7
Nuclear Pollution

7.1 Low-Dose Radiation

Radiation has many positive uses, such as medical diagnostics, cancer therapy, radiosurgery from many collimated beams, nondestructive testing of structures, smoke alarms, and food irradiation. However, the use of radiation must be controlled because of possible health effects. Without taking time to think about possible danger, Louis Slotin used his hands to separate a critical mass at Los Alamos on May 21, 1946. He died in nine days, the first victim of the postwar nuclear arms race. Slotin did not die of cancer; rather his body stopped functioning after a dose of over 10 sieverts (1 Sv = 100rem). A one-time dose of 4 to 5 Sv is lethal to 50% of victims. This chapter does not deal with such large doses, but rather with doses under 10–100 mSv, which can cause cancer after a latency period of some 10–30 years.

The additional death rate is linear at higher doses as seen in the data on Japanese atomic bomb survivors in Fig. 7.1. Can this linear relationship be extrapolated to risk at the low-dose region? Or is there a threshold dose below which biological repair is significant? Hiroshima/Nagasaki data show a linear mortality for radiation dose above 200 mSv (20 rem), but below this threshold the data are more uncertain.[1] Data for uranium miners above 100 mSv also point to linearity. Can this linear effect be extrapolated into low doses of less than 1 mSv? US citizens receive an average radiation dose of 3.60 mSv/year, most of it—3.0 mSv—from natural sources, including radon in buildings, and an additional 0.6 mSv from manmade sources, such as medical x-rays. Natural radiation damages most of the cells in our bodies every year. Experiments show that the number DNA breaks in cells is proportional to dose at a rate of 6.3 DNA breaks per human cell per gray (see radiation units in Section 7.1.1). These experiments show that most of the breaks were repaired

[1] The two atomic bombs dropped on Japan had quite different characteristics.
Hiroshima, at 1000 m, gamma ray dose = neutron dose = 3 gray
Nagasaki at 1000 m, gamma ray dose = 10 gray, neutron dose = 1 gray
(Peterson and Abrahamson, 1998).

after a relaxation time of several hours. Figures 7.1 and 7.2 display the 1994 United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) data on Japanese atomic bomb survivors.[2] Japanese copper samples are currently being measured for the content of ^{63}Ni, which is made from neutron irradiation of copper. It is planned to separate gamma rays doses (the highest source of radiation) from fast neutron doses.

7.1.1 Radiation Units

The SI radiation units of *gray* and *sievert* are defined below, along with the more colloquial *rem* and *rad* units.

Rate of decay:
1 curie (radiation from 1 g of radium) = 1 Ci = 3.7×10^{10} decay/s
1 bequerel (SI) = 1 Bq = 1 decay/s
Absorbed energy in air:
1 roentgen = 1 R = 87 ergs/g = 0.0087 J/kg
Physical dose of absorbed energy:
1 rad = 100 erg/g = 0.01 J/kg
1 gray (SI) = 1 Gy = 1 J/kg = 100 rad
Biological dose equivalent is absorbed dose times a *relative biological effectiveness* Q.
X-rays, γ-rays, and electrons have $Q = 1$, neutrons have $Q = 5$–20 and alpha particles and fission fragments have $Q = 20$.
1 Roentgen equivalent man (rem) = 0.01 J/kg
1 sievert (SI) = 1 Sv = 1 J/kg = 100 rem

Below some threshold, it is not clear *from the data* whether DNA breaks are *sufficiently* repaired to prevent the damaged cells from causing cancer. It is *very difficult* for epidemiology to settle this issue at very low doses. Some say that the threshold theory is valid, since the human system does repair DNA after radiation. Others say that a Taylor expansion of a continuous function of the relationship contains a linear term. Hence, damage eventually remains. Some say a double DNA break is needed to cause cancer, and this is continuous with dose. This requirement is

Dose (Sv)	Subjects	Cancer	Expected	Excess
< 0.01	42,702	4286	4267	19
0.01–0.1	21,479	2223	2191	32
0.1–0.2	5307	599	574	25
0.2–0.5	5858	759	623	136
0.5–1	2882	418	289	129
1–2	1444	273	140	133
2+	300	55	23	32
Total	79,972	8613	8106	507

[2] Japanese atomic bomb cancer data. Dose to the large intestine (colon) in siverts (Mabuchi, 1998).

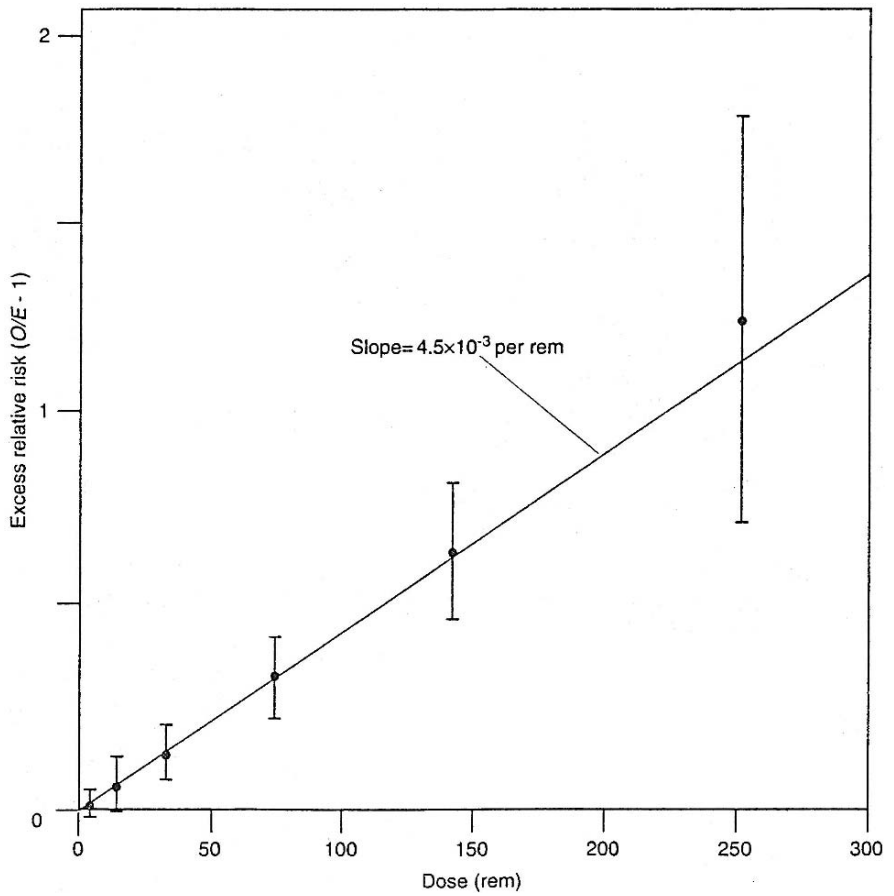

FIGURE 7.1. Excess relative risk for solid-tumor mortality versus dose for Japanese atomic-bomb survivors. The error bars correspond to plus or minus one standard deviation. A straight-line fit to the data yields the high-dose rate relative risk factor of 4.5×10^{-1}/Sv (4.5×10^{-3}/rem). The two data points below 20 rem are examined further in Fig. 7.2 (Schillaci, 1995).

fulfilled when a natural break and a radiation break occur, supporting the linear theory. Others say a double break from radiation alone is needed, an idea that supports a nonlinear theory.

Dose models are key in discussing regulation of nuclear materials in reactors, wastes, and stored weapons. *Low-dose radiation* is a predominant issue, as it makes a considerable contribution in estimates of potential deaths. The Committee on Biological Effectiveness of Ionizing Radiation (BEIR of the National Academy of Sciences) accepted the hypothesis that the rate of additional cancers is linear with dose. However, in 1990 BEIR commented that "at such low doses and dose rates, it must be acknowledged that the lower limit of the range of uncertainty in the

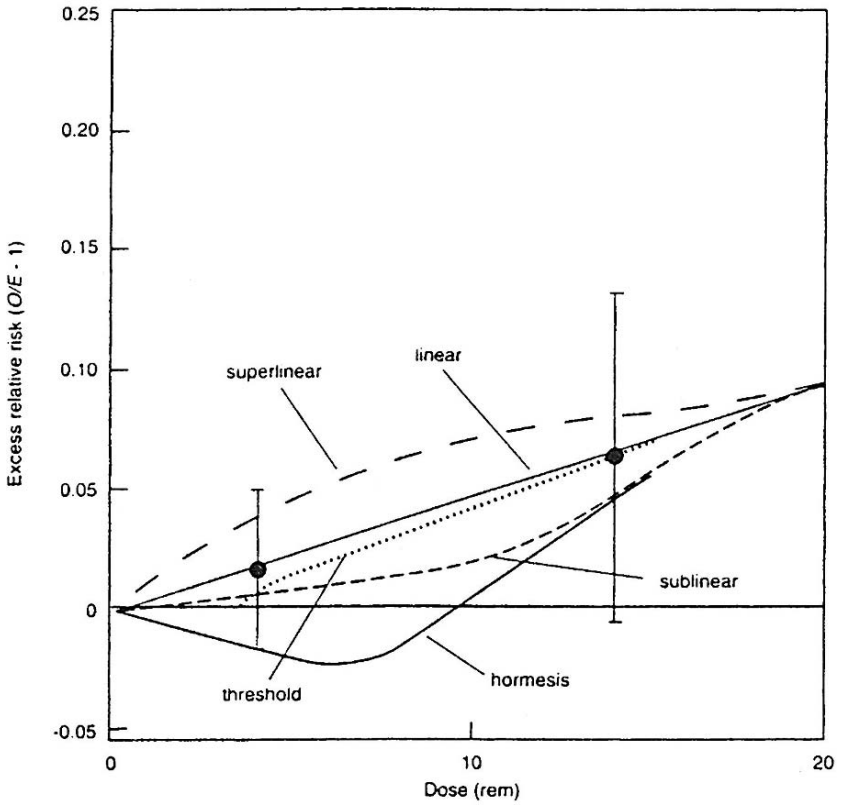

FIGURE 7.2. Extrapolation of high-dose data to doses below 0.2 Sv (20 rem). The low-dose data from Fig. 7.1 are compared to possible curve fits based on superlinear, linear, sublinear, threshold, and hormesis couplings (Schillaci, 1995).

risk estimates extends to zero." The experts cannot prove the linear theory with no threshold is correct, but they believe it is correct (2006). A controversial related issue is that of *hormesis*, which theorizes that very small radiation doses actually *reduce* cancer rates. In Kerala, India, radiation doses are 20 mSv/year, 6 times the US rate including radon, yet people live longer in Kerala than in the rest of India. Of course, this longevity might be due to other effects of living in Kerala. The 2006 BEIR report rejected the hormesis theory.

7.1.2 Linear-Quadratic Theory

The absolute risk model, which gives a total probability ($P_{\text{total cancer}}$) of getting cancer from radiation *and* other causes, is described with the relationship,

$$P_{\text{total cancer}} = P_{\text{nonrad cancer}} + P_{\text{rad cancer}} = \alpha_0 + (\alpha_1 D + \alpha_2 D^2)\ \exp(-\beta_1 D - \beta_2 D^2), \tag{7.1}$$

where α_0 is the cancer rate without radiation and α_1 is the coefficient for linear, low-dose radiation D. At higher doses, the quadratic $\alpha_2 D^2$ term is important, as multiple, closely spaced broken bonds enhance carcinogenic effects. It is generally believed that double-strand breaks in DNA do not easily self-repair, and are therefore more dangerous. The double breaks could be caused by one energetic particle causing multiple damage, or by higher doses. At still higher doses, the linear-quadratic prediction is diminished, as irradiated cells are destroyed and cannot cause cancer (β_1 and β_2). The natural cancer rate should be subtracted from the total cancer rate to determine the dependence on radiation. The usual choice of a linear low-dose radiation considers only the linear term, setting $\alpha_2 = 0$. The BEIR-VII committee rejected (2006) the existence of a threshold dose level, which would modify D to $(D - D_{\text{threshold}})$, or perhaps take some other form.

An alternative approach is the *relative risk model*, which uses radiation dose as a multiplicative factor to obtain cancer enhancement (Section 9.2). Perhaps the truth lies somewhere between the *absolute risk* and *relative risk* models. Radiation induces cancer that would not have taken place. It is the hot electrons produced by nuclear particles that break DNA bonds. Recent studies show that electron energies as low as 3 eV are sufficient to break these bonds. If DNA double breaks induce cancer, one can argue that a natural single break plus an ionizing break gives a linear coupling between radiation and cancer. Smoking and ionizing radiation acting together have a higher cancer rate by *compounding and additive* effects, as compared to acting separately.

7.1.3 Background Radiation

Radiation from natural and human-made sources give an average dose of 3.6 mSv/year (360 mrem/year) in the United States. This gives a death rate of about 1.5% of the total death rate, under the linear low-dose theory (1990 BEIR-V). Alternatively, background radiation causes about 7% of all cancer deaths. The major contributions to background radiation are as follows:

- 2.0 mSv/year (200 mrem) from radon in buildings
- 0.31 mSv/year (31 mrem) from cosmic radiation
- 0.28 mSv/year (28 mrem) from living at sea level
- 0.81 mSv/year (81 mrem) from living in Denver
- 0.39 mSv/year (39 mrem) from natural radioactivity in the body
- 0.3 mSv (30 mrem) from a mammogram
- 0.4 mSv (40 mrem) for a full set of dental x-rays
- 0.1 mSv (10 mrem) from a chest x-ray
- 0.53 mSv (53 mrem) US average annual yearly exposure from x-rays
- 14 mSv (1400 mrem) from a gastrointesinal (upper and lower) x-ray
- 2–9 mSv/year (200–900 mrem) for airline flight crews
- 0.05 mSv (5 mrem) for round trip transcontinental flights.

7.1.4 Radiation Standards

The limit on annual occupational exposure to radiation dropped from 700 mSv (70 rem) in 1924 to 300 mSv (30 rem) in 1934, to 50 mSv (5 rem) in 1958, and to an integrated dose unit of 10 mSv (1 rem) times a person's age in years in 1993. The annual limit for continual exposure of the public (nonnuclear employees) was set at 5 mSv (500 mrem) in 1960 and was lowered to 1 mSv (100 mrem) in 1990. To set standards *scientifically*, rule-making authorities need to know the low-dose coefficients, threshold values, benefit to society from radiation, value of a lost life, cost to mitigate radiation, and nonradioactive alternatives.

7.1.5 Radiation-Dose Conclusions

The 2006 BEIR-VII/2 report concluded the following on low-dose effects of radiation spread over many persons:

Effects from *single incidents of exposure* spread over many people:

- BeIR VII: 480 male or 660 female excess deaths per 10,000 person Sv (1 million person rem), which can be caused by 100,000 persons getting 100 mSv each (10 rem each), or by 10 million persons getting 1 mSv each (100 mrem each). The average of 570 excess deaths is in a background of 20,000 cancer deaths without radiation. The 100 mSv dose raises the cancer *death rate* from 20% to 20.3%. One statistical death results from 20.8 Sv (2080 rem) for males and 15.2 Sv (1520 rem) for females. The excess cancer rate is double the mortality rate.
- EPA/NRC (2003) used a risk value of 4×10^{-2}/Sv (4×10^{-4}/rem), which inverts to 25 Sv (2500 rem) for a statistical death. This gives a 0.8% probability of death for an exposure of 0.1 Sv (10 rem)

The International Commission on Radiological Protection concluded the following in 1991:

- 500 deaths from 10,000 person Sv (1 million person rem)
- 20 Sv (2000 rem) spread over many people = 1 death
- The US background rate of 3.5 mSv/year gives a total dose 0.28 Sv over 80 years. This dose gives a 1% cancer death rate at 20 Sv/mortality.
- 100 nonfatal cancers per 10,000 person Sv (1 million person rem)
- 130 severe heredity disorders per 10,000 Sv (1 million person rem)

7.1.6 Statistics

How large a population sample is needed to resolve the low-dose issue? About 20% of deaths are caused by cancer.[3] A population P has $0.2P$ deaths due to cancer. The standard deviation of the number of cancers in a sample of P individuals

[3] US annual cancer mortality rate was 200 per 100,000 persons (2×10^{-3}) during 1978–1988. US total annual death rate was 870 per 100,000 (8.7×10^{-3}) during 1980–1998.

is $\sigma = (0.2P)^{1/2}$. How large a sample would it take to observe the effects from the annual average of medical x-rays of 53 mrem/year (0.53 mSv/year)? Over an 80-year life, medical x-rays give an accumulated dose of 4.2 rem (0.042 Sv), causing (0.00057 cancer mortality/rem)(4.2 rem)$P = 0.0024P$, or 0.24% of the population. If we demand high confidence in our measurements, we require the additional deaths be *at least twice the standard deviation* of the measurement. This requires that

$$0.0024P > 2\sigma = 2(0.2P)^{1/2} \tag{7.2}$$

This condition requires a sample size of $P = 0.2$ million people who take medical x-rays and a control group of equal size that does not receive x-rays. A proper epidemiology study would have to make sure that confounding variables, such as demography, income, indoor radon, cosmic ray background, air travel, and so forth have no effect on the result. For this reason, low-dose effects have not been determined with significant confidence (Section 9.2)

7.1.7 Dose from 10 μCi of ^{137}Cs

What is the full-body dose to a person if he or she were to put 10 μCi of ^{137}Cs in a pocket for a full day? About 50% of the 660-keV (1.1×10^{-13} J) γ-rays is absorbed by an 80-kg body, and 50% radiates into space. The daily full-body dose for γ-rays ($Q = 1$) is

$$\begin{aligned} D &= (10^{-5}\ \text{Ci}/2)(3.7 \times 10^{10}/\text{s Ci})(1.1 \times 10^{-13}\ \text{J})(8.6 \times 10^{4}\ \text{s/day})/(80\ \text{kg}) \\ &= 0.02\ \text{mSv/day} = 2\ \text{mrem/day}. \end{aligned} \tag{7.3}$$

If the source stays in a person's pocket a year, it would give a dose of 7 mSv/year, an amount that far exceeds the 1-mSv/year limit on the public for continuous exposure to radiation, as well as the 5-mSv limit on infrequent exposure to the public. However, 7-mSv dose is legally permissible if the exposure is an occupational risk. The occupational limit for a nuclear power plant worker, for example, is 50 mSv (5 rem) for infrequent doses and 10 mSv/year (1 rem/year) for continual doses. If a radiation source is ingested, most of the gamma rays would be absorbed and dose would be doubled, with a specific dose to the abdomen rather than to the whole body.

7.2 Loss-of-Coolant Reactor Accidents

In general, nuclear reactor disasters do not happen because of a *single large failure* of safety procedures or technical problem. Rather they happen as a culmination of multiple, smaller operational failures or mistakes. Reactor malfunction is often due to poor maintenance practices or minor design errors. A nuclear reactor may suffer a loss-of-coolant accident (LOCA) from a pipe break that is followed by an *emergency core-coolant system* (ECCS) failure. The reactor core will then melt through the steel reactor vessel, perhaps into the ground below; hence, the nickname for

such an accident is the *China syndrome*. The Browns Ferry accident of 1975 was caused by a loss of all electrical power, which dangerously evaporated coolant, but power was restored before the core melted. The 1980 Three Mile Island accident occurred because cooling water for the core was stopped. The core was partially melted with the release of small amounts of radioactivity. The heat needed to melt a core comes from short-lived beta decay of fission fragments, and not from fission (which has stopped) or from alpha decay of transuranic elements. In this section we estimate the time for a reactor core to experience a catastrophic failure after a LOCA.

7.2.1 Reactor Radioactivity

The thermal efficiency η of reactor is 1/3, thus fission develops 3 GW_t for 1 GW_e at a fission rate,

$$(3 \times 10^9 W)(1 \text{ fission}/2 \times 10^8 \text{ eV})(1 \text{ eV}/1.6 \times 10^{-19} \text{ J}) = 9.4 \times 10^{19} \text{ fissions/s}. \quad (7.4)$$

Each fission event produces two neutron-rich fission fragments, each decaying about 4 times to reach stability, giving a steady state beta-decay rate 8 times the fission rate:

$$dN/dt = 8(9.4 \times 10^{19}/\text{s}) = (7.5 \times 10^{20}/\text{s})(1 \text{ Ci}/3.7 \times 10^{10}/\text{s}) = 2 \times 10^{10} \text{ Ci}. \quad (7.5)$$

7.2.2 Strontium Production

Strontium-90 is produced in 3% of fission events, annually producing ^{90}Sr at a rate

$$N_{\text{Sr-90}} = (0.03)(9.4 \times l0^{19}/\text{s})(3.2 \times 10^7 \text{ s/year}) = 9.0 \times 10^{25} \, ^{90}\text{Sr nuclei/year}, \quad (7.6)$$

which corresponds to a ^{90}Sr mass of

$$\begin{aligned} M_{\text{Sr-90}} &= (N_{\text{Sr-90}})(\text{atomic weight})/N_{\text{Avogadro}} \\ &= (9.0 \times 10^{25} \, ^{90}\text{Sr/year})(90 \text{ g/mole})/(6.02 \times 10^{23} \, ^{90}\text{Sr/mole}) \\ &= 14 \text{ kg/year}. \end{aligned} \quad (7.7)$$

^{90}Sr has a mean-life $\tau = 42$ years, giving a decay rate

$$dN_{\text{Sr}}/dt = N_{\text{Sr}}/\tau = (9.0 \times 10^{25} \, ^{90}\text{Sr})/(42 \text{ year})(3.2 \times 10^7 \text{ s/year}) = 2 \times 10^6 \text{ Ci}. \quad (7.8)$$

Since September 11, 2001, government agencies have focused on possible terrorist attacks on reactors and spent fuel ponds. Also of concern is the use of *dirty bombs*, made with conventional explosives surrounded with isotopes, such as ^{137}Cs, ^{90}Sr, or ^{60}Co. A dirty bomb in a large city would not kill a great number of people, but it would be very expensive to clear the area of the dispersed radioactivity. For example, there are potential sources of ^{90}Sr in 300 Russian radiothermal generators (RTG) that were used to make electricity in remote locations. An RTG can contain 40,000 curies of ^{90}Sr in a container with a total mass of 1000 kg. Removing ^{90}Sr from

the RTG produces serious health risks, a fact that serves as a deterrent to the use of ^{90}Sr in dirty bombs.

7.2.3 Loss-of-Coolant Rise Time

We will calculate the thermal rise time of a light water reactor (LWR) core after a LOCA. Thermal rise is the time for the core to get sufficiently hot to begin an exothermal reaction between zircalloy and water. The calculation is based on the following assumptions:

- Emergency core-coolant water (ECCS) does not arrive until fuel rods are over 1370°C, when zircalloy and water exothermically release hydrogen. This happens below the melting point of 2200°C.
- Core mass is 10^5 kg UO_2 for 1 GW_e size
- LWR thermal efficiency $\eta = 1/3$
- Average fuel temperature is 400°C before a LOCA
- Thermal power from beta decay after LOCA ($P_o = 3\ GW_t$)

$$P = P_o(0.0766t^{-0.181}), \quad 0 < t < 150\ \text{s} \tag{7.9}$$

$$P = P_o(0.130t^{-0.283}), \quad 150\ \text{s} < t < 4 \times l0^6\ \text{s}. \tag{7.10}$$

The temperature rise time is obtained by equating (a) the heat needed to raise the core to 1370°C to (b) the time integral of thermal power P. The heat needed to raise the core to 1370°C is

$$Q = Nc(\Delta T), \tag{7.11}$$

where N is the number of UO_2 moles, c is the UO_2 molar specific heat, and ΔT is the temperature rise for the core to be 1370°C, giving $\Delta T = 1370°\text{C} - 400°\text{C} = 970°\text{C}$. The number of UO_2 moles in the core is

$$N = (10^8\ \text{g})/(238 + 32)\text{g/mole} = 3.7 \times 10^5\ \text{moles}. \tag{7.12}$$

The high-temperature specific heat, $c = 3\text{R} = 24.9$ J/mole-°C, is used since the temperatures are considerably above the UO_2 Debye temperature of 100 K. Thus, the heat needed to raise the core to its critical temperature is

$$Q_{\text{rise}} = Nc(\Delta T) = (3.7 \times 10^5\ \text{moles})(24.9\,\text{J/mole}\,°\text{C})(970°\text{C}) = 8.9 \times 10^9\,\text{J}. \tag{7.13}$$

The thermal rise time is obtained by equating Q_{rise} to the time integral of the beta decay power,

$$Q_{\text{beta decay}} = \int_0^t P\ \text{d}t = \int_0^t 0.0766(3 \times 10^9)t^{-0.181}dt = (2.8 \times 10^8)t^{0.819}\ \text{J} = 8.9 \times 10^9\ \text{J}. \tag{7.14}$$

Solving for t gives a thermal rise time of 68 s, which is close to the published values of 1 min, calculated with the heat equation (Nero, 1979). Since the time scale for a LOCA is but a minute, essentially all beta-decay heat is trapped in the core.

7.2.4 Loss-of-Power Rise Time

A more gradual LOCA almost happened in 1975 when a workman at the Brown's Ferry, Alabama, boiling water reactor (BWR) used a candle to check airflow and inadvertently set fire to electrical cables, cutting off electrical power for cooling pumps. Beta-decay heat began evaporating the water coolant, which in turn initiated a process that would have uncovered the core and begun a LOCA. The beta-decay heat needed to evaporate 700 tonnes of water is

$$Q_{\text{evap}} = mL_{\text{evap}} = (7 \times 10^5 \text{ kg})(2.27 \text{ MJ/kg}) = 1.6 \times 10^{12} \text{ J}. \tag{7.15}$$

Setting Q_{evap} equal to the integrated beta-decay heat with two time ranges gives $t = 19$ h, similar to the stated 13 h available to recover the situation.

7.2.5 LOCA in Carbon-Moderated Reactors

Reactors that use carbon to moderate neutrons have a longer rise time because of the higher heat capacity of these reactors. However, the burning carbon moderator from the 1986 Chernobyl accident propelled radioactivity to great heights and far distances. Nonetheless, pebble-bed, carbon-moderated reactors could be the basis of a safer, second-generation of nuclear reactors. Additional thermal mass in smaller reactors could make LOCAs impossible: There would not be enough integrated heat to cause damage, but costs would be increased. An improved design might be one with a smaller core of 0.1 GW_e and a lower power density. Raising the heat capacity of the core with a carbon-moderator could extend LOCA rise times to over 80 h, hopefully enough time to make repairs. High-temperature gas reactors (HTGR) use graphite moderators and helium-gas coolant, in contrast to LWRs, which use water as both moderator and coolant. Helium coolant has the advantage that it can directly drive a turbine at higher temperatures to obtain efficiencies over 50%, which is higher than LWR's 32% using the steam cycle. In addition, new designs use passive valves and gravity pond pressure to reduce failures.

We calculate the thermal rise time for an HTGR after a LOCA, using the following assumptions:

- HTGR core contains 500,000 kg of graphite
- HTGR thermal efficiency $\eta = 39\%$
- Average temperature of the HTGR core is 750°C
- HTGR core should be kept below 1700°C.

HTGRs have long thermal rise times because their cores have much more heat capacity than LWRs and they can withstand higher temperatures (1700°C vs. 1370°C for LWRs). The HTGR core mass is 5 times greater than the LWR core (5×10^5 kg vs. 10^5 kg). In addition, the HTGR graphite moderator has 20 times more specific heat per unit mass than a LWR since carbon's mass is 20 times smaller than UO_2 (12 vs. 270). The factors of 5 for mass and 20 for specific heat give an HTGR core 100 times larger heat capacity than a LWR. The heat needed to raise an HTGR core

to 1700°C is

$$Q_{\text{rise}} = Nc(\Delta T) = (5 \times 10^8 \text{ g}/12 \text{ g/mole})(24.9 \text{ J/mole}\,^\circ\text{C})(1700^\circ\text{C} - 750^\circ\text{C})$$
$$= 9.9 \times 10^{11} \text{ J}, \tag{7.16}$$

which is 140 times greater than the heat we estimated to destroy an LWR. Equating the integrated beta-decay heat to Q_{rise} gives

$$Q_{\text{beta decay}} = (10^9 \text{ W}/0.39)[\int_0^{150} 0.0766t^{-0.181}dt + \int_{150}^{t} 0.13t^{-0.283}dt] \tag{7.17}$$
$$= 10^9 \text{ J}[0.46t^{0.717} - 2.3] = 9.9 \times 10^{11} \text{ J}. \tag{7.18}$$

This heat balance gives $t = 12$ h, which agrees with more sophisticated calculations. New designs with smaller modules, lower power density, and ceramic pellets raise this time to 80 h.

7.2.6 LOCA in Spent Fuel Ponds

The age of terrorism raises the issue of possible attacks on spent fuel ponds. After 1 year, spent fuel radioactive heating is 15 kW/ton and at 10 years it falls to 2 kW/ton. The spent fuel problem has been exacerbated because density of spent fuel in ponds was increased as a result of the 1977 decision not to reprocess spent fuel. The extra fuel rods give additional heating and their presence narrows the infrared and convection paths to remove heat. Some parameters give temperatures over 900°C after a LOCA, a point where zirconium cladding spontaneously ignites (Alverez et al., 2003). The problem could be lessened by moving the extra rods to the Yucca Mountain geological repository or by placing them in surface storage. The damage could be mitigated by quickly plugging pond holes with quick-setting material, spraying or pouring water on the ponds or using large air blowers.

7.3 Plume of ^{137}Cs from a LOCA

A more dangerous, but less likely, result of a LOCA can occur if a reactor's molten core comes into contact with enough water to cause a steam explosion. If the explosion is sufficiently large, it might burst the reactor's concrete dome. Most reactors have reinforced concrete structures designed to contain radioactivity in the event of a severe steam explosion accident. Further research seems to have concluded that it seems likely that the concrete domes would contain the steam explosion, but some scientists dispute this finding.

7.3.1 Wedge Model Calculation for ^{137}Cs Dispersal

The number of potential fatalities from an accident is estimated with the wind-driven diffusion equation (Section 6.4) by calculating deposition from a plume for each isotope as a function of time. However, there is an easier way to do this

problem. The shape of the plume is irrelevant under the assumption of a constant population density and acceptance of linear low-dose coupling to cancer without a threshold. For example, if turbulent air broadens the width of the plume by a factor of two, radioactive concentration is cut in half, but the number of involved individuals is doubled. Since the number of person-rems in the radioactive wedge is the same for narrow and wide plumes, the number of cancer mortalities is the same for both plumes. The American Physical Society's reactor safety panel obtained good agreement between the wedge model and results from diffusion equation models.

We will obtain the dose as a function of distance and then integrate the dose over the population density to obtain the number of fatalities. The *differential volume V* of a wedge-shaped plume is

$$\Delta V = H\theta r\,\Delta r, \tag{7.19}$$

where H is the inversion height, at which the plume stops rising, θ is the wedge angle, r is the distance from the accident, and Δr is the radial width of the material as it moves with the wind. The concentration of radioactivity in the passing plume (curies/m^3) is

$$c = S/\Delta V = S/H\theta r\,\Delta r, \tag{7.20}$$

where S is the amount of radioactivity (curies) released by the accident. Most of the radioactivity, such as ^{137}Cs, is transported on aerosol particles, not as a gas. As the wedge plume moves with a wind velocity u, the aerosol particles descend downward with a deposition velocity as derived from Stokes law,

$$v_{\text{dep}} = \rho g d^2/18\eta, \tag{7.21}$$

where ρ is air density, g is acceleration due to gravity, d is particle diameter, and η is air viscosity. For the case of 2-μ iron particles, the deposition velocity is about 0.2 cm/s. Small particles remain suspended for a longer time, traveling further, while larger particles settle closer to the reactor.

Ground contamination results from the downward flux of radioactivity from the shell over the time interval, $\Delta t = \Delta r/u$, as it passes overhead. This downward movement acts like a piston, pushing pollutants downward with the deposition velocity v_{dep}. If the plume height is 1000 m, it would take 5×10^5 s for the plume to completely fall to Earth at a deposition velocity of 0.2 cm/s. A wind velocity of 2 m/s extends the plume to a distance of 1000 km. (Plume radioactivity is considered in another way in Section 7.5.) Under these assumptions, the ground contamination $g(r)$ is obtained from the time integral of the deposition of downward flux:

$$g(r) = \int_0^{\Delta r/u} cv_{\text{dep}}dt = \int_0^{\Delta r/u} v_{\text{dep}}\,S/H\theta r\,\Delta r\;dt = Sv_{\text{dep}}/H\theta ru, \tag{7.22}$$

with $g(r)$ in curies/m^2. Note that the width of the radioactive shell Δr cancels out since a wider shell gives a lower radioactive density c, but also a longer integration time. Deposition is multiplied by 4/3 since ^{137}Cs causes 75% of the long-term ground contamination. One-half of the ^{137}Cs inventory ($S = 2.9 \times 10^6$ curies) is

assumed to be airborne (Cs melts at 677°C) with a wind speed $u = 3.5$ m/s. The 50% assumption is probably a worst case estimate. In addition, APS assumed inversion height $H = 1100$ m, wedge angle 0.25 radian (14°) and deposition velocity $v_{\text{dep}} = 0.2$ cm/s. These parameters give a ground contamination of

$$g(r) = Sv_{\text{dep}}/H\theta ru = (2.9 \times 10^6 \text{ Ci})(0.002 \text{ m/s})/(1100 \text{ m})(0.25 \text{ rad})(r)(3.5 \text{ m/s}) = 6000/r, \tag{7.23}$$

with $g(r)$ in μCi/m^2 and r in km from the reactor. The radiation received depends on gamma ray energies and shielding from buildings and soil. The APS calculated a lifetime integrated whole-body dose of 0.0155 sievert for every μCi/m^2 of ^{137}Cs for persons living their entire lives in the contaminated region. A person's whole-body dose is the ground radiation rate g times the dose radiation conversion factor times a shielding factor of 1/3, for a *biological dose equivalent*,

$$D_{\text{equiv}}(r) = (0.0155\text{Sv}/\mu\text{Ci/m}^2)(6000/r \ \mu\text{Ci/m}^2)/3 = 31 \text{ Sv}/r. \tag{7.24}$$

Therefore, a person living 60 km from the reactor receives a lifetime whole-body dose of 0.5 Sv (50 rem). At 200 km the dose is 0.16 Sv (16 rem) and at 800 km the dose is 0.04 Sv (4 rem). The APS used the 1975 value of 0.013 additional cancer death/Sv absorbed, 10–30 years after exposure (beyond the normal cancer death rate of 20%). This value inverts to 77 Sv (7700 rem) of low-dose radiation per death. This is about a factor of 3 higher than 25 Sv (2500 rem) used by EPA and NRC in the year 2003, (after the 1990 National Research Council's BEIR-V report) and about 4 times the BEIR 2006 value of 20 Sv. Respecting the APS report, we present its calculation, but we increase the result at the end of this section by a factor of 4. APS determined an increased cancer rate,

$$\text{Cancer}(r) = (31 \text{ Sv}/r)(0.013 \text{ death/Sv}) = 0.4 \text{ death}/r. \tag{7.25}$$

A person living at 60 km would have an *additional risk* of cancer death of 2% (on top of the normal 20% rate) and a person living at 800 km would have an additional death risk of about 0.8% (BEIR 2006). It is assumed that people would leave locations with dose rates higher than 100 μcurie/m^2 or at a distance of 60 km in the APS example. We should increase the death rate total to account for those that get a very large initial dose.

The number of radiation-related cancer deaths depends on population density σ downwind from a reactor and each person's decision to remain or move. The average population density of the lower 48 states is 30/km^2, with northeast states at 300/km^2 and large cities at a midrange of 3000/km^2. APS used the mid-level 120/km^2 to determine the mean number of additional cancers from full-life occupancy. By integrating the plume from the 60-km evacuation radius to 800 km, a point where most of the radiation has settled out, the mean number of additional cancer deaths is

$$N_{\text{cancer}} = \int_{r=60}^{r=800} \textit{Cancer}(r)\sigma r\theta \, dr = (0.4)(116/\text{km}^2)(0.25 \text{ rad})(740 \text{ km}) = 8600. \tag{7.26}$$

Since ^{137}Cs contributes about 75% of the total radioactive dose, the total number of cancers deaths due to ground contamination is $N_{\text{cancer}} = 8600 \times (4/3) = 11{,}500$ cancer deaths. The BEIR 2006 factor of 4 raises this to 46,000 cancer deaths. In practice, this number depends greatly on wind direction and population density, which is very different for urban and rural locations. Perhaps, the largest uncertainties lie in the probability of breaking containment and the radioactive fraction that becomes air borne, which was small for the Three Mile Island partial core melt but could be large for a large accident.

To place the above numbers in perspective, population P in the wedge is

$$P = \int_{r=60}^{r=800} \sigma r\theta \, dr = (116/\text{km}^2)(0.25 \text{ rad})(800^2 - 60^2)(\text{km}^2)/2 = 9 \text{ million}. \quad (7.27)$$

The integrated population dose is

$$(11,\, 500 \text{ cancers})(\text{Sv}/0.013 \text{ cancer}) = 880{,}000 \text{ person Sv}, \quad (7.28)$$

or an average of about 0.1 Sv per person for each of the 9 million residents. During 30 years of occupation, the residents also receive a background dose of 3.6 mSv/year times 30 year for a total of 0.1 Sv, which is the same for the hypothetical accident.

7.3.2 *Iodine Contamination*

Digested ^{131}I and ^{90}Sr from a grass-to-cow-to-milk pathway can be a concern. Iodine collects in the thyroid gland, which in turn enhances iodine concentration by a factor of 7 in adults and a factor of 100 in infants. Most likely, clean milk would be imported to an affected population after an accident for a period of weeks to months. Potassium iodide pills can flood the thyroid gland with iodine, reducing ^{131}I retention. It took time for the Nuclear Regulatory Commission to convince utilities to distribute KI since the utilities perceived that KI pills on the shelf would be too worrisome for residents. The relatively short 8-day half-life of ^{131}I and the avoidance of contaminated milk can greatly remove the threat of iodine contamination. However, KI pills will not protect against bone-seeking ^{90}Sr ($T_{1/2} =$ 28 year), nor would KI assuage against the effects of *dirty bombs*, which do not contain ^{131}I.

The 1979 Three Mile Island accident released only 20 curies of the core's 64 million curies of ^{131}I. This is not surprising since containment was not breached, but it has been conjectured that the relatively small release of iodine was a result of iodine bonding in nonvolatile CsI. At the other extreme, the 1986 Chernobyl accident released 150 MCi, which was widely dispersed by burning carbon. The estimated number of fatalities is about 20,000, but this figure has not been documented with evidence. Chernobyl's radioactive iodine caused 2000 cases of thyroid cancer in children under age 14, considerably above the normal rate. While thyroid cancer has a high cure rate, the effects of radioactive iodine could have been mitigated if KI pills had been readily available.

7.4 Weapon Accident Plutonium Plume

The threat of plutonium dispersal from a nonnuclear accident with a nuclear warhead is probably a slight risk, but it has deeper repercussions since it ties into the nuclear test ban debate. First, we discuss the issue of nonnuclear accidents with warheads. The key to safer weapon design is the use of *insensitive high explosives* (IHEs). The IHE is less likely to explode with impact, making it less prone to accidental detonation as compared to *sensitive* high explosives (HEs), which have higher explosive energy density than IHE. For this reason HE is used to implode the size-constrained nuclear weapons on MIRVed submarine-launched ballistic missiles (SLBMs). The rocket fuel on SLBMs is also more energetic and more vulnerable. Intercontinental ballistic missiles (ICBMs) are not so volume limited, hence IHEs and more resilient rocket fuel are used on ICBMs. However, this was not always the case. Both ICBMs and bombers were outfitted with more sensitive explosives until the 1960s. The shift to safer warheads with IHE and fire-resistant pits was encouraged because of the Pu dispersal after the 1966 B-52 collision over Palomares, Spain, and the 1968 B-52 fire at Thule, Greenland. The Polomares incident resulted in extensive crop damage and removal of plutonium-contaminated soil to the United States.

The HE on the Trident W-76 and W-88 warheads allowed designers to maximize Trident yields at 0.5 Mton for an 8000-km range. With the cold war over, the Trident SLBMs will be outfitted with only four or five warheads, instead of the previous eight. The empty space could be filled with larger and safer IHE warheads. But completely replacing W-76 and W-88 warheads is deemed too expensive by DoD, as they continue to support the use of HE on SLBMs. Some opponents of the Comprehensive Test Ban Treaty (CTBT) have called to reestablish nuclear testing to include testing of new IHE warheads for submarines. Analysis of potential deaths from nonnuclear warhead accidents is relevant to the CTBT debate.

7.4.1 Wedge Model Calculation for Pu Dispersal

An explosion could be triggered by a bullet shot into SLBM sensitive rocket fuel, a missile dropped upon loading, or a shipboard fire. All current US implosion warheads are designed to be "one-point safe." A warhead needs simultaneous initiations at two points on the sphere to obtain a useful critical mass. If only one point explodes, the fissile yield is constrained to exceed four pounds TNT-equivalent in one out of one million such events. The principal hazard of such an explosion is Pu-spreading in aerosols to human lungs, causing cancer. In 1990, Fetter and von Hippel used a wedge model to estimate number of potential fatalities from Pu released in a nonnuclear warhead explosion. They reviewed the literature to determine the connection between mortality and dose of weapons-grade Pu aerosols with *worst case droplets* with median diameter of 1 micron. They assumed no protection from the aerosols and determined that of 3 to 12 lung-and-bone cancer deaths are caused by inhalation of 1 mg of weapons-grade Pu aerosol after a 10–30 year latency period.

We estimate Pu dispersal with the wedge model used for reactor plumes (Section 7.3). The accident mortality rate is the product of the mortality from an accident times the likelihood of an accident. The combination of linear low-dose coupling with a constant population density greatly simplifies these estimates. The concentration c of Pu aerosol in air is a function of r, the distance from the accident:

$$c(r) = S(r)/\Delta(\text{plume volume}) = S(r)/H\theta r\,\Delta r, \tag{7.29}$$

where $S(r)$ is the mass of Pu in aerosol in the air, H is inversion height, and Δr is plume width. The Pu trapped in an individual's lungs is the product of the Pu concentration c, the breathing rate b in m^3/s, and the time for the plume to pass, Δt:

$$I_{\text{ind}}(r) = c(r)b\Delta t. \tag{7.30}$$

The equation for time for the plume to pass is $\Delta t = \Delta r/u$, where wind velocity is u. This simplifies $I_{\text{ind}}(r)$ to

$$I_{\text{ind}}(r) = [S(r)/H\theta r\,\Delta r]\; b\; [\Delta r/u] = S(r)b/H\theta r u. \tag{7.31}$$

Note that the moving shell width, Δr, cancels out. This makes sense, since a wider shell radius Δr gives a lower radioactive concentration c and a longer breathing time. If it is raining, the Pu aerosol is quickly deposited on the ground. If it is not raining, the quantity of airborne aerosol reduces with distance r as some is deposited on the ground. Hence, the decay equation for the amount of airborne Pu aerosol is

$$P(r) = P_o e^{-r/L}, \tag{7.32}$$

where L is the average distance that an aerosol particle travels before it is deposited. This distance is

$$L = uH/v_{\text{dep}}, \tag{7.33}$$

where v_{dep} is deposition velocity. The total amount of plutonium aerosol inhaled by all people I_{pop} is determined by integrating the individual amounts over the affected population:

$$I_{\text{pop}} = \int_0^\infty I_{\text{ind}}(r)\theta r\sigma\; dr = \int_0^\infty [P_{\text{o}}\text{e}^{-r/L}b/H\theta r u]\;\theta r\sigma\; dr, \tag{7.34}$$

where σ is population density. For a constant population density σ_{o}, this integrates to

$$I_{\text{pop}} = P_{\text{o}}b\sigma_{\text{o}}L/uH = P_{\text{o}}b\sigma_{\text{o}}/v_{\text{dep}}. \tag{7.35}$$

As in the case of the ^{137}Cs plume, wedge angle width θ and height H are not present in the final answer. The parameters used by Fetter and von Hippel give the amount of inhaled plutonium by the affected population:

$P_{\text{o}} = 10$ kg PuO_2
$b = 3.3 \times 10^{-4}$ m^3/s
$\sigma_{\text{o}} = 30$–3000 persons/km^2; median 300 persons/km^2
$v_{\text{dep}} = 0.003$–0.03 m/s; median 0.01 m/s
mortality rate of 3–12 deaths/inhaled mg.

Hence, the highest total amount inhaled is about

$$I_{\text{pop}} = P_o b \sigma_o / v_{\text{dep}} = (10^4 \text{ g})(3.3 \times 10^{-4} \text{ m}^3/\text{s})(3 \times 10^{-4}/\text{m}^2)/(0.01 \text{ m/s}) = 0.1 \text{ g}, \tag{7.36}$$

with mortality of

$$N_{\text{cancer}} = (100 \text{ mg})(3 \text{ to } 12 \text{ deaths/mg}) = 300\text{–}1200 \text{ deaths}. \tag{7.37}$$

The projected number of deaths is now compared to the individual cancer death rate of about 20%. The plume extends a distance of about twice the mean length, or

$$2L = uH/v_{\text{dep}} = 2(2 \text{ m/s})(1000 \text{ m})/(0.01 \text{ m/s}) = 400 \text{ km}, \tag{7.38}$$

for wind speed $u = 2$ m/s. The number of people irradiated in the wedge is

$$P = \int_0^{2L} \sigma r \theta \mathrm{d}r = (300/\text{km}^2)(0.25 \text{ rad})(400 \text{ km})^2/2 = 6 \text{ million}. \tag{7.39}$$

A cancer rate of 20% gives a background of about 1 million natural cancers in a population of 6 million. If the accident caused 600 deaths, it would raise the 20% cancer death rate by 0.01%, an amount that would be difficult to determine with epidemiology.

7.4.2 Cost of Weapons Versus Value of Life

Is the loss of 1000 lives, as projected from a worst-case plutonium dispersal accident, an *acceptable* risk? There are uncertainties in this estimate, particularly in the amount of Pu that attaches to aerosols, but we will assume the figure is correct. A true *risk assessment* should consider alternative possibilities. In this case, the alternative is the additional cost of building *safer* warheads and missiles, as well as the global political cost of renewed nuclear testing. Here we only compare the *value of human life* in contrast to the cost of building new nuclear weapons. If we assume an unlikely low cost of $2 billion for new SLBM weapons, the carrying cost would be about $200 million/year. This annual cost amount is equated to probabilistic annual cost of lost lives:

$$\$200\text{M/year} = N_{\text{cancer}} V_{\text{life}} n. \tag{7.40}$$

The right side is the product of the number of deaths from an accident (N_{cancer}), the dollar value of human life (V_{life}), and the number of nuclear accident accidents per year (n). We assign values to N_{cancer} and V_{life} to determine n, the number of accidents per year to establish financial equality.

We use $N_{\text{cancer}} = 1000$ and for V_{life} we begin with lifetime income of a person. Assuming 40 years of work at a national average annual income of $35,000 gives $1.4 million. To the denied income we add the cost of pain and suffering, to arbitrarily arrive at $V = \$5$ million. Now the equation is

$$\$200 \text{ M/year} = (1000 \text{ lives})(\$5 \text{ M/life})(n) \tag{7.41}$$

which gives $n = 1$ accident in 25 years. Thus far no accidents like this have happened. At \$10 million/life, n is reduced to 1 accident per 50 years. Hence the more one values human life, the smaller is the acceptable rate of nuclear warhead accidents. In 2003, EPA analysis reduced the value of a life from \$6 M to \$3.7 M. Further fine tuning uses the concept of *quality of life years*. For example, a suffering person that was saved 4 years through medical mitigation, but still had bad health, would get credit for 0.5×4 year $= 2$ quality-adjusted life years. Another approach in the analysis is to value a young life at \$6M and an older life at \$2million. Also used is the concept *willingness to pay* for mitigation, which should be higher for young people and smaller for older people.

The debate on new IHE warheads arose during debate on nuclear testing prior to consideration of the CTBT. Those opposed to CTBT said the warheads with regular HE were not safe enough and further testing of new warheads with IHE was needed. However, the Pentagon maintained that the HE-loaded warheads were safe enough and that it was too expensive to rebuild them. On the other hand, Department of Defense testified in 1992 that a test ban was not a good idea because DoD wished to continue to test weapons for reliability, safety and new designs. Legislation required the government to quantify these trade-offs with a cost versus safety analysis before testing could resume, but this has not been done since testing stopped. In 2003, DoD asked, and Congress approved, the removal of the 1993 legislative ban on designing new warheads under 5 kton. Since new weapons need testing, this would affect the Nuclear Nonproliferation Treaty regime (Chapter 5).

7.5 Dirty Bombs

7.5.1 Dirty Bombs

The 9/11 attack shows us that terrorists might detonate radioactive sources in large cities. A dirty bomb attack would probably be *more psychological than lethal*, because radiation doses from ground contamination would mostly not be large and they could be avoided by persons moving away from the area. The ^{137}Cs, ^{90}Sr and ^{210}Po isotopes could be used in dirty bombs. How much radioactivity is needed to convince a person to leave home? Fear of radioactivity can be illogical. Often the most educated are the most terrified. It is for this reason that radiological dispersal devices (RDD) have been called the "new WMD," *weapons of mass disruption*. The US government is responding by tracking down old sources of radiation on a global basis, developing alternative technologies to radiation (accelerators for cancer therapy), improving the detection of smuggled radioactive sources, and developing better decontamination procedures.

There are thousands radioactive sources that could be used in a terrorist attack: sterilization (100 to 10 million Curies), radioisotope thermal-electric generators (10–100,000 Ci), cancer therapy (10,000 Ci), blood irradiators (1000 Ci), radiography (1–100 Ci), and well logging (up to 100 Ci). One critical issue for a bombmaker is the

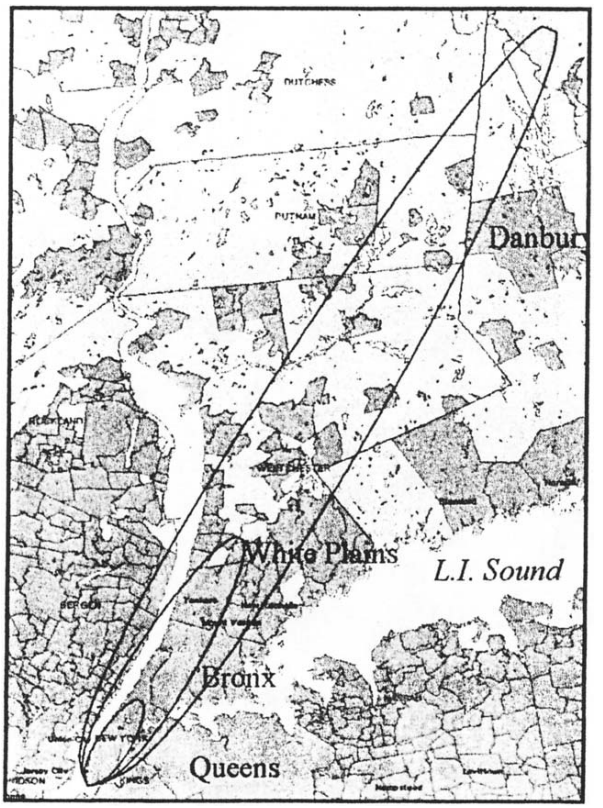

FIGURE 7.3. Long-term contamination from a cobalt bomb in New York City. *Inner ring*: One cancer death from radiation per 100 persons for those that remain. *Middle Ring*: One cancer death per 1000 people who remain. Outer Ring: One cancer death per 10,000 who remain, a region that EPA recommends decontamination or destruction. The Nuclear Regulatory Commission might use a standard 20 times higher, at a death rate of 1 in 500 for full-time occupation. In comparison, the US background rate of 3.5 mSv/year gives a total dose of 0.28 Sv over 80 years. This dose gives a 1 part in 100 cancer death rate from natural radioactivity at a rate; of 20 Sv-persons per mortality, spread over many persons. (M. Levi and H. Kelly, Dirty bombs: Response to a threat, *Public Interest Report*, Federation of American Scientists, March/April 2002)

form of the radioactivity material, for example, fine powders and aerosols increase plume size. Figure 7.3 displays estimates of dirty bomb contamination from a *cobalt pencil* used in food irradiation. Clean-up after a bomb explosion would be difficult. EPA recommends decontamination or destruction within the outer ring where the death rate is 1 part in 10,000 for continuous occupation. Several bills have been introduced before Congress to increase controls on radioactive materials, but these are in conflict with the concerns of medical and industrial users.

7.6 Fault Tree Analysis

Nuclear power has produced 20% of US electricity since the early 1990s, but its growth has stopped completely. A 1972 projection of 1200 GW_e capacity was given for the year 2000, but this projection fell far short, as actual capacity is 98 GW_e. Global nuclear power capacity remained fairly constant over the past 5 years at 350 GW_e (2000). Seventeen nations use a higher percentage of nuclear power than the United States, although the United States has the largest capacity. French

capacity is 63 GW_e, which is 76% of its grid, while Japanese capacity is 43 GW_e for 35% of its grid. Globally 16% of electricity was produced from nuclear power plants, while 22% comes from renewables (mostly hydroelectric), 63% from fossil fuels [coal (34%), natural gas (19%), petroleum (10%)]. US electricity (2001) was produced from coal (53%), nuclear (22%), natural gas (15%), hydro/renewables (8%), and petroleum (3%).

Increased cost of nuclear power and the 1979 Three Mile Island and 1986 Chernobyl accidents halted plans for new plants. Low cost electricity from natural gas from combined-cycle gas turbines further removes nuclear power as a competitor. The continuing unrest about radioactive waste disposal has effectively forestalled the addition of new nuclear plants.

Under a linear low-dose assumption, the annual number of deaths from nuclear power is a product of at least eight functions, each of which must first be first multiplied for each failure mode and then summed over all failure modes. The eight functions are

- n, number of nuclear plants
- P, annual probability for a failure mode
- S, amount of released radioactivity
- B, biological function, coupling radiation and mortality
- A, plume area
- ρ, population density in the plume
- W, wind and weather function
- t, time spent in irradiated region.

Estimates of an extremely serious reactor accident in a populous location point to numbers that could be devastating with 3,000 immediate fatalities, 240,000 thyroid nodules, 45,000 latent cancer fatalities, 30,000 latent genetic effects, and a cost of over $10 billion, contaminating an area of 8,000 km^2. Three Mile Island was fearful but not lethal. Nuclear reactors have not had a serious accident and they collectively have not had a poor record, with total radiation exposure of 5 person-Sv/year, causing 0.3 of a death per year (Section 7.1). Safety could be enhanced with smaller cores, lower power densities, and greater heat capacity to totally prevent LOCAs (Section. 7.2). New reactor designs are not totally passive-safe, but rather they use passive-safe circulation systems.

Fault tree analysis is widely used by industry to analyze accident scenarios and estimate relative and absolute accident rates P_{accid} (Fig. 7.4). Probabilistic risk assessment (PRA) was used to determine P_{accid} for nuclear power plants in the 1975 *Reactor Safety Study* under Norman Rasmussen of MIT. This report was criticized for its underestimation of error bars and for not adequately considering common-mode failures, such as earthquakes, which can remove more than one safety system at a time. The study predicted that very serious accidents would be infrequent. Such accidents could be caused by overlapping small problems. There is consensus that PRA is useful in determining *relative* risks, and the Nuclear Regulatory Commission continues to use this approach.

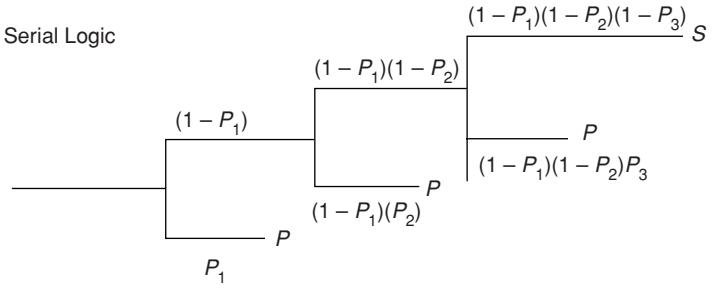

FIGURE 7.4. Series fault tree for dinner. The upper part is the fault tree for the serial logic problem of cooking dinner *with failure probabilities* P_{dinner}, P_{valve}, P_{pilot}, and P_{gas}. At path junctions, the paths split into an upper leg with probability of success S and a lower leg with probability of failure P with $S + P = 1$.

7.6.1 Serial Logic

A process made up of many different tasks, each depending on the success of the previous task, is a problem in *serial logic*. If there are i different serial tasks, the probability that the serial process is successfully completed is *the product of the success probabilities for each individual task*. Because failure probabilities are small numbers ($P_{\text{failure}} = \varepsilon$) and success probabilities are close to unity ($S = 1 - P_{\text{failure}} = 1 - \varepsilon$), risk analysis uses failure probabilities rather than success probabilities. The formula describing a system's success after several serial tasks is

$$S_{\text{system}} = 1 - P_{\text{system}} = (1 - P_1)(1 - P_2)\ldots(1 - P_{\text{n}}) = \prod_{i=1}^{n}(1 - P_{\text{i}}). \quad (7.42)$$

To prepare a meal from uncooked ingredients, we need a stove with a working valve, a working pilot light, and available nature gas. If all task failures $P_i = 10\%$, the probability of obtaining a cooked meal is 73%, obtained from

$$S_{\text{dinner}} = 1 - P_{\text{dinner}} = (1 - P_{\text{valve}})(1 - P_{\text{pilot}})(1 - P_{\text{gas}}) = (1 - 0.1)^3 = 73\%, \quad (7.43)$$

or a probability that cooking dinner fails of 27%. The more tasks involved in a serial process, the less likely that the process will be successful. See Fig. 7.4.

7.6.2 Parallel Logic

Duplicate back-up systems enhance success by operating in parallel. Reactors have operating back-up power in case there is a loss of line electricity. A back-up motor-diesel generator is available when external power fails, and a second generator is available if the first generator fails. The fault tree diagram in Fig. 7.5 shows branch points after an electrical power failure. Each branch indicates a chance to recover with a new, parallel system. The overall probability of maintaining electricity to operate a reactor depends on the failure probability for line voltage P_{line} and the failure probabilities of the two diesel generators, P_{G1} and P_{G2}. The path at the

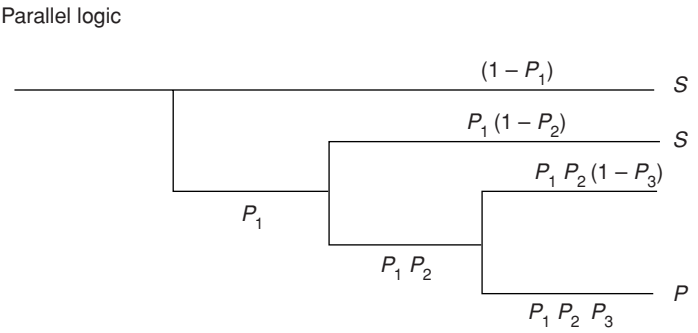

FIGURE 7.5. Parallel fault tree for reactor operating electric power. Parallel logic describes back-up power at a nuclear reactor. The failure probabilities are P_{elec} for reactor operating electrical power derived from P_{line} for exterior line voltage and P_{G1} and P_{G2} for the reactor's motor-generator systems.

bottom of Fig 7.5 is the only one that ends in failure with a probability of

$$P_{\text{elec}} = P_{\text{line}} P_{\text{G1}} P_{\text{G2}}. \tag{7.44}$$

The probability for maintaining electrical operating power is the sum of the successful probabilities for the three task paths,

$$S_{\text{elec}} = (1 - P_{\text{line}}) + P_{\text{line}}(1 - P_{\text{G1}}) + P_{\text{line}} P_{\text{G1}}(1 - P_{\text{G2}}) = 1 - P_{\text{line}} P_{\text{G1}} P_{\text{G2}}. \tag{7.45}$$

Note that with $S_{\text{elec}} + P_{\text{elec}} = 1$. If each power source has a 10% failure probability, the *system* failure rate is

$$P_{\text{elec}} = (0.1)(0.1)(0.1) = 10^{-3} \quad \text{or} \quad 1 \text{ in } 1000, \tag{7.46}$$

which is much better than a failure rate of 27% for a meal prepared by three serial tasks.

The Rasmussen report estimated a median accident probability of 5×10^{-5}/reactor-year for a core meltdown, with an upper bound of 3×10^{-4}/reactor-year (See Table 7.1). The 100 US power reactors, operating for 22 years, have had 2200 reactor-years experience. The pessimistic, *highest probability* estimate, combined with the US 2200 reactor-years experience, gives a probability for a core melt

TABLE 7.1. Probabilistic risk assessment. Accident probability per reactor-year for small, medium, and large accidents at a light water reactor. [*Reactor Safety Study*, Nuclear Regulatory Commission, 1975]

Annual deaths	Deaths over 30 years	Accident probability
1	30	3×10^{-5}/reactor-yr
100	3000	2×10^{-6}/reactor-yr
1000	30,000	1×10^{-8}/reactor-yr

accident of

$$P_{\text{core melt}} = (3 \times 10^{-4}/\text{reactor-year})(2200 \text{ reactor-year}/25 \text{ year}) = 0.5 \text{ accident}/25 \text{ years}, \quad (7.47)$$

which, by chance, equals the US experience with one-third core melt at Three Mile Island with a hydrogen bubble. It has often been assumed that 90% of core-melt accidents would be contained in the concrete domes and that 10% of core melts would cause a steam explosion that would break containment and spread a plume. Some claim this assumption is now too pessimistic, based on further research. See Fig. 7.6 for a complex fault free diagram.

7.7 Geological Repositories

In the year 2000, civilian nuclear power wastes contained 33,000 MCi, which is slightly larger than military nuclear wastes of 25,000 MCi. Scientists have long encouraged geological burial of nuclear wastes, but it is imperative that the repository effectively contain wastes over long periods of time. The debate for and against burial hinges on the definitions of *effective* and *risk* when compared to alternative disposition. Debate on waste sites also turns on the issue of "not in my backyard."

The nuclear waste problem has been badly handled. Liquid waste tanks at Hanford, Washington, leaked because of a combination of bad chemistry and single-shell construction. The tanks no longer leak because the radioactive liquids have been removed. The plutonium pit factory at Rocky Flats, Colorado, has been closed for years because of dispersed plutonium. The former Soviet record is worse. The dumping of 120 million curies into Lake Karachai is enough to give a lethal dose to a person standing an hour near the discharge pipe. At another lake the situation is exacerbated by weather, as drought spreads radioactivity with the wind, and rains push polluted water over the dam. The Russian government is now filling the lakes with large stones.

Spent fuel ponds could be terrorist targets, since explosions could make ponds leak, allowing uncooled rods to melt, burn, and disperse. This could be serious since the ponds have considerable radioactivity and a uranium fire would propel radioactivity into a large plume. It might be possible to mitigate such a threat by spraying water on the pond by plugging the pond holes with fast-drying materials or by using large fans to blow air. This problem is lessened if cooler rods are moved into the Yucca Mountain repository or into dry surface storage. This reduces heat production and increases accessibility of the remaining rods to cooling.

7.7.1 Pu content

A typical 1-GW_e LWR discharges about one-third of its 100 ton core every 1.5 years. Since 0.9% of discharged heavy metal is Pu, the annual discharged Pu from a 1-GW_e

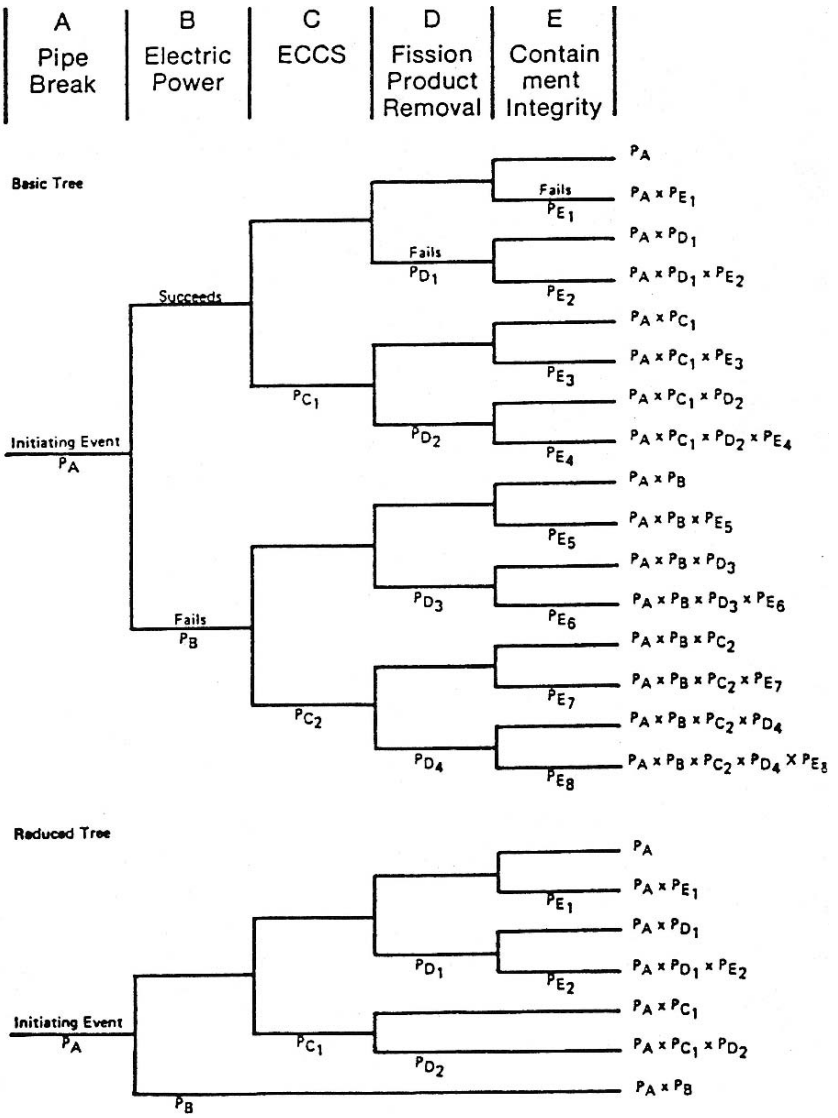

FIGURE 7.6. Fault tree of a LOCA from a pipe break. The sequence begins with a failure probability for a pipe break P_A, followed by the failure probability of electrical power P_B, the failure probability of the emergency core-cooling system P_C, the failure probability of the fission-product removal system P_D and the failure probability of the containment structure P_E. Since the probability of success for many of these steps is close to one, this value is assumed to be unity when that is sufficiently accurate. The reduced tree considers only the most likely fault paths (Nuclear Regulatory Commission, 1975).

reactor is

$$(100 \text{ ton core}/3)(0.009 \text{ Pu})/(1.5 \text{ years}) = 200 \text{ kg Pu}/\text{GW}_\text{e} \text{ year}. \quad (7.48)$$

The US 2200 years of operation or power plants produced

$$(0.2 \text{ ton}/\text{GW}_\text{e} \text{ year})(2200 \text{ GW}_\text{e} \text{ year}) = 400 \text{ ton Pu} \quad (7.49)$$

as part of the global total of 1200 tons in 1998.

Reactor-grade plutonium contains over 20% ^{240}Pu. Nonnuclear weapon states can make weapons of only about 1 kton yield with reactor-grade plutonium, while experienced nuclear weapon states can obtain full yield with reactor-grade Pu. Thus far, the eight nations that have Pu weapons all use reactor-grade Pu for their weapons. Nevertheless, there is concern that spent fuel containing reactor-grade plutonium remains in many places without adequate physical security. A PWR fuel assembly contains 5-kg Pu, enough to construct a nuclear weapon. Its radiation barrier at a distance of 1 m drops from 65 Sv/h after 5 years to 9 Sv/h after 50 years, an amount sufficient to deter *rational actors*. A much greater threat is Russia's 150 tons of weapons-grade Pu and 1000 tons highly enriched uranium. The United States and Russia have agreed to work together to dispose of their excess weapons grade materials. In general, Pu in glass or ceramic logs can be placed into a geological repository. It can be used as plutonium–uranium mixed oxide (MOX) fuel in reactors; it can be transmuted in accelerators (unlikely because of expense); it can be shot into space (very unlikely since 1% of rocket launches fail and it is expensive); it could be deposited in very deep ocean trenches, such as the Challenger Deep, located in the Marianas Trench. The Challenger Deep is 11-km deep and slowly subducts into the Earth. This is technically sound but it violates the treaty that bans ocean dumping.

7.7.2 *Funding for Nuclear Waste Disposal*

In 1977 the US government offered to accept utility spent fuel for a repository fee of 0.1 ¢/kWh. The electrical utilities have charged the government with not fulfilling this agreement. The courts agreed, requiring DOE to pay utilities to keep spent fuel on-site until such time as Yucca Mountain repository can accept it, perhaps by 2010. By 2002, the trust fund received some $10 billion and it will have $15 billion by 2010. If Yucca Mountain cannot accept the fuel, retrievable surface storage is likely to be used until another repository can be found. In 2004, the US Court of Appeals in DC ruled against the 10,000 year limit on radiation safety at Yucca Mountain. The court concluded that EPA must either issue a revised standard that is "consistent with" the NAS peak-dose standard "or return to Congress and seek legislative authority to deviate from the NAS report" used until another repository can be found. US spent fuel in 2000 from 2200 GW_e years of operation is about

$$(20 \text{ ton}/\text{GW}_\text{e} \text{ year})(2200 \text{ GW}_\text{e} \text{ year}) = 42{,}000 \text{ tons}, \quad (7.50)$$

with 80,000 tons expected by 2020, to complete the first generation of nuclear power plants. Yucca Mountain will have an initial capacity of 77,000 tons (70,000 tons spent

fuel plus military waste), which allows it to handle US commercial spent fuel until about 2015.

7.7.3 *Heat Loading*

In the first several hundred years, spent fuel beta-decay heat comes primarily from fission fragments ^{90}Sr, ^{90}Y, ^{137}Cs, and ^{137}Ba with half-lives of 3 to 30 years. After 1000 years, heat comes primarily from alpha decay of the actinides ^{239}Pu, ^{240}Pu, and ^{241}Am. After a public rule-making process, EPA used a time horizon of 10,000 years for regulatory decisions on Yucca Mountain. Some estimates give doses up to 0.15 mSv/year at 18 km from the repository after 10,000 years, which was the limit recommended by a National Research Council study. This is less than the public's limit of 1 mSv/year. Some estimates show that it could rise to 0.03 Sv/year after 400,000 years, but there is little certainty on this. The discovery of ^{36}Cl, a by-product of 1950s testing, indicates water seeps downward at a faster rate than expected. A regulatory issue is how to link the risks of each step in a multiplicative process. Should parameters for estimating risk be mid-range estimates or extreme values? Another issue is whether a rigid radiation standard in a region with little population is the correct logic. One might think that it is more logical to compare the number of projected deaths from Yucca Mountain with the projected number of deaths from other storage choices, since the radioactive material must be disposed somewhere.

Spent fuel rods can be placed in geological storage at varying heat loads, ranging from 2 kW_t/ton at 10 years to 1 kW_t/ton after 30 years. See Table 7.2. Since the Yucca Mountain site is oxidizing, there is concern that metal containers will be breached over a period of 1000 to 100,000 years. Because water percolation rates to the repository are higher than expected, the design uses engineered barriers to supplement geological barriers. There are very few metals other than gold that can resist corrosion for such long times, but stainless steel/nickel canisters with titanium drip shields are believed (but not completely tested) to be robust for thousands of years. Radioactive heat should keep the canisters above 100°C to keep water away over the initial 1000 to 2000 years.

TABLE 7.2. Fuel rod heat and radioactivity. The thermal heat rates (kW_t) and radioactivity rates (Ci) are given for 30 tons of spent fuel, the amount removed from a 1-GW_e reactor every 18 months. [D. Bodansky, *Nuclear Energy*, American Institute of Physics Press, 2004]

Age	Thermal power	Radioactivity
1 year	300 kW_t	70 MCi
10 years	70 kW_t	14 MCi
100 years	10 kW_t	1.4 MCi
1000 years	2 kW_t	61 kCi

One possible design for a waste package contains 21 fuel assemblies, each having a 12-ton mass with 12 kW_t heat at 30 years of age. To simplify matters, we assume the cylindrical package is a sphere for distances larger than its size. The decay heat power P_{heat} from the "spherical" container in thermal equilibrium causes a temperature gradient ΔT between spherical shells of thickness Δr. This allows us to write

$$P_{heat} = -k4\pi r^2 \Delta T/\Delta r, \tag{7.51}$$

where r is radial distance of the shell and k is thermal conductivity of the geological media. Letting $\Delta T/\Delta r = dT/dr$ and integrating r from the canister surface to a distant point, we obtain the temperature $T(r)$ as a function of radial distance r,

$$\Delta T = T_{surface} - T(r) = (P_{heat}/4\pi k)(1/r_{surface} - 1/r). \tag{7.52}$$

The temperature rise at the surface of the container is obtained by letting the "spherical" radius of the cylinder be 2 m for a cylinder with a 1-m radius and a 5-m length. The temperature rise ΔT at the surface is with respect to the temperature at a distant location, $r = \infty$. Using $k = 2.1$ W/m °C for the volcanic tuff at Yucca Mountain, we obtain the temperature rise for 30-year old fuel,

$$\Delta T = P_{heat}/4\pi k r_{surface} = 12 \text{ kW}/(4\pi)(2 \text{ m})(2.1 \text{ W/m °C}) = 230°\text{C}. \tag{7.53}$$

This result is consistent with formal calculations. Spent-fuel heating will drop after 1000 years to allow water to collect and corrode the package, but the package is designed to deflect the water. The primary radioactive leakage would be the Pu and Am actinides and not fission fragments, which would have mostly decayed by that time.

7.7.4 Pu Migration

The calculation of dispersal of SO_2 in power plant plumes (Section 6.4) depended on empirical parameters, such as the weather, air turbulence, and local geography. Similar corrections would have to be made to estimate radioactive water flow in *underground* plumes. Estimates can be obtained using the diffusion equation for water flow and *Darcy's law*, which determines water discharge flux ($kg/s\,m^2$) from factors of media permeability, fluid density, fluid dynamic viscosity, and groundwater pressure. Such a calculation can be done in high-porosity media, but it cannot be done well in low-porosity media, since flow through cracks surpasses flow through low-porosity pores. It would be *misleading* to calculate water flow at Yucca Mountain since its geological stratum is *heterogeneous* and *does not consist* of concentric layers of *homogenous* materials. Thus, caveat emptor.

The 1978 American Physical Society panel on radioactive wastes concluded that "Pu [is] efficiently confined" to regions close to the 1.8-billion year old Oklo, Gabon, natural reactor. This conclusion was readily accepted because Pu has low solubility in water and it has a tenacious capacity to cling to mineral surfaces. However, in the past 15 years there has been some evidence that Pu can adhere to colloids smaller than a micron in size. In one case a DOE group discovered that Pu had

migrated 1.3 km in 30 years from its nuclear weapons test origin. For this case, the rate of Pu travel was consistent with the local flow of groundwater. The amount of Pu found was small, some 10^{-14} mole/l, but it could accumulate over the years. On the other hand, some argue that the data are misleading, since the migration might be a result of nuclear weapons explosions that created underground fissures, increasing Pu transport. Transportation of Pu is only one factor, as there are several steps to determining human risk, including the size of the population in the region. Perhaps the issues should be broadened. Perhaps the surface radiation rate (an area within 15-km radius from Yucca Mountain in 10,000 years) is less relevant than the number of people affected in Las Vegas and near the Colorado River, as compared to those affected by alternative disposal approaches.

7.8 Indoor Radon

7.8.1 Radon

One 1984 morning upon arriving at work, an employee at a Pennsylvania nuclear power plant triggered the plant's alarm. It was assumed that he had taken radioactivity home for the night, but it was soon determined that he went home without a trace of radioactivity. Surprisingly, what happened was that he carried *radon daughters* from *home to work*. The radon level in his house was 700 times the EPA-recommended indoor limit of 4 nCi/m^3. The average level *inside* US buildings estimated by EPA is 1.3 nCi/m^3, which is about 3.5 times the average *outdoor* level of 0.4 nCi/m^3. Six million homes exceed the EPA level, 100,000 of them have levels above 20 nCi/m^3. Radon exposure is a major issue because the average radon dose of 2 mSv/year (200 mrem/year) is over 50% of the total background rate of 3.6 mSv/year (360 mrem/year). This is partly due to the fact that people spend 86% of their time indoors (with the other 6% in vehicles and 8% outdoors).

The principal health risk from radon arises not from ^{222}Rn, which does not adhere to lungs, but rather its four radioactive daughters (^{218}Po, ^{214}Po, ^{214}Bi, ^{214}Pb), which chemically attach to aerosols that are trapped in lungs. Radon concentration is increased with increased local radon source strength, with reduced air infiltration through walls/ceilings that traps radon inside, and with increased air coupling between radon ground sources and house interiors. (Increased air infiltration through walls and ceilings reduces radon, but it also increases infiltration heat transfer, which is about a quarter of cooling/heating energy.) The radon level in your home can be measured with a $20 kit. We estimate both energy savings and adverse health effects from reduced infiltration. One can both save energy and reduce radon hazards by using air-to-air heat exchangers.

7.8.2 Energy Savings from Reduced Infiltration

Let us estimate the energy savings if the US reduced infiltration from 1.5 to 1.0 air changes per hour (ach). The *infiltration energy loss rate* is

$$dQ/dt = (dm/dt)c\Delta T/\eta, \tag{7.54}$$

where mass infiltration rate is dm/dt; specific heat of air is $c = 1000$ J/kg °C, temperature difference between the inside[4] and outside of a house is $\Delta T = 18.3°\text{C} - T_{\text{outside}}$, and furnace/duct efficiency is $\eta = 2/3$. The rate of air mass infiltration is

$$dm/dt = N_{\text{ACH}} V \rho, \tag{7.55}$$

where the number of air changes/hour is N_{ACH}, house interior volume is V, and air density is $\rho = 1.3$ kg/m^3. Summing the infiltration energy loss over the year gives the annual infiltration energy loss (Section 11.3),

$$Q = N_{\text{ACH}} V \rho C(dd/yr \times 24 \text{ h/day})/\eta. \tag{7.56}$$

The number of *heating degree days per year* (*dd/yr*) is calculated by summing temperature difference over a year on an hourly basis:

$$dd/yr = \sum_{i=1}^{8766} \Delta T_{\text{i}}(1 \text{ h})/24 \text{ h}. \tag{7.57}$$

Since the average US heating season can be described as having an average temperature of 38°F over 6 months, Eq. 7.57 becomes

$$\begin{aligned} dd_{\text{US}}/\text{yr} &= \Delta T \Delta t = (65°\text{F} - 38°\text{F})(180 \text{ days/year}) = 4800°\text{F day/year} \\ &= 2670°\text{C day/year}. \end{aligned} \tag{7.58}$$

US energy savings are estimated using the assumption of an N_{ACH} reduction from 1.5 to 1 ach in each of the 100 million living units, each with volume $V = 325$ m^3 (area 130 m^2 × ceiling height 2.5 m). The US annual energy savings could be as large as

$$\begin{aligned} \Delta Q_{\text{savings}} &= 10^8 \Delta N_{\text{ACH}} V \rho C(dd \times 24 \text{ h/day})/\eta \\ &= 10^8(1.5 \text{ ach} - 0.5 \text{ ach})(325 \text{ m}^3)(1.3 \text{ kg/m}^3)(10^3 \text{ J/kg °C})(2670°\text{C dd/yr}) \\ &\quad \times (24 \text{ h/day})(1.5) \\ &= 2.0 \times 10^{18} \text{ J} = 1.9 \times 10^{15} \text{ Btu} = 15 \text{ quads}. \end{aligned} \tag{7.59}$$

This annual energy savings is equivalent to 0.9 million barrels/day of oil or 1.9 trillion cubic feet/year natural gas. Additional savings come in summer from reduced air conditioning.

7.8.3 Radon Levels in Houses

The slight underpressure inside a house sucks underground radon into houses at rates between 0.1 to 100 pCi/sec m^2. Equating inward radon flux f over floor area A to the outward flow gives radon concentration c_{Rn} at one ach (radon decay will be added later):

$$f A = (1 \text{ pCi/s} \cdot \text{m}^2)(130 \text{ m}^2) = c_{\text{Rn}}(\Delta V/\Delta t) = c_{\text{Rn}}(325 \text{ m}^3/3600 \text{ s}). \tag{7.60}$$

[4] The US uses 65°F (18.3°C) as the reference point for calculating degree days. The 68°F inside temperature is reduced by 3°F to take into account the inside "free temperature" gained by the thermal resistance of the house. (Sections 11.3 and 11.5.)

Using $f = 1$ pCi/s m^2, $A = 130$ m^2, $V = 325$ m^3, and 1 ach ($\Delta t = 3600$ sec) gives $c_{\mathrm{Rn}} = 1.4$ nCi/m^3. A house with N_{ACH} reduced to 0.35 ach raises c_{Rn} to the suggested EPA limit of 4 nCi/m^3. Radon's atomic density n at 1 ach is

$$n_{\mathrm{Rn}} = c_{\mathrm{Rn}}\tau = (1.4 \times 10^{-9}\ \mathrm{Ci})(3.7 \times 10^{10}/\mathrm{s\,Ci})(4.7 \times 10^5\ \mathrm{s}) = 3 \times 10^7/\mathrm{m}^3, \qquad (7.61)$$

using $c_{\mathrm{Rn}} = 1.4$ nCi/m^3 and radon mean life $\tau = T_{1/2}/\ln 2 = 3.8\ \mathrm{days}/0.693 = 4.7 \times 10^5$ s. Radon density is very small, only 10^{-17} of atmospheric density. For very low infiltration rates, radon concentration is reduced by 1–10% because of radon decay in the house. The corrected radon radioactivity density c_{Rn}' is determined by balancing incoming radon rate with the sum of the decay and exhaust rates:

$$f A = c_{\mathrm{Rn}}/\tau + c_{\mathrm{Rn}}\Delta V/\Delta t. \qquad (7.62)$$

7.8.4 Cancer Rates

We estimate an increase in radon cancers from reducing infiltration, using results from the UN Scientific Committee on Radiation (UNSCEAR). Uranium miner data show that 100 additional lung cancers would be caused every year if 1 million persons spent all their time in 1 nCi of ^{222}Rn/m^3. If N_{ACH} is reduced from 1.5 to 1 ach, the radon level would be increased from 1 to 1.5 nCi/m^3. The number of additional cases of lung cancer for 300 million Americans, who are inside 86% of the time, is about

$$(1.5 - 1)(\mathrm{nCi/m}^3)(10^{-4}/\mathrm{nCi/m}^3)(0.86)(3.0 \times 10^8\ \mathrm{persons}) = 13{,}000/\mathrm{year}. \qquad (7.63)$$

This is similar to EPA estimates 14,000 radon deaths/year (from 7000 to 30,000) and National Academy estimates of at 11,000 deaths/year (BEIR VI, from 3000 to 33,000). An alternative approach is to use the 1990 BEIR average radon exposure estimate of 2.0 mSv/year (55% of the background rate of 3.6 mSv/year). Using this with the International Commission on Radiological Protection estimate of 20 Sv for one statistical death (EPA has used 25 Sv), the US fatality rate from radon is

$$(2.0\ \mathrm{mSv/year})(300\ \mathrm{million\ persons})/(20\ \mathrm{Sv/death}) = 30{,}000/\mathrm{year}. \qquad (7.64)$$

Using these results, EPA recommend a radon limit of 4 nCi/m^3. Radon measurements costing \$15 to \$50 can determine if radon is a problem. Some 50,000–100,000 houses have radon levels in primary living spaces greater than 20 nCi/m^3. Thirty years occupancy in such a house can cause a lung cancer rate of about 2–3% among nonsmokers and 12% among smokers. Remediation can cost \$1000–1500 for *sub-slab* depressurization by installation of an electric fan and other measures. EPA estimates that it would cost \$19 billion to save some 83,000 lives, or \$200,000/life.

Air-to-air heat exchangers can reduce radon and save energy. Heat exchangers transfer 75% of heat/coolth from exhaust air to incoming air, while radon and chemicals are released to the outside. To find infiltration leaks, blower doors overpressurize houses so *house doctors* can follow smoke from miner's smoke sticks to find and caulk air leaks. The energy and health tradeoff depends on the number of air exchanges per hour. On the one hand, energy consumption from infiltration is

proportional to N_{ACH}. On the other hand, cancer rate is proportional to radon concentration, which is inversely proportional to N_{ACH}. The *optimal* solution depends on a comparison of the value of a life as compared to the value of energy saved, a difficult comparison.

Problems

7.1 **^{40}K universe.** How long ago was potassium produced if ^{39}K and ^{40}K were equally produced in early supernovas? Potassium contains a 0.012% (1.2×10^{-4}) ^{40}K, which has a 1.3 billion year half-life while ^{39}K is stable.

7.2 **^{40}K dose.** A typical person receives 0.39 mSv/year (39 mrem/year) from internal sources, about 50% of this from ^{40}K. (a) How much potassium is in an 80-kg adult, assuming that 1 MeV per ^{40}K decay is deposited in the body? (b) What annual dose does a person absorb while sleeping 0.5 m from a 80-kg spouse? Assume 50% of the *incident* 1.5-Mev γ rays, which are emitted in 10% of the ^{40}K decays, are absorbed by the body.

7.3 **Full-body dose.** What is the full-body dose of an 80-kg person ingesting 1 Curie of tritium, which deposits 6 keV per decay. The half-life of tritium is 12.3 year, but its biological half-life is 10 days.

7.4 **MW-days.** Show that the fission energy from 1 g of ^{235}U is 1 MW_t-day.

7.5 **Nuclear policy.** (a) Why did the US choose LWRs? Why did Canada choose heavy water reactors? (b) Why are heavy water reactors both more and less dangerous for proliferation of nuclear weapons? (c) What are three main factors that affect commercialization of breeder reactors? (d) How can proton accelerators breed plutonium (50 neutrons/GeV) or "burn" actinides? What are some difficulties?

7.6 **Finite, cheap uranium fuel.** The United States has about 5 million tons of inexpensive uranium ore. How many GW_e would this sustain if each reactor were to last 40 years, and 5/7 of the 0.7% ^{235}U were available from enrichment?

7.7 **Single decay.** What is the radioactive decay rate in nuclear weapons made with 5 kg of plutonium, 94% ^{239}Pu ($T_{1/2}$ = 24,000 year) and 6% ^{240}Pu (6,600 year). (b) What would be the rate from today's weapons in 10,000 year?

7.8 **Double decay.** One gram of pure ^{239}U is produced in a reactor. It decays with a half-life of 24 min to ^{239}Np, which decays with a half-life of 2.4 days to ^{239}Pu. Write and solve the two coupled differential equations that describe the radioactivity. Sketch a graph of time dependence of the decays and populations of these isotopes for first 5 days.

7.9 **Annual dose of 3.6 mSv.** Your 80-kg body gets a dose of 3.6 mSv/year. How much energy is deposited per year? How many cells does your body contain if a cell's average diameter is 20 μ? On average, how much radiation energy does each cell in receive per year? How many chemical bonds are broken in each of your cells per year if the bond energy is 5 eV?

7.10 **Cosmic ray dose.** The average dose from cosmic rays is 0.31 mSv/year (31 mrem/year). If we assume this dose is mostly from muons with a flux

of $100/\text{s}\cdot\text{m}^2$, what is the average energy deposited per muon (decay, kinetic energy loss, other reactions) in an 80-kg person with a 0.1 m^2 area? How does this compare to 106-MeV muon decay energy and 3-GeV kinetic energy?

7.11 Mass of nuclear waste. (a) How much nuclear waste does a 1-GW_e plant produce each year if it is 32% efficient with an 85% load factor? What is the volume of waste, with and without reprocessing? (b) What is the waste activity after 5 years storage if the average lifetime of all fission fragments is 20 years and each fragment decays 2–3 times?

7.12 ^{240}Pu/^{239}Pu/^{238}U. Uranium is placed in a reactor with neutron flux $10^{14}/\text{cm}^2\cdot\text{s}$. What are the $^{239}\text{Pu}/^{238}\text{U}$ and $^{240}\text{Pu}/^{239}\text{Pu}$ ratios after 2 months with thermal $\sigma(^{238}\text{U}) = 2.7$ barns and $\sigma(^{239}\text{Pu}) = 271$ barns?

7.13 Passively safe reactors. What amount of carbon in a 1-GW_e, high temperature gas reactor would keep its temperature below 1700°C after a LOCA?

7.14 Fault-tree analysis. (a) Design a fault tree with the following features: five sensors to detect coolant loss, each with successful probability of 99%; two sets of electrical connections to open the emergency cooling water at 99% each; two valves at 98% each; the availability of line power at 99%; two back-up generators at 98% each; the presence of water 99.9%. What is the probability of failure? What common-mode failures from an earthquake does this ignore?

7.15 Breeder doubling time. A breeder reactor with a plutonium core creates about 2.5 neutrons/fission with 1 neutron to maintain the power, 1 to convert ^{238}U to ^{239}Pu, and 0.5 going to losses. (a) How long would it take a 3-GW_t reactor to produce 3 tons of plutonium, recalling that 1 MW_t-day = 1 g ^{235}U. (b) What is the Pu gain each year? (c) How long would it take to double the 4-ton Pu core?

7.16 Liquid metal cooling. To avoid geometrical neutron-spreading that raises the cost of Pu, the core of a breeder must be compact with 20% fissile content. To remove 3 GW_t of heat, a large flow of liquid sodium cools the core, a process that avoids high-pressure water-cooling. (a) What is the outlet temperature of sodium if 10 m^3/s enters at 620°C? (b) What is sodium velocity with pipe areas 0.1 m^2 to 1 m^2? (The specific heat of Na at 620°C is 1.3 J/g-°C with density 800 kg/m^3.)

7.17 Coal vs. nuclear. Discuss and quantify the health, safety, and environmental parameters for a comparison of power production from 100 GW_e of coal versus 100 GW_e of nuclear.

7.18 Wedge plume with threshold. (a) Redo the APS calculation for reactor accidents, but with a very arbitrary choice of 0.01 Sv (1 rem) for a threshold dose of radiation. (Below 0.01 Sv radiation is arbitrarily assumed not to be harmful.) (b) The APS calculations assumed a person lived continually in a region with ^{137}Cs on the ground. How did the SLBM accident calculation differ from this?

7.19 Radon guideline. The EPA recommends radon be kept below $c_{\text{Rn}} = 4\ \text{nCi}/\text{m}^3$. (a) What is the decay/$\text{m}^3$ for ^{222}Rn? (b) How many ^{222}Rn nuclei are in a cubic meter? (c) A daughter of ^{222}Rn has a half-life of 30 min. How does this affect your answer to the previous question? (d) What is the concentration of ^{222}Rn?

7.20 Radon and energy. Is it economically viable to reduce infiltration in Chicago with 6000°F-day/year from 1.5 *ach* to 1 *ach* if a human life is valued at $5 million? Assume infiltration energy saved is 10 MBtu/year and natural gas costs $5/MBtu and electricity costs $14/MBtu.

7.21 Correction for radon decay. Redo the text calculation of radon density for 0.1 and 1 ach, but include radon decay in the house.

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