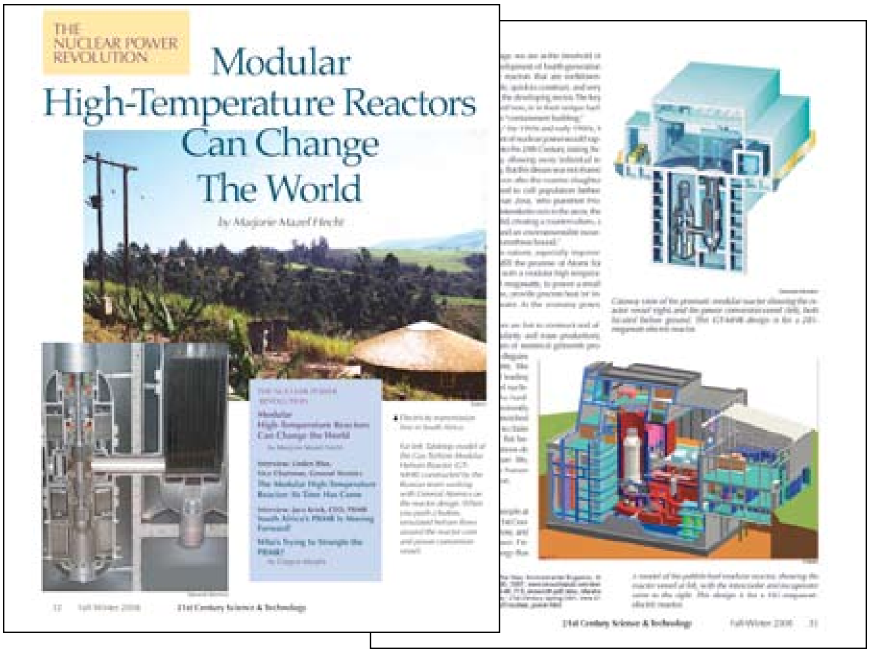
Fourth-Generation HTRs And Recycling: A Dialogue

Dr. George Stanford, a retired nuclear reactor physicist from Argonne National Laboratory, commented on the feature in the Fall-Winter 2008 issue "The Nuclear Power Revolution: Modular High-Temperature Reactors," http://www.21stcenturysciencetech.com/Articles%202008/F-W_2008/HTR package.pdf. Dr. Stanford helped develop the Integral Fast Reactor, a liquid metal breeder reactor that was stopped before it could be commercially introduced. Here he raises the difficulties in recycling the used fuel particles in the modular HTR designs.

The issues he posed are responded to by Dr. Ken Schultz for the General Atomics GT-MHR and Dr. Albert Koster for South Africa's PBMR. Instead of our usual letters format, we print the letter from Dr. Stanford with the responses interpolated.



GEORGE STANFORD Recycling is the elephant in the living room.

The pebble-bed reactor is appealing in many ways, and might well have useful applications. But I can't get enthusiastic about it until there is convincing indication that the spent fuel can be economically recycled.

Here's the situation. The fuel enrichment is not given in the article (at least I can't find it), but values in the range of 8 percent to 20 percent are quoted elsewhere for PBMRs. Let's say it's 12 percent (the bottom line isn't very sensitive to the enrichment). Enriching natural uranium to 12 percent leaves about 95 percent of the ore's energy in the depleted uranium (DU). The article says that the burnup is 65 percent, and 65 percent of 5 percent is 3.2 percent—which is indeed better than the ~0.8 percent that current thermal reactors give us, but even so, some 97 percent of the ore's energy remains unused.

KEN SCHULTZ Well, he's right, this is the magic of the breeder reactor, but the 97 percent is really "potential energy": You have to convert it into plutonium to turn it into available energy.

ALBERT KOSTER The argument is disingenuous. Even when (if ever) breeder reactors become economical and technically proven, there will be a large amount of depleted uranium left over as it will be impossible to convert everything to Pu. It is in any case possible, and proven in the THTR [Germany's Thorium High Temperature Reactor] that a reactor like the pebble bed can become a near-breeder; it is all a question of economics. As light-water reactor (LWR) fuel has to be recycled in some way to encase the fission products, it may make economic sense to extract the Pu and make it into mixed oxide (MOX) fuel, but this is far from a certainty [The British plant at] Sellafield is closing down a 10-year old MOX fuel plant.

Spent Fuel

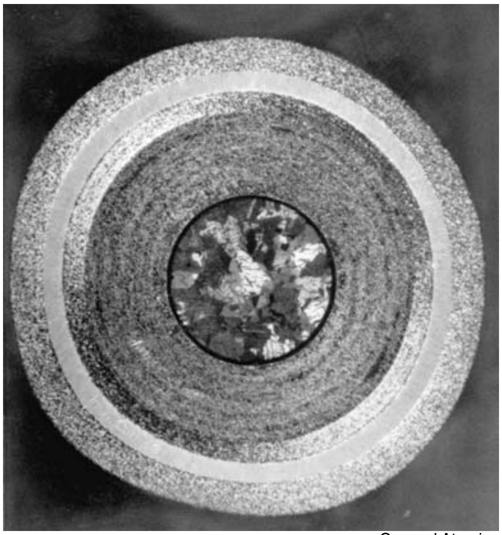
GEORGE STANFORD The article says, "The HTRs produce just a tiny amount of spent fuel, the less to store or bury." I think "tiny amount" overstates the case. Maybe someone more conversant with reactor dynamics than I am will estimate the amount of transuranics left in the used fuel. I suspect that the amount must be ~50 percent or more of the 240 kg/GWe-yr that remains in LWR spent fuel, and considerably more than that in terms of heat generation, because of a larger proportion of higher actinides—and it is the rate of heat generation that determines the capacity of an underground repository.

In other words, if the PBMR's spent fuel is not recycled, there will still be a significant amount of long-term, transuranic waste to be dealt with. Quantitative info here would be helpful.

KEN SCHULTZ The HTGR (pebble or block) has higher thermal efficiency (48 percent) than a light water reactor (32 percent), so it produces less waste per unit of electricity produced. It also has deeper burnup of the fuel and so produces about 40 percent as much actinides as a light water reactor.

The big benefit of an HTGR for actinides is that the spent fuel—or even spent light water reactor fuel—can be recycled ("self-generated recycle") without the uranium (so no additional actinides are produced). The final spent fuel actinide waste volume would be reduced 87 percent and the heat load by 94 percent, compared to once-through LWR fuel.

So, each year, fresh fuel is put in, once-through fuel removed and repro-



General Atomics

Inside a fuel particle: This is a magnified photograph of a .03-inch fuel particle for an HTR, cut away to show the layers of ceramic materials and graphite surrounding a kernel of uranium oxycarbide fuel. The fission fuel stays intact in its "containment building" up to 2,000°C (3,632°F). This containment makes recycling the fuel more difficult, but not impossible.

cessed, and the actinides are put back in (separate blocks or pebbles from the fresh), and the twice-through fuel is retired with about a 90 percent reduction in the amount of long-lived stuff to take care of.

ALBERT KOSTER Figures for the amount of transuranics are available, but it is a fallacy to think they can be used on their own to produce power without mixing with uranium, as such fuel will exhibit a positive temperature coefficient which can only be corrected by adding other metals in a way never yet tried and proven except for thorium in the THTR.

The only way to get rid of transuranics is with an accelerator and it leaves open the question of transporting significant amounts of dangerous materials to such installations, which are, in any case, far into the future. Removing transuranics has the only advantage that it reduces the time that spent fuel needs to be stored from 100,000 years to a few thousand, which is hardly worth the effort as a permanent storage is still needed.

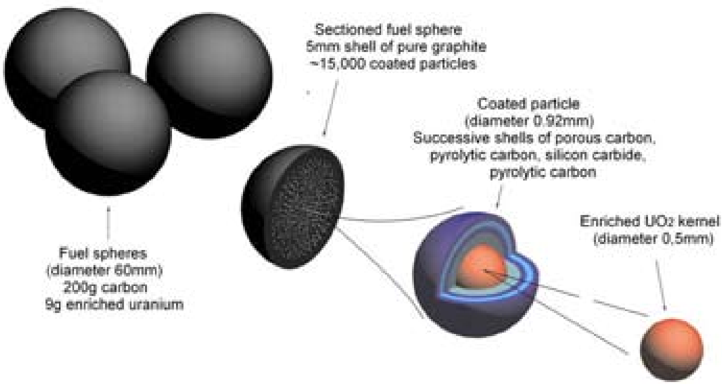
KEN SCHULTZ The concern that Dr. Koster raises about avoiding a positive temperature reactivity coefficient is valid, and for a light water reactor or a fast neutron spectrum reactor does indeed mean that plutonium cannot be burned without adding uranium-238 or some other material to provide a negative temperature reactivity coefficient.

However, with the epithermal neutron spectrum of the graphite-moderated GT-MHR or PBMR, a negative temperature coefficient of reactivity can be maintained, even with pure plutonium or spent light water reactor plutonium plus actinides. Thus the GT-MHR or PBMR can achieve a high degree of burnup while not producing additional plutonium.

This idea, called "Deep Burn," would allow the current store of spent light water reactor fuel to be burned down by about 90 percent, while producing useful energy. The remaining 10 percent could be eventually incinerated completely by continual recycling in a fast spectrum reactor or by use of an external source of neutrons, such as an accelerator or a fusion reactor.

Fast Reactors to the Rescue

GEORGE STANFORD Without recycling, perhaps more serious than the waste prob-



HTR FUEL CONFIGURATIONS FOR THE PBMR AND GT-MHR

The HTR fuel particles for South Africa's Pebble Bed Modular Reactor are are coated with containment layers and then inserted into a graphite sphere to form pebbles the size of tennis balls (at left). Each pebble contains about 15,000 fuel particles. Pebbles travel around the reactor core about 10 times in their lifetime. During normal operation, the reactor will be loaded with 450,000 fuel pebbles.

In the General Atomics GT-MHR, the fuel particles are fashioned into cylindrical fuel rods, about two inches long. These fuel rods are then inserted into holes drilled into the hexagonal graphite fuel element blocks, which measure 14 inches wide by 31 inches high. The fuel blocks, which also have helium coolant channels, are then stacked in the reactor core.

lem is the loss to the nation of valuable fissile material. But all is forgiven if the fuel can be recycled into fast reactors, because then the transuranic inventory becomes an important fissile resource that can be used as seed material for priming fast reactors to meet the growing energy demand, and the long-term waste problem disappears.

KEN SCHULTZ YES!

ALBERT KOSTER While the statement is correct, the economics of extracting and reusing the fuel will depend on the cost of fresh uranium (of which there is plenty) and the cost of recycling. Economics rather than politics should dictate how the fuel is used. Intermediate storage for a few hundred years would retain the usable part (fertile material) if it should become economic to reuse.

Is Recyling Feasible?

GEORGE STANFORD In the Hecht article, the comparison depicted in Figure 1 does, in fact, assume recycling into fast reactors. But so far, I have seen nothing but hand-waving to indicate that recycling is practical. Here's a quote from the article: "As one longtime General Atomics nuclear engineer told me, reprocessing used HTR fuel is absolutely possible—*you just have to want to figure out how to do it."* (Emphasis added.)

ALBERT KOSTER In the last three HTR conferences of 2004, 2006, and 2008, there were several articles describing how used HTR fuel can be deconsolidated and recycled. As pebble fuel is ideal for direct disposal and more proliferation-resistant than LWR fuel, the decision to reprocess or not has many facets and is not determined particularly by the remaining fuel.

Not recycling implies a large volume with a low heat content. After reprocessing, the volume is smaller but has a high heat content, posing problems with heat load on the intermediate and final storage solutions.

An Engineering Challenge

GEORGE STANFORD It's also worth noting that, in other PBMR literature, one often sees the difficulty of reprocessing cited as a proliferation advantage. The microparticle cross-section on page 22 gives one an inkling as to why reprocessing might be a significant engineering challenge.

KEN SCHULTZ *Both* views are right. We developed a reprocessing line for HTGR fuel and operated it with non-radioactive fuel here in San Diego in the early 1970s. The fuel rods were pushed out of the blocks, the coated particles were separated from the rod binder material by crushing and burning, the coated particles were crushed to expose the fuel kernels, which were dissolved in acid to recover the fuel.

So it **is** possible—we've done it. However, it is more difficult to do than simply dissolving an LWR fuel rod in acid; it requires specialized equipment and more effort, which would make it more difficult to do without detection.

Transuranics

GEORGE STANFORD Without recycle, the PBMR waste stream will inevitably contain transuranic isotopes—neptunium, plutonium, americium, curium. Per GWe-yr, the amount of transuranics will presumably be somewhere in the range of 100-600 kg (an LWR produces about 250 kg per GWe-yr). It would be useful to have a more accurate estimate of the amount and the heat load per kg.

KEN SCHULTZ The actinides for a once-through HTGR would be about 100 kg/GWe-yr. For the "deep burn" self recycle it would be about 30 kg/GWe-yr.

ALBERT KOSTER The assumption that transuranics increase linearly with burnup is wrong, as they will in turn burn off and reach a constant level long before the fuel is removed from the reactor. Indicative values are available in paper HTR-2008-58054.

Repository Requirements

GEORGE STANFORD You need to know that the capacity of a waste repository does not depend on the weight of the waste products, but on the heat generated by their radioactive decay. And the long-term capacity of the repository is determined, not by the fission products, but by the heat generated by that small amount of transuranics, which tend to have very long half-lives. The worry that Yucca Mountain might not contain the waste safely for a million years is almost entirely due to the activity of the at-first-sight trivial transuranic content. Predictably, the heat load from PBMR high-burnup waste will be significantly greater, per kg, than from light water reactor transuranics.

Without recycle, the PBMR waste is far from "tiny," being comparable with light water reactor waste in terms of the repository requirements. If the transuranics are recycled into fast reactors such as IFRs [integral fast reactors], the waste from nuclear power—LWRs and PBMRs and IFRs—consists essentially of nothing but a ton of (relatively short-lived) fission products.

In short, PBMRs without recycle will have much greater repository requirements than light water reactors with recycle. With recycle, the PBMR waste does not differ from light water reactor waste, in either nature or quantity.

KEN SCHULTZ Well, a factor of two improvement without recycle is certainly better than nothing, but he's right, we need to go to reprocessing both to get rid of virtually all the long-lived waste and to access the huge fuel reserves of uranium and thorium. The ideal system is to have our current light water reactors and future HTGRs creating spent fuel (and energy!), the HTGR "deep-burning" the spent fuel, and the fast breeder reactor incinerating the final residue.

Eventually using fusion to do that final incineration and to breed new fuel from uranium and thorium would be better yet. And pure fusion would be best, finally ending all the squabbling.

ALBERT KOSTER Both writers assume that there is a huge cost of storage for PBMR fuel. In fact, the cost is in the transport of large quantities when not recycled. PBMR policy is to store all the fuel for about 40 years after the core is emptied. This makes it about 100 years from now to make a decision, and the world is going to be much different. Until then the decision on recycling or not is merely academic and/or political.