Spent fuel handling and interim storage

Spent fuel characteristics

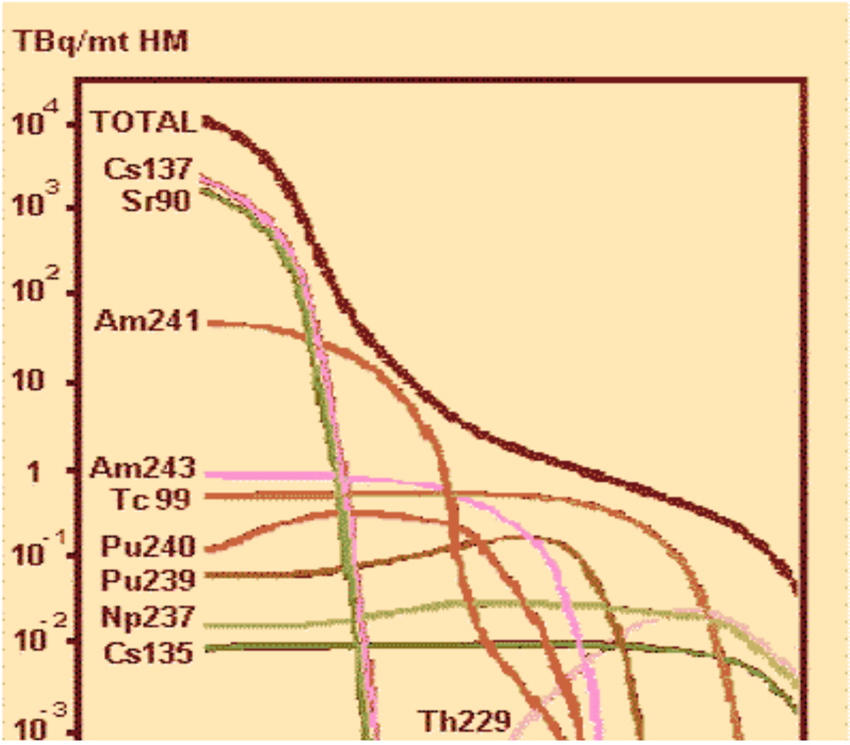
After 3 or 4 years of irradiation, the spent fuel still consists of some 94% U-238. There is about 1% U-235 left over and also 1% plutonium, of which some 65% is still fissile. Only a small fraction of the fuel consists of other transuranics (like 0.1%). Finally, the fission products make up 3 to 4% of the spent fuel. Nearly all of them are radioactive, some decaying very fast and thus radiating very strongly, others decaying more slowly.

It is not really useful to discuss all the factors that determine how radiotoxic a certain fission product really is, since apart from physics, the biology of the human body and even the whole human food chain might be of crucial importance. Unshielded exposure to a spent fuel element which just came out of the reactor can kill you very quickly due to the massive amount of radiation you will receive. If you remember the firemen at the Chernobyl accident, you'll know what I'm talking about.

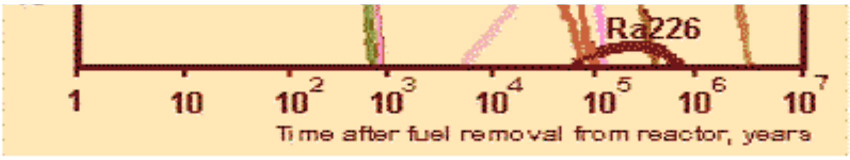
But also in the longer term there are many nuclei that should not be allowed to enter the biosphere. In the first 100 years Cs-137 (cesium) and Sr-90 (strontium) produce most of the radioactivity and the heat associated with that. Both have a half-life of about 30 years. In the longer term, the long-lived mobile isotopes Tc-99 (technetium) and I-229 (iodine) are of major concern, as well as the transuranic elements which by that time are responsible for most of the heat production. The most important of these is Np-237 (neptunium). Heavier transuranics that are also long-lived decay via Np-237 or one of the long-lived plutonium isotopes. Thus Np-237, which has a half-life of 2 million years, might be considered the waste "bottleneck". Also, the fission product Cs-135 is a long-term problem.

When reprocessing, cesium and strontium can be isolated from the rest. In Sellafield this can be done now. It is also in principle possible to isolate neptunium. Americium and curium are still problematic. In La Hague however, all this is not included in the processes. Instead, they merely keep the transuranics mixed with the fission products.

Figure 1: Activity of spent fuel through time



In figure 1 you can see the radioactivity of the spent fuel components which together make up the long-term waste problem. Note that both the years and the activity are on a logarithmic scale and that the latter is measured in TBq per metric ton of heavy metal (= uranium mass prior to irradiation without the oxide = uranium plus transuranics plus fission products afterwards). One TBq equals 10^{12} decays per second. This means that at 10,000 TBq/tHM about 0.1% of the fission products decay every second. One might also make a similar plot of the heat generation as a function of time (they are not equivalents though, since each isotope has its



specific decay energy release).

So, when storing a spent fuel element as it is one has one package containing almost all radioactivity and that's it. Almost, because there is also some other waste arising from reactor use, some of which is also high level waste (like parts of the reactor itself). Most of this will appear when decommissioning the reactor. This particular waste can be considered a constant when comparing the reprocessing option to direct disposal.

Reprocessing HLW

Reprocessing results in a few distinct waste streams. Please remember that the total amount of radioactivity should be equal in any case. Some people think that reprocessing in some mysterious way decreases radioactivity, which is nonsense.

The fission products and non-plutonium transuranics are glassified (see figure 2a) and can be stored in special canisters, the remainders of the fuel tubes and structural material are compressed, cemented and packed in drums. The first is obviously almost the same as packed spent fuel elements. In the vitrified high level waste (VHLW) however, the fission products and transuranics are more concentrated, thus the VHLW volume itself will be smaller than the corresponding spent fuel volume. On the other hand, the cemented high level waste (CHLW) which does not produce significant heat, increases the total waste volume. You can see drums with non heat producing HLW in figure 2b.

Figure 2a: HLW vitrification

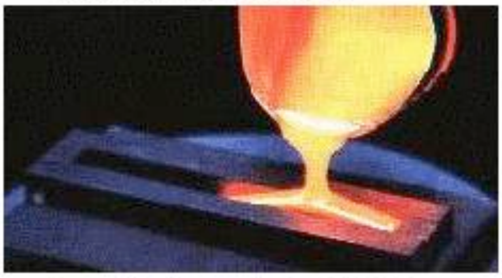


Figure 2b: Cemented solid HLW

There is also some additional waste arising from the reprocessing process, for example filters and ion exchangers which are also used in nuclear power plants. In short: Every contaminated glove or tool adds up. Part of this adds up to the cemented high level waste, the rest is low level or medium level waste, which is often also cemented.

The uranium separation is of no real significant importance for radiotoxity reduction. The plutonium separation is, be it to some degree. You can understand this from the waste plot above, since the plutonium and americium-241 (!) should be left out to get an idea of VHLW characteristics in terms of radioactivity (the measure of which should then become Bq per unit of volume or something equivalent). Also, the neptunium curve would not show an initial increase, since this is mainly due to americium decay.

But this is merely advantageous for the long-term radiotoxity of the VHLW itself! The reprocessing lobby wants us to believe that the plutonium vanishes or something, or can be totally burnt up (as you might have learnt from the section "What happens in the reactor", both are not realistic). Eventually, whether the plutonium is merely stored or used as MOX fuel, the remainder needs to be taken care of and re-use gives rise to new transuranics -- even more than in the normal uranium cycle.

And there is another objection regarding long-term waste management: If the idea of creating waste that should be isolated for up to millions of years (Np-237 is just as radiotoxic as plutonium) gives you the creeps, you should not create it at all. That is the only way, since the trouble with this kind of waste is the fact that you have it rather than just how much you have of it. In this very simple perspective, the whole idea of long-lived waste reduction by means of reprocessing becomes a mockery. If one separates waste into distinct fractions, one still has the same waste all together. A child understands that.

I think in general this is the most powerful argument for me to state that reprocessing has the purpose to extract more energy out of the initial uranium or to produce plutonium for non-peaceful uses or both, but certainly *not* rational waste management. This is merely used as a political argument and one has to be rather ignorant to fall for it.

Some figures

I hope by now you will agree that volumes are not very suitable measures to compare the waste production for different waste management strategies. However, since there isn't much else one can do, I feel obliged to present some comparable numbers. This is meant to be an indication rather than a very precise calculation.

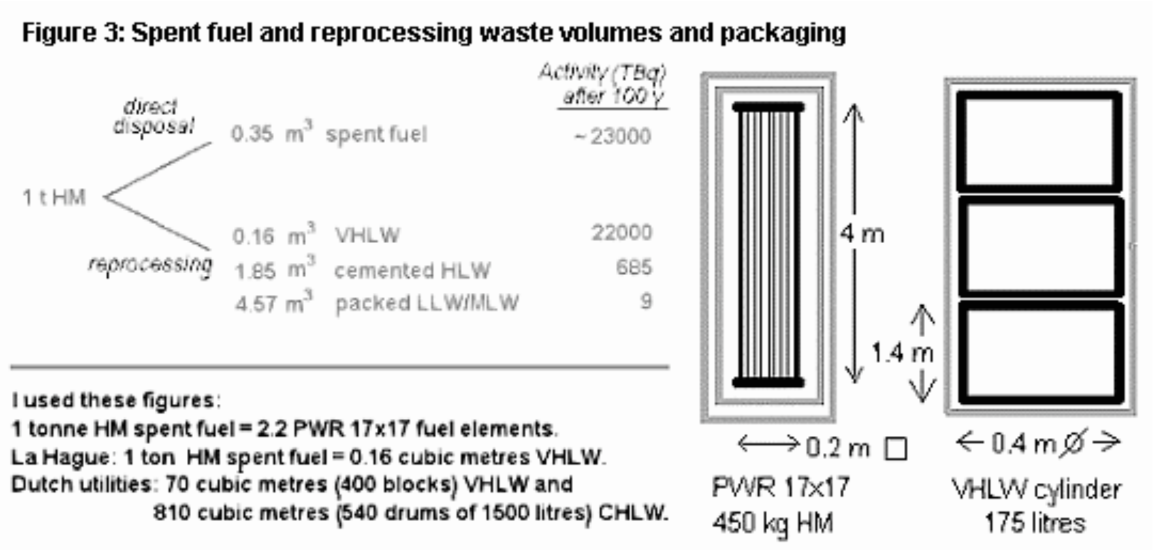
With figure 3, below, you can compare the heat producing HLW volume when storing spent fuel elements with the heat producing VHLW volume and the non heat producing CHLW and LLW/MLW when reprocessing. The spent fuel volume is simply calculated by using a reference PWR element containing 450 kg HM, with realistic (and convenient) dimensions. By comparing the volumes of VHLW, CHLW and LLW/MLW after reprocessing (using numbers from the Dutch utilities) one can get a good indication of the reprocessing waste volumes per ton initial HM.

Hence Greenpeace is right when claiming that reprocessing increases waste volumes by a factor of twenty or so. But to find out what those numbers really mean, we have to remember the special nature of heat producing waste: It cannot simply be stacked like CHLW drums, so the actual space needed might differ significantly from what one would expect from the volumes.

It may also be interesting to get an idea about the mass concentrations in the VHLW and CHLW: Since there are some 35 kg fission products in 1 metric ton of spent fuel, the VHLW contains about 220 kg FP per m^3 of glass. And since the solid residue from dissolving the fuel weighs about 300 kg per ton fuel, the CHLW has a radioactive material density of some 160 kg per m^3.

On the right side of figure 3, you can get an idea of the packaging. This is in the Dutch case of in-vault storage, or more general, in any case where the surrounding medium should not become contaminated (the Swedish case of underground wet storage is sort of an exception).

Figure 3: Spent fuel and reprocessing waste volumes and packaging



		Activity (TBq) after 100 y
0.35 m^3	spent fuel	~23000
0.16 m^3	VHLW	22000
1.85 m^3	cemented HLW	685
4.57 m^3	packed LLW/MLW	9

I used these figures:
1 tonne HM spent fuel = 2.2 PWR 17x17 fuel elements.
La Hague: 1 ton HM spent fuel = 0.16 cubic metres VHLW.
Dutch utilities: 70 cubic metres (400 blocks) VHLW and
810 cubic metres (540 drums of 1500 litres) CHLW.

Note that the spent fuel element needs a double containment, since the element itself is contaminated. First it is packed in order to be clean on the outside, and then there is a second containment with helium between the two, which makes pressure measuring possible. In the VHLW case, the inner clean containment is already present when leaving the vitrification plant. Since one VHLW canister only has a volume of 175 liters, there can be three in a containment which is more or less equivalent to that of a spent fuel element (this is how the Dutch initially designed the in-vault containments, in order to be able to store both spent fuel and VHLW). In both cases, the containments have a cylindrical shape.

In case you feel more comfortable with numbers in terms of drums or canisters: 100 metric tons of initial heavy metal would -- in this example -- result in about 220 spent fuel canisters (one element each), or 53 VHLW canisters (3 VHLW blocks each), about 120 CHLW drums of 1500 liters and some 380 LLW/MLW drums of 1200 liters. If you're confronted with such figures without any specification about dimensions, do yourself a favor and throw them away.

Figure 4: VHLW storage in air-cooled vaults

You have already seen that in terms of waste quality there is no major difference between reprocessing and direct disposal and that in terms of absolute quantities reprocessing creates a much bigger volume of waste -- not even counting the uranium, which up to now is hardly re-used, and the plutonium, or whatever waste results from its re-use.

But clearly, the most complex and expensive part of interim storage is the nature of the heat producing waste. The canisters therefore need some space in between (if a storage container with a liquid fission product solution explodes in a reprocessing plant, this is caused by overheating, not nuclear reaction). From the numbers above one might draw the conclusion that one has to store roughly four times as much canisters with heat producing content in the case of direct storage compared to reprocessing. However, the difference in heat generation is almost a factor of 6. This is easy to understand, since fission product concentrations in VHLW are higher than in spent fuel elements. So, on the whole, spent fuel storage may even be more advantageous in this respect.

The costs of extra packaging in a hot cell are a disadvantage when performing direct storage, but these are small compared to the total reprocessing costs and nothing compared to the costs of final disposal. With this heat producing waste, once again, the trouble is that you have it rather than exactly how much you have to store. This generally results in high constant costs compared to variable costs, for interim storage, and in particular for final disposal.

Figure 1 is a modified scan of an illustration in a public brochure from the Kernforschungsinstitut in Karlsruhe. The VHLW and CHLW pictures in figure 2 are scans from a public brochure of the Dutch ILONA commission (on nuclear waste research), primary source: BNFL. The numbers used for calculating the waste volumes in figure 3 originate from COVRA, the Dutch radwaste company. Figure 4 is a scan from a EC report on radwaste management, primary source: BNFL.