About fuel burn-up rates

It was only after I made the pages about MOX and uranium use when I realized that the burn-up concept plays a crucial role in the underlying physics. I have seen parts of reports by Green groups go wrong because of misunderstanding of burn-up and related subjects (like fissile material requirements, "burnt" amounts, etc). I therefore decided to devote a small section to burn-up rates and their relation with some other reactor operation parameters like enrichment. It only requires very basic physics, yet I'm not embarrassed to say that during my studies I sometimes needed to draw diagrams similar to those below to find out where I went wrong.

Plutonium build-up and U-235 decrease

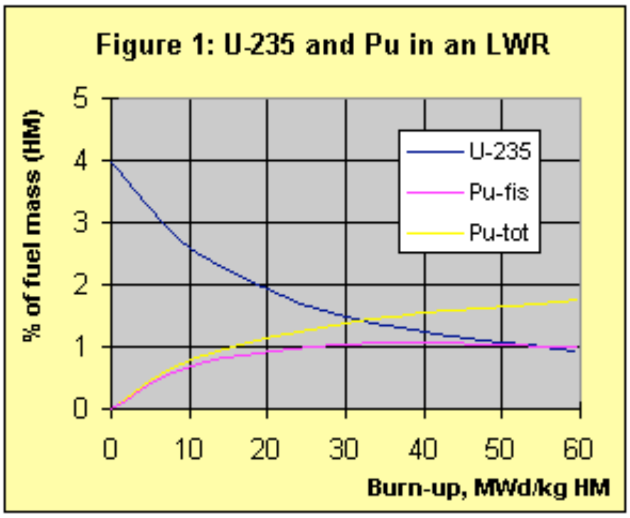

Figure 1 shows a typical PWR inventory plot as a function of burn-up. It is only a sketch, the numerical values are not reliable. In this case, the initial U-235 enrichment is taken to be 4%. This graph could describe a fuel element which is removed from the reactor after it has brought up 50 Megawatt-days of energy per mass unit of heavy metal. Such a plot shows us the amount of plutonium formed during irradiation and how much U-235 "disappeared" (fissioned or converted to U-236). The higher the burn-up becomes, the lesser the relative amount of fissile plutonium gets (due to transmutation).

The plutonium curve is clearly a function of burn-up, but it is also determined by the amount of U-235. After all, it takes a fission event to "make" neutrons and since the primary neutron source is U-235 a higher U-235 content should lead to more plutonium breeding. For reactors using only a low U-235 enrichment or even none, the much larger amount of U-238 can be viewed as an "infinite" source for Pu-239. The limiting factor is always the amount of neutrons available. But the fissile plutonium isotopes themselves are of course also potential neutron sources, so there is an interdependence between the two with feed-back effects which become stronger as the irradiation period progresses. For a variable U-235 content and some fixed burn-up, a plutonium curve would have an S-shape (for highly enriched uranium reactors, like over 90%, this is not true anymore).

More about burn-up

Burn-up is **not another measure of irradiation time**. It is proportionally related with time, but since the factor between the two is not a constant in the sense that one might compare different fuels with different enrichment levels or different specific masses, it is not correct to "replace" burn-up with time. That only holds true for one specific plot as in figure 1.

By definition, the burn-up is defined as the **amount of energy, usually expressed in terms of MWd or kWh if you like, per unit mass of fuel, expressed in terms of heavy metal (HM: only U, Pu, etc, without the oxyde and structural material weight of fuel rods and elements).** In other words, the reactor power (assumed constant) times the irradiation time equals the (thermal!) energy generated in the reactor in that period. Let's put this into a formula:

Burn-up = P * T / M,

where P is the reactor thermal power (the electrical power is normally about 1/3), T is the time of irradiation (the time actually spent in the reactor is of course no good measure, since fuel replacement and maintenance take time as well), and M is the total fuel mass. Note that the burn-up can really describe the state of a single fuel element or even a fuel rod, if we take the actual T of that element and if necessary the actual M's in case the fuel mass has varied. Please don't assume that the latter is merely academical. If the initial fuel enrichment is raised, and if we assume that the particular reactor itself will be operated in the same manner with the same power output, the fuel mass can be lowered proportionally. This means that due to a higher enrichment the burn-up already rises proportionally by definition. Here is where confusion may emerge, since this does not mean that there is any more energy extracted on the whole, only **per mass unit**.

But also, because of enhanced plutonium breeding, the **irradiation period can be prolonged** since reactor criticality can be maintained longer. This really is "extra" energy, and this is the reason why fuel burn-ups tend to rise more than proportionally compared to the rise in initial U-235 content. Of course, one may also choose not to lower the fuel mass, but to prolong the irradiation time even more, or anything in between. The sky is not the limit however, since the structural material of the fuel becomes more and more damaged as burn-ups go up, and reactor criticality has to be assured up to the last minute.

Maybe I should also warn you that burn-up rates for different kinds of reactors or even different kinds of fuels are not comparable. You might know that the breeder reactors, for example, could easily reach burn-up levels up to 60 MWd/kg. This is absolutely incomparable with a LWR element of such burn-up, which probably would be damaged. This is only logical, since the breeders used 20 up to as much as 35% of reprocessed plutonium as their "enrichment". Breeder MOX with a 60 MWd/kg burn-up is actually comparable with some 20 MWd/kg for LWR fuel (although the fuels are very different as well).