Fast Reactors in China's Future

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These are the views of Richard Garwin and not a position of the National Academy of Sciences or CISAC

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This presentation draws upon two earlier papers,

- "Fast Reactors When?" by R.L. Garwin. Presented at Erice, Sicily, International Seminars on Planetary Emergencies and Associated Meetings - 43rd Session, August 21, 2010.
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- "The Future of Nuclear Energy," by R.L. Garwin. A presentation in the Transforming Energy Lecture Series sponsored by the University of Maryland Energy Research Center, College Park, MD, December 9, 2011.

PRESCRIPTIONS

1. The world and the nuclear power sector need competitive, commercial mined geologic repositories for (a) casks containing spent reactor fuel or (b) vitrified or ceramic fission products from reprocessing fuel

2. Dry-cask storage of spent fuel or reprocessing wastes is an important near-term tool for waste management and for eventual reduction in cost of eventual geological repository.

3. Fast-neutron reactors with a conversion ratio of 1.0 offer the possibility of fissioning all of the uranium rather than just the 0.7% fissile content.

4. Such a fast reactor must be developed together with its specific fuel form (e.g., pellets, rod, or plates; metallic or ceramic) and reprocessing and refabrication process—the “fuel cycle.”

5. A “world breeder reactor laboratory” or its equivalent should be created in real or virtual form to develop detailed computer tools to simulate every aspect of the reactor and its fuel cycle—both in normal operation and in all conceivable accident scenarios or other threats to the reactor or the fuel cycle.

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% of 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.

THESE GENERAL CONCLUSIONS APPLY TO VARIOUS FAST REACTOR CONCEPTS, INCLUDING

- Terrapower's Traveling Wave Reactor—"TWR"
- GE-Hitachi's "PRISM," an evolution of the Integral Fast Reactor
- China's several approaches, with which I am unfamiliar
- General Atomics' Energy Multiplier Module—"EM^2".

In August 2009, at Erice there was a presentation of the Terrapower program for a fast-neutron Traveling-Wave Reactor (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 concept was for 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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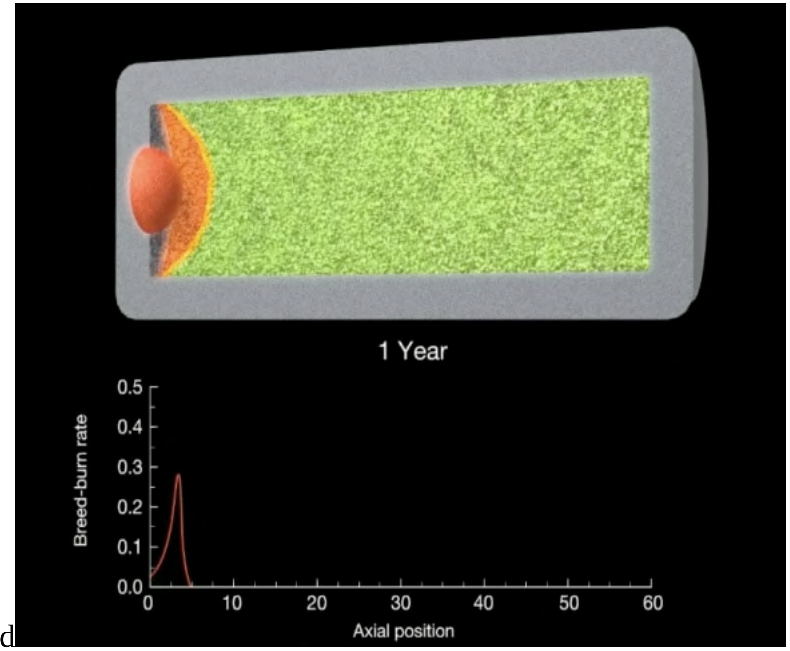
[1] http://www.fas.org/rlg/3_15_2010%20Fast%20Breeder%20Reactors%201.pdf


1 Year
Breed-burn rate
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Axial position
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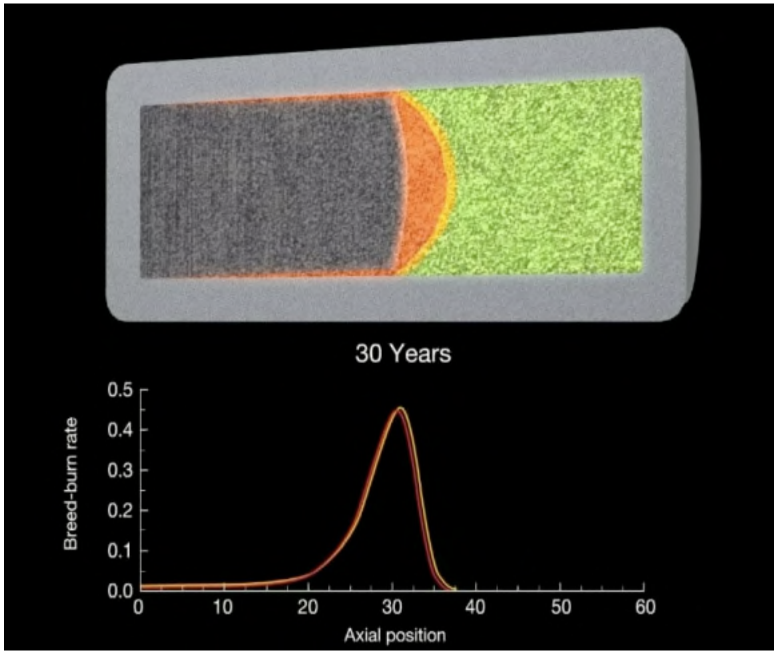
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Breed-burn rate
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0.3
0.4
0.5
Axial position
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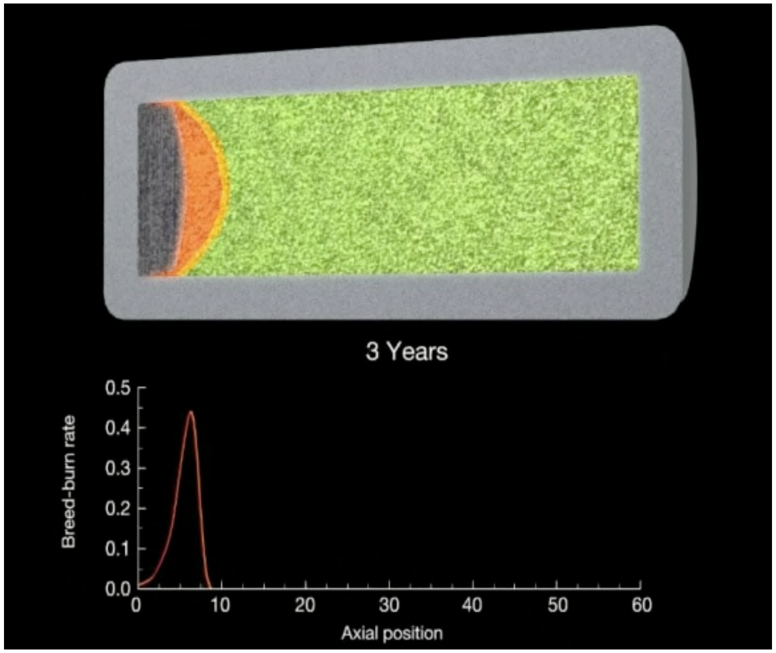
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Breed-burn rate
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Axial position
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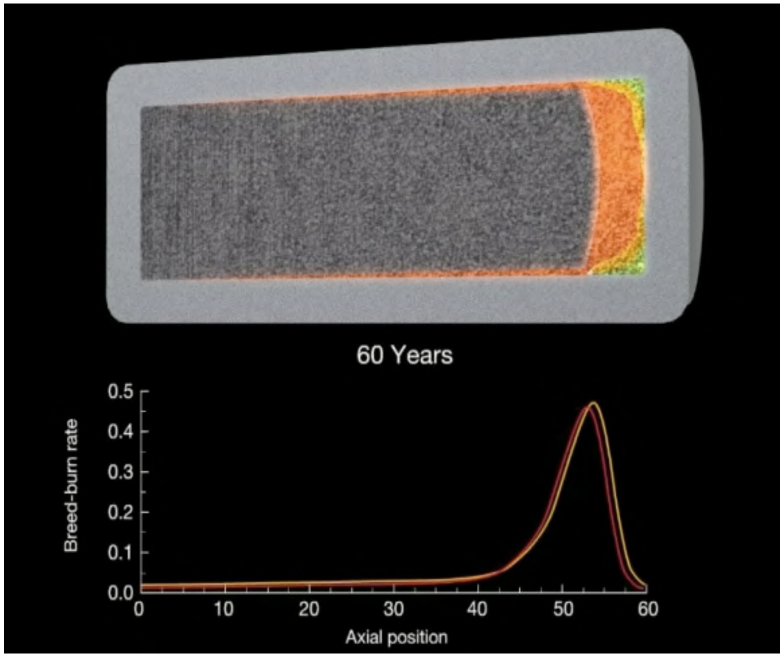
60 Years
Breed-burn rate
0.0
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Axial position
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Further work by Terrapower has changed the baseline approach to a relatively static configuration of fission power, with fuel elements being shuffled into and out of that region[2], with the configuration exemplified in Fig. 2.

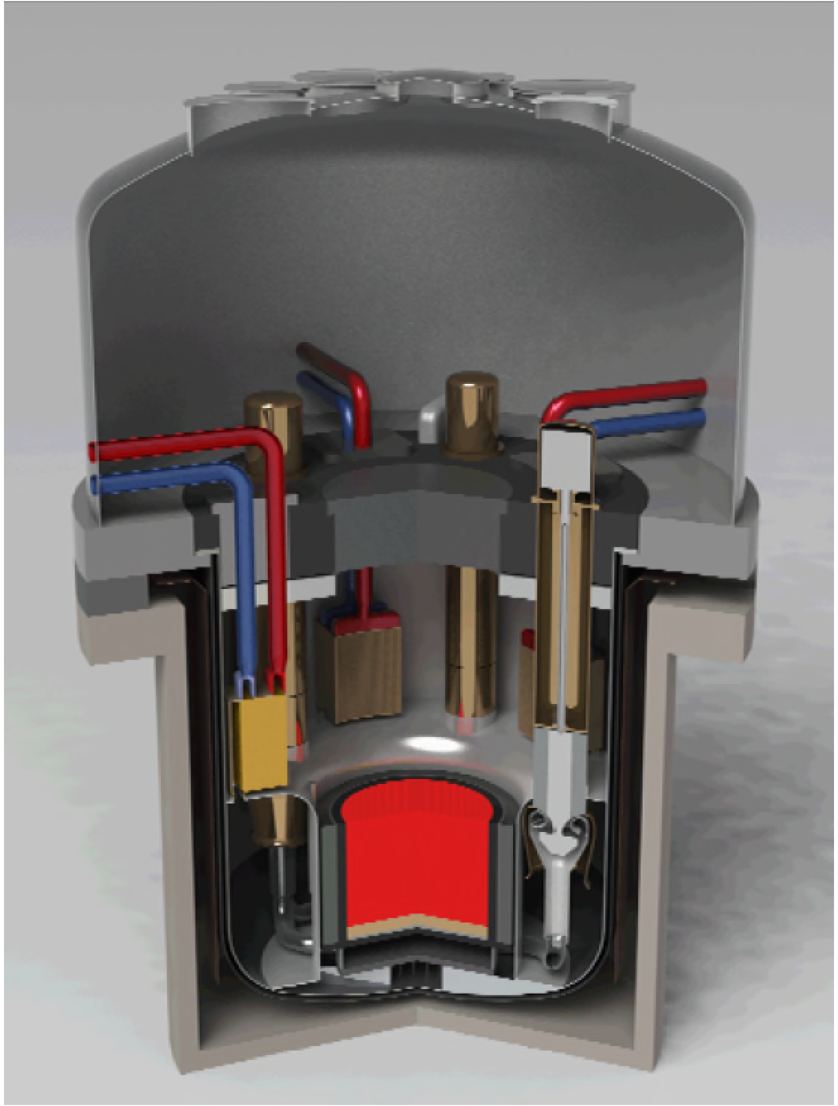

Fig. 2 “Possible practical engineering embodiment of a TWR” (from Ref. 2)

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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 producing at full power 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, or the 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 the growth rate

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

in numbers for an economical breeder reactor could be so large that it could be filled only by enrichment.

One virtue of a fast reactor is that it is not 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 successor'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. The initial fissile core content 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,

> *"Although the impression might be given that the uranium content is 100% consumed, I figure 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 LWR, it is far from the 100% suggested 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 indicates 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.

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 depleted uranium in order to fabricate a new core for the TWR.

According to Ref. 2, the TWR could support a growth rate of about 3% per year on self-generated plutonium. 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, and also the “civil plutonium” stocks separated from some LWR spent fuel, the TWRs must be started on enriched uranium from ore, creating a substantial and enduring requirement for enrichment capacity. The 2000 tons of depleted uranium left from the separation of 10 tons of U-235 would sustain a 1 GWe fast reactor for more than 2000 years.

It would be useful to have available Terrapower’s comparative analyses of the linear vs. the stationary breed-burn “waves” so that the world could learn from the great investments made in this work.

Although the eventual deployment of breeder reactors will eliminate any concern about the availability of uranium, a waste disposal solution is still required, since fission products will still result in the same amount as at present, dominating at least the short and intermediate term heat load, which is the constraining limit on a geological repository. My arguments are given elsewhere, particularly in my testimony and analyses of the Global Nuclear Energy Partnership (GNEP) that burst upon the scene in 2006 during the administration of George W. Bush. I provide this illustrative figure from the Argonne National Laboratory[4]. The baseline is 1.1 metric tonnes of spent fuel per meter of drift (tunnel).

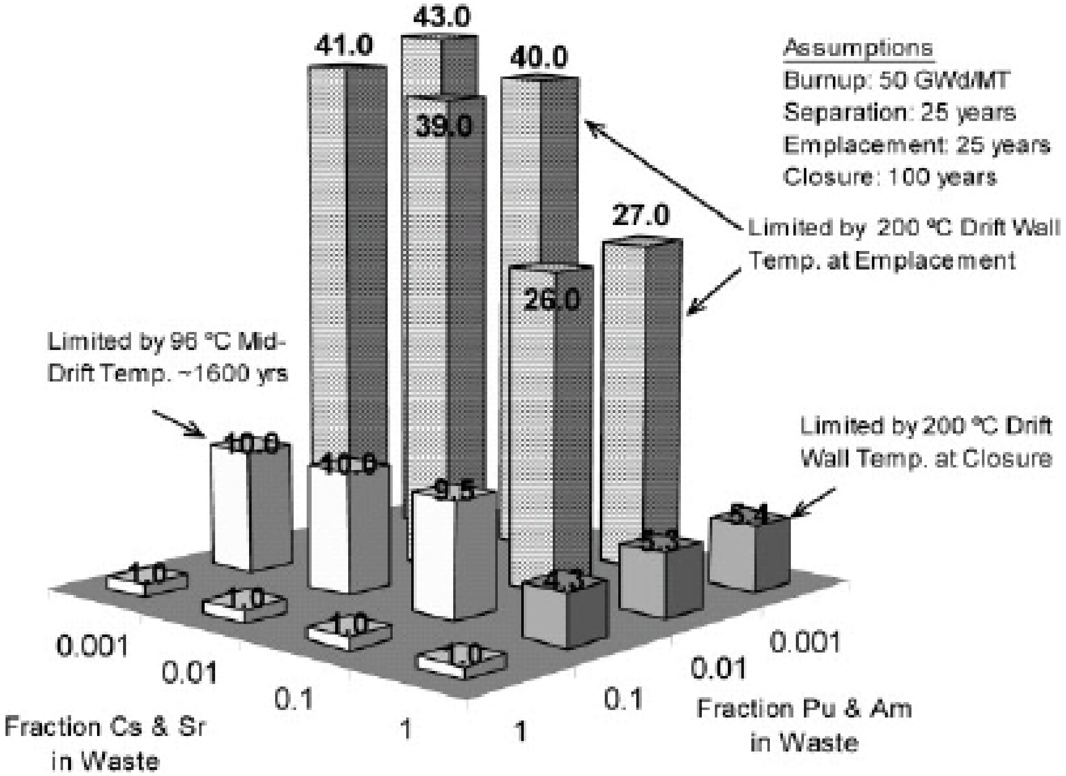

Fig. 7. Potential repository drift loading increase as a function of separation efficiency for plutonium, americium, cesium, and strontium.

President Obama's decision of February 2011 to terminate and to de-fund the Yucca Mountain repository was a serious blow to the U.S. energy future. Yucca Mountain should never have been made the sole repository

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[4] R&D Priorities for GNEP, by R.L. Garwin, Testimony of April 6, 2006. http://www.fas.org/rlg/060406-gnep.pdf (Figure 7. From Wigeland, et al, Argonne National Laboratory)

for spent fuel or reprocessing wastes, and the arguments for it were, in any case, unwarranted-- that entombment above the water table was safer, and that there was no water flow within YM. But Yucca Mountain is good enough, particularly if one adds additional features, such as granite "tile" roofs above the storage drifts.

But there is far more space available below the water table, and, in any case there should be a priority on an international agreement that permits and encourages competitive, commercial deep geologic repositories under strict control by the IAEA, as I have advocated now for at least 20 years. In this regard, the Council of Europe on 19 July 2011 issued a "Radioactive Waste and Spent Fuel Management Directive"[5] that, in short, from September 2011 permits two or more member states to agree to use a disposal facility in one of them and also to export to countries outside the EU under strict conditions: The third country needs to have a final repository in operation when the waste is being shipped, fitting the

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[5] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2011:199:0048:0056:EN:PDF

international definition of a deep geological repository. So I regard this as a helpful step, even revolutionary.

In the meantime, there is consensus between the industry and environmental organizations in the United States, at least, that dry cask storage is far preferable to continued expansion of spent fuel pools, and that dry cask storage is suitable for at least a century of storage of spent fuel, which also eases the initial heat load on the repository.

WHAT BREEDING RATIO?

I have frequently published since 1977 my assessment that anyone who believes in the future of breeder reactors cannot possibly believe that their population will grow significantly by the self-generation of plutonium, but must depend upon starting each breeder and its successor by the use of enriched uranium. So I was pleased to read in the MIT Fuel Cycle Study,

"Historically it has been assumed that the pathway to a closed fuel cycle included recovery of plutonium from light water reactor spent nuclear fuel and use of that plutonium to start sodium-cooled fast reactors with high conversion ratios. The conversion ratio is the rate of production of fissile fuel from abundant fertile materials in a reactor divided by the rate of consumption of fissile fuel. Conversion ratios greater than one imply more fissile nuclear fuel is produced than consumed. This future was based on two assumptions: (1) uranium resources are extremely limited and (2) a high conversion ratio is required to meet future needs. *Our assessment is that both assumptions are false.*

> "-- *Our analysis leads to the conclusion that a conversion ratio of one is a viable option for a long-term closed sustainable fuel cycle and has many advantages: (1) it enables use of all fissile and fertile resources, (2) it minimizes fissile fuel flows — including reprocessing plants throughput, (3) there are multiple reactor options rather than a single fast-reactor option, and (4) there is a wider choice of nuclear reactor core designs with desirable features such as omitting blankets for extra plutonium production*

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"Some of these reactor options may have significantly better economic, nonproliferation, environmental, safety and security, and waste management characteristics. There is time for RD&D to evaluate options before major investment decisions are required. A corollary is that:

> *"--We must use the available time effectively if real options are to materialize in a few decades. This conclusion has important ramifications. For example, a future closed fuel cycle could be based on advanced hard-spectrum LWRs rather than the traditional fast-spectrum reactors, possibly with rather different costs and fuel forms, or it could consign current LWR SNF to a geological repository rather than recycling. Such fundamentally different technology pathways underpin the importance attached to preservation of options over the next several decades."*

This in fact eliminates a lot of uncertainty in the availability of LWR-derived Pu for the initial fueling of a large population of breeders or near-breeders, in view of the certainty that all but early breeders will need to be started with enriched uranium. But this realization does nothing to ensure the cost reduction that would be a prerequisite for early large-scale introduction of breeders.

Among the disparate 4th generation nuclear reactors, the GE-Hitachi PRISM[6] is offered in November 2011 for construction at Sellafield, UK. PRISM is a pool-type liquid sodium fast reactor with metal fuel elements containing Pu and minor actinides from spent LWR fuel. The separation is made by an electrometallurgical process. The fuel remains in the pool for 6 years, one third being replaced each year. A commercial plant under this concept contains an Advanced Recyling Centre and three "power blocks", each of two reactor modules. Each module generates 311MWe, so that the complex generates 1866 Mwe. Each reactor is capable of dissipating decay heat with passive cooling of the fuel and the reactor. GE declined to provide current information for my review.

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[6] From : Advanced Nuclear Power Reactors (updated October 2010, World Nuclear Association, at http://www.world-nuclear.org/info/inf08.html

The conclusion of the 2011 MIT Future of the Nuclear Fuel Cycle Study that a conversion ratio of 1.0 is sufficient to exploit all uranium and thorium in breeder reactors provides much greater flexibility in the choice and design of breeder approaches than does the requirement to maximize breeding ratio. It will be of near-term importance if it enables substantial capital cost reduction, but also in favoring the dry-cask storage of LWR spent fuel in order to defer the reprocessing step until it can be combined with the manufacture of fuel for a specific type of breeder.

What is needed is the ability to model and simulate all aspects of the fast reactor operation and behavior in off-normal situations, as well as the fuel cycle, in order to infer cost and safety to guide decisions to develop and deploy fast reactors in accordance with the prescriptions I now recall,

PRESCRIPTIONS

1. The world and the nuclear power sector need competitive, commercial mined geologic repositories for (a) casks containing spent reactor fuel or (b) vitrified or ceramic fission products from reprocessing fuel

2. Dry-cask storage of spent fuel or reprocessing wastes is an important near-term tool for waste management and for eventual reduction in cost of eventual geological repository.

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