

Ionizing Radiation Hazards: Dangerous Goods IV

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If system safety engineering had to be described in one sentence, one could do worse than to describe it as, “The study of unwanted flows of charge (electronics problems), information (software and cyber security problems), matter and energy (both dangerous goods problems)” [Ref. 1].

The unwanted flow of matter is governed by chemical equations like Fick’s Law (diffusion of mass), the Arrhenius Law (rate of reaction), and most importantly the Nernst Equation (yielding the electrochemical potential of species). In addition to these chemical equations, the other unifying sutra (or “suture”) of eclectic dangerous goods problems, and the one that will be employed in this paper, is the construction of Gaussian surfaces through which *energy* may flow. This energy could be electromagnetic radiation, heat, ionizing radiation, non-ionizing radiation (light), acoustic energy, or even just fields. Once an equation is developed for the flow through a unit area of a Gaussian surface, a comparison can be made between an *exposure* and some *Exposure Limit*. And, there are many different types of limits depending on the conditions of the exposure. But, in general, if an exposure is below the Exposure Limit, then safety is implied. Above the limit, steps must be taken to provide *shielding*.

In this paper, attention will be focused on the hazards produced by flows of *ionizing radiation* energy emitted from a *source*. Ionizing radiation can penetrate deeply into matter and is capable of removing electrons from neutral atoms all along its path. Such widespread damage can disrupt DNA and, ultimately, result in carcinogenic tumors.

Ionizing radiation includes cosmic rays, γ -rays, X-rays, β -rays, and α -rays, in the order of decreasing penetrating power, but does not include visible laser light, infra-red (IR) radiation, and usually not ultra-violet (UV). Cosmic rays are a mixture of energetic particles (primarily protons from space, but also secondary neutrons produced in the upper atmosphere) that continually bombard the Earth. X-rays are simply the high energy electromagnetic photons emitted from the lower energy levels of cathode target atoms during electron bombardment in a vacuum tube. α , β , and γ rays are emissions from an unstable atomic nucleus and consist of helium nuclei, electrons (or positrons) and *very* high energy photons, respectively. Consequently, sources of ionizing radiation include the sky, X-ray tubes, cobalt-60 point sources, lumps of uranium ore, the earth (since some radioactive elements and isotopes are natural con-

stituents of the Earth’s crust), and even ourselves (since we contain small amounts of radioactive carbon-14 and other radioisotopes).

So, the first lesson learned is that we can *never* completely escape from exposure to radiation. In fact, 33.3% of our natural radiation exposure comes from cosmic rays, another 47.6% comes from the Earth, and 19.0% comes from ourselves [Ref. 2]! In this paper, low and medium levels of radiation will be of primary interest, because that is generally all that most system safety engineers will have to deal with. High-level ionizing radiation hazards, such as the handling of significant quantities of synthetic isotopes of plutonium or californium, or managing nuclear fallout, are specialties outside the scope of this work and will only be touched upon briefly.

Definitions and Units

Fundamental to any quantitative discussion of ionizing radiation is the units by which it is measured. Therefore, the following definitions are seminal [Refs. 3 & 4]. All radiation energies are in thousands or millions of electron volts (Kev or Mev, respectively), where 1 electron volt (ev) equals 1.6×10^{-19} joules.

1. **1 Roentgen (R)** = the quantity of X (or γ) radiation needed to form 1 esu of charge (equivalent to 2.082 billion electrons) in one cubic centimeter of air at standard temperature and pressure (STP). One roentgen is the basic unit of ionizing radiation intensity.
2. **1 RAD** = 1 “Radiation Absorbed Dose” = the deposition of 100 ergs of energy per one gram of any medium. Note that 1R of X radiation (250 Kev) will deposit 83.8 ergs of energy per gram of standard air, and approximately 93.8 ergs per gram of body tissue.
3. **Relative Biological Efficiency (RBE)** = the efficiency of various forms of ionizing radiation to produce human biological damage relative to X-rays (250 Kev), *given the same amount of absorbed energy*. The RBE is an empirical value that varies with radiation energy, tissue type, the biological effects considered, and the amount of tissue O_2 . Table 1 represents conservative values for the most sensitive cell types.
4. **1 REM** = 1 “Roentgen (Radiation) Equivalent Man” = the amount of ionizing radiation of any type which produces the same damage to humans as 1R of approximately 250 Kev X radiation. Conversely, the equivalent number of X-ray roentgens needed to produce the same amount of human

Table 1 – Radiation Type vs. RBE [Ref. 4]

Radiation Type	Relative Biological Efficiency (RBE)
X rays (250 Kev) and γ rays (Co-60 source)	1
β rays (~1 Mev)	1
α rays (4-8 Mev)	20
Fast neutrons (Cosmic ray component)*	10
Thermal (slow) neutrons (near nuclear reactor cores)	5

*Having energies in the range 0.1 to 10 Mev. Above 10 Mev, the RBE increases rapidly.

biological damage caused by another form of ionizing radiation is approximately

$$\text{REM} = R \times \text{RBE}, \quad (1)$$

where **REM** is the number of REMs of radiation, **R** is the number of roentgens of radiation, and **RBE** is the Relative Biological Efficiency for a given radiation type. Note: for X-rays (250 Kev), 1 REM \approx 1 RAD.

5. **1 Sievert** = 100 x (1 REM). One Sievert is a lot of radiation and, according to some models, produces a 5.3% chance of developing cancer at some time in the future. The microsievert (μSv) is a more convenient unit of measurement that is used by many γ -ray detectors and will be used for the remainder of this discussion.
6. **1 Curie (1 Ci)** = a measure of radioactivity equal to 3.7×10^{10} disintegrations per second. The radioactivity of 1 gm of ^{226}Ra is approximately 1 Ci. Unlike the other measures of radioactivity above, the Curie is intrinsic to the source, not the target.

7. **Linear Energy Transfer (LET)** = A measure of the energy lost per micron of tissue (ergs/μ) along the track traveled by any ionizing particle. Slow highly charged particles (e.g., α -particles) cause more tissue damage (have a higher LET) than particles that are faster and less highly charged (e.g., high energy protons).

Detectors

Geiger Counters

The definition for R is particularly suitable for determining radiation levels with a Geiger-Müller Tube (Geiger counter). Today, these devices have been largely replaced by modern solid-state detectors; however, the Geiger counter still has pedagogic value because the basic principle of these detectors is simple and easy to understand. Consider Figure 1 — if a γ ray produces an electron/+ion pair in the gas-filled Geiger-Müller Tube, these charges will be swept toward high voltage electrodes (i.e., the positive central wire and the negative cylindrical shell). This, in turn, will generate a current that is proportional to the intensity of the incident radiation and can be measured. The Geiger counter will

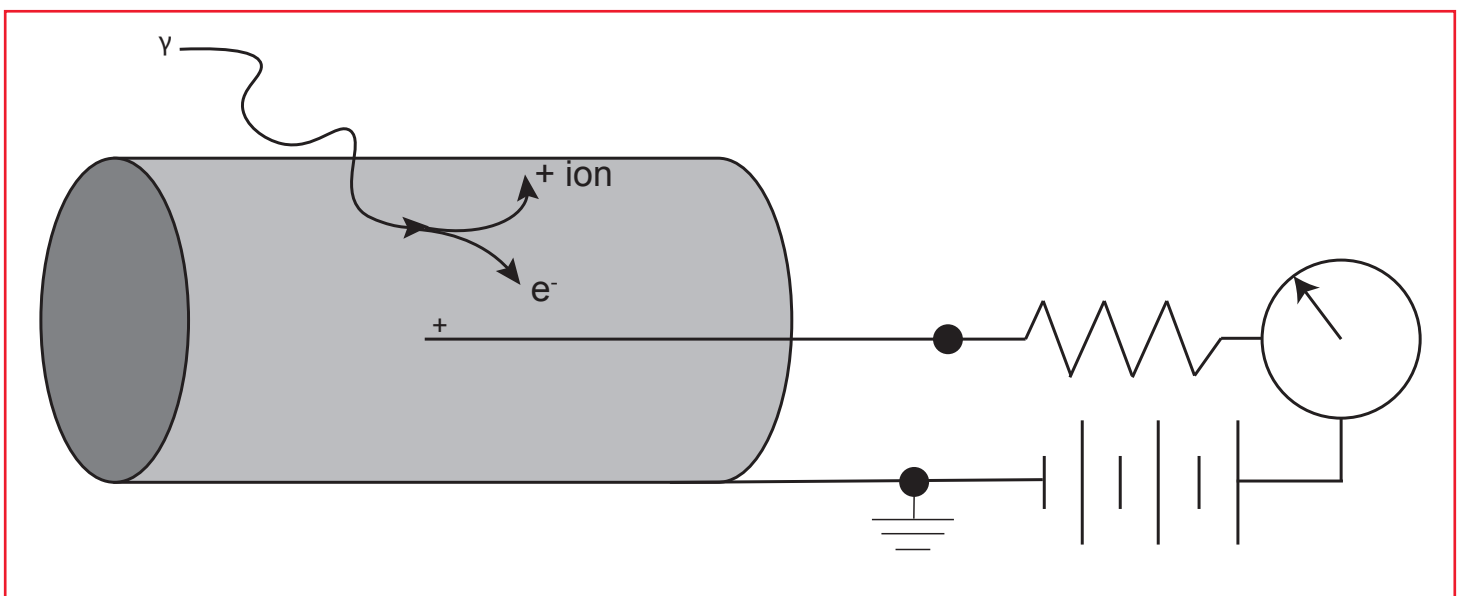


Figure 1– Basic Geiger counter operation. Alternately, detections can also be made by monitoring the positive electrode potential above ground (i.e., between the two black dots) with an electrometer.

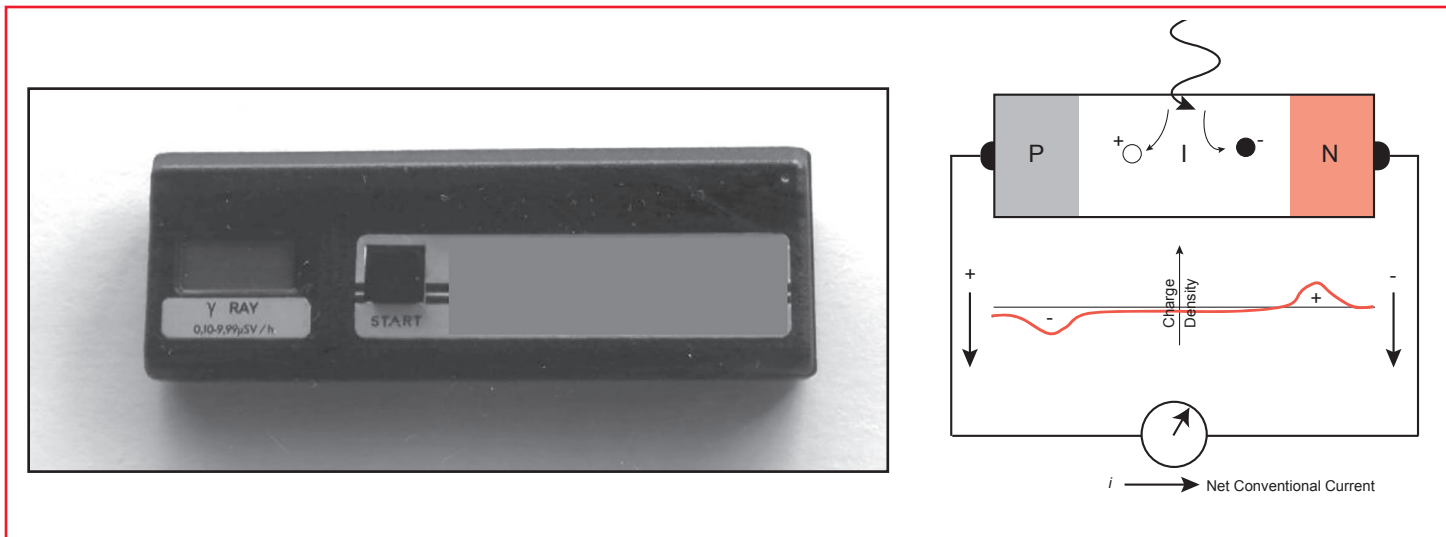


Figure 2– A solid state γ ray detector (photo by author). The PIN diode is being operated in the “zero-biased” or “photo-voltaic” mode and functions like a Geiger-Müller tube.

respond to any ionizing particle that *can enter the tube*. Therefore, low-energy α and β rays go undetected.

Solid-State Detectors


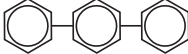
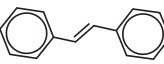
Most solid-state detectors are germanium PIN diodes. The acronym comes from the *positive* or P-type material at one end of the device, the *intrinsic* (I-type) material in the center, and the *negative* or N-type material at the opposite end as shown schematically in Figure 2. Intrinsic material is the pure un-doped germanium; a metal that is much heavier than Si and better able to stop (capture) γ rays. It has a valence of +4, like silicon and carbon, and forms four bonds with its neighbors, like the other members of the periodic table in group IV.

The P-type material is germanium typically doped with one part in 10^6 to one part in 10^9 of indium (In). This element has three valence electrons, but it is bound into a germanium crystal lattice by four bonds. Therefore, P-type material is electron deficient. The N-type mate-

rial is germanium typically doped with arsenic (As), also to one part in 10^6 to one part in 10^9 . Arsenic has five valence electrons, but is also trapped in the germanium lattice by four bonds. Therefore, it has one excess electron not involved in lattice bonding. What would happen if the P-type material was joined to N-type material using a long piece of I-type material in between as a “wire”? In that case, electrons would migrate from N to P, and holes (deficient, or missing, electrons that are effectively positive charges) would migrate from P to N, creating two charge build-ups as shown in Figure 2. Of course, this charge separation cannot go on forever. It will be checked by the attraction of the negative and positive charge concentrations for each other.

Next, suppose that a γ ray produces an electron-hole pair in the wide central intrinsic region. What will happen then? Clearly, the electron will move toward the + charge concentration in the N-type material while the hole migrates to the P-type material. That will produce

Table 2– Common scintillators and their primary application.

Scintillator	Chemical Formula	Peak Emission Intensity Wavelength (A)	Primary Application
Anthracene	$C_{14}H_{10}$ 	4400	β particles
p-terphenyl	$C_6H_5C_6H_4C_6H_5$ 	4100	Slow neutrons (<1 Mev)
Stilbene	$C_6H_5CH=CHC_6H_5$ 	4100	Fast neutrons (>1 Mev)
Thallium doped sodium iodide	$NaI(Tl)$	4100	γ , X rays
Fluorescent zinc sulfide	$ZnS(Ag)$	4500	α particles

a current that can be measured. The more γ rays, the greater the current. So there an analogy between the operation of the old Geiger-Müller tube and the solid state PIN detector. But, again, low-energy α and β rays will not be counted.

Scintillation Counters:

When it is necessary to count low energy α and β particles (e.g., the β^- emissions from tritium or ^{14}C), it becomes necessary to make intimate contact between the emitter and the detector. This contact is made as follows. First, a *scintillator* is dissolved in a solvent. A scintillator is simply a material that will emit a minute flash of light if it is struck by an ionizing particle. Scintillators exist for the detection of α , β , γ , X-rays, and neutrons in various energy ranges [Refs. 2, 5 & 6]. Table 2 lists several common scintillators with their empirical (and structural) formulas and primary application. However, many other scintillators also exist. Next, the radioactive sample to be studied is placed in the scintillator solution (called a *liquid scintillator*). A photomultiplier tube can now count flashes.

Naturally, the vial of liquid scintillator containing the sample, and the photomultiplier, must be enclosed in a light-tight housing. It is important to note that the wavelength of maximum intensity emitted by the scintillator should match the peak response wavelength of the photomultiplier as closely as possible. Most photomultipliers have an “S-11” response with a peak at about 4500Å. This last figure should be compared to the peak emission wavelengths of the scintillators in Table 2.

Many other types of detectors exist in addition to the three discussed in this section. However, these are the most common and the ones that the system safety engineer is most likely to encounter in everyday use.

Everyday Radiation Exposure

When it comes to low levels of radiation exposure, establishment of a clear cause-and-effect relationship between exposure and *human* health consequences is difficult. This is because the statistical noise due to other interfering factors may be just as large, or larger, than the “signal” (correlation) of interest. For example, did a cancer come from living indoors, or did it come from eating too many bananas? How many bananas did the other members of the test group eat each day? What about other foods? What about the drinking water? Its quality is not the same everywhere. Does water from the aquifer contain trace amounts of arsenic that are currently considered “safe” but may have unknown long-term health consequences? Some water sources are also known to contain radon, a radioactive decay product of uranium, an element that is ubiquitous in the environment in trace amounts. And what about the germ content of the drinking water where you live?

Did subjects who spent less time indoors expose themselves to the sun? What effect does the sun have on cancer? Furthermore, if you live in South Dakota, your estimated external exposure from the Earth’s natural radioactivity is almost three times (highest in U.S.) the external exposure that you would get if you lived in Nevada (lowest in U.S.). And what complicating effect does breathing in all those gasoline vapors have when you’re fueling up at the pump? What about the use of household cleaning chemicals? Can they lead to cancer? What about the propellant in cans of hair spray that we release into household air? What about hair dye? What effect does that have? Etc.

However, one thing that can be measured accurately is the *relative* health risk involved in various exposures. It is up to the individual to decide if a particu-

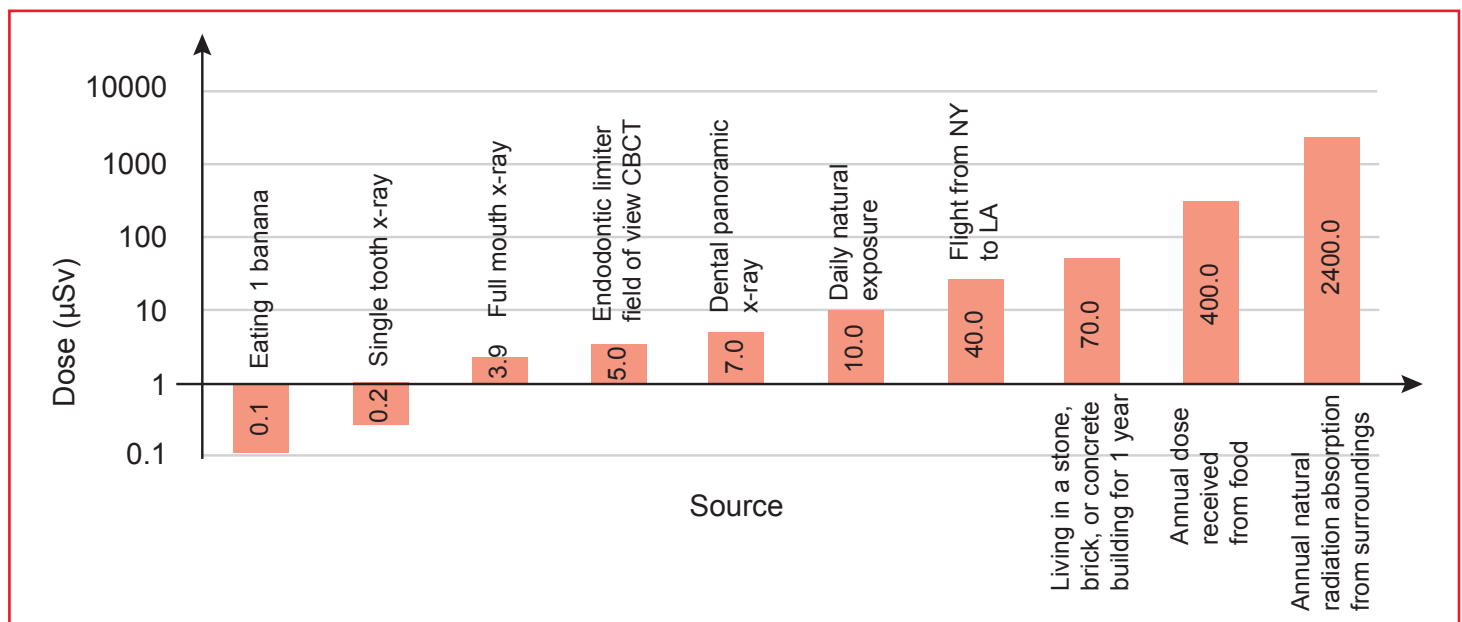


Figure 3 — Dose (logarithmic scale) vs. source [Refs. 7, 8 & 9].

Table 3 — The radioactivity of various food groups relative to fruit [Ref. 3].

Food or Food Group	α Radioactivity Relative to Common Fruits
Brazil Nuts from Brazil	14,000
Cereals	600
Tea	400
Organ Meats (e.g., Liver and Kidney)	100-150
Flour	100-150
Peanuts and Peanut Butter	100-150

lar exposure is worth the relative risk. Eating a single banana exposes a person to a 0.1 μSv dose. Should we all stop eating bananas? “No way! I like bananas!” What about a single tooth X-ray? Perhaps I’ve developed a cavity from eating too many sweet ripe bananas (one a day)? Well, a single tooth X-ray delivers a 0.2 μSv dose. But since I ate 365 bananas last year, and received 36.5 μSv of radiation, who cares about the 0.2 μSv dose from the X-ray!

That would be the author’s call, anyway — another person might have a different opinion. Figure 3 summarizes the dose received from a variety of sources.

In addition to weighing the relative risk of various exposures, a person must also weigh the risk of radiation exposures against other risks in the environment, such as chemical risks. Here, the word “risk” may be taken in its colloquial sense as a vague threat to well-being (whatever that may mean to any given person), or in its more scientific sense as severity (in U.S. year 2000 dollars) times probability of occurrence.

So, does a single tooth X-ray cause more potentially carcinogenic harm than, say, the nitrates (preservatives) ingested by eating a bologna sandwich? “But, I like bologna!” Each of us must pick our own risks. There is no way to avoid all risks because, as Figure 3 clearly shows, there is an annual natural radiation absorption from the surroundings (cosmic rays, etc.) that amounts to a whopping 2,400 μSv per year, whether you like it or not! If you try to live in a cave to avoid cosmic rays, you will just be bombarded by the decay products of uranium and thorium. Oh, and by the way, you still have to eat! That will cost you another 400 μSv per year! What did *you* have to eat today?

Not all food was created equal! Fruit is known to be especially low in radioactivity [Ref. 3], and is the

standard by which the radioactivity levels in other foods are measured. For some reason fruit trees simply don’t absorb many radioactive isotopes from the soil. They are not needed for the plant’s metabolism. Bananas are the exception to this rule. Bananas (and avocados) are particularly rich in potassium, and one of the naturally occurring isotopes of potassium (^{40}K) is radioactive!¹ The natural abundance of ^{40}K is 0.0117% of all the potassium found in nature. The half-life of ^{40}K is 1.277 billion years, so this isotope has been around since it was first formed in old stars.

All soil on Earth contains potassium, so all plants contain some ^{40}K , as well as other naturally occurring radioisotopes like ^{14}C , ^3H , ^{238}U , ^{235}U , ^{232}Th , etc. Therefore, all herbivores are radioactive because they eat plants, and all carnivores are radioactive because they eat herbivores. People are radioactive because we eat them all!

Table 3 lists the α radioactivity levels of various foods relative to fruit. Because only α radiation is considered (due to absorbed U and/or Th), the effects of ^{40}K , ^{14}C , and ^3H have been ignored, even though these isotopes may contribute massively to the radiation dose that the foods in Table 3 might deliver. Brazil nuts from Brazil head the list with an α radiation level 14,000 times that of most common fruits! The author avoids Brazil nuts.

At this point the reader might reasonably ask, “If the risks from radiation in foods cannot be completely eliminated, can the *additional* risks from pesticides be eliminated, or at least controlled?” First of all, eating so-called “organic” foods does not *completely* protect the consumer from pesticides. However, such foods are grown using *fewer* pesticides, provided these foods really are “organic” and are not just labeled as such. Today, most supermarkets carry “organic” foods, and, although their price has

¹ Strangely, ^{40}K has three decay modes: beta electron emission (89.33%), electron capture (10.67%), and positron emission (0.00103%) [Ref. 16]. Electron capture occurs when the ^{40}K nucleus absorbs an orbital electron from an *inner* atomic shell because of the relatively large overlap of the electron wave-function with the nuclear volume. The electron vacancy left behind is quickly filled as outer electrons emit an X-ray, lose energy, and fill the hole. Essentially, electron capture accomplishes the same thing as positron emission, but is more energetically favorable.

come down, they are still expensive compared to their “non-organic” counterparts.

Another option for eliminating pesticides might be to eat “green-house” grown foods (e.g., mushrooms). Greenhouses keep insects out. And, they have another advantage — climate control! Therefore, three harvests a year are possible instead of one or two, or none in some cold countries (e.g., Iceland, Greenland, etc.). The increased production, coupled with the savings accrued from not purchasing insecticide, makes greenhouse grown foods more competitive by the foods grown with usual farming methods. Many universities operate experimental greenhouses for hydroponic research and, at the end of the harvest cycle, sell off their produce at super-market prices.

Finally, it should be noted that many foods are naturally pesticide free. Such foods may be shrouded in husks that are peeled off, or they may be thick-skinned, or they may contain an irritating substance. Consequently, there is little reason to buy “organic” onions, sweet corn, pineapple, avocado, asparagus, sweet peas, mangos, eggplant, cantaloupe, kiwi, cabbage, watermelon, sweet potatoes, grapefruit, and of course, mushrooms. Note that although avocados are pesticide free, they are also high in ^{40}K . So, there are trade-offs! John Milton’s advice paraphrased from *Paradise Lost* seems appropriate here, “Everything we do has both good and evil consequences. The best that we can do is intend toward the light.”

Beyond the suggestions already discussed, it would be prudent to drink demineralized (or distilled), sterilized, drinking water (available from vending machines at very modest prices). Your body only wants pure H_2O . Beneficial minerals come from your food, not your water, and harmful minerals like arsenic, uranium, etc. should be completely removed. Furthermore, the heat applied during sterilization will also drive off any dissolved radioactive radon gas. Wash all produce carefully and when possible, peel foods to remove all soil which contains trace amounts of uranium and thorium. And, of course, avoid sunbathing and smoking.

The Decay Law, Secular Equilibrium, and ^{14}C Measurements

The Decay Law

Probably the single most important law concerning radioactivity is the *Decay Law*. The reason for its importance is easy enough to understand; people simply want to know how long they will have to wait before radioactivity disappears, or at least becomes a negligible concern. The decay law may be derived as follows. Let dN equal the number of decays that occur in a “short” time interval dt . “Short” in this context means that the radioactivity of the specimen being measured changes negligibly during time dt . Early studies indicated that

dN was proportional to the total amount N of radioactive atoms in a specimen, so that

$$dN = -\lambda N dt \quad (2)$$

The negative sign implies that dN atoms are *removed* from the specimen by decay, and λ is a constant of proportionality called the *decay* (or *disintegration*) constant. Dividing both sides of Equation 2 by N and integrating from time $t = 0$ (with initial number of radioactive atoms N_0) to time T (with N radioactive atoms left) yields

$$\int_{N_0}^N (1/N) dN = \int_0^T (-\lambda) dt = -\lambda \int_0^T dt, \quad \text{or} \quad (3)$$

$$\ln(N/N_0) = -\lambda T \quad (4)$$

From this last equation two important results can be generated. First, and foremost, is the all-important exponential decay law resulting from taking the exponential (\exp) of both sides of Equation 4 to yield, after multiplying by N_0 ,

$$N = N_0 e^{-\lambda T} \quad (5)$$

That is to say, there will only be N radioactive atoms left after time T . An important related definition is that of Activity, defined by $A = \lambda N$ and measured in disintegrations per second. One Curie is the unit of activity and is defined as the number of disintegrations of 1 gram of ^{226}Ra per second (see the previous Definitions and Units section). The other important result is the expression for the *half-life* of a source (i.e., the time $T_{1/2}$ that it takes for half the radioactive atoms to decay away). In that case, $N = N_0 / 2$, and Equation 4 becomes $T_{1/2} = 0.693 / \lambda$. A related definition that is occasionally useful is the *mean lifetime* per radioactive atom (\bar{T}), where $\bar{T} = 1.44 T_{1/2}$ [Ref. 2].

Secular Equilibrium

When a radioactive species (e.g., ^{14}C) is created by one process (e.g., Cosmic ray bombardment, or decay of a parent atom in a decay chain), and is simultaneously destroyed by its own disintegration, a *secular equilibrium* results. That is to say, the concentration of the radioisotope will build up until its rate of decay via Equation 2 exactly matches its rate of creation. When this creation/destruction balance point is reached the concentration of the radio-isotopic species will be constant forever. The conditions of secular equilibrium are very closely approximated for the naturally occurring isotope ^{14}C here on Earth, as will be discussed. For

now, proof of steady-state behavior will be demonstrated mathematically. Suppose a radioisotope (e.g., ^{14}C) is produced at a uniform rate by cosmic rays incident upon the Earth's upper atmosphere.



Similarly, the naturally occurring isotope tritium can be produced by absorption of a neutron by deuterium (heavy hydrogen, ^2H , another natural isotope). Then in time dt there will be κdt atoms of the radioisotope produced by cosmic rays, where κ is the number of radioactive atoms produced per second. But, radiocarbon (and also tritium) are also decaying away at a rate $-\lambda N dt$, where N is the total number of radioisotope atoms at time t . The net result is that the number of radioisotope atoms produced in time dt is given by

$$dN = \kappa dt - \lambda N dt \quad (7)$$

which may be written as the first order differential equation

$$dN/dt + \lambda N = \kappa \quad (8)$$

with the well-known solution [Ref. 10]

$$N = \kappa/\lambda [1 - \exp(-\lambda t)] \rightarrow \kappa/\lambda \text{ as } t \rightarrow \infty. \quad (9)$$

So, the radioisotope concentration approaches a steady state level as $t \rightarrow \infty$. In reality, ^{14}C levels may vary slightly, but only on the parts-per-thousand scale due to a variety of complex processes. As long as a plant is alive, it will consume $^{14}\text{CO}_2$ at the steady state abundance of this gas in the atmosphere relative to $^{12}\text{CO}_2$. And, so long as herbivores eat plants, and carnivores eat herbivores, they too will contain a steady state abundance of ^{14}C in their tissues. The same holds true for

people. It is only after living things die that their ^{14}C abundance relative to ^{12}C begins to dwindle according to the Decay Law (Equation 5). Therefore, by carefully measuring $^{14}\text{C}/^{12}\text{C}$ ratios of, say, a stick of wood in an Egyptian tomb, an archaeologist can get a close estimate of the age of that structure. That is how ^{14}C dating works.

Although natural abundances of ^{14}C are only of interest to the system safety engineer as a source of "Everyday Radiation Exposure" discussed previously, and as a benchmark against which dangerous levels of radiation may be compared, it should be noted that dangerous steady-state levels of radioactive decay products can be established in natural radioactive ores and spent reactor fuel rods due to the establishment of secular equilibria. Furthermore, the concept of secular equilibrium carries over to chemical species as well if the reservoir of an undesirable polluting or toxic molecule is being added to while it is simultaneously being destroyed, remediated, or sequestered.

Radiation Range and Stopping Power

α Particles

Naturally emitted α particles (as opposed to high-energy alphas from an accelerator) lose their energy almost entirely by ionizing collisions with atoms as they pass through matter. The *range* of α particles in any given medium is the distance they travel before they lose all their energy, and this range is almost constant for any given initial kinetic energy. The reason for this constancy is easy to understand. A 5 Mev (initial kinetic energy) α particle will, on the average, make 140,000 collisions before it is stopped, and this number varies by only ± 370 collisions from particle to particle [Ref. 2]. Since the range depends on the number of collisions, and since the number of collisions is almost constant, the range must be almost constant. Figure 4 gives

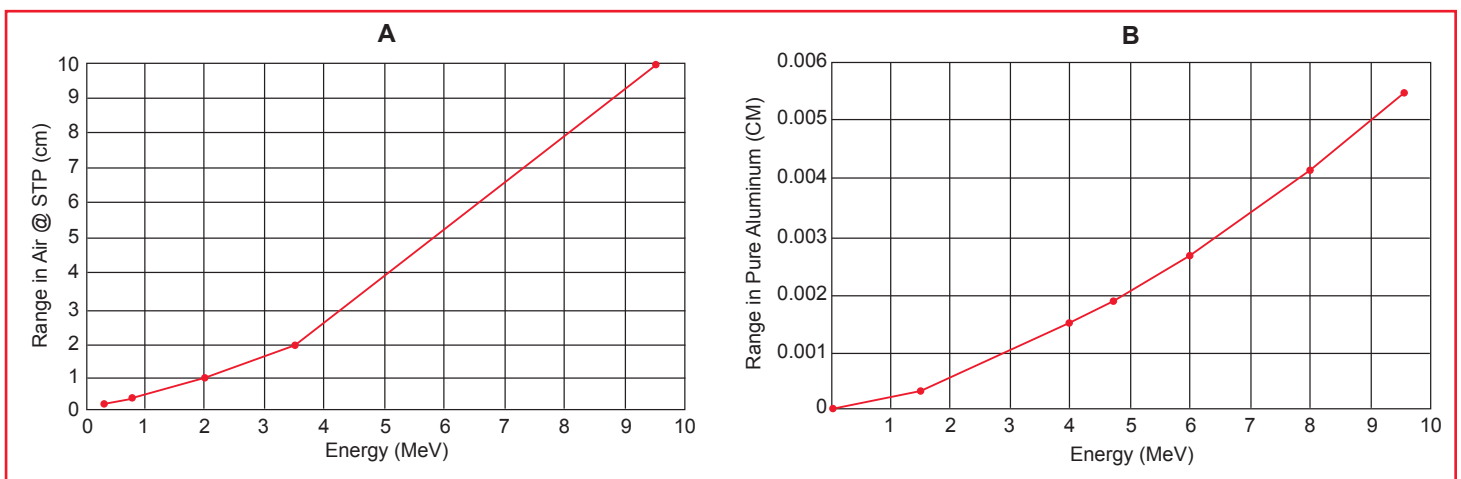


Figure 4 – A) α particle energy (E in Mev) vs. range (R in cm) for air at STP. Above 2 Mev the curve is better approximated by the empirical equation $R \approx 0.325E^{3/2}$ rather than a straight-line segment. B) α particle energy (E) vs. range (R) for aluminum (density = 2.7 gms/cc), an important standard shielding material for all types of radiation.

Table 4: Various α particle absorbers vs. relative stopping power S_r [Ref. 2].

Absorber	S_r
Mica	2000
Aluminum	1660
Copper	4000
Silver	3700
Gold	4800

the range of α particles as a function of energy for air and aluminum [Ref. 2].

Another important concept is *stopping power* (S) defined as the loss of energy per unit path length x ,

$$S \equiv dE / dx \quad (10)$$

Still more important is the *relative stopping power* S_r defined as the stopping power of some substance s relative to air,

$$S_r \equiv (dE / dx)_s / (dE / dx)_{air} \quad (11)$$

The relative stopping power is approximately constant for any given material (Table 4). It may be surprising that mica has a slightly greater relative stopping power than aluminum. But micas (e.g., biotite and muscovite) contain potassium, iron and silicon, all heavier elements than aluminum with more electrons, thereby offering greater stopping power. The three times greater S_r of gold compared to aluminum, however, agrees with intuition. *It takes only 50 microns (half the thickness of a piece of paper) of mica to stop a 10 Mev α particle!*

β Particles

Electrons (β^-) and positrons (β^+) are light particles (or leptons). As such, they decelerate significantly via interaction with the coulomb fields of absorber atoms along their paths. As β^- particles decelerate, they radiate

X-rays called *bremsstrahlung radiation* (breaking radiation). By comparison, α particles emit very little bremsstrahlung because they are so massive (more than 7200 times the rest mass of the electron) that they are negligibly decelerated by coulomb interactions. Therefore, the stopping power equation of any material for β^- rays has both a collisional part (S_{col}) and a radiative part (S_{rad}). However, it is only the radiative part that is of interest here. As might be expected,

$$S_{rad} = (dE/dx)_{rad} \propto nEZ^2 \quad (12)$$

where n is the number of absorber atoms per unit volume, and where E and Z^2 show the increasing importance of radiation losses at high β energies E and in absorbers with a high atomic number Z (high fields). Strangely, it is for this reason that aluminum is often used as a shielding material instead of lead! Although lead has a higher stopping power than aluminum for β^- radiation, most of the stopping (or breaking) is accomplished by the concomitant production of high levels of penetrating bremsstrahlung radiation (X-rays) that escape from the shielding. As a result, the number of detector counts may be *higher* when shielding a β^- source with 2 mm of lead than 2mm of aluminum! *The system safety engineer should never replace an aluminum radiation shield with one made of lead because he/she thinks it will be safer!* There may be bremsstrahlung effects that the safety engineer is unaware of! Further-

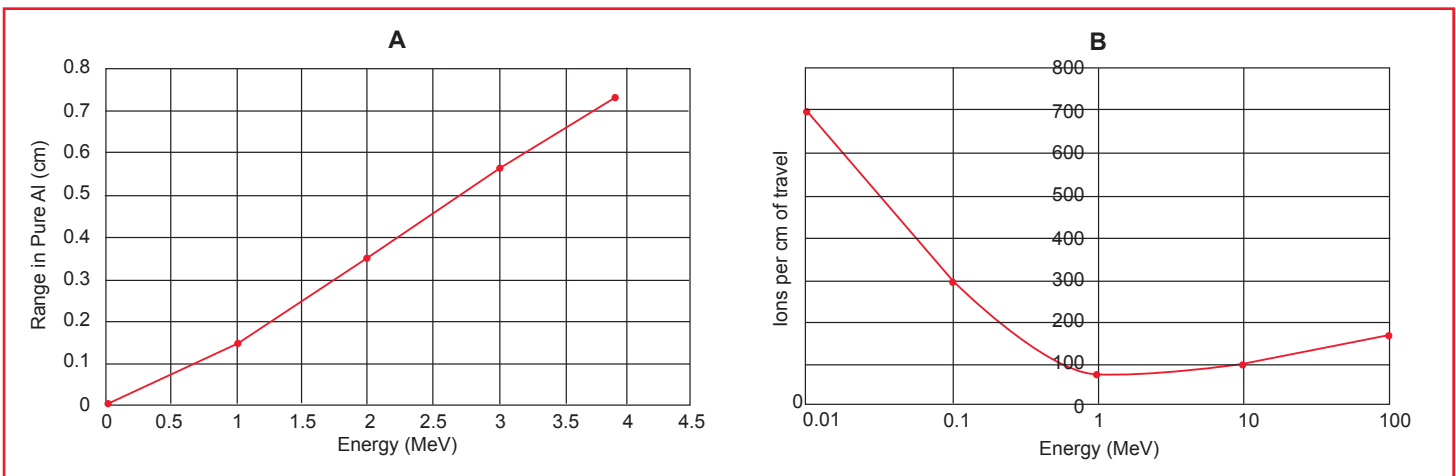


Figure 5– A) Range of β^- particles in aluminum (density = 2.7 gms/cc) as a function of radiation energy. B) Ion production in air from β^- radiation as a function of energy.

more, a 10 Mev β^- particle can be stopped by only 1.5 mm of aluminum (Figure 5 – left), so there is very little reason to replace aluminum with any other material unless an insulator is required.

As previously mentioned, $S_{\text{Total}} = S_{\text{col}} + S_{\text{rad}}$, and ions can be produced by both collision and bremsstrahlung X-rays. The graph in Figure 5 (right) shows that *ion production for β^- particles is a minimum near 1 Mev*. This is the energy that produces the least biological damage. Hence, the β^- emissions of ^{14}C (0,16 Mev), an isotope contained in all living tissue, does more than minimal damage. *The system safety engineer needs to be aware that biological damage is a function of both dose and radiation energy!*

γ and X-rays

Penetrating radiation of this type is difficult to stop. Generally speaking, radiation absorption as a function of distance travelled is a gradual process dominated by multiple *Compton scattering* events in the 1 to 4 Mev energy range. Compton scattering involves the interaction of an energetic photon with an electron. When this happens, the electron picks up kinetic energy from the original γ ray (or X-ray) and is deflected through an angle Φ , while a new lower-energy photon is created and deflected through an angle Θ relative to the direction of the original photon. The electron quickly comes to rest, as described above for β^- radiation, and the new photon is now slightly depleted in energy relative to the original by an amount

$$\Delta E = m_0 c^2 (1 - \cos\Theta) \quad (13)$$

where m_0 is the rest mass of the electron and c is the speed of light in vacuo. Notice that this drop in photon

energy does not depend on the initial photon energy, or the material of the absorber, but only on the scattering angle of the new γ photon. Also note that equation 13 says nothing about the probability of interaction. Clearly, the absorber with the most electrons maximizes the probability of a Compton scattering event. As this process continues, together with several other competing processes, all the original photon energy is eventually lost.

Below 0.5 Mev the photoelectric effect is the principal energy loss mechanism for γ rays, while above 5 Mev electron-positron pair production is dominant. Other loss mechanisms also exist, especially for X-rays, but these will not be discussed here.

Absorption as a function of distance follows Beer's Law. If I_0 is the original γ ray (or X-ray) intensity, then the intensity I remaining after traversing a thickness d of absorber is given by

$$I = I_0 e^{-\mu d} \quad (14)$$

where μ is the linear absorption coefficient. According to Equation 14, *all* penetrating photons can never be completely stopped. However, thick lead is the shielding of choice because it is cheap and its large atoms contain an almost maximum number of atomic electrons. Hence, Compton scattering will be maximized. A ^{60}Co medical radiation source might be kept in a lead capsule (cylinder) about 8 cm (3 in.) long and 5 cm (2 in.) wide with walls about 7 mm ($\frac{1}{4}$ in.) thick. If it is necessary to view a γ source (i.e., if transparency of the shielding is important), then lead glass is used (Figure 6A). This yellowish glass may be several inches thick. All of these last shielding thicknesses are approximate

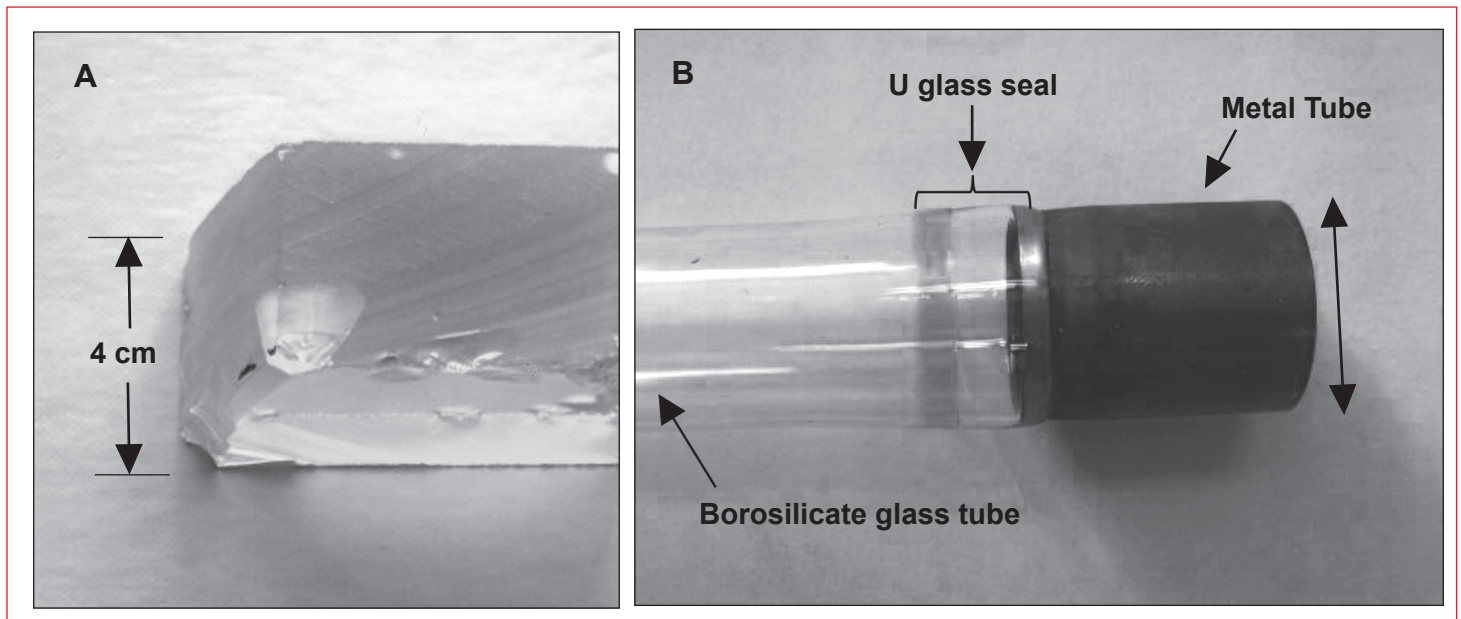


Figure 6 – A) γ -ray absorbing lead glass (PbO/SiO_2 mixture; 50% PbO by wt.). Radiation proof glass may be much thicker than 4 cm when handling certain isotopes. B) Pale yellow uranium glass (α emitter) used to make borosilicate glass to metal seals. The system safety engineer should be able to distinguish between the two types of glass.

and will depend on the energy of the emission as well as its intensity.

Point Sources of Radiation

In this section, attention will be focused on the fall-off of radiative intensity with distance. Since α and β rays are absorbed so easily by thin shielding, penetrating γ rays from localized sources offer a useful, interesting, and instructive example of “safety by separation.” First consider a point source of γ radiation. A microgram of ^{226}Ra will do quite nicely. Around this speck of radioactive matter construct an imaginary sphere of radius r called a “Gaussian Surface” (Figure 7).

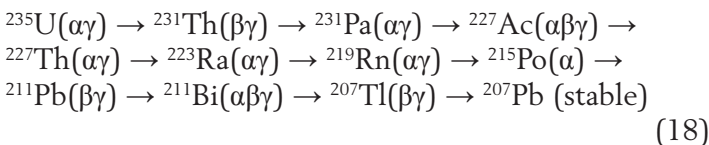
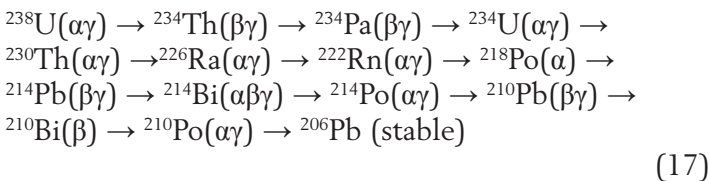
The sphere has the same symmetry as the point. In fact, a point can be considered a sphere with zero radius. Now, each unit area of the Gaussian surface has some flux of ionizing particles passing through it. And the surface area of the sphere *increases* by r^2 . Therefore, at the Gaussian surface, the intensity I (measured in counts/cm²/sec) must *decrease* as $1/r^2$. Therefore,

$$I = k/r^2 \quad (15)$$

where k is a constant of proportionality. Therefore, the ratio of the radiation intensity at distance r_1 from the source to the intensity at distance r_2 from the source is given by

$$I_1/I_2 = (r_2/r_1)^2 \quad (16)$$

It is instructive to test this last formula with a real-world sample. Consider the uranium specimen in Figure 8. It consists of uranophane, $\text{Ca}(\text{UO}_2)_2[\text{SiO}_3(\text{OH})]_2 \cdot 5\text{H}_2\text{O}$ in a fluorite lined cavity within a uraninite (UO_2) matrix [Ref. 11]. A uranium ore of this kind also contains many of the decay products of uranium, and most of these decay products are themselves radioactive γ emitters. The decay chains of the two common isotopes of uranium are as follows [Ref. 2]:



Each element in these decay chains is listed with its emissions in brackets. So, uranium ore is clearly capable of piling up counts on a solid state γ ray detector. In

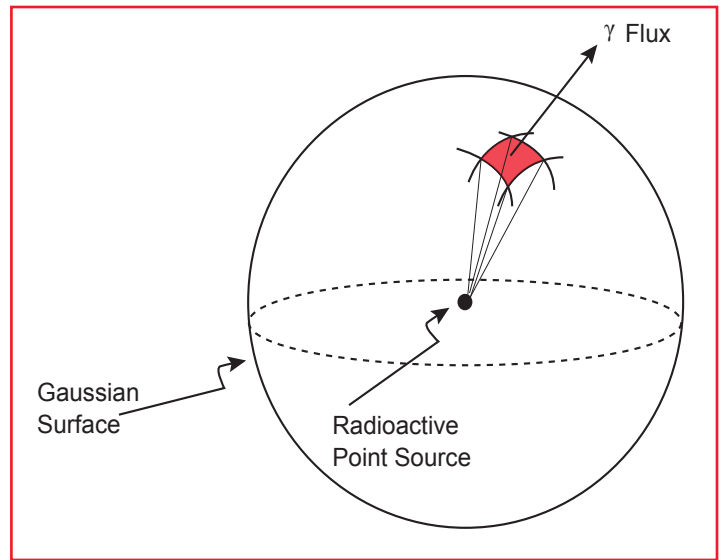


Figure 7 — A point source of radiation and its Gaussian surface.

order to use equation 16, the background radiation intensity I_{bg} must be subtracted off the measurements for I_1 and I_2 . That is to say $I_1 = I_1(\text{measured}) - I_{bg}$ and $I_2 = I_2(\text{measured}) - I_{bg}$. In Tucson, Arizona, (altitude ~ 3000 ft.), the author’s home town, the background γ radiation level is $0.18 \mu\text{Sv/hr}$ ($\pm 0.02 \mu\text{Sv/hr}$). At 15 cm (1 ft.) from the sample in Figure 8, the γ radiation level (1 trial with a 36 sec integration time) was $0.63 \mu\text{Sv/hr}$. At 91 cm (3 ft.) the radiation level was $0.19 \mu\text{Sv/hr}$. Therefore, $I_1 / I_2 = 45$ when it should ideally be 9. The difference is explained by the fact that the denominator (i.e., $I_2(\text{measured})$) is very close to the background level. That amplifies the effect of radiation measurement fluctuations. Many measurements need to be taken before stable results can be obtained. Complicating matters further is the fact that the sample is not a true point source of radiation. Instead, it is an inhomogeneous sample of finite extent with pockets having a greater or lesser concentration of uranium. Some atmospheric absorption may also have taken place. This calculation gives the reader some idea of the limitations of calculations based on Equation 16.

Planar Sources of Radiation

The next radiation problem to be considered is γ emission from a uniformly radioactive planar surface. Again, it will be assumed that absorption of γ rays by air is negligible. Figure 9 summarizes the geometry of this problem.

A cylindrical Gaussian surface is drawn in such a way that its flat ends are parallel to the flat radiating plane, with the top flat end lying infinitesimally above that plane. At distance r_1 , point 1 receives radiation of intensity I_0 (measured in counts/cm²/sec) from the flat end of the Gaussian surface directly below (at the base

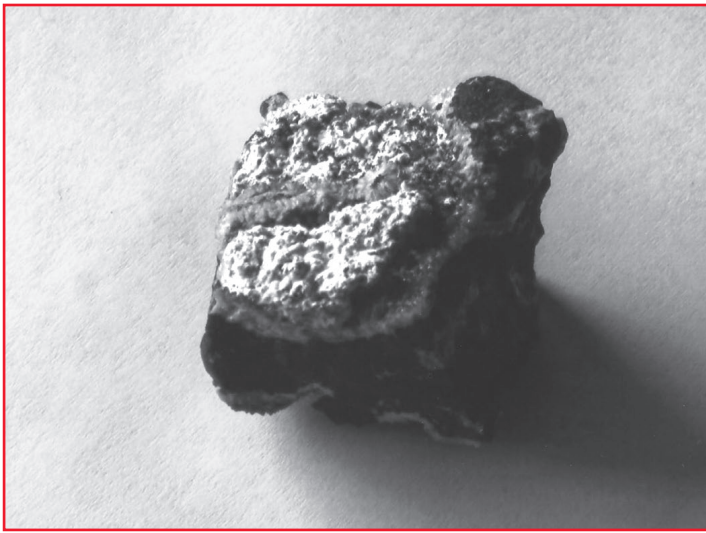


Figure 8— Uranophane is a brilliant yellow ore of uranium. The host rock is uraninite (black). Uranium minerals are typically either black, or a brilliant yellow or green, and the system safety engineer should learn to recognize them. In fact, uranium compounds were once used as coloring agents in kitchen glassware such as dinner plates! Very dangerous, especially when in contact with acidic foods which can mobilize uranium. The naturally occurring isotopes ^{238}U and ^{235}U are both α emitters, which are very dangerous when ingested. Clearly, this specimen (4 cm x 4 cm x 3 cm) is a poor approximation to a point source on the 15 cm (1 ft.) scale. Nevertheless, applying equation 3 at 1 ft. and 3 ft. will give some idea of the magnitude of the errors that can be incurred by applying idealized calculations to finite irregular samples. Photo by author.

of the altitude for point 1; Figure 9). However, point 1 also receives radiation (solid arrows) from the flat ends (differential areas) of neighboring Gaussian surfaces, that lie on rings of ever-increasing radius outside the Gaussian surface under point 1. Each differential area is approximately a point source of radiation that falls off as $1/r^2$, while the rings increase their size by r . Therefore, the intensity contribution from each ring falls off as $1/r$. Furthermore, as the emission angle Θ of the γ rays becomes smaller and smaller, it becomes harder and harder for radiation to escape from the subsurface (e.g., through the curved side walls of the Gaussian surfaces). The net result is that the total radiation received by point 1 converges to some constant k' times I_0 .

Now, suppose that a detector is moved to point 2 at a distance r_2 from the radiating plane. In that case, each emission received (dashed arrows) at point 2 can be paired with a parallel emission received by point 1. Therefore, $I_2 = I_1 = k' I_0$. In other words, the intensity of the radiation received is constant and independent of the

distance r ! This is one reason why underground mining of uranium is so dangerous. Between tunnel walls, *no matter where you stand, you are continuously bathed in a uniform field of radiation!* The solution to the infinite planar radiator is messy compared to that for the point source because a Gaussian surface cannot be found that encloses the *entire* radiator. Here, one must be content with “coring” a section of the plane and then integrating.

Neutrons, Nuclear Fission, and Nuclear Reactors

Neutrons

The half-life of a free neutron is 10.61 minutes. During that time they can do some very unusual things. First of all, since a neutron has no charge, it does not interact strongly with atomic electrons and can range over significant distances (meters) in matter. However, once a neutron encounters an atomic nucleus, it can interact via the nuclear strong force and be absorbed. This is especially true of thermal neutrons (i.e., 0.025

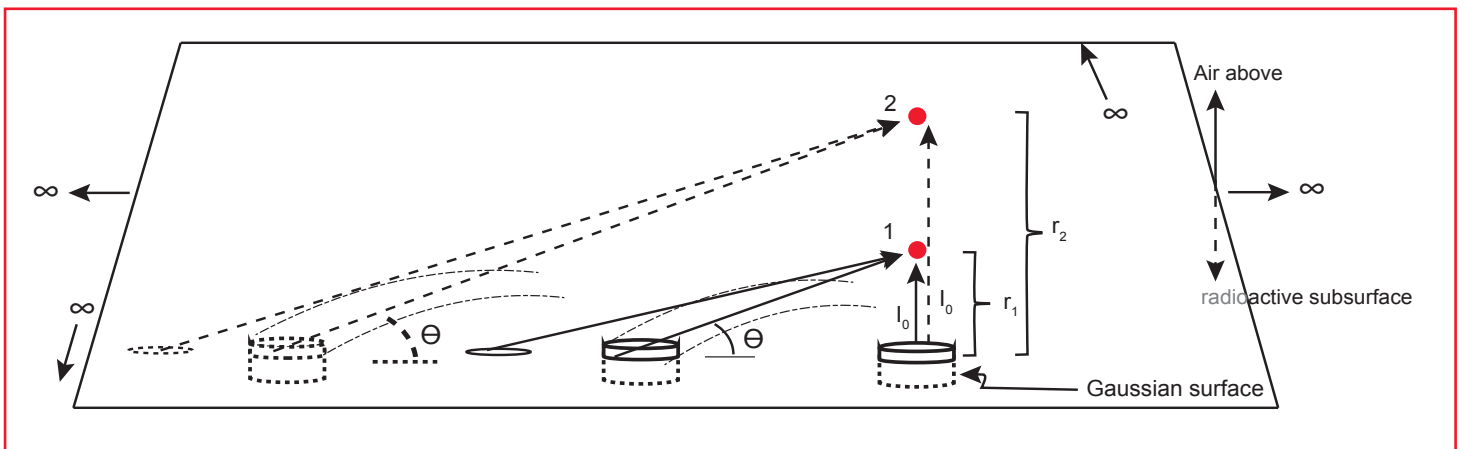
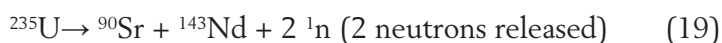


Figure 9 — An infinite planar source of radiation and its Gaussian surfaces. The depth of the Gaussian surfaces below the plane is determined by the thickness of the layer through which radiation can escape to a detector that measures intensity I_0 directly above. Point 1 receives a total intensity $I_1 = k' I_0$, where k' is a constant. Point 2 also receives a total intensity $I_2 = k' I_0$.

eV neutrons, the mean neutron Maxwell-Boltzmann kinetic energy at room temperature), and some isotopes (e.g. ^{113}Cd and ^{235}U). The larger the neutron capture *cross-section* of a given isotopic species, the greater will be the probability of neutron absorption. And, once absorption occurs, the target nucleus may have an undesirable excess of neutrons. Atomic nuclei try to maintain a more-or-less equal number of protons and neutrons so that a nucleus with a neutron excess may be radioactive, ejecting an electron (β^- particle) to change a neutron into a proton and thereby regain an acceptable proton/neutron ratio.

Nuclear Fission

Very heavy nuclei (e.g., the nuclei of U, Pu, and Am isotopes) are unstable because the Coulomb repulsion between their many protons is constantly trying to disintegrate (explode) these nuclei. To counterbalance these repulsions, a great deal of nuclear “glue,” in the form of neutrons, is required. So, very heavy nuclei are also neutron rich, and the absorption of still one more neutron leaves these nuclei with only one route to reduce its overall electrostatic repulsive energy *and* its excess of neutrons. It must simply fission (split) into two (usually unequal) pieces (lighter nuclei) and additionally release one or more free neutrons. Of course, if these free neutrons are absorbed by another heavy nucleus, more fissions can occur and a chain reaction can be established. A typical fission reaction is as follows:



However, there are many possible fission reactions and Table 5 below lists the many possible fission products (usually radioactive) with their half-lives.

On the molecular scale, chemical reactions proceed with the release of electron volts of energy (eV, the energy released by one electron falling through a potential of 1 volt). But nuclear reactions involve energies on the order of a million electron volts (Mev). That makes fissile isotopes about one million times more energy dense than chemical fuels.

Nuclear Reactors

It was once thought by some scientists that a self-sustaining nuclear reaction was impossible. Their argument was based on the belief that only two neutrons are emitted in Equation (Reaction) 19. Parasitic losses, such as escape of neutrons from the boundary of a reactor, neutron decay, etc., would prevent chain reaction. Even Niels Bohr did not believe the neutron output from fission was high enough to sustain a chain reaction [Ref 13]. And then there was the nagging problem of how to separate all the required ^{235}U from

^{238}U . The scale of that job was just too big. Although such arguments were qualitatively correct, they were also quantitatively wrong. Careful measurements showed that the neutron multiplicity was actually closer to 2.5 for thermal neutron fission of uranium isotopes [Ref. 12]. And, isotope separation was eventually accomplished by gaseous diffusion. Hence, the first self-sustaining chain reaction was demonstrated in 1942 under the University of Chicago stadium by Enrico Fermi.

Figure 10 shows the core of a small nuclear reactor consisting of 91 enriched ^{235}U fuel rods, clad in stainless steel. The reactor core is only 15 inches across and lies under 20 feet of water (the “swimming pool”). Small reactors of this kind are used for research and isotope production. They can also be used for energy generation in remote locations. Notice that the fuel rods are arranged in concentric rings forming a quasi-close packed array. Fuel configuration is a critical consideration for all types of energy producing reactors. For example, consider an ordinary campfire. It’s hard to build a fire with a single log, or a few sticks that are improperly arranged. But if you build a little “teepee” of sticks, then the radiation produced on one side of the fire is captured by sticks on the interior opposite side, and the fire will blaze with a very hot interior cavity. More will be said about fuel geometry in the next section on fusion.

It should also be noted that the central rod has been pulled from the core. This is so that samples can be inserted. In 1986, the author was involved in a neutron activation experiment to determine the amount of uranium and thorium in the ceramic casings of Dynamic Random Access Memory (DRAM) devices [Ref. 14]. After irradiation, samples are very dangerous and must be allowed to “cool,” or decay, for about one week. After that, counting can begin and requires another week or two. In this case, “counts” of a particular characteristic energy were proportional to the ceramic’s U and Th content. The entire process from start to finish takes about one month. To put things in perspective, a small reactor of this kind might produce one 55-gallon drum of medium-level radioactive waste in five years.

But now comes society’s great dilemma: “What should be done with the radioactive waste?” Many possible solutions have been proffered; everything from storage in stainless steel containers to pouring the waste into salt domes, to launching it into the Sun. All containers eventually leak, and have already leaked, even though they were made of stainless steel. Salt domes are geologically stable, but once you pour the waste in, how do you get it out again if you get a better idea for waste disposal? The idea of pouring radioactive waste into a water-soluble substance like salt isn’t all that appealing to this author [Ref. 15]. As far as the trip to the solar dump yard

Table 5 — Percentage yields (% to four significant figures if known) for the thermal neutron induced fission of ^{235}U . Yields less than 0.0001 have been omitted. Table arranged by increasing atomic weight (At. Wt.) [Ref. 12].

Element	At. Wt.	T _{1/2}	%	Element	At. Wt.	T _{1/2}	%	Element	At. Wt.	T _{1/2}	%
Ga	73	4.9h	0.0001	Mo	97	∞	6.09	Xe	134	∞	8.06
Ga	74	7.8m	0.0004	Nb	98	52m	0.064	I	135	6.7h	6.1
Ge	77	11.3h	0.0031	Mo	98	∞	5.78	Xe	135	9.2h	6.3
As	77	38.7h	0.0083	Mo	99	66.5h	6.06	Cs	135	2.95my	6.41
Ge	78	2.1h	0.020	Mo	100	∞	6.30	I	136	86s	3.1
As	78	91m	0.020	Ru	101	∞	5.0	Xe	136	∞	6.46
As	79	9.0m	0.056	Ru	102	∞	4.1	Cs	136	13d	0.0068
Br	80m	4.42h	0.0004 (total)	Ru	103	39.7d	3.0	Cs	137	30y	6.15
Br	80	17.7m		Ru	104	∞	1.8	Ba	138	∞	5.74
Se	81m	57m	0.0084	Ru	105	4.45h	0.9	Ba	139	83m	6.55
Se	81	18.4m	0.14	Ru	106	1.01y	0.38	Ba	140	12.8d	6.35
Se	83	25m	0.22	Rh	107	22m	0.19	Ce	140	∞	6.44
Br	83	2.4h	0.51	Pd	109	13.4h	0.030	La	141	3.8h	6.4
Kr	83	∞	0.544	Ag	111	7.6d	0.019	Ce	141	33d	~6.0
Br	84	31.8m	0.92	Pd	112	21.0h	0.010	Ce	142	∞	6.01
Kr	84	∞	1.00	Cd	115m	43d	0.0007	Ce	143	33h	5.7
Se	85	39s	~1.1	Cd	115	53h	0.0097	Nd	143	∞	6.03
Kr	85	10.6y	0.293	Cd	117m	3h	0.011	Ce	144	280d	~6.0
Rb	85	∞	1.30	Sn	121	27.5h	0.015	Nd	144	~∞	5.62
Kr	86	∞	2.02	Sn	123	136d	0.0013	Nd	145	∞	3.98
Se	87	16s	~2	Sn	125	9.6d	0.013	Nd	146	∞	3.07
Rb	87	50by	2.49	Sb	125	2.0y	0.021	Nd	147	11.1d	~2.7
Sr	88	∞	3.57	Sb	127	91h	0.13	Sm	147	130by	2.36
Sr	89	50.5d	4.79	Te	127m	105d	0.035	Nd	148	∞	1.71
Sr	90	28y	6.77	Sn	128	57m	0.37	Sm	149	∞	1.13
Sr	91	9.48h	5.81	Te	129m	37d	0.35	Nd	150	∞	0.67
Y	91	58.51d	~5.4	I	129	17my	0.8	Sm	151	80y	0.44
Zr	91	∞	5.84	Sn	130	2.6m	2.0	Sm	152	∞	0.281
Sr	92	2.7h	5.3	I	130	12.36h	0.0005	Sm	153	47h	0.15
Zr	92	∞	6.03	Te	131m	30h	0.44	Eu	153	∞	0.169
Y	93	10.3h	6.1	I	131	8.05d	~3.1	Sm	154	∞	0.077
Zr	93	1.1my	6.45	Xe	131	∞	2.93	Sm	155	24m	0.033
Zr	94	∞	6.40	Te	132	77h	~4.7	Eu	155	4y	0.033
Zr	95	65d	6.2	Xe	132	∞	4.38	Eu	156	15.4d	0.014
Mo	95	∞	6.27	I	133	20.8h	~6.9	Eu	157	15.4h	0.0078
Zr	96	∞	6.33	Xe	133	5.27d	6.62	Eu	158	60m	0.002
Nb	96	23h	0.0061	Cs	133	∞	6.59	Gd	159	18.0h	0.0012
Zr	97	17h	5.9	I	134	52.5m	7.8	Tb	161	6.9d	0.0001

Note 1: Not all fission waste is radioactive! A very significant fraction of fission products consists of stable isotopes.

Note 2: Half-lives are measured in seconds (s), minutes (m), hours (h), days (d), years (y), millions of years (my), billions of years (by), a time much greater than the age of the universe (~∞), or the isotope is stable (∞).

Note 3: An “m” in the “At. Wt.” column indicates a metastable isotope excited state. De-excitation is usually via a γ ray emission.

Note 4: The numbers for % are considered “best” numbers as measured by *different* researchers without concern for consistency. Consequently, they do not sum to 100%. In fact, they sum to 279.6%. Therefore, they should only be taken as approximate to within a factor of 3, in spite of the number of significant digits provided.

Note 5: Similar % values are obtained for the fissionable isotopes ^{233}U and ^{239}Pu .

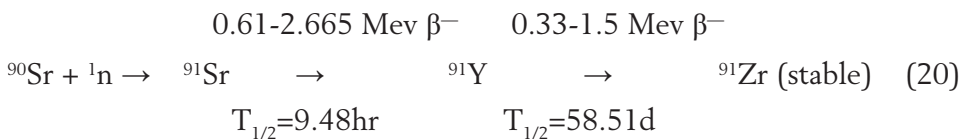
goes, it's too costly to be practical. Here, a more promising down-to-Earth approach will be reviewed.

As mentioned above, the central aperture in Figure 10 can be used for isotope production. If long-lived isotopes like ^{238}U or ^{232}Th are placed in the central aperture, they will absorb neutrons and be transmuted into the more radioactive, and faster decaying, ^{239}U and ^{233}Th (half-life 23.5 min. and 22.3 min., respectively; we'll touch upon *breeder reactors* later in this paper) [Ref. 14].

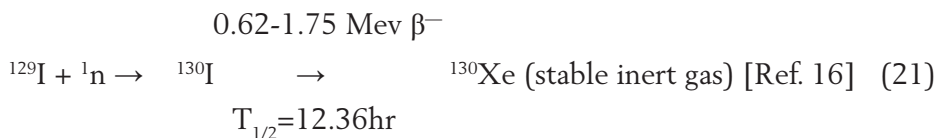
Simple observations of this kind have given physicists the basic idea for fission waste removal:

1. Remove any useful fissionable isotopes from the spent fuel (reprocessing).
2. Separate any "bad-actors" from the remaining waste (e.g., ^{90}Sr , ^{129}I , etc.), because they live too long, are too radioactive and can be readily absorbed by the human body.
3. Insert "bad actors" into a small isotope production reactor like the one in Figure 5 and irradiate them in the neutron flux to make them even more radioactive and faster decaying.

As a practical example, consider ^{90}Sr . Strontium is chemically similar to calcium and is readily absorbed by the human body. From Table 5, the half-life of this dangerous isotope is 28 years. If safety requires 10 decay half-lives (i.e., reduction of radioactivity by a factor of 1024), a society would have to "babysit" this waste for 280 years. Not practical! However, if ^{90}Sr is re-irradiated with neutrons, then two rapid, relatively low-energy, serial β^- decays will produce a stable (non-radioactive) isotope [Ref. 16]!



Now, society only has to wait 10 x (58.51d+9.5h), or about 1.6 years, to achieve the same safety level. That's much more reasonable. Dealing with ^{129}I , another common and very dangerous fission product (Table 2), is even more promising. This isotope has a half-life of 17 x 10⁶ years, but after neutron irradiation 10 half-lives will pass in 5 days!



At least in principle, the idea of a nuclear "radioactive waste disintegrator" is not impossible. There are, however, many practical problems to overcome. For example, how does one keep stable ^{130}Xe from being irradiated and becoming still another radioactive isotope? In this case, if the secular equilibrium concentration of ^{130}I is low so that it is unlikely to absorb another neutron during irradiation, then *inert stable* ^{130}Xe gas can be quickly removed from an irradiated solution of ^{129}I by heating, without any risk of complicating chemical reactions. In fact, the reactor heat will do the latter job automatically. Once ^{130}Xe is removed from the reactor, it can no longer be activated by further neutron absorption. A more complex ques-

tion is whether continuous processing, or irradiation-decay-removal cycles, are most efficient at destroying ^{129}I .

So it is clear that system safety engineers will have to do some very creative thinking to make this waste disposal scheme practical. And, spent fuel will have to undergo a lot of chemical and isotopic separation (expensive) before its wastes can be disposed of ("disintegrated") by irradiation. The extra costs can be paid for by the value of the fissile materials removed during reprocessing. Nuclear fission reactors fell into disfavor after the Three Mile Island Accident. Also, many nuclear engineering departments at universities were closed. If fission research had continued and was funded at even a fraction of what fusion programs received, many — and perhaps all — of fission's waste problems might have been solved. Nevertheless, fission may make a comeback, with a lot of work for future system safety engineers with a background in radiation safety, nuclear engineering and physics.

However, it must always be remembered that, although uranium is widespread in the environment, mineable deposits are relatively rare. Some countries like France, which rely heavily on nuclear energy, are already beginning to feel the pinch. There may be enough uranium to generate the world's energy for the next century, but then what? One answer might be more extensive use of *breeder fission reactors* that produce both energy and plutonium fuel (via ${}^1_0\text{n} + {}^{238}\text{U} \rightarrow {}^{239}\text{U} \rightarrow {}^{239}\text{Pu} + \beta^-$), as well as the usual radioactive isotopic waste already discussed. These reactors could extend the use of fission much further into the future, but the Chernobyl disaster (1986) retarded experimental reactor development. Another possibility is controlled nuclear fusion.

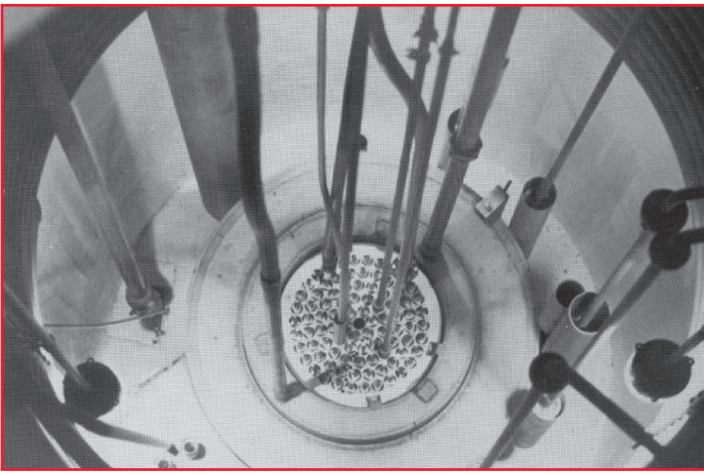


Figure 10 – A small General Atomic research and isotope production reactor. Notice the underwater lamps on the right and left side of the “swimming pool.” If these lights are turned off, an eerie blue light can be seen to come from the reactor core. This is the Cerenkov radiation. It is caused by charged particles traveling through water faster than the local in-media speed of light. In the author’s opinion, unless you have been specially trained, if you can see the Cerenkov radiation you are too close to the reactor core. Photo by author.

Controlled Nuclear Fusion Research Motivation

There are currently 7.7 billion people on the Earth (as of 2020). Human beings are by far the most populous large animals on the planet. The eminent physicist Stephen Hawking estimated that “by the year 2600, the world’s population will be standing shoulder to shoulder and the electricity consumption would make the Earth glow red-hot” [Ref. 17]. However, crisis population levels will be reached long before that, because each person requires a minimum of 2,279 square feet of arable land to grow enough food to stay alive²; that’s optimistically assuming that everyone’s patch of land is capable of yielding three harvests a year and there are no losses due to disease, insects, spoilage, or weather. Currently, the Earth’s land masses have a total surface

area of about $132.5 \times 10^6 \text{ km}^2$, not counting Antarctica and Greenland [Ref. 18]. However, rising sea levels due to global warming are reducing that land area every day. Worse still, is the fact that one third of dry land is desert (about $44.2 \times 10^6 \text{ km}^2$) — and the deserts are growing in size each year.

All this means that more and more people are going to have to migrate to a steadily decreasing land area. At present, there is $88.3 \times 10^6 \text{ km}^2$ of non-desert land left for farming — assuming there is enough unfrozen desalinated water available. If this area is divided by the current population of the Earth, the result is 0.0115 km^2 ($1.24 \times 10^5 \text{ ft}^2$, i.e., a square patch of land 352 feet on a side) per person. And, this area per person will be cut in half with each population doubling. In that case, the population stagnation point will be reached by about 2250, assuming the Earth’s human population continues to double every 40 years.

How will humanity survive 230 years from now? Will there be enough potable drinking water? Or will energy expensive desalination be required? Will arable soil become depleted? Will people eat synthetic food? Will people farm the deserts with drought resistant genetically modified organisms? Will people farm the oceans for nourishing plankton?³ What will we do with our garbage and our sewage? Will humanity choke under a pall of CO_2 and air pollution as global warming continues? Or will humanity learn to sequester CO_2 ? And where will the energy come from to do that on a global scale? Complicating these problems even more is that the current global diaspora is targeting relatively few countries. Will *population concentrations* (“popcons”) devastate parts of the globe prematurely? Canada and Greenland are not overpopulated because they are too cold. However, that too may change due to global warming.

The outlook for energy is similar. The 2020 electric energy consumption is expected to be about $2.9 \times 10^{13} \text{ kwhr}$ per year, and global electric energy consumption is doubling approximately every 20

² Assuming each person requires 2,500 calories per day, and that each 16 square feet of land is capable of producing (per harvest) a varied diet of four heads of oak leaf lettuce, 16 standard sized carrots, nine bunches of spinach, 32 radishes, 16 scallions, four heads of salad bowl lettuce, 16 beets plus four bunches of beet greens, 5 lbs. of sugar snap peas, four heads of ruby lettuce, nine Japanese turnips, eight bunches of Swiss chard, one head of cabbage, four heads of romaine lettuce, one head of cauliflower, one head of broccoli, and 16 small round carrots [Refs. 35 & 36].

³ There are two kinds of plankton: zooplankton (microscopic animals) and phytoplankton (microalgae). Farming the oceans for plankton as a human food source has been suggested, and phytoplankton is available as a food supplement in tablet form. It is claimed to be rich in essential fats (e.g., Omega-3 fatty acids), trace minerals, B vitamins, and protein [Ref. 38]. The enormous size of filter feeders, like whale sharks (20 tons and 40 feet long) and manta rays (2 tons and 25 feet across), attests to the nutritional value of plankton. Phytoplankton also sequester CO_2 from the air.

⁴ The doubling time has been much shorter in the past. It was 8.9 years between 1950 and 1974 [Ref. 18].

years (actually every 19.5 years) [Ref. 19].⁴ If all the deserts of the world were covered with photovoltaic cells (solar cells), and if these cells were 100% efficient at capturing energy (they are only ~20% efficient, maximum [Ref. 20]), and given that the solar constant for deserts (sea level) is 0.970 kw/m² [Ref. 20], then the maximum amount of power that can be generated is 42.9 x 10¹² kw. Or, since there are 8,760 hours per year, a maximum of 3.76 x 10¹⁷ kwh (or 1.35 x 10²¹ j) of energy can be generated *each year*. If the current growth of electric energy consumption continues, all of that energy will be consumed each year 265 years from now. Furthermore, between farming and generation of electricity, no room will be left on Earth for any wild habitats, save Greenland, Antarctica and the oceans. All these future problems cannot be solved here. The scope of this section is limited to controlled nuclear fusion and its associated radiation hazards. Nevertheless, this “techno-sociological” background information is necessary motivation for what is to come.

Reactions

Nuclear fusion can be accomplished using pure deuterium, or a mixture of deuterium (²H or d) and tritium (³H or t). In the pure deuterium case, the two most likely reactions are [Ref. 21]:



Deuterium is abundant on Earth (~0.015% of all hydrogen) [Ref. 16]. Deuterium will be available so long as there are oceans. Reactions 22 and 23 are about equally likely. The dominant exothermic reaction for d/t mixture is [Ref. 21]:



Tritium fuel (³H) used in Reaction 24 is made from ²H, ⁶Li, or ⁷Li by neutron absorption. The free neutrons produced by Reactions 23 and 24 are, of course, problematic. As discussed in the previous section, neutrons can be absorbed by any nuclei that they encounter with a probability that depends on the *neutron absorption cross-section* of the target atom. Therefore, whatever material vessel is used to contain Reactions 23 or 24 will eventually become radioactive. So controlled nuclear fusion, although cleaner than fission, does produce radioactive waste that will have to be dealt with via the methods of the previous section. The occurrence of tritium (³H) as a waste product in Equation 22 should also be noted since it played a curious role in an incident in the late 1980s that will be briefly discussed later.

Results

Many devices have been constructed to confine deuterium and tritium long enough, and under sufficient pressure, to initiate nuclear fusion. And, although these experiments have been successful, none have produced more energy than they consume. At this time, two basic schemes have been employed. There are magnetic bottle methods and laser confinement methods. Magnetic methods try to confine, and then crush, a plasma of deuterium and tritium with a magnetic field until fusion is initiated [Ref. 22]. Laser methods try to crush a pellet of deuterium, either directly or indirectly, with laser heating (so-called “inertial confinement”) [Ref. 22]. As the outer shell of the pellet is blown off, the interior is crushed, thereby initiating fusion.

The author made a small contribution to one of these exotic experiments. The *Shiva* experiment had the output of 20 giant lasers directed into a vessel within which a deuterium pellet was dropped [Ref. 22]. It was essential that the mirrors used to direct this laser energy be very clean. A speck of dust would absorb energy and locally heat a mirror to damaging levels. The author’s task was to ensure the safety of those mission-critical mirrors by building a fast, efficient, mirror-cleaning system. No liquids, solution stains or fingerprints were allowed. The work was completed in 60 days. So there *is* work on these experimental projects for system safety engineers with hands-on experience and “know-how.” *Shiva’s* lasers consumed a lot of energy — much more than was ever produced by fusion. However, a great deal was learned, and physicists moved a little further along the learning curve.

Once again, some physicists feel that practical controlled fusion will never be achieved. After all, the equivalent of hundreds of millions of U.S. dollars have been spent by research teams all over the globe (Japan, Europe, Russia and, of course, the U.S.) over the last half century or more without unambiguously achieving “break-even” (i.e., getting just as much energy out as you put into a controlled fusion reactor). Charles Seife summarizes this position nicely in his book *Sun in a Bottle — The Strange History of Fusion and the Science of Wishful Thinking* [Ref. 22].

On the other hand, others point to the progress that *was* made over 50 years, from the early experiments with Fermi Bottles in the 1950s that output 1/1,000,000th of the power that was put in, to *Shiva* in the 1980s that output 1/10,000th of the input energy, to JET (Joint European Torus) that was shy of break-even by 40% in 1997. JET was an astonishing achievement. Even Seife admits that. Japan Tokamak 60 in 1998 might have even surpassed break-even by 25%. That, however, is debatable. Some researchers claim that a d-t fuel mixture would be needed, instead of pure deuterium fuel, to achieve that performance.

In September 2013, a small pellet of hydrogen fuel was compressed by 192 beams from the world's most powerful lasers at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory in Livermore, California. Although the amount of energy released by fusion exceeded the amount of energy absorbed by the pellet overall, NIF never produced more than a third of the energy needed for break-even in the years that followed [Refs. 23 & 24]. Seife, writing in 2008, seemed to view the creeping approach toward break-even as just one more "proof" that a controlled fusion reactor is little more than another attempt to build a "perpetual motion machine." However, there is a difference. No fundamental law of physics forbids the construction of a controlled fusion reactor. The limitations seem to be primarily practical, and such limitations are always overcome eventually (e.g., consider powered flight).

Furthermore, there clearly are some conditions under which a deuterium/tritium mixture can be confined sufficiently to initiate a fusion reaction; otherwise an H-bomb could never have been built. Funded by the EU and six other countries, the International Thermonuclear Experimental Reactor (ITER) is the next-generation magnetic confinement machine after JET, and is currently being constructed at Cadarache, France. It will be interesting to compare its performance with the NIF.

Hybrid inertial/magnetic systems have also been proposed by the General Fusion company of Canada (proof of concept experiments began in 2002). Other imaginative fusion possibilities have been explored as well, including neutron free $^1\text{H} + ^{11}\text{B}$ fusion [Ref. 25]. And, now that fusion power is closer to being a reality, several companies (e.g., Lockheed Martin, Tri Alpha Energy, General Fusion, Helion Energy, etc.) and universities (MIT, Max Plank Institute of Plasma Physics, UCLA, etc.) have their own fusion programs as well [Ref. 25]. These smaller efforts have also made some significant contributions to the controlled fusion problem [Ref. 25]. While 60 years may seem like a long time to study a problem, consider how long it took to detect gravity waves (from the time of Weber's false detection in 1969 until direct detection in 2015). Or, consider how long it took to prove Fermat's Last Theorem (357 years)!

In the author's opinion, fusion research will continue. It may take some new technology to make fusion practical, but the work *will* continue. Not because of "wishful thinking," or because people like to spend money on multi-billion-dollar projects, but because the human race *must* solve this latest "fuel configuration" problem within the next century, or irreparable damage will be done to the Earth. As Edison would say, "After the one thousandth try, there was light!" Until then, a mix of solar energy, wind energy, hydroelectric power, tidal power (largest plant in S. Korea), geothermal power (used extensively in Iceland), and "clean fission" (not yet

available) including *safe* breeder reactors, seem the best, and most easily attainable, options.

The Biological Effects of Ionizing Radiation

α -Particles:

Typically, α particles from natural sources lie in a narrow energy band of 4 to 9 Mev. There is usually little risk from α emitters because their range is so short. A piece of paper is sufficient to stop them. However, intimate contact of α emitters with the epithelial tissues that line the digestive tract, the respiratory system and the eyes is dangerous and decontamination of such tissue surfaces is required.

The problem arises from a combination of circumstances. First, epithelial cells have a naturally high rate of division. This is necessary because they die so quickly when they are scraped by roughage in the digestive system, when they are ejected from the lungs as germs and dust are removed from the respiratory system (especially during times of infection – colds, etc.), and when they are dehydrated by dry air at the surface of the cornea. So, it doesn't take much genetic damage to push the number of epithelial cell divisions beyond their naturally high Hayflick limit (maximum allowable number of cellular divisions) to infinity, thereby avoiding apoptosis (genetically programmed cell death) and creating a carcinoma. The large amount of epithelial tissue in a mammary gland is what makes breast cancer so prevalent and so deadly.

When this natural tendency toward carcinoma is combined with the high LET and RBE of α particles, and the close contact that a uranium atom might make with an epithelial cell in the digestive tract, or a ^{222}Rn atom with the lining of the lungs, it is clear that a danger exists from both inhalation and ingestion. In the early 1900s, before people were aware of the dangers of radiation, a study on uranium miners indicated a cancer rate 50% higher than the rest of the population due to uranium dust inhalation [Ref. 3]. Radon is a natural decay product of ^{238}U (see the decay chain above), the principal isotope of uranium, an element that is widely distributed on the Earth. All common rocks contain uranium (typically ~3ppm) [Ref. 26]. Radon gas collecting in homes has been implicated in lung cancer. Contact of α emitters with the eye is limited to wind-blown dust — a condition that might be encountered when living near tailing mounds from uranium mining operations. In Moab, Utah, bright yellow particles and small pebbles can be seen on tailing mounds, indicating a high uranium content that was confirmed by radiation counter measurements. The extraction of uranium minerals during mining is not completely efficient and some ore is invariably left behind.

There are also man-made α emitters to contend with. Californium-252, a synthetic element and isotope,

is used in smoke detectors in microgram quantities. The attenuation of radiation over centimeter scale distances is a measure of smoke in the air. ^{252}Cf only emits short range α particles, no γ or β radiation, so it is safe to use *within the confines of a smoke detector*. Similarly, ^{218}Po and ^{215}Po (see the decay chains above) only emits short range α particles, and can be used to neutralize static electric (electron) buildup.

β -Rays

There are two types of β radiation: electron emissions (the most common type) and positron emissions. The LET of electrons is much smaller than that of α particles because they only carry a single electronic charge. Although their range is much greater than α particles in air, electronic emissions often carry very little energy, do little biological damage, and are easily stopped by a thin sheet of aluminum. Therefore, they are usually not much of a radiation hazard.

The principle sources of electronic β radiation in the environment are ^{14}C (discussed earlier) and tritium (^3H). The latter being a very rare, but naturally occurring, isotope of hydrogen that is a good model for other electron emitters. Small amounts of tritium are not dangerous because its β emission carries very little energy (0.0186 Mev) and cannot do any non-repairable damage to DNA. In fact, tritium used to be painted onto watch dials to make them visible (glow) in the dark. The half-life of tritium is only 12.346 years. So, by that standard, it is very radioactive, and can supply plenty of energy to neighboring phosphorescent atoms in “glow paint.”

The amount of tritium in the world has increased from its natural steady-state (secular equilibrium) level due to the testing of hydrogen fusion bombs in the late 1950s and early 1960s. This, actually, has had one good side effect, if testing an H-bomb could be said to have any good effects. The presence of bomb tritium in groundwater can be detected with scintillation detectors, and the disappearance of this “tritium pulse” over time (after correcting for radioactive decay) has given us a temporary window into the recharge rates of aquifers. Now, of course, after almost six decades of radioactive decay, only $1/2^6$ (or about 1.5%) of the original tritium pulse is left, so tritium levels are pretty much back to normal.

Tritium is notoriously mobile because it is an isotope of hydrogen, and hydrogen is the smallest atom.

Therefore, spreading by diffusion is a problem when low-level tritium measurements are being made. Even the presence of someone with a tritium watch dial in a dating laboratory will ruin all measurements. As an amusing aside, in 1989 there was a belief among some scientists that the “cold fusion” of hydrogen (fusion induced by electrochemical means) was possible [Ref. 22]. Some of the evidence for this claim rested on tritium measurements (see Equation 22) [Ref. 27]. Workers from the radiation community of practice who were familiar with the difficulties of making low-level tritium measurements were immediately suspicious. And, of course, the whole episode turned out to be one more exercise in “bad science.”

The health risks of positron emitters are very different. A positron is a positively charged electron — the anti-matter counterpart of an electron. As a positron slows, it will eventually encounter and capture an electron. The two particles will orbit about one another around a mutual center of mass. However, this dance will not go on forever. Eventually the overlap of the two wave-functions will allow the two particles to find, and mutually annihilate, each other. When that happens two half Mev γ -ray photons will be created and move in opposite directions as demanded by conservation of momentum. These γ -rays are penetrating and pose a health hazard to be discussed next.

γ and X-Rays

The system safety engineer should note that the ionization produced by γ rays is a minimum for 0.075 Mev photons [Ref. 2]. Therefore, the least amount of biological damage is to be expected at this energy. The system safety engineer should also be aware that an ingested γ emitter (e.g., an atom of ^{226}Ra) can affect cells in any part of the body due to the penetrating power of γ and X rays. Although medical/dental X-rays are usually considered to be harmless, this may not be the case since the effect of X-rays is probably cumulative! Repeated low-doses of radiation received during routine chest X-rays and low-dose mammography might actually increase a woman’s chance of developing breast cancer [Ref. 3].⁵ However, this small increase in risk must be counterbalanced against the risk of letting an early stage cancer go undetected. Finally, it should be noted that “many scientists believe there is no threshold level of radiation exposure

⁵ It is important to understand the ionization (and biological damage) minimum at 0.075 Mev. Wilhelm Röntgen, the discoverer of X-rays, died of intestinal cancer [Ref. 37]. His laboratory assistants also died of cancer. Yet, the Varian TrueBeam™ STx machine [Ref. 29] is used to *kill* cancer cells. Why? The TrueBeam STx X-ray tube operates in the 4 to 20 megavolt range. High-energy X-rays produced by such tubes create heavy ionization and massive biological damage resulting in (cancer) cell death. By contrast, the lower energy X-rays (with $\lambda \approx 1\text{\AA}$), used by Roentgen for imaging, create less fatal damage, thereby allowing a radiation-induced mutation to produce a carcinoma.

below which danger ceases to exist and that any radiation dose, regardless of size, subjects the person exposed or any potential offspring to a certain amount of risk” [Ref. 3].

Cosmic Rays

For most of us, cosmic rays are a negligible health hazard, but there are some instances where the dose of radiation received by cosmic rays should be taken into account. Commercial airline crews flying at altitudes of 30,000 to 35,000 feet receive 1/200th of a REM on just one flight from the United States to Europe [Ref. 3]. Personnel who fly the high-altitude transcontinental routes regularly are limited to 1,000 hours a year by FAA rules. That amounts to a total of about 1 REM of radiation exposure.

Passengers who fly frequently should observe the same limits, although to the author’s knowledge no such monitoring exists. Technically, airline crews are considered radiation workers whose annual dose by federal standards is limited to 5 REM (but no more than 3 REM per quarter) [Ref. 3]. Pilots or passengers who fly supersonically at altitudes between 50,000 and 60,000 feet receive much higher doses of radiation per unit time. For every 10,000 feet, cosmic ray intensities increase by a factor of three [Ref. 3]. Moving from an altitude of 3,000 feet in Tucson, Arizona, to 7,500 feet atop Mt. Lemmon (5 miles from Tucson) increases the radiation intensity by about 30%.

Neutrons

A question that is often asked of a system safety engineer is: “If an object is placed in contact with a radioactive source, will it become radioactive as well?” That is usually not possible. In the case of γ rays, the energy of the incident radiation must precisely match the transition energy between two allowable energy levels of the target nucleus. Positively charged particles of radiation lose energy through processes already described, and then they must overcome the repulsive coulomb barrier of the target nucleus. In addition, β rays are much more likely to interact with an atom’s atomic electron cloud before they ever see a positively charged nucleus suitable for an electron capture event.

Neutrons, however, are different. Although neutrons are not ionizing radiation because they have no charge and cannot interact with atomic electrons to create an ion, they can, nevertheless, induce radioactivity (α , β and γ radiation) by being absorbed by an atomic nucleus. When this happens in the human body, the human body itself becomes radioactive — with all the consequent damage to be expected from intimate unshielded exposure to these radiation types. Neutrons are *very* dangerous. However, thermal neutrons can be effectively stopped with a Cd shield [Ref. 16].

In the 1980s, the author participated in an experiment to measure thermal neutron activity in a deep mine shaft [Ref. 28]. A Cd shield about 2 mm thick was used to isolate a detector from the uniform ambient neutron flux (see the previous section on “Planar Sources of Radiation”). By comparing counts with and without the shield in place, the small subsurface neutron density (neutrons per cubic meter of rock) could be measured. Making radiation level measurements is a common task for system safety engineers.

Radiation Sickness and Dose

In this subsection, the symptoms of radiation exposure as a function of *whole-body* absorbed dose are discussed [Ref. 3]. Here, the caveat is that individuals *vary greatly* in their tolerance and response to radiation. A dose that might produce hair loss in one person may leave another completely asymptomatic.

- **Dose Level 1** — Under 50 RADs, there is usually no overt sign of illness.
- **Dose Level 2** — At 100 RADs, overt symptoms may not be present, but subtle changes in blood chemistry/biology can be measured (e.g., drop in white blood cell count, etc.).
- **Dose Level 3** — At 200 RADs, overt symptoms appear (fever, hemorrhage, hair loss). Very sensitive people may die.
- **Dose Level 4** — At 450 RADs, half the people exposed will die.
- **Dose Level 5** — At 600 RADs, most people will die. Survivors will suffer gastrointestinal symptoms.
- **Dose Level 6** — Doses from 800 to 1,000 RADs are always fatal.
- **Dose Level 7** — Above 1,000 RADs, central nervous system symptoms, cardiovascular collapse, and death result.

During radiotherapy for cancer, some patients may *locally* receive in excess of 1,000 RADs [Ref 3]. This radiation dose is intended to definitely kill cancer cells without leaving a single diseased cell behind. Invariably, some healthy cells will also be destroyed, but improved targeting is rapidly reducing the chances of collateral damage [Ref 29 & 30].

Fallout

Fallout is not just limited to the debris of nuclear weapons. Nuclear accidents like Three Mile Island and the Fukushima Daiichi nuclear reactor disaster also produce fallout. A complete discussion of fallout cannot possibly be presented here and is far outside the scope of this work. However, a few relevant points are worth presenting here for the average system safety engineer.



Figure 11– This shirt was worn by a citizen of Hiroshima at the time of the bombing. The black smudges are stains from the “black rain.” Photo by author.

First, the groundwater in Hiroshima is completely safe 75 years after its bombing at 8:15 AM on August 6, 1945. This is somewhat surprising, since a black, sticky, radioactive rain fell (fallout) after the air detonation 580 m (1,900 ft.) above ground [Fig. 11]. The combination of naturally high rainfall, complete flushing of the aquifer many times over, and capture of radioactive species by ground minerals, rocks and clays, seems to have saved the groundwater [Ref. 26].

The other surprising relic of the Hiroshima blast is the fact that not all buildings were destroyed. Figure 12 shows the famous “A-Bomb dome” — a building that provides a few lessons for structural engineers. The dome essentially marks Ground Zero, almost directly under the blast, and demonstrates the astonishing ability of masonry walls to resist compressive force. Also note that the steel skeletal ribs of the dome have been stripped bare of their intervening construction materials by that same downward force. The only reason the steel skeleton itself survived is because it forms a shell and, like a bird’s egg, is naturally robust under uniform external compressive loads [Ref. 31].⁶ Hence, the dome of the Pantheon in Rome has survived 2000 years of nature’s (and man’s) insults as well as the downward force of its own weight (it is very thick). Nothing more will be said about fallout except to mention that radiation levels are still being monitored in Fukushima, nine years after the 2011 reactor mishap.

Conclusion

This survey of ionizing radiation hazards was necessarily brief, but very broad. It concisely summarizes the detailed facts, equations and “know-how” that most system safety engineers will need to protect themselves and others from the harmful effects of ionizing radia-



Figure 12– The “A-bomb building” as it appeared in July of 2019. Many Japanese would like to have this relic torn down since it is structurally dangerous and, understandably, is an unpleasant reminder of an event that they would rather forget. Photo by author.

tion. It also helps put the risks of common exposures into perspective. Furthermore, current problems in radiation science have been introduced to show how the system safety engineer fits into the radiation technology culture of the near future.

The discovery of ionizing radiation must certainly be considered one of the most profound events in human history. Between 1901 and 1965, 28 Nobel prizes were awarded for radiation physics. Ionizing radiation has changed medical practice, the way we generate energy, economics, and unfortunately, international politics and warfare. It should always be remembered that the greatest radiation hazards of all are people and the belligerence of nations! Some leaders think that the introduction of nuclear weapons into a region will guarantee national security. They probably will not do so. What they will guarantee is an endless, and very expensive, theater nu-

⁶ Careful examination of the dome skeleton in Figure 12 reveals a slight outward bulge about a third of its height above its base (left side). This is a very typical type of deformation for a steel dome under extreme uniform downward compressive load [Ref. 31] and is evidence of structural instability.

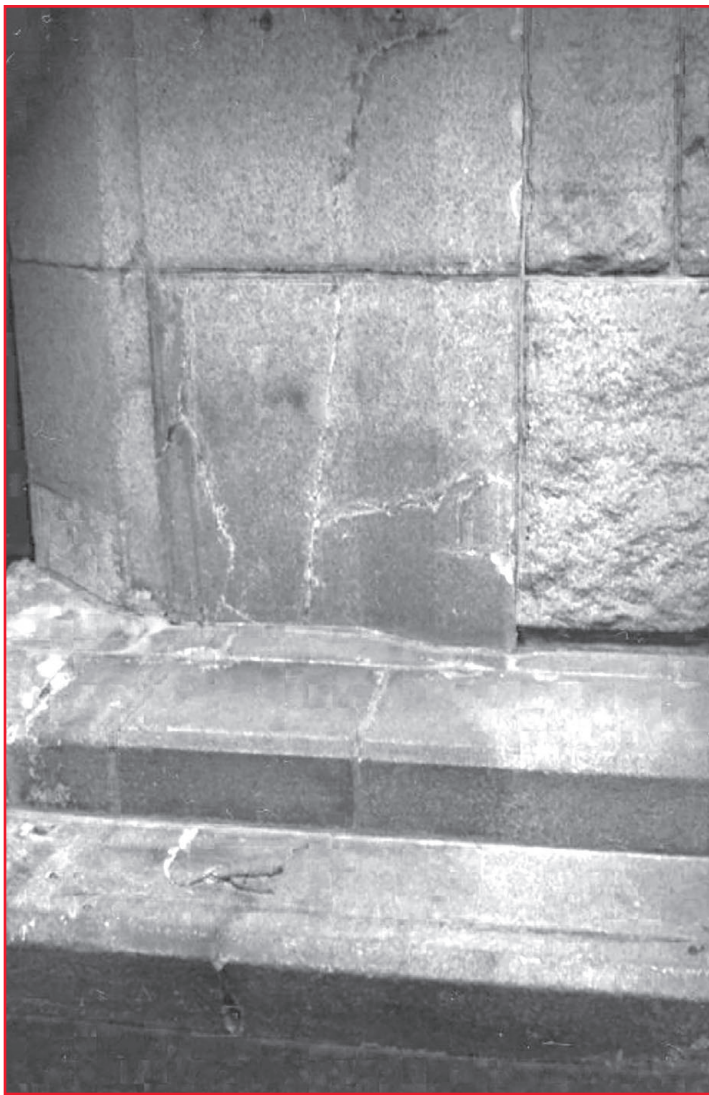


Figure 13– These are the outside steps of the Sumitomo Bank building in Hiroshima. The person who was sitting on these steps on the day of the bombing was instantly vaporized! Only this so-called “shadow” was left behind. It is difficult to say exactly what this “shadow” is. Perhaps the intense radiation bleached the granite around the human form that absorbed the radiation. Or perhaps the “shadow” is simply that person’s atoms blasted into the rock. This photo by the author is a grim reminder of an old Roman saying, “Homo homini lupus” (“Man is wolf to man”).

clear arms race, and radioactive waste that will somehow have to be dealt with sooner or later.

There have been many near-nuclear-accidents, some of which have been discussed at International System Safety Conferences [Refs. 32, 33 & 34], and the specter of an accidental nuclear release is always waiting in the background, sly and unforgiving. It is a miracle that the “Cold War” did not end in disaster. The author closes this paper with one last photograph [Figure 13]. Think about it!

About the Author

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