The Nuclear Waste Problem

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There are two two keys to understanding the nuclear waste problem:

1. The quantities involved.
2. The difference between gamma and alpha radiation.

Figure 1 shows the dry cask storage facility for Connecticut Yankee near Haddam Neck on the Connecticut River.

Figure 1: Connecticut Yankee Dry Storage Facility

Connecticut Yankee (CY) was a 619 MWe pressurized water reactor that ran for 28 years between 1968 and 1996. During that time the plant produced 110 million MWh. There are 43 casks on a concrete pad, 78 feet by 228 feet.[1] These casks contain about 1020 tons of spent fuel. The fuel is surrounded by 3.5 inches of steel and then 21 inches of reinforced concrete. Each cask weighs about 126 tons, of which about 25 tons is the spent fuel itself. Each cask also has internal passages for natural draft circulation to remove the heat produced by the spent fuel's radioactive decay. These show up in Figure 1 as the rectangular slots at the bottom and top of each cask.

If Connecticut Yankee had been a coal plant, it would have produced between 3,000,000 and 6,000,000 tons of toxic ash in its operating life, not to mention 110 million tons of CO2. If we attempted to store this ash on the CY fuel cask pad, we would have a column of ash about 7000 feet high.

Almost all the material in these casks falls into one of three categories:

1. Spent uranium.
2. Fission products.
3. Transuranics.

For practical purposes, spent uranium is not radioactive. By weight it represents about 96% of the spent fuel.

Fission products are the result of the nuclear fuel splitting into two pieces. They represent about 3% of the spent fuel. Most fission products decay by emitting electrons and photons. These photons or gamma rays are what makes spent fuel so difficult and expensive to handle. The electrons have very little penetrating power. Few can penetrate the outer layer of skin. But a gamma ray can easily penetrate all the way through a human body. Gamma rays are the reason the casks in Figure 1 are as big as they are. Fission product decay is relatively rapid. The spent fuel in the casks in Figure 1 was stored underwater for at least five years during which time the fission product decay heat dropped by a factor of 400. If the fission products were to stay in the casks for 500 years, the gamma radiation from the fission products would be down to near background levels.

Some of the neutrons in the reactor do not result in fission but are absorbed by the fuel transmuting the uranium into still heavier elements, such as neptunium and plutonium, known as transuranics (TRU). By weight the TRU represent about 1% of the spent fuel. Transuranics decay by emitting electrons and alpha particles. As we have seen, electrons have little penetrating power. Alpha particles have still less. Most alpha particles cannot penetrate a piece of paper. In order for alpha particles to do any damage, they must be ingested or inhaled.

Transuranic decay tends to be very slow with some important TRU isotopes having half-lives of the order of 100,000 years. TRU's also can be quite valuable. Some such as ^{238}Pu can be used to power deep space probes. Others are either fissile or fertile and can be processed into excellent

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[1] 40 of the casks contain spent fuel. Three contain other material that did not meet the Class C standards for landfill disposal. This material will decay faster than the spent fuel.

nuclear fuel, although currently this is not economic, in part because the fission product decay makes handling the spent fuel so difficult.

Figure 2 puts some numbers on the decay process.[2]

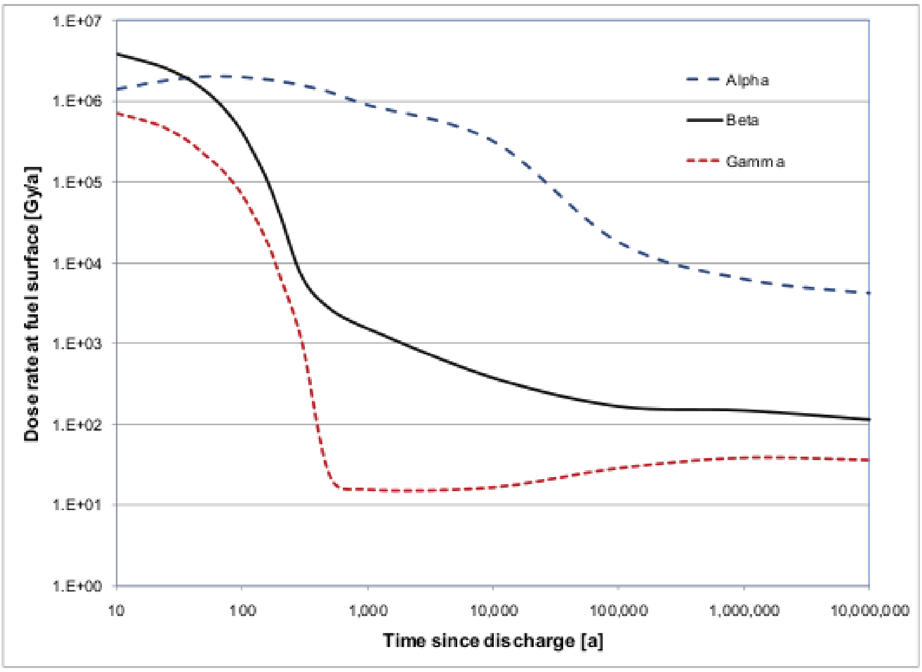

Figure 5-13: Radiation Dose Rate in Water at the Fuel Surface (220 MWh/kgU Burnup)

Figure 2: Candu Dose Rate at Fuel Element Surface

The graph is in grays per year (Gy/a). Radiation dose is measured in sieverts. For gamma radiation, grays and sieverts are the same. At year 500, the gamma dose rate ***on the surface of the fuel element*** is about 11 Sv/y or 30 mSv per day. The graph is for Candu fuel which is low burn up, meaning it contains fewer fission products than a typical light water reactor fuel. So we double this to 60 mSv/d at the surface. At a distance of 1 m from the assembly, the dose rate will be down by a factor of 20.[3] The dose from standing 1 m away from a 500 year old, completely unshielded fuel assembly for an hour will be 0.125 mSv. That's about one-third of

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[2] Nuclear Waste Managment Organization, Used Fuel Repository Conceptual Design, Canadian NWMO Pre-Project Report TR-2012-16, December,2012.

[3] Croff, A, Hermann, C., Alexander, C., Calculated Two-Dimensional Dose Rates from a PWR Assembly, ORNL-TM-6754, 1979, Figure 8.

a mammogram. At 2 m from the surface, the dose rate will be 1 mSv/d, which is less than the limit for astronauts. It is also below the level at which we have reliably observed any negative health effects.

These facts suggest an obvious solution to the nuclear waste problem.

1. Keep the spent fuel in dry casks for say 100 years. At this point, the fission product decay will be down by another factor of ten. In 2012, the USA consumed 3826 million kWh. If all this power had been produced by Connecticut Yankees at the not very good capacity factor CY averaged over 28 years, we would need just under 1000 Connecticut Yankees. The CY pad is just over 0.4 acres. If the US were all nuclear, every 28 years the nation would have to set aside roughly 400 acres for dry cask storage.
2. Transfer the 100 year old fuel to fewer, larger dry casks. The factor of ten reduction in decay heat will allow every ten casks in Figure 1 to be replaced by a single cask with twice the diameter and twice the height. This transfer could be combined with a consolidation of the individual plant casks into one or two sites serving the entire country.
3. Repeat for 2 or 3 cycles. Now the fission product gamma decay is down to levels at which the spent fuel can be safely handled with modest protection.
4. At this point, it will be quite cheap to separate the non-radioactive uranium from the rest of the fuel by fluoride volatility, the same process that was used in enriching the fuel. This will reduce the amount of waste be more than a factor of twenty. The remaining 40 tons could easily be stored in a single cask. A facility the size of the CY pad could handle the TRU waste from 40 Connecticut Yankees. The spent uranium could be fed to a breeder reactor or re-enrichment; but, even in the unlikely event this is not economic, the uranium presents no disposal problem.
5. However, given the low level of gamma radiation, it will almost certainly pay to separate the valuable TRU from the decayed fission products. The fission products — some of which, such as platinum, are also valuable — could then be put in a Low Level Waste (Class C) landfill.[4] We are now down to 10 tons of TRU. 10 tons of TRU is a cube about 2.6 ft on a side.
6. This cube could be dumped down a borehole. A single borehole could take a 1000 Connecticut Yankees operating for 30 years. But a more intelligent approach would be to separate out the extremely valuable isotopes such as ^{238}Pu and ^{241}Am, and then burn the rest in a fast reactor. Due to processing losses, we will not be able to fission all the TRU, but we will get at least another order of magnitude reduction in waste. The material in Figure 1 is now down to a cube about 1 ft on a side. This material, dangerous only if ingested or inhaled, can go to deep geologic disposal, if this is deemed necessary.

The solution to the nuclear waste problem is both obvious and cheap.

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[4] The gamma radiation in Figure 2 levels off after 500 years. The transuranics are primarily alpha emitters; but they do indirectly produce a small smount of gamma when they decay. With their removal, this source of gamma will be gone.