Fast Reactors When?

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The Planetary Emergencies Seminar has long considered nuclear power as an important resource for the future. These considerations have included various reactors, including the existing thermal reactors, high temperature gas-cooled reactors, and fast reactors of various types.

We have also taken up fuel cycle issues. Among these has been the availability of importance of improving our knowledge of the cost of acquisition of uranium from seawater, and also from low-grade terrestrial ores.

Furthermore, the disposition of spent nuclear fuel has been discussed extensively, highlighting the benefits of long-term interim storage of spent fuel and of rationalizing the structure for operating mined, geologic repositories. The proposal would be to allow such large commercial activities, in contrast with the national programs that re now the norm, although none is yet in operation except perhaps that of Finland.

The benefits of fast-neutron reactors are well known since the advent of nuclear power, and indeed fast reactors were assumed to be the normal progression, especially before substantial uranium resources were discovered. The benefit lies in the breeding of fissionable material from the 99.3% or natural uranium that is not fissile (fissionable with thermal neutrons)—namely the U-238 in contrast with the 0.7% of natural uranium that is U-235.

It has always been considered that a 50 to 100-fold sparing of uranium would be possible in this way, expanding uranium resources at any given cost by that same factor, and, furthermore, allowing a similar increase in the cost of natural uranium feed without impairing the economics of nuclear power. The paper by Tanju Sofu at this session yesterday, on “Passive Safety in Fast Reactors” showed the experience in one small sodium-cooled reactor that serves as a feasibility demonstration and goal for larger, commercial reactors.

In August 2009, this seminar was treated to an exposition of the Terrapower program for fast-neutron Traveling-Wave Reactors (TWR).with very attractive properties. At that time, however, there was no public documentation on which to base a critical evaluation of the proposal, although I did make an attempt to infer from the presentation what must have been assumed for fuel burn-up, initial U-235 load, and the like.

The 2009 TWR was considered an axially propagating burn wave, in which enriched uranium or Pu fuel at one end of a long cylinder of fuel in the reactor would be critical, breeding Pu-239 in the axially adjacent region, and then burning that Pu-239 as the breed-burn wave moved along the axis of the cylinder. I comment on this configuration (Fig. 1) in my Beijing paper of March 15, 2010 [1] .

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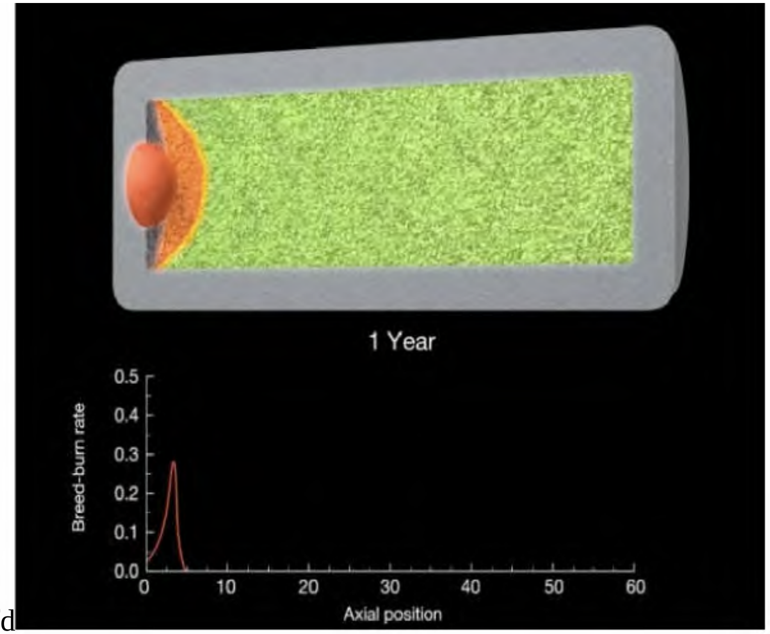
[1] http://www.fas.org/rlg/3_15_2010%20Fast%20Breeder%20Reactors%201.pdf


1 Year
Breed-burn rate
0.5
0.4
0.3
0.2
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0.0
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10
20
30
40
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60
Axial position

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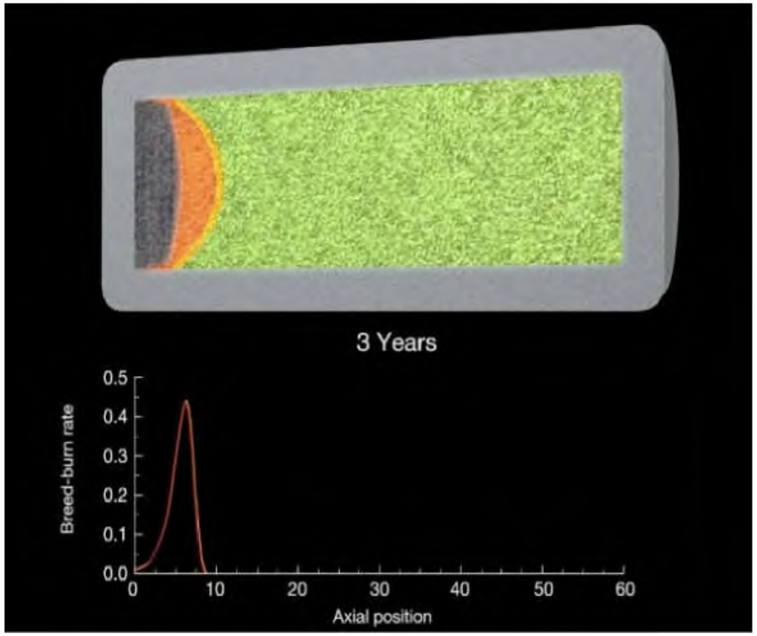
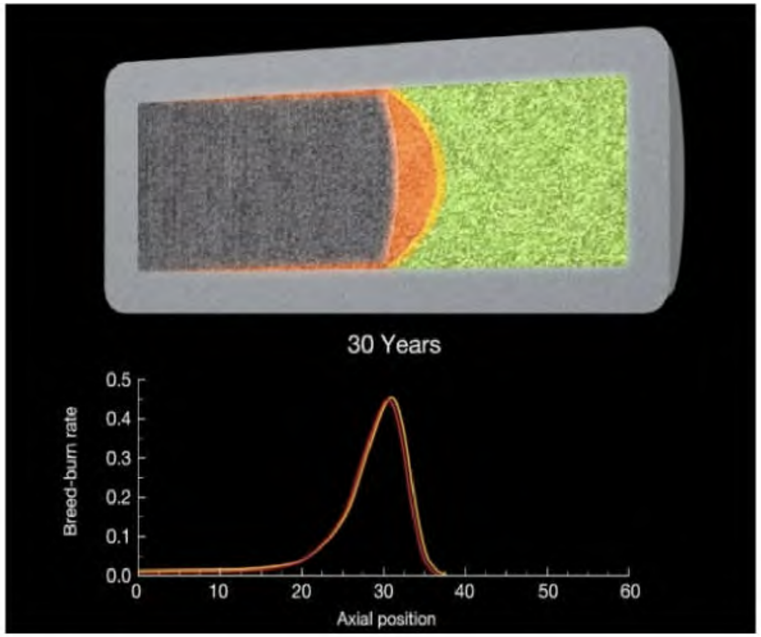

3 Years
Breed-burn rate
0.5
0.4
0.3
0.2
0.1
0.0
0
10
20
30
40
50
60
Axial position


30 Years
Breed-burn rate
0.5
0.4
0.3
0.2
0.1
0.0
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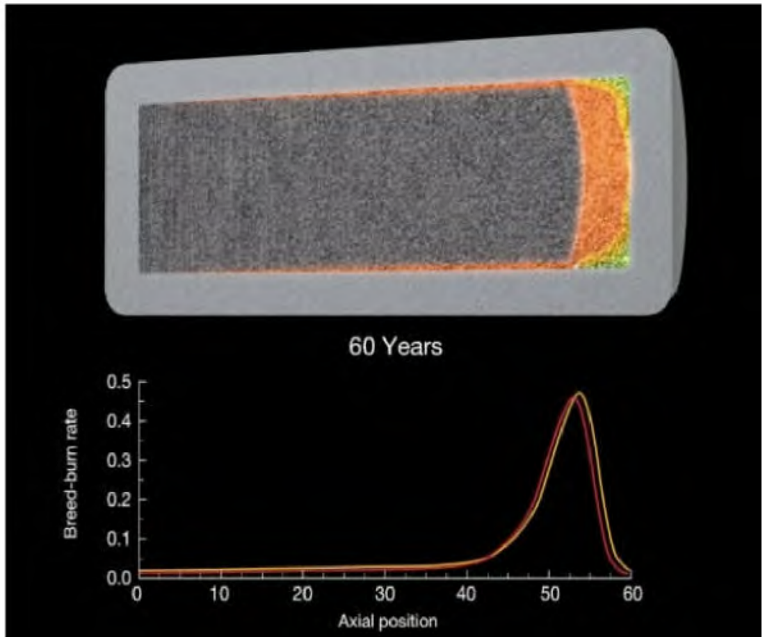
Axial position


60 Years
Breed-burn rate
0.5
0.4
0.3
0.2
0.1
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Axial position

Further work by Terrapower has changed the baseline approach to a relatively static configuration of fission power, with fuel elements being shuffled into and out of that region[2], with the configuration exemplified in Fig. 2.

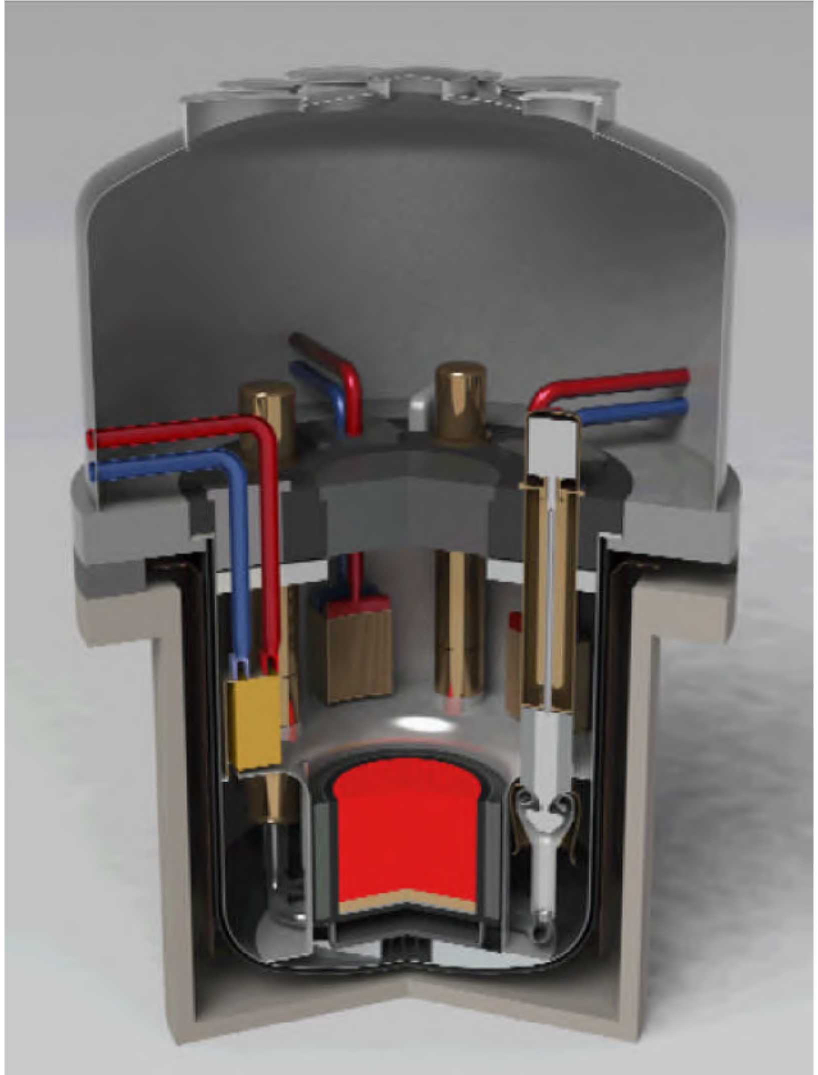

Fig. 2 “Possible practical engineering embodiment of a TWR” (from Ref. 2)

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[2] "Traveling-Wave Reactors: A Truly Sustainable and Full-Scale Resource for Global Energy Needs," by Tyler Ellis, et al, Proceedings of ICAPP'10, June 13-17, 2010, Paper 10189.

The 2010 TWR Report (Ref. 2) indicates a burn-up (BU) of the fuel of an average of 15%, noting that “1 at % is equivalent to 9.4 MWd/kgHM.” A core that produces 1.25 GWe at 80% capacity factor (that is on for full-power production an equivalent of 80% of the days) fissions about 1 ton[3] of fuel per year, corresponding to a core mass of Yr/BU, where Yr is the residence time in years and BU the fractional burnup. For Yr = 6 years, the core mass would be about 6/0.15 = 40 tons.

Thus the cylindrical core contains approximately 40 ton of “heavy metal,” which is at the beginning of operation mostly depleted uranium (DU) left over from enrichment of a vast amount of uranium already used for nuclear power in light-water reactors. The “starter fuel” could be Pu-239 from excess weapon plutonium, more complex or less neutronically reactive plutonium in the form of MOX from reprocessing the spent fuel of LWRs. Importantly, newly enriched uranium from newly mined ore, could be used, simply because the demand for electrical power and for an economical breeder reactor could be so large that could be filled only by enrichment.

One great virtue of a fast reactor is that it is not very sensitive to the enormous absorption cross-sections of certain fission products for slow neutrons. Furthermore, it is provided with a large amount of fertile material, so as to breed the next generation’s plutonium starter fuel. According to Ref. 2, “the comparable TWR (1-GWe) requires an initial core load that in the early TWRs may contain on the order of two times as much fissile material as an LWR first core.” The LWR has about 100 tons of 4.4% U-235, so an initial fissile inventory on the order of 4.4 tons. That for the TWR is thus stated to be on the order of 9 tons. In my August 24, 2009 commentary on Terrapower’s linear TWR, I estimated that “For a large utility reactor with 60-yr core life, such a reactor might start with 60 t of fuel enriched to 15% U-235 (so 9 tons of U-235) plus 320 tons of DU. It would therefore generate 3 GWt for 60 years from 380 t of heavy metal, for a burn-up of 173 GWd/t. I noted there, and here also,

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[3] The unit “ton” in this paper is taken to mean “tonne”—1000 kg.

> *"Although the impression might be given that the uranium content is 100% consumed, Ifigure that the 173 GWd/t compares with about 790 GWd/t for 100% conversion of uranium to fission products, so is a burn-up of about 22%. "*

The estimated 9 t of fissile material for starting the linear TWR is consonant with the approximately 9 t inferred from Ref. 2. It is conventional in LWRs to do fuel shuffling at the time of refueling, in order that fuel elements should be downloaded at the typical 54 months, having had the same exposure to flux, and therefore in fuel burn-up. Unfortunately in LWRs, as is the case in the TWR, the ends of the fuel elements have much lower burn-up than does the center.

Furthermore, although the 15% burn-up is better than the 0.5% burn-up of raw uranium in a TWR, it is far from the 100% advertised by supporters of breeder reactors. The additional factor of 6 or so is to be obtained by "fuel repurposing," which term the authors prefer to "fuel recycling" with its implication of chemical separation and refabrication of fuel. Because the TWR is to use metal fuel, it is argued that physical processes can do an adequate job of separating out fission products that occupy volume in the fuel rod. Thus, fuel rods would be chopped and the ends which are not much depleted in fissile material could be used in more valuable positions than the centers, which are more highly burned. Ref. 2 indicate that they will have a "peak burn-up in the range of 28-32%," so that several such cycles (perhaps 6) would be planned.

For most of the past decade, I have been urging the creation of a world laboratory for breeder reactors, with the purpose of thoroughly exploring the design of three of four different types of breeder reactors, each with its own fuel form and fuel cycle. Evidently, the fuel cycle is a necessary part of the breeder, and the fuel form greatly influences the fuel cycle. My proposal builds on the great advances that have been made in computing in the Stockpile Stewardship Program for U.S. nuclear weapons. The advances include faster hardware, mostly by building very highly parallel machines of consumer electronics, and the pioneering of efficient means of having these "cores" operate effectively in parallel.

In fact, reactor design and safety analysis is a more difficult problem than is nuclear weapon design and maintenance, essentially because there are so many ways in which a system designed to do one thing can do something else by accident or intent. For stockpile stewardship, the important questions are whether the weapons maintain their intrinsic safety, and whether they will, with some reasonable probability, give the yield for which they were designed and assumed to function when they were first put into the stockpile.

Nuclear weapons also have certain specific safety requirements including that there should be less than one part in a million probability during an accident that the weapon will give a yield greater than that of 2 kg of high explosive equivalent, and that in non-accident scenarios, the probability should be less than one in a billion throughout the weapon lifetime.

The World Breeder Lab would have open technology and computing, and therefore would forego the industrial competition that is often a great spur to innovation. But the field of particle physics and great accelerators have long functioned in this way, with outstanding results.

In any case, Terrapower seems to be moving ahead with the substance of one of the sub-programs of a World Breeder Laboratory, in analyzing thoroughly not only the reactor itself, but the solid metal fuel, undersized for the ferritic steel sheath, with the gap at operating temperature filled with molten sodium. This is essential, especially with high-burn-up metal fuel, because the fuel density is so much greater than that of the fission products produced. The fuel would soon fail and the fuel rod cladding swell, if there were not extra space provided in this way. The sodium spacer also facilitates splitting the sheath in order that the metal fuel be available for melting, during which process most of the fission products will combine with a reagent (perhaps including the zirconium oxide of the crucible!) to allow purified metal fuel to be drawn off. In large part, the residual metal consists of the fissionable fuel material plus the residue of the depleted uranium that has not yet been transformed to Pu-239. Obviously, there must be makeup with fresh raw uranium or fresh DU in order to fabricate a new core for the TWR.

According to Ref. 2, the fuel could be withdrawn from the TWR at the end of life, with “a factor 3 multiplication” of the initial fissile content, so with the capability of fueling 3 new TWRs. Alternatively, Ref. 2 proposes removing fuel during the 15-20 year life to fuel another TWR. Assuming this doubling time of 20 years leads to a compound growth rate of 3.5% per year. The fueling of three reactors from a first-generation TWR after 40 years (thus, presumably, plus time for fuel processing and fabrication and loading into the reactor) would be an accomplishment, but it would correspond to a growth rate of the TWR population itself of about 2.7% per year. If one is planning an all-TWR future, then they must take over not only from the LWRs, but also from fossil fuels, and that will require a growth rate in excess of 10% per year. Thus, by far the most of the TWR population must be other than autogenous, and after the modest amount of separated HEU and weapon plutonium are exhausted, the TWRs must be started on enriched uranium from ore, creating a substantial and enduring requirement for enrichment capacity.

Looking to the long-term future, Ref. 2 places great emphasis, as do I, on the utilization of uranium from seawater, where there is 4,000 million tons. This resource would, of course, be valuable for fueling existing LWR-type reactors, and breeder reactors could afford essentially any cost for seawater uranium, given that it can be obtained in an environmentally acceptable fashion.

In summary, Terrapower may contribute to a bright future for safe, economical breeder reactors, as their baseline approach under intensive analysis has become more conventional than the linear traveling-wave reactor presented at Erice in 2009. It would be useful to have available the comparative analyses of the linear vs. the stationary breed-burn “wave” so that the world could learn from the great investments made in this work.