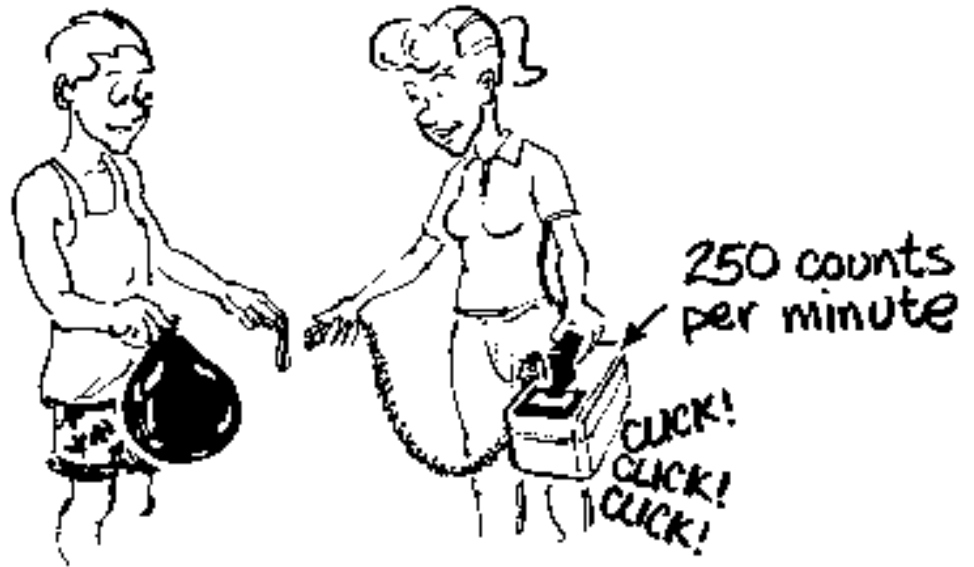
these estimates highly provisional, and a great deal of controversy surrounds the issue of radon. However, a linear relationship between radon exposure and incidence of lung cancer has been observed among uranium miners, where exposures to radon are hundreds of times greater than the average exposures in homes.

The propensity of the radon daughters to stick to a charged surface is so great that racquetballs and handballs have been found to acquire easily measurable radioactivity after being slammed around an enclosed court during a game. If you're not a handball or racquetball fan, a similar experiment is to blow up a balloon, charge its surface by rubbing it on a wool sweater or in your hair, and then walk around the room you want to sample for 10 minutes. Radon concentrations close to 4 picocuries per liter of air (the level at which the EPA recommends remedial action) increases the background counts on a simple Geiger-Müller counter held near the collapsed balloon by a factor of 10 or 20. You can even plot the decay rate and see the composite half-life for the radon daughters of about 45 minutes.

Home Radon Measurements

Many hardware stores carry radon measurement devices. These are usually of two types—charcoal canisters and alpha-track monitors. The charcoal canister is opened for several days, allowing the radon daughters to be absorbed on the charcoal. The canister is then sealed and returned to the lab, where the gamma radiation is measured. This type of device is especially good for initial screening tests, but atypical conditions during the measurement period could lead to an unrealistic value for the radon level.

The alpha-track monitor provides a better measurement of average exposure because it can be hung on a wall for months before it's returned to the lab for analysis. The device is called an alpha-track monitor because the alpha radiation from the radon daughters creates damage tracks in a piece of plastic. An etching process at the laboratory makes these tracks visible so they can be counted. The density of tracks is a direct measure of the amount of daughters that had been deposited next to the plastic.

A more accurate way to measure radon levels is to take a series of measurements with EPA-approved radon devices. A series, or a long-term measurement, is necessary because there are many variables that influence radon levels, including the time of day, the season, the geology of the soil, home construction, barometric pressure, humidity, moisture in the soil, rate of ventilation in the home, and so forth. As a result of so many variables, two similar houses built on adjacent lots may show vastly different concentrations of radon.

Cosmic Radiation. The heavens contribute further to our background with *cosmic radiation*. In outer space, such radiation consists of the complete spectrum of photons from radio frequencies to ultra-high-energy gammas as well as high-energy particles (protons and other atoms stripped of their electrons). On their way to the moon, the Apollo astronauts literally "saw" this last type of cosmic radiation—when their eyes were closed, they would occasionally notice tiny flashes of light as energetic heavy nuclei hit their eyeball.
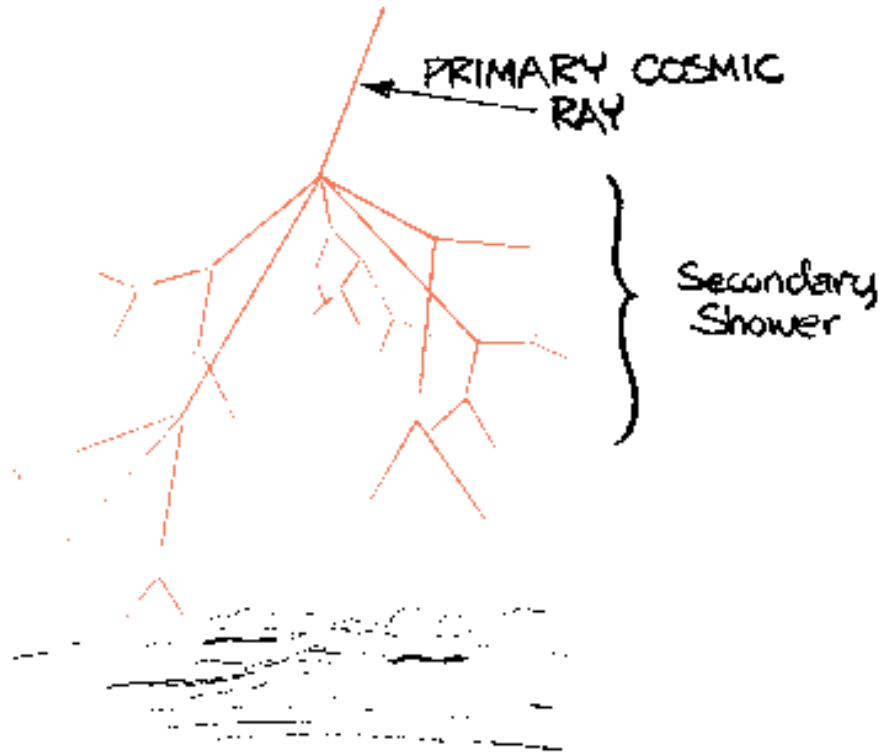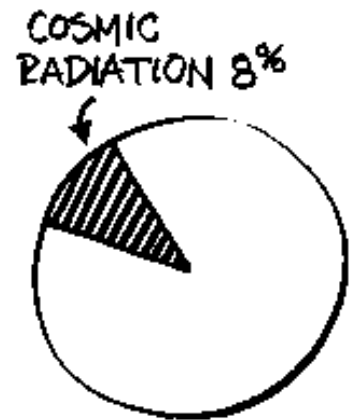
Cosmic radiation is constantly bombarding our atmosphere. This radiation has a very wide range of energies, but on the average, it's about 1000 times more energetic than that emitted by radioisotopes. Fortunately, the high-energy primary radiation is degraded by the upper atmosphere in collisions with atoms and molecules that generate a shower of lower-energy secondary radiation.
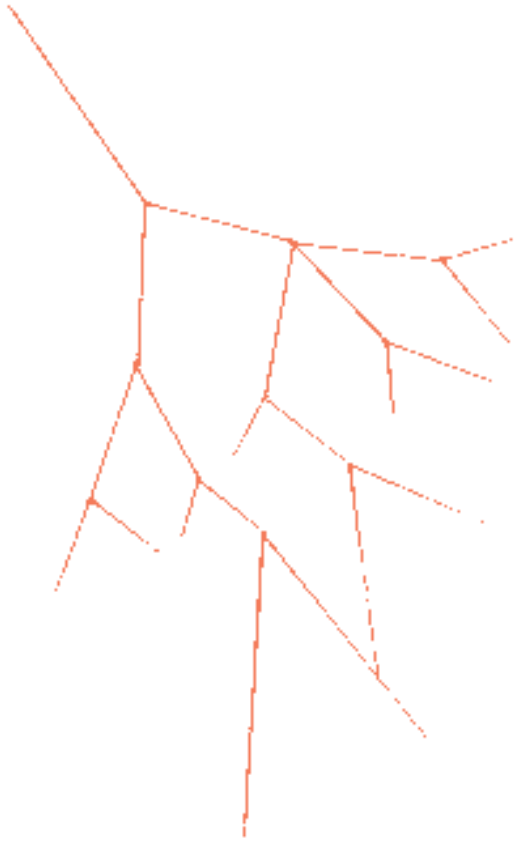
By the time the shower reaches the lower atmosphere, it has undergone many transformations and now consists of electrons, gamma rays, and more exotic but highly penetrating particles, some of which travel deep into the Earth. Roughly 20 particles per square centimeter arrive each second at the top of the atmosphere, but even with the many-particle showers occurring, only one particle per square centimeter per second remains at sea level.

Occasionally, an ultra-high-energy cosmic ray hits the atmosphere, generating a shower of millions of particles that spreads over several square kilometers of the Earth's surface. The initial particles have energies up to 10^{13} times that of normal radioactivity, but they hit the upper atmosphere with a frequency much less than one per square kilometer per year.

On the average, your dose-equivalent from cosmic radiation is about 39 millirem per year. People living at sea level receive the least—26 millirem. People living in a mile-high city receive 55 millirem, adding about 7 percent to their total annual dose.

Traveling 2000 miles in a jet airliner, adds another 2 millirem. A Geiger-Müller counter that reads about 10 to 15 counts per minute at sea level, will record about 400 counts per minute at 40,000 feet. It has been estimated that airline pilots and crew members receive a higher occupational radiation exposure than x-ray technicians or nuclear power plant workers!

40,000 feet

400 counts per minute

500

400

300

200

100

0

READING (counts per minute)

Irene's and Carl's Geiger-Müller Counter Readings at Different Elevations

10,000   20,000   30,000   40,000
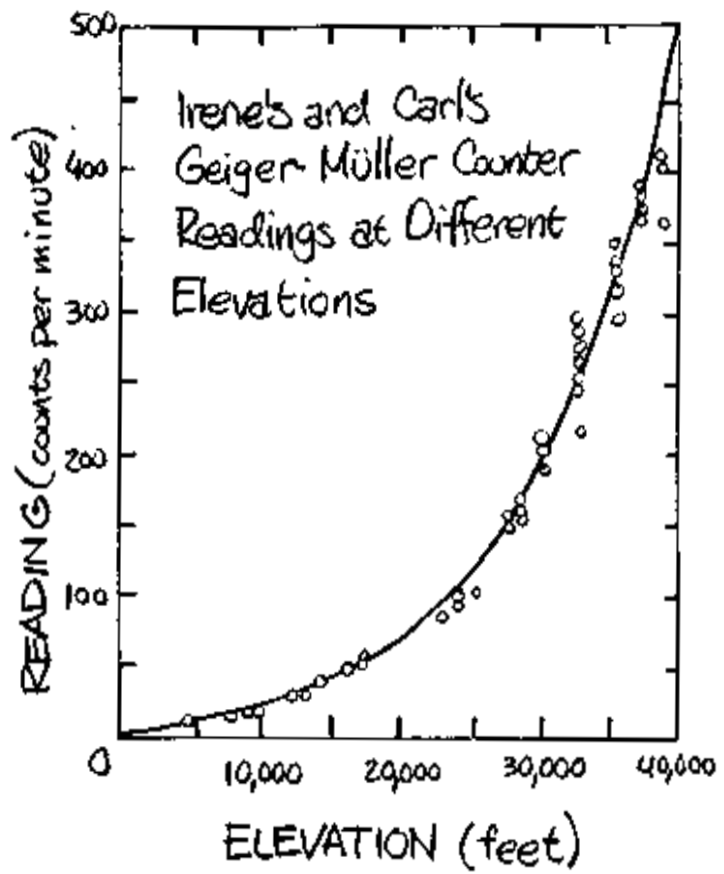
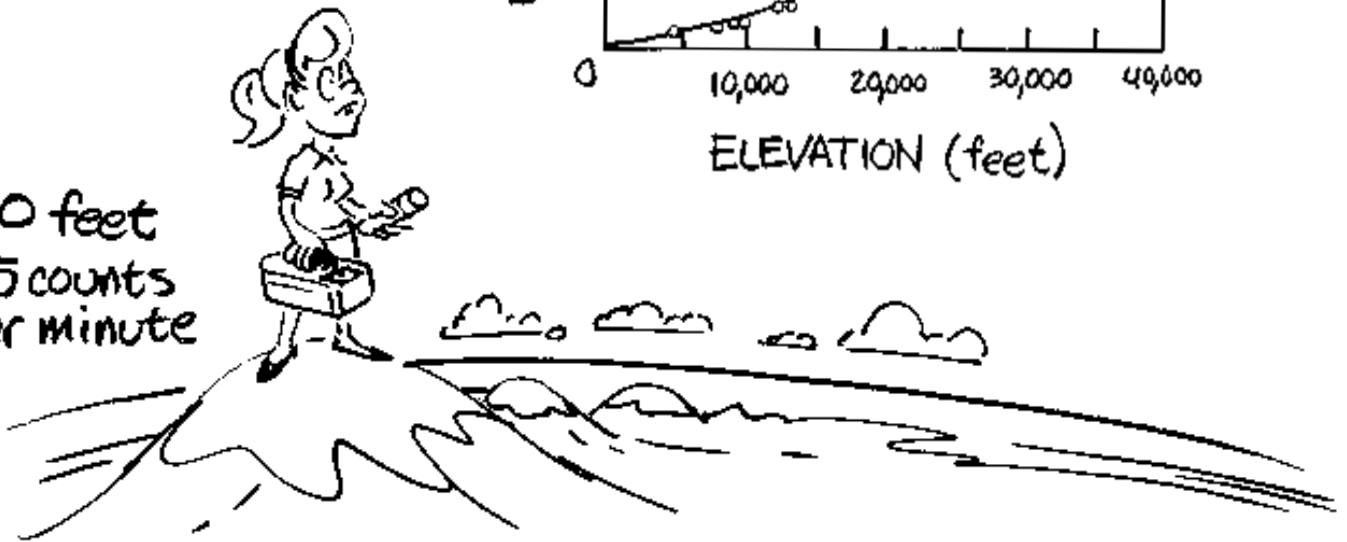ELEVATION (feet)

Geiger-Müller readings in counts per minute collected by Irene and Carl at various elevations while in a boat on a lake (lowest elevations), in a small plane with an altimeter (9000 to 17,000 feet), or during commercial flights while on business or vaction (above 20,000 feet) with the elevations announced by the pilot.
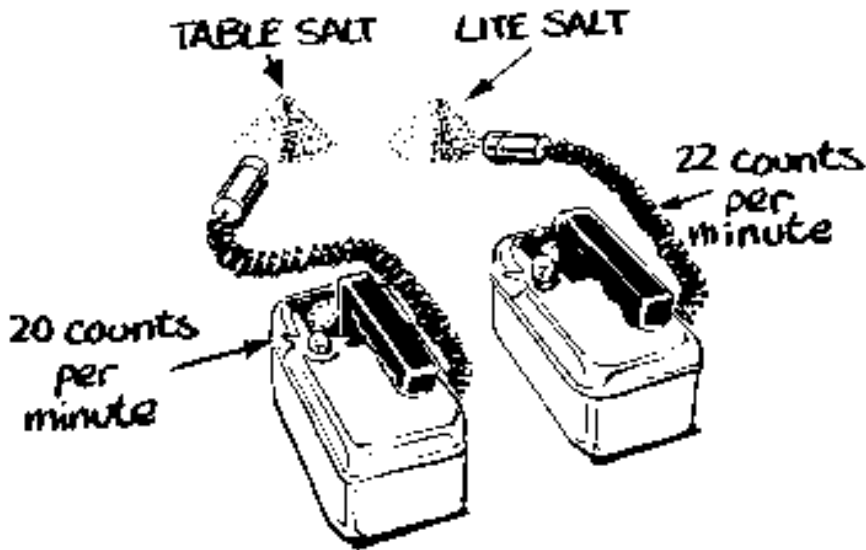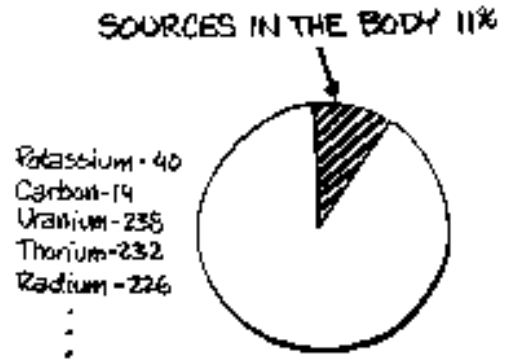
10,000 feet
25 counts per minute

Internal Exposures.   Because we are the stuff of stars, we also have long-lived radioisotopes in our own bodies! In fact, about 11 per cent of our total annual dose of ionizing radiation is from internal exposures. This amounts to an effective dose of 39 millirem per year.

There are two main sources of these radioisotopes—long-lived primordial elements and radioisotopes generated by cosmic rays. The most important example of the first type is potassium-40, which has a half-life of 1.3 3 10^9 years. Potassium is a major element in the biochemistry of life and is distributed throughout our bodies, particularly in muscle. Potassium-40 constitutes only 117 parts per million of natural potassium, but this small amount is enough for a 70-kilogram person to have more than 4000 beta disintegrations occurring in his or her body every second! This isotope is by far the predominant radioactive component in normal foods and human tissues.

SOURCES IN THE BODY 11%

Potassium-40
Carbon-14
Uranium-238
Thorium-232
Radium-226
:
:

TABLE SALT   LITE SALT

22 counts per minute

20 counts per minute

We also ingest uranium, radium, and thorium in the food we eat. For example, the skeleton of an average person is estimated to contain about 25 micrograms of uranium, which translates to about 0.3 disintegration per second (or one every three seconds). Thorium is the least active and least soluble of these three elements, so its contribution to our internal dose is small compared to uranium and radium.

Radium-226 and its daughters are responsible for a major fraction of the internal dose we each receive. An isotope a third of the way down the uranium-238 decay chain just before radon, radium-226 is present in both soil and water. It's chemically similar to calcium and barium, so it passes easily into the food chain. Although most foods, especially cereals, have radium in them, brazil nuts, which concentrate barium, have been found to have radium concentrations a thousand times greater than those in the foods making up the average diet (although this sounds large, it's still hard to detect with an ordinary Geiger-Müller counter and is not a particularly good reason to stop eating brazil nuts).

Eighty percent of the radium that stays in the body ends up in the bone. It has been estimated that the average adult skeleton receives several disintegrations per second from radium and even more disintegrations per second from its daughters, all of which emit mainly alpha particles. The original estimates for the health hazards of plutonium were based on knowledge about the effects of radium, because it was suspected that plutonium would also migrate to the skeleton.

A radioisotope that's a product of cosmic radiation is carbon-14. This isotope is generated when a neutron collides with a nitrogen-14 atom in the atmosphere and a proton is ejected, converting the atom to carbon. Carbon-14 has a half-life of 5730 years and so can circulate through the atmosphere and become incorporated in growing plants, trees, and other life. Such incorporation stops when the organism dies. Measuring the remaining concentration of the isotope in organic debris is a standard method for determining the age of archeological discoveries when the age is of the order of hundreds to tens of thousands of years.

A typical adult has enough carbon-14 to have about 4000 beta decays per second, the same as potassium-40. However, in this case, the energy of the beta is very low (155 keV compared to the 1.31 MeV betas and 1.46 MeV gammas of potassium-40), so the ionization energy deposited in the tissue is about a factor of 8 less.

Variations in Background. The choice of where you live is a major factor in your day-to-day exposure to ionizing radiation. Living in the Rocky Mountain states, such as Colorado, Wyoming, or New Mexico, can more than double your average exposure from environmental sources over the national average. This increase is due to both the geology (adding 65 millirem per year) and the mile-high altitude of the region (adding 28 millirem per year of solar radiation). On the other hand, living in the gulf region, such as Texas and Louisiana, an area close to sea level with a sedimentary geology, can reduce your average exposure from the national average by 6 or more millirem per year.
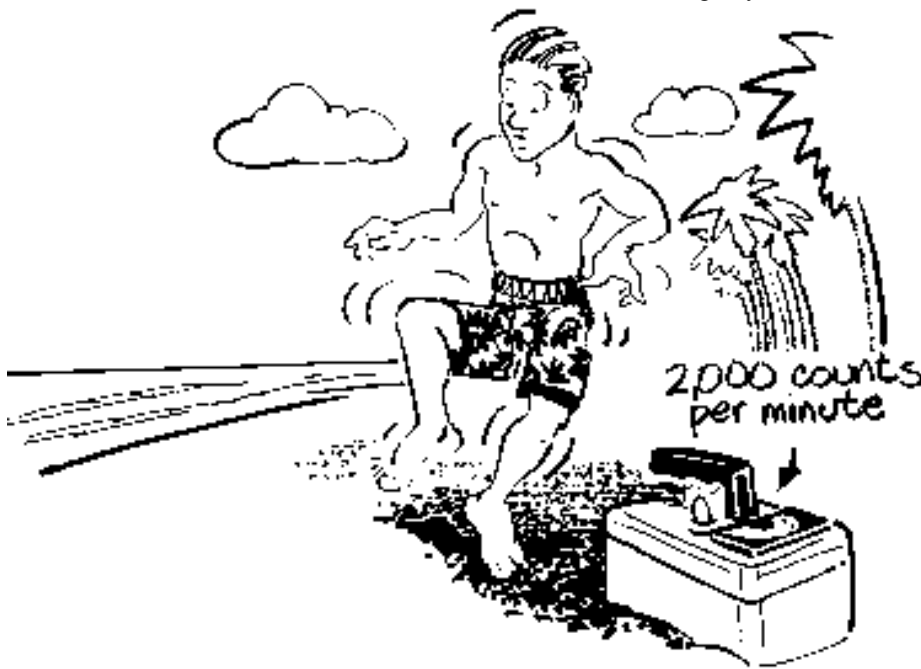
Several locations in the world are unique in having very high concentrations of thorium and thorium daughters in the soil that give rise to high external radiation exposures. For example, areas along the Brazilian coast and in the State of Kerala in India have monazite sands or soils containing thorium concentrations that can be as high as 10 per cent. Measurements on the black-sand beaches in Brazil, for example, show external dose rates that are a thousand times larger than the average terrestrial exposure (5 millirem per hour versus the normal 3 *micro*rem per hour).

People living in these areas do not, of course, spend most of their time directly on the beach but may, nevertheless, receive annual exposures higher than the maximum permissible occupational exposure to ionizing radiation in the United States (5 rem per year). Studies have tried to measure whether or not such continually high levels of radiation have caused detectable biological effects on populations in these areas, but so far they've been inconclusive.

Where's the best place to minimize the natural background radiation? One possibility is to live in a mine shaft that's been drilled into a thick layer of salt several thousand feet below the ground! The salt will contain very little uranium, and the earth will shield out most of the cosmic radiation. In this environment, a Geiger-Müller counter would record, say, about 2 counts per minute, rather than 10 to 20. However, only physicists trying to do experiments in an environment free of radiation, such as detecting the highly penetrating exotic particles in cosmic radiation, consider spending much time in such a habitat. If you continued eating normal food, you'd be the most radioactive object down there!

A tongue-in-cheek recommendation is that it's better for you and your companion to sleep in twin beds so as not to receive additional radiation from each other's bodies. However, at high elevations, it might be preferable to sleep close together so that your bodies provide a degree of mutual shielding from cosmic rays!
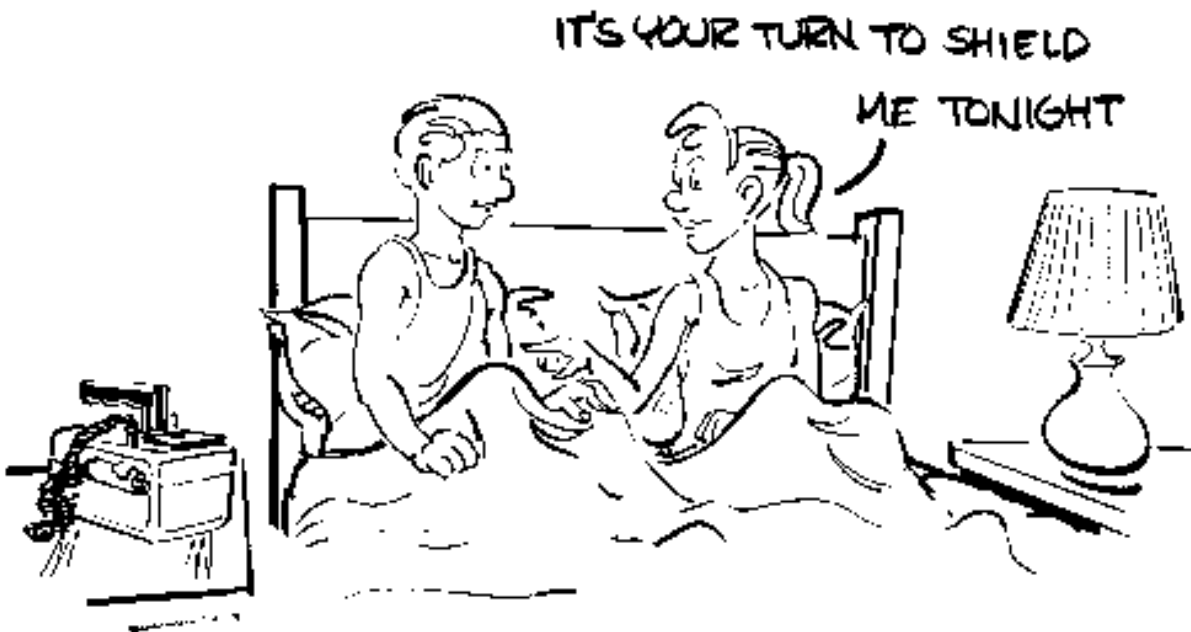
Man-Made Sources of Ionizing Radiation

"Well," you say, "What about our highly technological society? Aren't we adding all sorts of radiation sources?"

"Let's find out?" Irene says, and the three of you expand your search by exploring man-made sources of ionizing radiation. These sources include medical diagnostic procedures and treatments, consumer products, such as video displays and anti-static devices, life-style choices, such as airline travel and smoking, occupational exposures, such as mining and the nuclear-power industry, and world-wide exposures to the public, such as the fallout from atmospheric weapons testing (which peaked in the mid-sixties) and radiation leaks from nuclear facilities.

Medical Exposures. The greatest man-made exposures to average individuals are from medical procedures. For example, a typical diagnostic chest x ray increases a person's annual dose by about three per cent (10 millirem), a thyroid

scan using radioactive iodine may double the dose (adding another 300 or 400 millirem), and a dental x ray may only add 1 percent (1 millirem).

The purpose of diagnostic exposures is to see if a medical problem exists. As a result, there's a need to balance the potential benefit of learning about a serious but treatable problem against the damage that the radiation itself may do. The controversy over the use of x rays for detection of breast cancer in women, for example, is essentially a social exercise in deciding how to weigh the benefits against the costs. How often should such exams be given? At what age should they be started? What role should factors such as the latency period or the genetic predisposition to breast cancer play? The frequency of breast cancer in young women is so low that, for this age group, the risk of x rays generating damage or even the economic cost may outweigh the infrequent benefit of detecting an early tumor.

Advances in technology (such as more sensitive x-ray film) allow medical facilities to use lower exposures to gain the same information. Also, longer-lived radioisotopes that emit particle radiation are being replaced with shorter-lived radioisotopes that do not emit particle radiation. Iodine-131 has an 8-day half-life and emits beta particles, whereas iodine-123 has a 13-hour half-life and decays
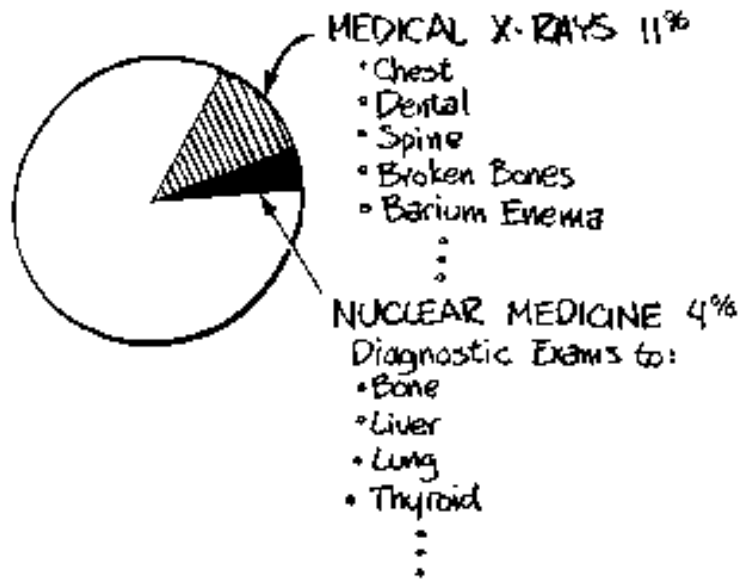
without emitting particle radiation, yet either can be used to examine the thyroid (if the patient is not so far from where the iodine-123 is produced that the isotope decays to too low an activity before it arrives).

In general, diagnostics that increase one's exposure to ionizing radiation by a fraction of the annual background appear to be a risk that the public finds acceptable. When other symptoms indicate the presence of a serious problem, higher exposures become acceptable.

Besides diagnostics, ionizing radiation can be used for medical treatment. Frequently, the purpose of the radiation is to kill a life-threatening cancerous growth, and exposure levels jump by orders of magnitude. Cancer patients undergoing radiotherapy receive many thousands of times their annual exposure to natural sources. Once again, though, advances in nuclear and accelerator technology are helping to make the radiation for certain therapies more site-specific, using the ionizing energy to kill the targeted cells with less collateral damage to healthy tissue.

Consumer Products. "What if I manage to stay out of my doctor's and dentist's offices?" you ask. "Where am I most likely to be exposed to ionizing radiation from man-made sources?"

Carl answers that it depends on life style and choice of consumer products. He and Irene discuss several examples to show the wide range of possible sources.

Before and during World War II, radioluminous paint containing radium was used on gauges, markers, instrument dials, and clocks and watches to make the numbers and marks visible in the dark. After the war and into the seventies, millions of radioluminous timepieces were sold annually. Gradually, though, radium was replaced by other radioisotopes, such as tritium and promethium-147, both of which emit relatively low-energy betas that, unlike the gamma radiation of radium and its daughters, can be stopped by the watch or clock face. The average annual exposure to radioluminescent sources is now probably less than 10 microrem.

Many smoke detectors use an alpha source of americium-241 to detect smoke. How does this work? In the detector, a continuous current flow is created by using a voltage on a metal plate to accelerate and capture the alpha particles and the ions they create as they travel through the air. The distance between the source and the metal plate is about an inch, just at the edge of the normal range of the alpha particles. If smoke particles float into this stream, they alter the current flow, and the alarm goes off.

Is the smoke detector a significant source of radiation exposure to the public? The metal plate and the plastic case of the detector easily block the alpha rays and only a tiny amount of gamma radiation (from impurities and the neptunium daughters) escapes. Even with a radiation detector placed against the case of the smoke detector, radiation above normal background is difficult to detect. The main exposures from the americium-241 are to workers assembling the devices. Another concern, of course, is the possible leakage of the radioisotope into the environment when the detectors are discarded.

CONSUMER PRODUCTS 3%
• Tobacco
• Building Materials
• Natural Gas
• Smoke Detectors

30,000 Counts per minute

One of the most radioactive of consumer devices is the static eliminator, such as certain brushes used to clean negatives and CDs. These devices also take advantage of the ionizing power of alpha particles—in this case, reducing electrical-charge buildup. The brush is constructed so that the range of the alpha particles in air is about the distance from the source to the surface being cleaned. Generally, these devices use polonium-210 and are extremely active when you first buy them. However, the half-life of polonium-210 is only 138 days, so after seven half lives (2.5 years), the ionizing ability of the device will be a hundredth of what it was when purchased. If the brush has been used regularly for that long, the bristles will be dirty anyway.
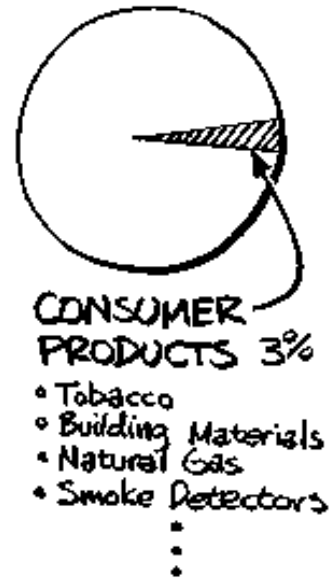
In past years, a source of ionizing radiation in the home was certain types of ceramic dinnerware. Manufacturers would mix uranium oxides or sodium uranite in their glazes to render colors of black, brown, green, and the spectrum from yellow to red. Such tableware can add tiny amounts to a person's annual exposure. More important, though, is ingestion of uranium if the glaze is cracked or hasn't been applied properly. Also, in some cases, the uranium can be leached from the glaze. The main hazard, however, is the chemical toxicity of the uranium (and lead) rather than the radiation. But it's interesting to check your ceramic dinnerware, such as the older, red-orange Fiestaware, with a Geiger-Müller counter to see if it's radioactive.

Other surprising sources of small but steady exposures (tenths of a rem per year) to ionizing radiation are dental products and eyeglasses. Uranium has commonly been used in porcelain teeth and crowns to add whiteness and fluorescence—sparkling white! Certain ophthalmic glasses used for lenses and eyeglasses contain oxides of thorium and rare earths that make them radioactive. Rose-tinted glasses that have had thorium salts added as the tinting compound are especially bad. With increased regulation and the greater use of plastic lenses, this type of

1800 counts per minute

25 counts per minute
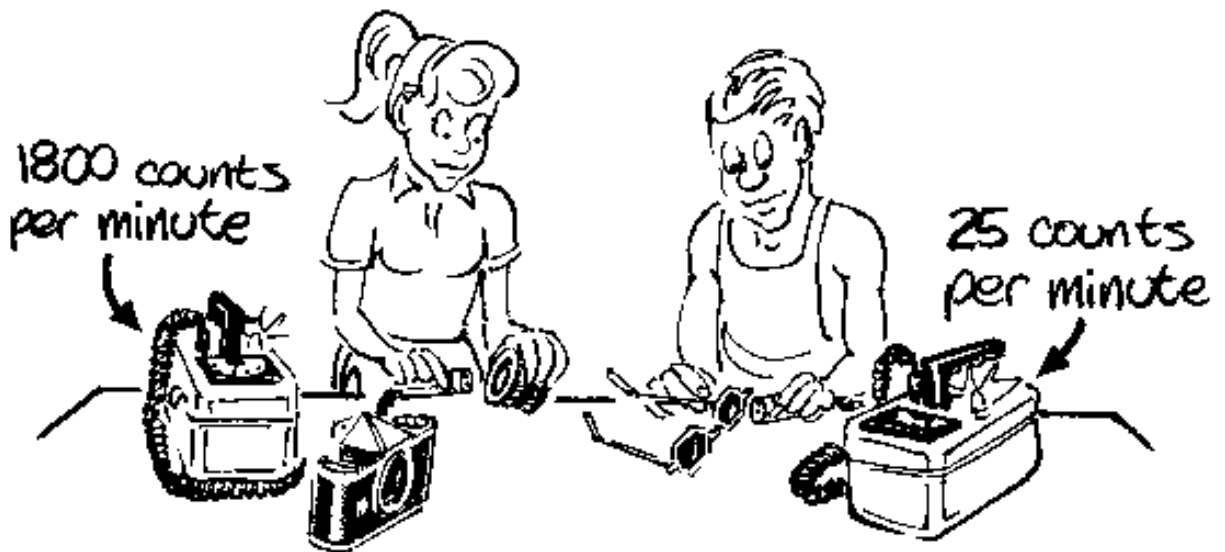
exposure to the public is being reduced. However, you may find that some of your camera lenses are radioactive because of thorium that has been added to increase the index of refraction.

Life Choices. Potentially one of the most serious radiation exposures for many people is cigarette smoking. The large tobacco leaf—like the absorbing surface of charcoal in a radon test device—provides an excellent surface for collecting the

long-lived daughters of airborne radon. As a result, tobacco has above-average concentrations of lead-210 and polonium-210. A 1987 report by the National Council on Radiation Protection and Measurements states that "tobacco products probably contribute the highest dose to the U.S. population of all consumer products."

Although external exposures to people from these radioisotopes is minute, smoking the tobacco creates large exposures to the lungs. The compounds of polonium-210 are generally volatile and are probably just breathed in and out. However, insoluble particles of lead-210 may concentrate in "hot spots" where the bronchi divide, leading to the growth there of the polonium-210 daughter and high local exposures. Small portions of the lungs receive annual dose equivalents that are huge (16,000 millirem) compared to the dose other cells in the body are getting from natural background radiation (360 millirem). This estimated dose equivalent is 8 times larger than that to lung cells from radon (2,400 millirem).

It's suspected that such radiation may be one of the major causes of lung cancer for smokers. In fact, certain studies of radon exposures show a synergistic relationship between smoking and radon—the combined risk appears to be greater than simply an additive effect of the two risks.
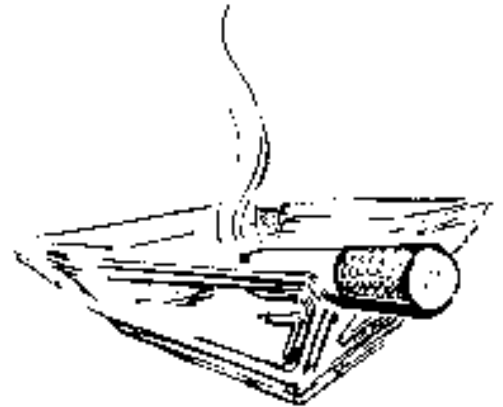
Another life choice that affects your annual exposure to ionizing radiation is the type of buildings you live and work in. For example, a masonry home, such as brick, stone, concrete, or adobe, can add another 2 per cent (7 millirem) to your annual exposure from radioisotopes in the building materials. This exposure is in addition to any effects the type of construction has on radon accumulation in the building.

Occupational Exposures. "But what about the people who have to work with this stuff?" you ask. "Aren't there problems for radiation workers?"

Indeed, one of the major ways people can be exposed to ionizing radiation at levels significant compared to the natural background is through the workplace. The medical application of x rays, industrial radiography, and work at nuclear power plants or for nuclear-weapons defense contractors obviously have the potential to expose workers to significant doses. Such occupations are carefully regulated and the workers are continuously or frequently monitored. Other workers, such as

OTHER
MAN-MADE
<1%

• Occupational 0.3%
• Fallout < 0.3%
• Nuclear Fuel Cycle 0.1%
• Miscellaneous 0.1%
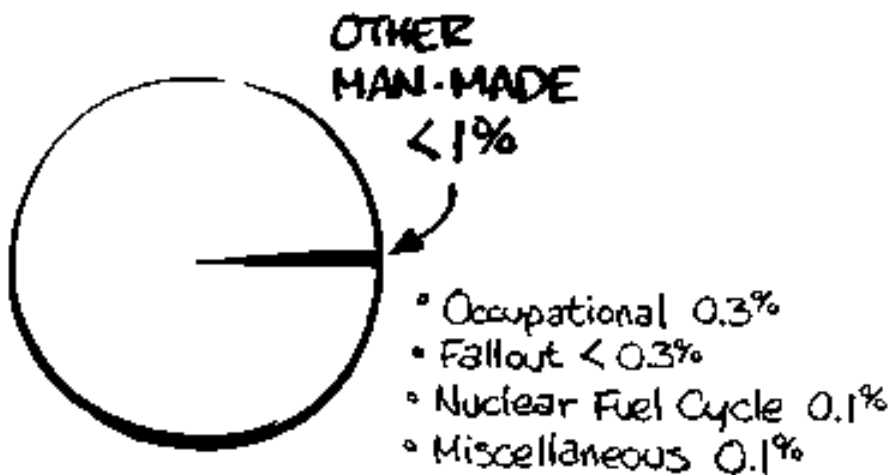
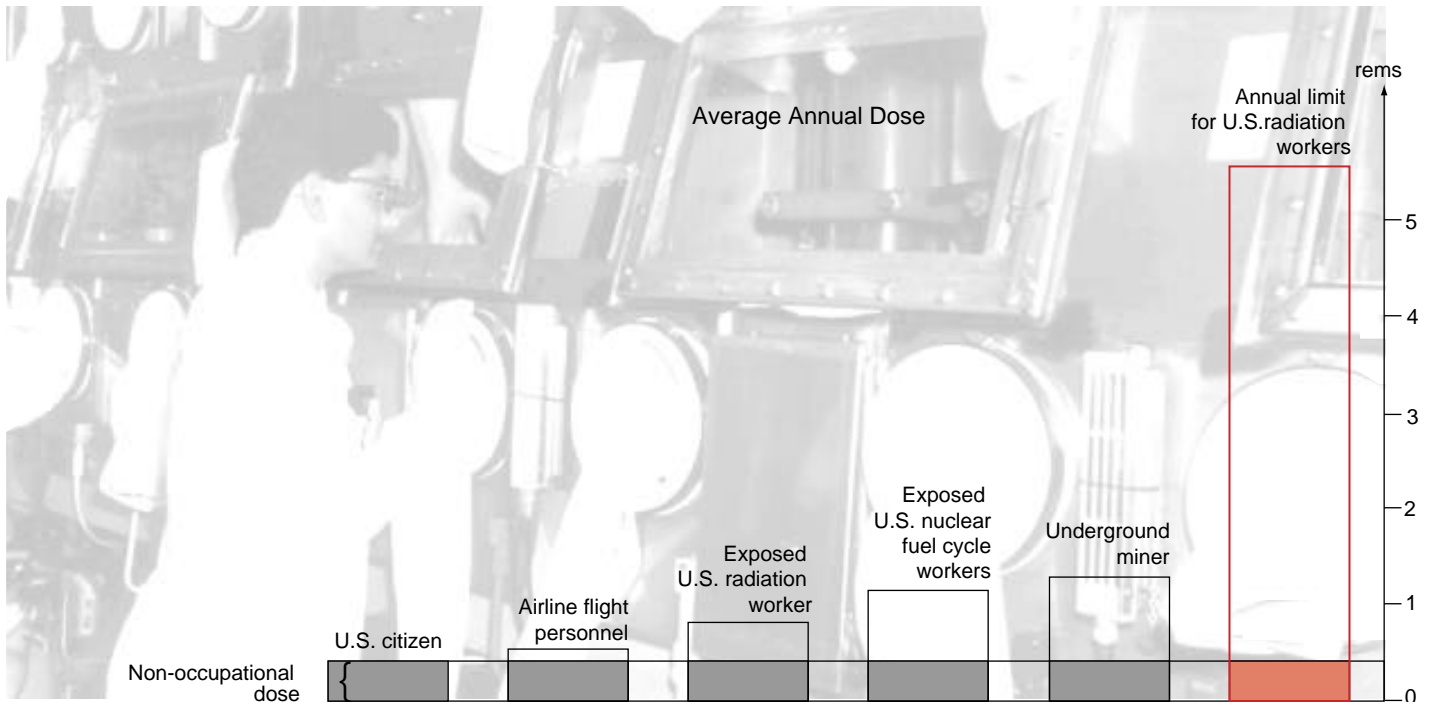mining or airline personnel can also receive significant exposures.

The 1987 report by the National Council on Radiation Protection and Measurements estimates that about 1.6 million workers were potentially exposed occupationally to ionizing radiation in 1980, but only about half of those received measurable doses. The average effective dose to those in the latter group added about 60 per cent to their annual dose (210 millirem).

Exposures within certain groups were, of course, higher than the average. Exposed workers involved with the nuclear fuel cycle, on the average, added 600 millirem to their annual effective dose of ionizing radiation, almost tripling their total. The annual limit established by national standards for people in this group is 5 rem per year, 14 times larger than the national annual average.

Underground miners, on the average, tripled their annual effective doses (an addi-

tional 700 millirem), chiefly because of the alpha radiation of radon daughters. This type of exposure is minimized by using proper safeguards, such as adequate ventilation or filtered breathing devices. During World War II, such provisions were not used with the uranium miners in the southwest, resulting in high numbers of lung cancers among the miners.

Flight personnel on airlines flying at altitudes around 20,000 or 30,000 feet, receive, on the average, about 100 millirem per year (the same as ten diagnostic chest x rays, except the exposure during flight is to the whole body, not just the chest). This example illustrates the importance of the time of exposure, because everyone, including the passengers, receive only 0.2 millirem per hour, but the flight personnel are in the air about 500 hours a year.

Exposures to the General Public. "But how much of the radiation from these occupational sources leaks out to the public," you ask next.

Splitting the Nucleus

The heaviest nuclei, those of plutonium and uranium for instance, may break into two large fragments, a process called *fission*. Sometimes fission may occur in the undisturbed nucleus (spontaneous fission), and sometimes energy has to be added to the nucleus, perhaps by the collision of a slow neutron (slow, or thermal fission) or perhaps by the collision of a more energetic neutron (fast neutron fission). Usually, several energetic neutrons fly out in addition to the two large fragments. If these neutrons collide with other unstable nuclei, further fissions can take place. Thus, each fission increases the number of neutrons available to generate more fissions, which is the basis of the chain reaction that powers nuclear reactors and the nuclear-fission bombs.

An example of a neutron-induced fission is:

$$_{0}n^{1} + {}_{92}U^{238} \rightarrow {}_{56}Ba^{139} + {}_{36}Kr^{97} + 3\,{}_{0}n^{1}$$
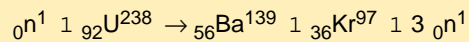
where the subscript on the left gives the atomic number, the superscript on the right is the nucleon number, and $_{0}n^{1}$ stands for a neutron. Note that the total number of protons (92) and the total nucleon number (239) is conserved in the reaction.

The two main fission fragments are typically unstable and, thus, subject to further decay and release of radiation. Neutron-induced fissioning of uranium or plutonium creates a large distribution of such fragments, typically ranging in nucleon number from 80 to 160. The most unstable of these decay rapidly. Others, including daughters of the short-lived fragments, are more stable with longer lives.

In any fission chain reaction, large numbers of neutrons are flying around. Because neutrons are neutral, they're not repelled by the nucleus and are frequently absorbed by the nuclei of other atoms, creating new radioisotopes. This process is called *neutron activation*. (It should be noted that when materials are exposed to alpha, beta, gamma, or x rays, any similar activation processes only occur at much, much lower levels. Thus, irradiating strawberries with gamma rays to kill bacteria does not make them radioactive.)

Much of the radioactive fallout of atmospheric weapons testing is a result of neutron activation of ground debris and materials in the air. Likewise, one of the main design considerations with nuclear reactors is to minimize production of radioisotopes by choosing structural materials and coolants that are low neutron absorbers. It's equally important to eliminate corrosion products and other impurities that can be activated as they circulate through the core.

The radioactive waste that the nuclear power industry is struggling to figure out how to store or eliminate consists of both fission fragments and neutron-activated radioisotopes. The main concern in accidental releases from reactors are the more volatile fission fragments present in the core. However, much of the neutron-activated material is present in aqueous waste, which can leak into the environment over long periods.

It's been estimated that on the first day of a nuclear power plant accident around 83 per cent of the dose received by people downwind is from iodine-131. The major contributor to the dose integrated over several years is from another radionuclide, cesium-137, which emits beta and gamma radiation and has a thirty-year half-life. ∎

"Actually, very little," Irene answers. "For example, it's estimated that the U.S. population receives only an average of about 0.4 millirem, or 0.1 per cent of their average total annual dose, from all operations related to nuclear power generation."

"From all operations?"

"Yes. That includes mining, milling, and enrichment of the ores, fabrication of fuel elements, releases by nuclear power plants, waste storage, and transportation. Of course, these numbers have been averaged over the entire U.S. population."

"What about someone living right next to one of the sites?"

The 1987 report by the National Council on Radiation Protection and Measurements estimates that the "maximally exposed individual member of the public" receives only 0.6 millirem per year from pressurized water reactors and 0.1 millirem per year from boiling water reactors, the two common types of reactors in the U.S. People living close to other types of operations can receive higher doses. For example, the maximum effective dose from airborne effluents might be 260 millirem per year from certain milling operations and 61 millirem from certain underground mining operations. In both cases, these numbers were based on the assumption that the exposures were at the maximum allowed levels. In practice, much lower exposures are usually experienced, and many operations have lower maximum values than the ones given here (some milling operations are as low as 0.4 millirem per year).

"That's fine for normal operations, but what if there's an accident?"

Certainly, the potential doses to the U.S. population from a major nuclear power plant accident could be very significant. The worst accident to date in the U.S. occurred at the Three Mile Island Nuclear Plant on March 28, 1979. The maximum individual effective dose to the public from that accident was less than 100 millirem, and the average dose to people living within a 10-mile radius of the plant was 8 millirem.
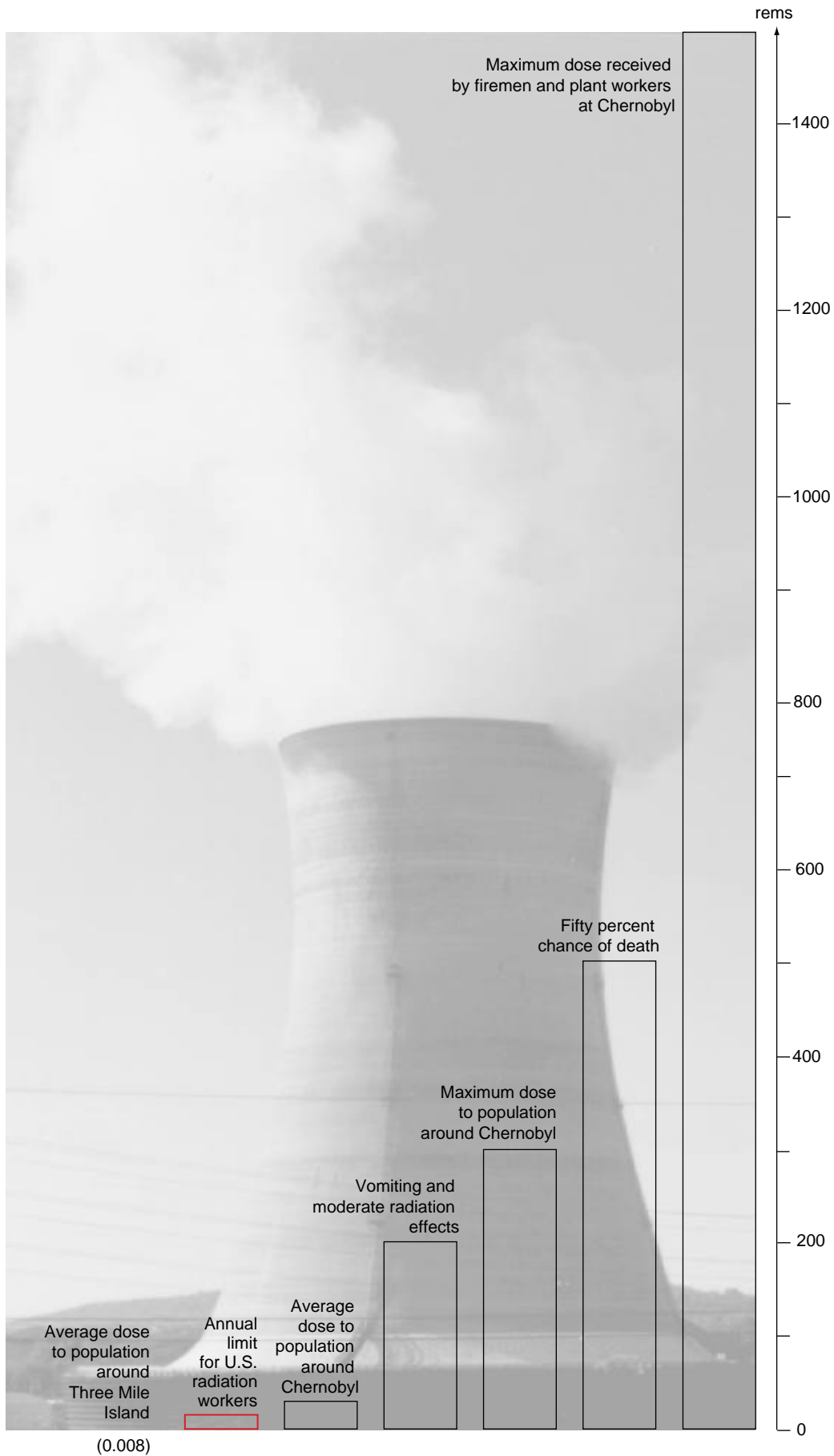
The Chernobyl accident in Russia on April 26, 1986, was much worse. Thirty-one people (firemen and workers at the plant, who received exposures up to 1600 rem) died from the accident, and 135,000 people in the region were permanently evacuated. Reports by the Russians to the International Atomic Energy Agency (IAEA) give the average dose to the evacuees as 12 rem—1500 times greater than the average dose to people around the Three Mile Island plant.

The distribution pattern of exposures around Chernobyl was very uneven, so that doses to the public ranged from 0.4 to 300 rem (which means some people received a dose of up to 800 times their annual background in only a few days!). A dose of 100 rem to an adult normally produces clinical signs of radiation sickness and requires hospitalization. These total doses included external gamma radiation, beta radiation to the skin, and internal doses to the thyroid from iodine-131.

In the first year after the accident, it has been estimated that residents of seven western European countries received doses that, for adults, ranged from 130 millirem in Switzerland to 2 millirem in southern England. Adults in Poland received up to 95 millirem.

Pripyat is now a radiation ghost town. Nearly 3 million acres of agricultural land

rems

Maximum dose received
by firemen and plant workers
at Chernobyl

—1400

—1200

—1000

—800

Fifty percent
chance of death

—600

Maximum dose
to population
around Chernobyl

—400

Vomiting and
moderate radiation
effects

—200

Average
dose to
population
around
Chernobyl

Average dose
to population
around
Three Mile
Island

Annual
limit
for U.S.
radiation
workers

0

(0.008)

The Collective Effective Dose: Looking at Populations

Absorbed dose, dose-equivalent, and effective dose all apply to individuals—or at the most, to an average individual. How does one estimate the risk of exposures to various populations?

To start with, we calculate the average effective dose for the people being exposed and then multiply by the number of people who have been exposed. The resulting value, the collective effective dose in units of person-rem (or person-sieverts), is a measure of the expected cancer risk in the exposed population.

Let's compare two drastically different exposures to see how this might work. The NCRP reported that in 1980 nuclear-fuel-cycle workers received an average effective dose of about 600 millirem. There were 91,000 people in the exposed group, so their collective effective dose was 54,600 person-rem. The NCRP also estimated that people using natural gas cooking ranges received (from radon in the gas) an average effective dose of about 0.37 millirem—1600 times lower per person than what the nuclear workers received. However, 125 million people were exposed to natural gas cooking ranges, so their collective effective dose was about 46,200 person-rem, almost the same as the nuclear workers. This means that about as many cancers should result from the use of natural gas for cooking as from workers involved with the nuclear fuel cycle.

Do you believe this? Remember, estimates enter the calculations in at least two places. First, radiation weighting factors are used so that the nuclear workers irradiated with neutron and gamma irradiation can be compared with people using gas ranges irradiated with the alpha and beta radiation of radon daughters. Second, tissue weighting factors are used to compare the whole-body irradiation of nuclear workers to the lung-tissue irradiation from deposited radon daughters.

A key assumption in all such calculations is that risk is linearly proportional to dose and independent of dose rate! Thus, high doses to a small group of people are assumed to lead to the same number of cancers as low doses to a proportionately larger group of people. Likewise, a one-rem dose from a short, single exposure is assumed to create the same harm as a one-rem dose from a slow, continuous exposure.

Now what is the increased risk to the entire U.S. population of people cooking with natural gas or of other people working in nuclear power plants? We divide the collective effective dose by the entire U.S. population (230 million in 1980) to obtain the average effective dose per capita. In other words, the dose has been spread out over the entire population.

With 54 per cent of the population cooking with gas, the annual dose is 0.2 millirem per person in the U.S. instead of the original 0.37 millirem per person exposed to gas-range cooking. With the nuclear workers, however, the annual dose is 0.2 millirem per person in the U.S. compared to the very large original dose per exposed worker of 600 millirem.

In many ways, of course, the average effective dose per person in the U.S. is highly artificial, especially when the group of people actually exposed is small. But this dose is a measure of the expected increase in cancers in the U.S. due to the particular activity. Such a number is the basis of statements you may read in the newspaper (at least, it should be the basis) that cite the additional cases of cancer that may occur in the U.S. if, for example, the number of nuclear power plants is doubled.

Of course, the people most likely to contract those cancers are the individuals in the "exposed" population, and going further, those individuals within the group who received doses well above the group average. ∎

in the region have been lost for decades because of contamination with fission-product radioisotopes and plutonium. As this single accident shows, the potential damage from nuclear power plant accidents is very serious.

How Much Do I Get?

As our discussion of natural and man-made radiation sources makes evident, the types and amounts of exposures to ionizing radiation vary considerably from place to place, from person to person. The pie chart we've been using (page 29) summarizes the averages for people living in the United States based on the average annual effective doses.

As we've shown, doses from natural sources, including radon, account for 82 per cent of the average dose. Radon by itself, including radon in water pumped from underground, accounts for 55 per cent—the largest single factor. Cosmic and terrestrial sources each add another 8 per cent. Internal sources, such as potassium-40, make up the final 11 per cent for doses from natural sources.

Man-made sources account for 18 per cent of the dose, the largest being 11 per cent from medical x rays. Consumer products add another 3 per cent. Occupational exposures and exposures to the public from nuclear power plants and the fallout from weapons testing add less than 1 per cent.

Does our chart represent fair comparisons? For example, the internal dose and the medical x ray dose are both 11 per cent. You might say your own body is irradiating you from inside to the same extent that you're being irradiated from the outside by medical x rays. Of course, the internal dose is a slow, continuous bombardment; medical x rays are occasional, relatively intense doses. Furthermore, the dose given here is *averaged over the entire U.S. population*, an average based on the *collective effective dose* (see previous page). Clearly, actual individual doses may have large variations about this average. This is especially true for such exposures as medical x rays where many people have no x rays during the year and others may have several.

Why is such averaging useful? If the response to dose is linear, then the averages allocate the damage among the various sources, and suggest, for example that medial x rays and internal dose lead to the same number of cancers nationwide. It says nothing about individual risk, and it's certainly not correct if the dose response is nonlinear. Nevertheless, the average collective effective dose remains one of the more useful ways to draw risk comparisons between apples and oranges—or rather, between cosmic rays and thoriated camera lenses.

The table that follows (next page) is an attempt to help readers make a more satisfactory assessment of their own annual radiation doses. Remember, the average annual dose of ionizing radiation per person in the United States is about 360 millirem per year.

As you can see, we live in a sea of ionizing radiation, most of which has been here from the birth of the planet. Man's ability to manipulate radioactive materials and to create new sources of radiation is adding to the amount of ionizing radiation we receive each year.

Personal Radiation Dose Chart

(*Adapted from Personal Radiation Dose, American Nuclear Society, 1990
with further data from NCRP Report No. 93 and NCRP Report No. 95.*)

Estimate your average annual effective dose in millirem by adding the numbers in the right column, including the numbers you choose for each category with a blank space.

Where you live:

Cosmic radiation at sea level 26
For your elevation in feet:

500-1000 ft:	2	1000-2000 ft:	5	2000-3000 ft:	9
3000-4000 ft:	15	4000-5000 ft:	21	50000-6000 ft:	29
6000-7000 ft:	40	7000-8000 ft:	53	8000-9000 ft:	70
9000-10,000 ft:	107				

_____

Terrestrial:
Live in state bordering the Gulf or Atlantic from Texas east and north: 23
Live in Colorado Plateau or Rocky Mountain State: 90
Live anywhere else in the United States: 46 _____

Internal:
What you eat and drink 40
Radon: Insert a value equal to your average radon level (in picocuries per liter x 100)
or use the U.S. average of 200 _____

Life Choices:

Live in a stone, brick, concrete, or adobe building: 7 _____
Live within 50 miles of a coal-fired electric utility plant: 0.03 _____
Live within 50 miles of a nuclear reactor: 0.01 _____
Jet airline travel - each 1000 miles traveled annually: 1 _____
Smoke cigarettes - multiply packs per day by 870 (high degree of uncertainty) _____
Use a typical distribution of modern consumer products (U.S. average): 10 _____
Cook and heat with natural gas: 2 _____
Work with commercial fertilizer products (e.g., farming): 1 _____

Medical Exposures:

Received a diagnostic x-ray (U.S. average): 40 _____
Received a thyroid scan: 590 _____
Wear a plutonium-powered cardiac pacemaker: 100 _____
Received other medical radiation exposure (ask physician): _____

Occupational:

If you work with radiation sources, add your annual dose in millirems, or select
the 1980 average value for exposed workers in you occupation:

Air flight crew: 670	Nuclear fuel cycle: 600	Medicine: 150
Industry: 240	DOE Contractor: 180	Well logger: 420
Government: 120	U.S. Public Health Service: 47	
Open-pit uranium mining: 115	Underground mining: 700	_____

Public Exposures from Nuclear Age:

Transportation of radioactive materials: 0.6
Fallout from atmospheric testing: 0.5 _____

Your Annual Effective Dose (millirem): Sum the numbers in the right column: _____
(U.S. Average: 360 millirem)

Many of the new radiation sources are highly beneficial to man and society as sources of energy, as research tools, and as diagnostic and therapeutic tools for medicine, but each source presents additional risks as well. Other sources of ionizing radiation are an incidental result of our consumer goods and life styles.

For our society to use radiation wisely, it's necessary to understand the specific dangers of individual sources rather than to bring wholesale condemnation to ionizing radiation. Reaching such understanding certainly requires more effort, but in the long run, such effort will certainly serve our society. We will be much more capable of finding the most satisfactory balance between the risks and the benefits of ionizing radiation. ∎

Acknowledgements

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