RADIATION EXPOSURE

from

FISSION PRODUCTS

We have seen how tedious it is to calculate radiation exposure from 1 g of uranium, but uranium *itself* is **not** what people worry about in nuclear reactor accidents. Enriched uranium containing more ^{235}U or plutonium (^{239}Pu) have a propensity to ***fission*** (split) into lighter nuclei and fast neutrons, and the neutrons (after moderation) can capture on a nearby ^{235}U or ^{239}Pu nucleus, causing it to promptly fission in its turn. If this process is *unregulated*, the "**chain reaction**" can make a fission ***bomb***. In a reactor it is kept under control. But the fission products include many even more radioactive nuclides like ***iodine-131*** which don't fission but do *decay*, giving off penetrating radiation much more hazardous than the alpha particles of decaying uranium.

Shortly after the Fukushima disaster, milk in the USA was found to have 0.8 pCi/liter of ^{131}I activity. What does that mean? It means that a *33 liter* tank of milk would produce ***one*** gamma ray per second, about the same as the number of cosmic ray muons piercing every 10 cm square area of your body every second.

Recall ***ACTIVITY units***

1 **Bequerel (Bq)** ≡ 1 radioactive decay per second.

An isotope with a ***half-life*** of $T_{1/2}$ has a ***mean lifetime*** of

$$\tau = T_{1/2} / \ell n 2 \quad (\text{where} \quad \ell n 2 = 0.6931478\ldots)$$

and a ***decay rate*** of $\lambda = 1/\tau$

so a sample of N such nuclei will have an ***activity*** of

$$A = \lambda N = N \, \ell n 2 / T_{1/2} \text{ Bq}$$

(if $T_{1/2}$ is measured in *seconds*)

But it matters what the isotopes decay ***into***!

940 PBq of ^{131}I equivalent

It is estimated that the net release of radioactivity from the Fukushima disaster was 940 peta-Bequerels of "iodine-131 equivalent".

Remember, a sample of N atoms of an isotope with a ***half-life*** of $T_{½}$ has an ***activity*** of $A = N\,\ell n\,2/T_{½}$ Bq (if $T_{½}$ is measured in *seconds*).

^{131}I, with a short half-life of ***8 days***, decays by β-emission (averaging190 keV) with an accompanying γ (mostly 364 keV). From this and the mass of ^{131}I we can calculate the number N of ^{131}I nuclei and the mass m of same needed to produce an activity of $A \approx 0.94 \times 10^{18}$ Bq. The answer? $N = 0.94 \times 10^{24}$ and $m = 0.204$ kg.

Multiplying A by the energy released per decay yields a ***power*** of about **81 kW**. That's just from the activity that ***escaped***. The ***entire*** content of the Fukushima cooling ponds generated enough heat to cause a *steam explosion*, which is *how the disaster happened*!

Note: ***It's all gone now***.

Recall ***DOSE units***

1 **rad** ≡ 100 erg/g (energy deposited per unit mass)

1 ***gray*** (**Gy**) ≡ 100 **rad** ≡ 1 J/kg. (standard international unit)

*R*elative *B*iological *E*ffectiveness (***RBE***) "fudge factor":

- X-rays, γ-rays & β-rays (fast electrons): $RBE = 1$ (by definition)
- Slow neutrons: average $RBE \approx 3$. (Variable!)
- Fast neutrons, protons & α-rays: $RBE = 10$.
- Fast heavy ions: $RBE = 20$.

REM (**R**, *R*oentgen *E*quivalent to *M*an):

R ≡ *RBE* × **rad**.

(1 mR ≡ *milliREM* ≡ 10^{-3} R.)

sievert (**Sv**, standard international unit):

Sv ≡ *RBE* × ***Gy*** = 100 **R**

EFFECTS of Penetrating *Radiation*

- **Instant Death**: ~ **50** Sieverts [Sv] "*whole-body*" can wipe out the central nervous system (CNS) *when delivered all at once*.
- **Overnight Death**: ~ **9** Sv whole-body may accomplish the same thing in about a day.
- **Ugly Death**: ~ **5** Sv → severe *radiation sickness* (nausea, hair loss, skin lesions, *etc*.) as short-lived cells fail to provide new generations to replace their normal mortality. Complications (infection) often kill. Some recover completely but may develop leukemia years later; offspring (if any) may have genetic mutations.
- **Sub-Acute Exposures**: ~ **1** Sv whole-body delivered all at once → no immediate symptoms, but possible leukemia (rarely, years later).

DOSE from 0.2 kg of ^{131}I

Whereas an α-emitter held at arm's length with tongs is harmless, because none of the alphas make it to you, *betas* and *gammas* are *penetrating* and *long-range*. So your best protection is actually to *get further away* from such a source and rely on Gauss' Law ($1/r^2$).

The entire inventory of escaped activity from Fukushima generates **81 kW** of heat and ionization. But where could that energy be ***deposited***? The gammas can go a long way without interacting; the betas are less penetrating — they probably stop in a few cm of water. So suppose (for a "worst case scenario") *all* the escaped activity from Fukushima were dissolved in an Olympic-sized swimming pool and *you went swimming in it*. You'd get gammas from all around, but betas only from the water right next to you. I estimate that about 0.25×10^{-4} of that 81 kW would be deposited in your body, so that's 2 Watts per 80 kg (you) or, at an RBE of one, 0.025 Sv/s or **1.5 Sv/min**. Yes, in that scenario you'd probably be dead within a few days, unless you scrambled out of that swimming pool in less than about 5 minutes. :-(

DOSE from 0.2 kg of ^{131}I, cont'd

Now *dilute* that 200 grams of ^{131}I in the *entire Pacific ocean*… that's 710 million cubic kilometers, 0.28×10^{15} times the volume of the Olympic swimming pool. So now your body immersed in the ocean would represent 8.7×10^{-20} of the volume absorbing 81 kW of radiation from that ^{131}I. That adds up to 7×10^{-15} Watts of ionizing radiation deposited in 80 kg of you, for a grand total of 9×10^{-17} Sv/s or 3×10^{-9} Sv/year.

Are you concerned? Why? My calculations could be (and probably *are*) off by orders of magnitude, since I have not considered ocean currents and the probability that contaminants do *not* mix uniformly through the whole ocean. But we have quite a few orders of magnitude to spare!

How, then, can anyone ***detect*** the ^{131}I from Fukushima in our seawater? The gammas from the "contaminated" seawater have a long range and a very specific characteristic energy, so patient physicists with a big gamma detector will see one occasionally; after a while, they will have enough statistics to make a positive identification.

Ionizing Radiation → DNA Strand Breaks

Single strand breaks (SSBs) usually *heal* in *milliseconds*.

NIH: SSBs occur *naturally* more than 10,000 times a day in any single mammalian cell.

Double strand breaks (DSBs) can take longer to heal, and may even be *permanent*, causing…

- **Cell Reproductive Death** [most common]

  Cells usually survive for their natural lifetimes — a few days for hair follicles, skin and mucous membrane cells; "forever" for brain cells and some muscle cells.

- **Genetic Mutation** [most subtle]

  Damaged *gamete* cells → *mutations* (usually fatal to foetus; almost always detrimental to the individual offspring…)

- **Cancer** [most unpleasant]

  Runaway replicative zeal of a misguided cell…

Recall ***Thresholds and Linearity***

We have data on the survivors of *Hiroshima* and *Nagasaki*. We also have data on the people exposed to high radiation levels at *Chernobyl*. We know roughly how much their probability of (*e.g.*) thyroid cancer was heightened over time by exposure to Iodine-131, and we know how many suffered immediate effects of "radiation sickness". What we *don't* know so well is how people are affected by much *lower* levels of radiation exposure. One reason for this is that we don't have a "**control group**" of people who are not exposed to *any* radiation. There are no such people! Your *bones* are radioactive.

One model is "***LNT***" — a simple ***L***inear model with ***N***o ***T***hreshold: that is, we assume there is *no such thing* as a "*harmless*" amount of radiation and that the probability of harm is *proportional* to the radiation dose. This model has the advantage of simplicity.

The "***Threshold***" model assumes that the "normal background" radiation level is *harmless*, and may even be *beneficial* up to a point ("***hormesis***"). There is actually some evidence for the latter.

Natural Background Comparisons

Because rigorous calculations of dose are so difficult and interpretation of their implications are so controversial, we often rely on *comparisons* with “natural background radiation”.   The guys at xkcd.com whipped up an excellent graphic for this, but of course it makes a few apples-to-oranges comparisons:

https://xkcd.com/radiation/