Fast Breeder Reactors

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Presented at the U.S.-Chinese Dialog
on Nuclear Energy and Nuclear Security
Session V: Future of Nuclear Energy and Reprocessing
Harvard-Tsinghua Workshop on Nuclear Policies
Beijing, China
March 15, 2010

FAST REACTOR BACKGROUND

"Fast reactor" is an abbreviation for "fast-neutron reactor", which has been understood conceptually from the earliest days of nuclear energy.

The nuclear weapon, the object of the Manhattan Project in the United States, depends on a fast-neutron fission chain reaction, in which a mass of uranium or plutonium is "assembled" rapidly without a neutron present, and when it assumes the condition of maximum super-criticality, the chain reaction is initiated by the injection of a few or more than a few neutrons. The neutron travels a distance on the order of 10 cm in metal of normal density before causing fission or losing its energy in an inelastic collision. A fission neutron in plutonium produces on the average about 3.5 neutrons; in U-235 the multiplicity is about 2.5. The fission reaction takes no time on the scale of the 5 nanoseconds (ns) required for a 2-MeV neutron to travel 10 cm, so the exponentiation time for the neutron density (and the energy produced) is on the order of 10 nanoseconds.

Almost all nuclear energy is now produced by *therma*l nuclear reactors, in which the fission neutrons are *moderated* by repeated collision with hydrogen (protons or deuterons) in the ordinary-water or heavy-water moderator (or in the carbon of a graphite moderator), in order that they have a higher probability (cross-section) for causing fission in the carefully structured U-235 or Pu in the reactor core. A typical million kilowatt (kW) civil reactor is about 30% efficient, so generates 3.3 million kW of heat which is transferred to a coolant (often to the water moderator) that then typically operates a steam turbine that runs a generator to power the grid. The thermalization of the neutron requires only a few microseconds, but the reactors are easy to control because of a phenomenon that is irrelevant to nuclear weapons—the existence of *delayed neutrons* amounting to about 0.65% of the neutrons born from U-235 fission and about 0.35% for Pu.

POWER REACTORS ARE CONTROLLABLE BECAUSE OF THE FRACTION OF ONE PER CENT OF "DELAYED NEUTRONS"

In reality, these delayed neutrons arise from short-lived energetic fission products. They have relatively low energy when born—of the order of 0.25 MeV compared with 2 MeV for the prompt fission neutrons—and groups of delayed neutrons are important up to delays of a minute or more.

For a reactor operating near *delayed criticality*, as is the case with all civil reactors, the reactor response time is of the order of many minutes, so long as the *control rods* loaded with absorbing material are not removed sufficiently far to approach *prompt criticality*, as was the case with Chernobyl, in which case the exponentiation time is of the order of milliseconds.

Since it is not the thermalization delay that is important in controlling a reactor, if the moderation of the fission neutrons was eliminated to the greatest extent possible one could have a fast-neutron reactor similarly controllable. For a fast reactor in which the control rods or the reflector are adjusted so as to exceed prompt criticality, the scale of exponential growth is of the order of microseconds—impossible to control by any mechanical motion.

The operation of fast reactors is similar to that of thermal reactors in the sense that they produce heat which is then used to run a steam turbine, or in some cases a gas turbine because the temperature can be higher than can be accommodated at reasonable pressure in water. Thus a gas-cooled fast reactor could have 50% Carnot efficiency, in comparison with a typical 33% for a thermal reactor.

High temperatures and the use of gas (helium) for transfer of energy (cooling) are possible also in thermal reactors, for instance in the General Atomics design for a modular high temperature gas turbine reactor, under development by contract with Russia. However, here we are discussing fast reactors.

FAST REACTORS CAN BURN PLUTONIUM AND OTHER TRANSURANICS—A PORTION OF LONG-LIVED NUCLEAR WASTE

Fast reactors have also the feature that transuranics have a reasonable fission cross-section for fast neutrons, whereas many have essentially zero fission cross section for thermal neutrons, as is the case with U-238 itself. Thus, the fraction of the neutrons that ultimately go to make transuranics can benefit not only the neutron economy but also the energy extracted from uranium, when used in a fast neutron reactor. With an ongoing nuclear power economy the disposition of the fission products and residual radioactive material from the energy-producing reactors impose a reduced long-time heat load on the geological repository than does the unreprocessed “spent fuel” from the typical (thermal neutron) light-water reactor--LWR. But reprocessing for recycle of spent fuel in LWRs only worsens the repository problem and adds to the cost, because of the accumulation of non-fissile transuranic isotopes.

In the Global Nuclear Energy Partnership (GNEP) program announced February 2006 by President George W. Bush, there was to be deployed essentially immediately in the United States a set of fast-neutron Advanced Burner Reactors (ABR) devoted to burning the plutonium and other transuranics to be extracted from spent fuel emerging from the 104 operating light-water reactors in the United States. In fact, because each LWR burns about one ton of U-235 per year and produces about 250 kg of Pu and other transuranics, it would appear on first thought that a net population of ABRs with a total of 25% of the thermal output of the LWRs would be adequate to reprocess the spent fuel from the LWR population.

In fact, this is not true, because it is very difficult to make a safe fast reactor with a Conversion Ratio less than 65% (CR = 0.65) , in which case the assumed population of ABRs would burn up only (1 - CR) = 35% of the fuel, because it is making additional plutonium as it is burning the transuranics from the spent LWR fuel. Thus the ABR population must be increased by a factor 1/(1-CR) = 2.86; so that to keep up with the current production of spent fuel from LWRs, the ABR population would need to have some 0.25 * 2.86 = 71% of the fissions as the LWRs. Given the higher thermal efficiency of fast reactors, the electricity generation from the fast reactors would be about that from the LWRs. If the ABRs were given the task of cleaning up the many decades of LWR spent fuel, it would take a far larger population of ABRs. They would be producing much of the electrical power, with all of the potential problems of fast reactors and without their primary benefit.

Repeated fast-reactor processing of LWR waste can provide a benefit for the repository even if Cs and Sr fission products are not removed, as is clear from this chart of allowable “drift” loading as limited by heating of the rock.

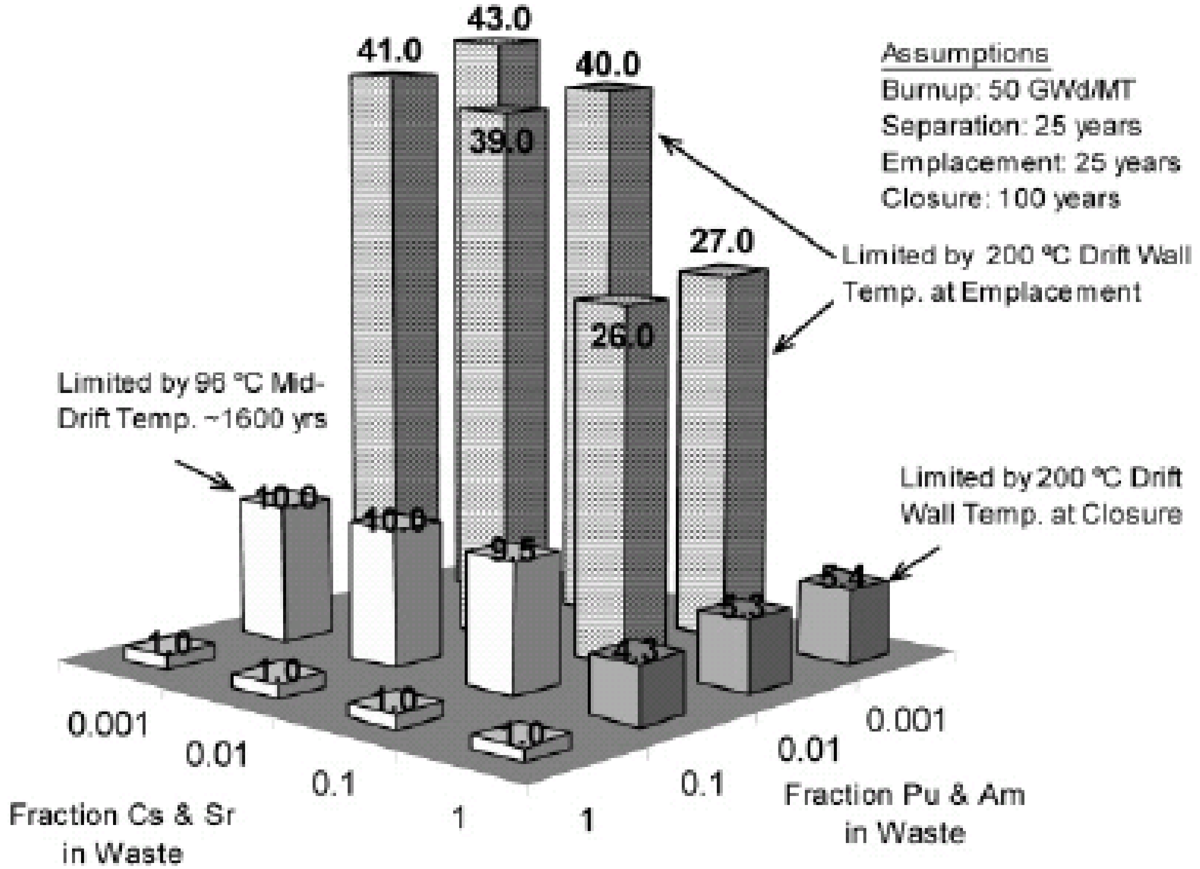


Fig. 7. Potential repository drift loading increase as a function of separation efficiency for plutonium, americium, cesium, and strontium.

From "Separations and Transmutation Criteria to Improve Utilization of a Geologic Repository," by R.A. Wigeland, T.H. Bauer, T.H. Fanning, and E.E. Morris, Nuclear Technology, vol. 154, pp. 95-106, (April 2006).

Note the factor 4.3 improvement in repository capacity by the removal of 90% of the Pu and Am from the waste, without segregating the Cs and Sr. The waste is emplaced 50 years after removal of fuel from a PWR, where it has been burned to 50 GWD/MTHM of fuel.

The origin of these limits is indicated in these graphs of thermal behavior of the repository,

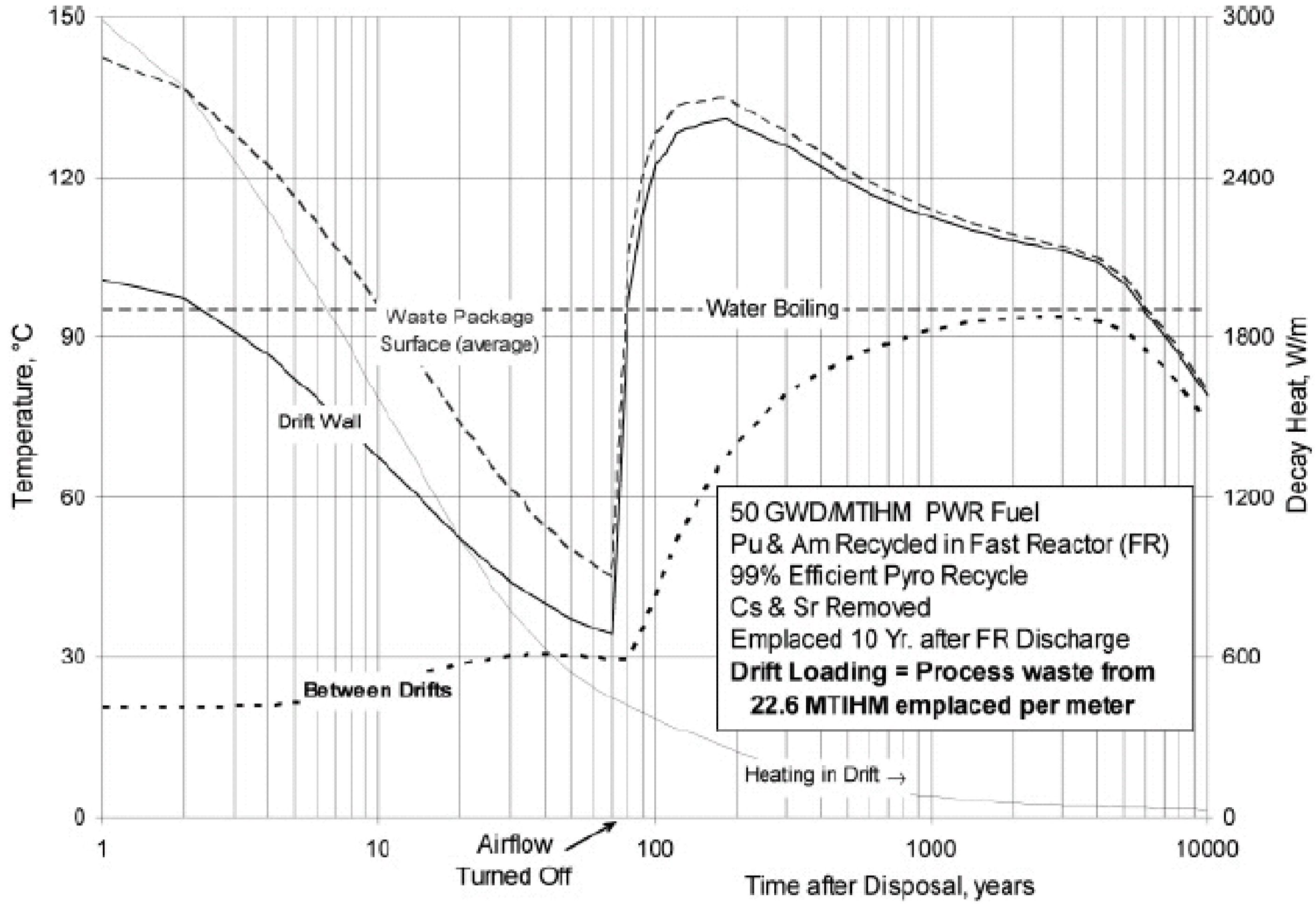


Fig. 6. Transient thermal response of a repository at Yucca Mountain with removal of plutonium, americium, cesium, and strontium from spent PWR fuel, recycling plutonium and americium in a fast reactor, with increased drift loading.

From "Separations and Transmutation Criteria to Improve Utilization of a Geologic Repository," by R.A. Wigeland, T.H. Bauer, T.H. Fanning, and E.E. Morris, Nuclear Technology, vol. 154, pp. 95-106, (April 2006).

WASTE DISPOSAL IS NOT A GOOD ROLE FOR FAST REACTORS.[1] ENERGY PRODUCTION MAY BE

So the decision is really whether to build ABRs for energy production, in which case one should frankly build fast breeder reactors (FBR) with a CR = 1.3 or so.

Ultimately, of course, if fast reactors could be developed to be as safe as LWRs and no more costly than LWRs, there would be little difficulty in making a decision to deploy only FBR. In fact, at that time it would be a terrible loss to humanity to burn up the plutonium without producing more plutonium from either depleted uranium stocks or from freshly mined uranium. In reality, though, there might be a mix of FBR for the large-scale grid, together with some packaged fast or thermal reactors for remote areas and a much lower electrical output.

Even clearer is the loss of value in reprocessing LWR fuel and recycling the Pu as mixed-oxide fuel (MOX) into the same LWRs. This can save no more than 20% of the raw uranium that would otherwise be used (and 20% of the enrichment). As a matter of economics, this is unjustified until the price of raw uranium rises[2] to some $750/kg.

Analysis of the GNEP program made it clear that we have no fast-neutron reactor ready for the ABR role. And it would be a great loss to take the detour to develop and demonstrate the first of a

[1] View of Richard Garwin, but also of Robert Dautray, who built the first French fast reactor.

[2] This calculation has been done thoroughly by Matthew Bunn, Steve Fetter, John P. Holdren, and Bob van der Zwaan, *The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel* (Cambridge, MA: Project on Managing the Atom, Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, December 2003, available as of June 9, 2005 at http://bcsia.ksg.harvard.edu/BCSIA_content/documents/repro-report.pdf).

generation of ABR with conversion ratio as low as 25%, which experts at the Argonne National Laboratory have indicate may be possible.

WORLD COLLABORATION ON GENERATION IV REACTORS

In 2002 many nations of the world agreed to collaborate on these specific next-generation reactors[3]:

1. Very-High-Temperature Reactor (VHTR): a graphite-moderated, helium-cooled reactor with a once-through uranium fuel cycle

2. Supercritical-Water-Cooled Reactor (SCWR): a high-temperature, high-pressure water-cooled reactor that operates above the thermodynamic critical point of water

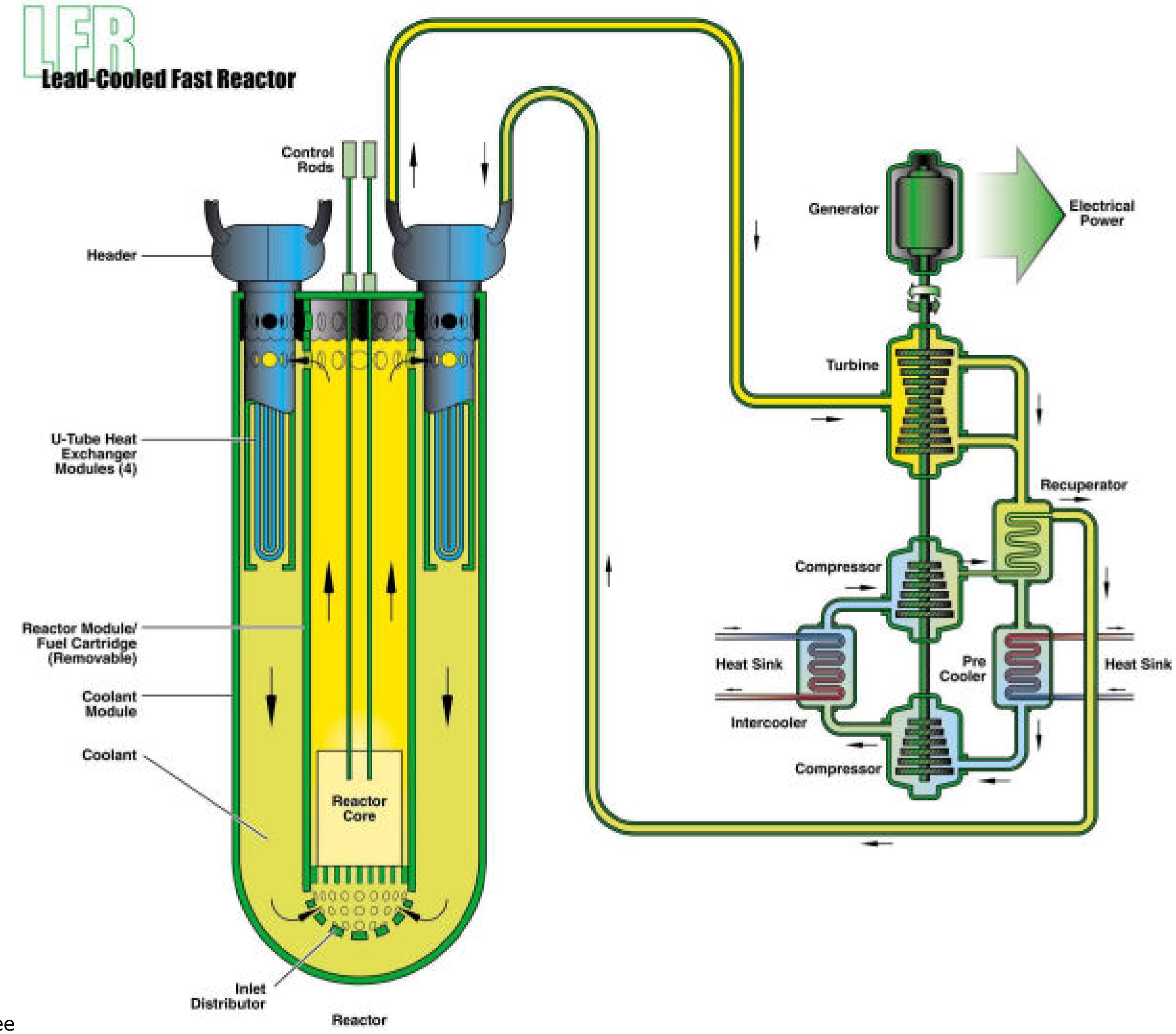
3. Gas-Cooled Fast Reactor (GFR): features a fast-neutron-spectrum, helium-cooled reactor and closed fuel cycle

4. Lead-Cooled Fast Reactor (LFR): features a fast-spectrum lead of lead/bismuth eutectic liquid metal-cooled reactor and a closed fuel cycle for efficient conversion of fertile uranium and management of actinides

5. Sodium-Cooled Fast Reactor (SFR): features a fast-spectrum, sodium-cooled reactor and closed fuel cycle for efficient management of actinides and conversion of fertile uranium

[3] From **http://tinyurl.com/yfe8e63 (Idaho National Laboratory--INL.**

6. Molten Salt Reactor (MSR): produces fission power in a circulating molten salt fuel mixture with an epithermal-spectrum reactor and a full actinide recycle fuel cycle



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Sketch of lead-cooled fast reactor, LFR

I like the pool-type coolant system and the fact that it is lead with "natural circulation" and not sodium. But lead is more corrosive to many materials than is molten sodium and much research and engineering needs to be done, with no assurance that the outcome will be satisfactory. And of course, a fast-reactor commercial power system will need fuel fabrication, typically of 20% and 30% U-235 or somewhat smaller concentrations of plutonium, in order to compensate for the smaller fission cross section of the neutrons in the 100 keV energy range typical of those in the fast reactor. And for breeder reactors or even the proposed ABR, fuel reprocessing and recycle is very essential, because the fast reactor burns only a modest fraction of its fuel and to burn the remainder the fission products must be removed and the fuel refabricated with the addition of natural or depleted uranium—fertile material—to breed the Pu fuel needed to continue the self-supplying chain reaction.

In general, a reactor should be designed and evaluated together with its fuel form and the accompanying reprocessing system, not only for safety and economy but also to minimize the potential for weapon-use use of the plutonium.

INDIA'S COMMERCIAL PROTOTYPE FBR, PROTOTYPE FBR, or PFBR

India has been building a 500 MWe fast reactor, now reportedly delayed until 2011, and proposes to deploy 500 times this PFBR capacity by 2052—i.e., 250 GWe. Unlike thermal-neutron reactors, fast reactors can liberate significant amounts of explosive energy in a criticality excursion, and it is an essential design element to determine this amount.

From years of his pioneering work in reactor safety, Edward Teller cautioned[4],

"For the fast breeder to work in its steady-state breeding condition you probably need something like half a ton of plutonium. In order that it should work economically in a sufficiently big power-producing unit, it probably needs quite a bit more than one ton of plutonium. I do not like the hazard involved. I suggested that nuclear reactors are a blessing because they are clean. They are clean as long as they function as planned, but if they malfunction in a massive manner, which can happen in principle, they can release enough fission products to kill a tremendous number of people.

...But, if you put together two tons of plutonium in a breeder, one tenth of one percent of this material could become critical.

I have listened to hundreds of analyses of what course a nuclear accident can take. Although I believe it is possible to analyze the immediate consequences of an accident, I do not believe it is possible to analyze and foresee the secondary consequences. In an accident involving a plutonium reactor, a couple of tons of plutonium can melt. I don't think anybody can foresee where one or two or five percent of this plutonium will find itself and how it will get mixed with some other material. A small fraction of the original charge can become a great hazard."

An up-to-date contribution to fast-reactor safety analysis in general and of the PFBR in particular is available in a 2008 publication[5], which argues that the energy release from a Core Disruptive Accident--CDA, as calculated by the Indian Department of Atomic Energy—DAE—as 100

[4] Quoted in my presentation, "The Role of Fast-Neutron Reactors in the Treatment of Nuclear Waste and a Major Expansion of Nuclear Power Worldwide" by Richard L. Garwin, presented at a Mini-Symposium on Nuclear Technology at the Eisenhower Institute, April 9, 2007. at http://www.fas.org/rlg/Eisenhower_Institute_040907h1A.pdf

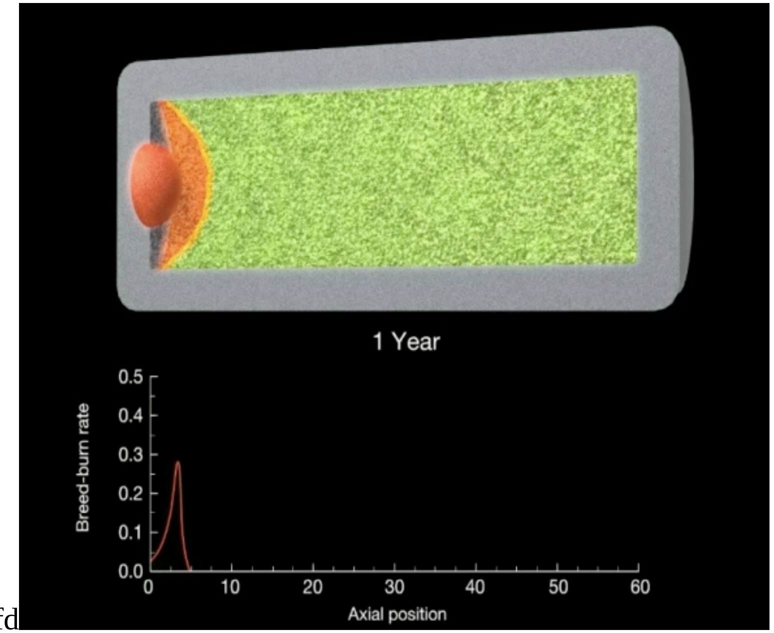
[5] "Compromising Safety: Design Choices and Severe Accident Possibilities in India's Prototype Fast Breeder Reactor," by A. Kumar and M.V. Ramana, Science and Global Security, 16:87–114, 2008, http://www.princeton.edu/sgs/publications/sgs/archive/Kumar-and-Ramana-Vol-16-No-3.pdf

megajoules might be 10 times that, or more. At 1000 MJ, for instance, and 4 MJ per kg of high explosive, this would correspond to 250 kg of high explosive detonated in the heart of the power reactor.

THE TERRAPOWER TRAVELING WAVE FAST REACTOR PROGRAM

The Terrapower team has been talking about a 60-year life in a Pu-U breeder of which these 4 sketches[6] illustrate the concept. This work is supported by new and intensive calculations on a 1996 concept of a linear traveling breeding/burning wave in a fission reactor.

[6] From a talk by Lowell Wood in Erice, Sicily, August 21, 2009, “Exploring the Italian Navigator’s New World: Toward Economic, Full-Scale, Low-Carbon, Conveniently-Available, Proliferation-Robust, Renewable Energy Resources.”


1 Year
Breed-burn rate
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Axial position

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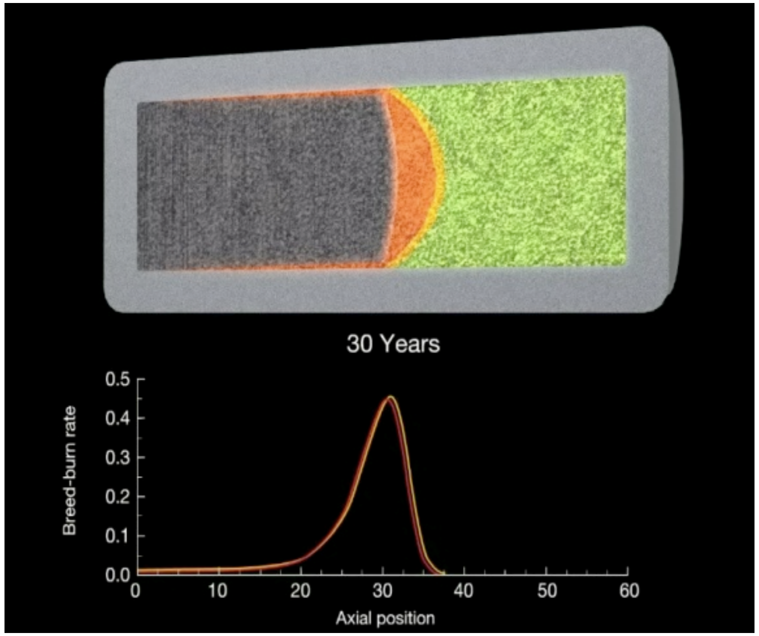
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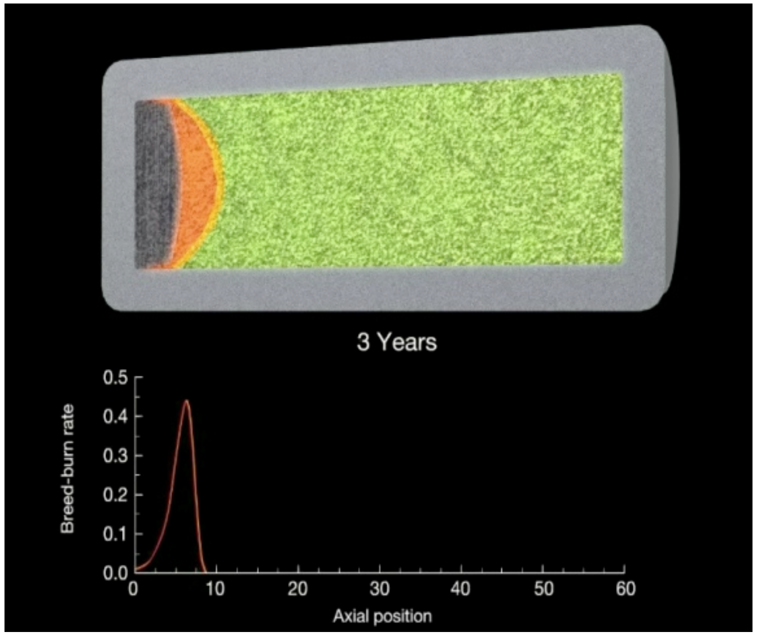
3 Years
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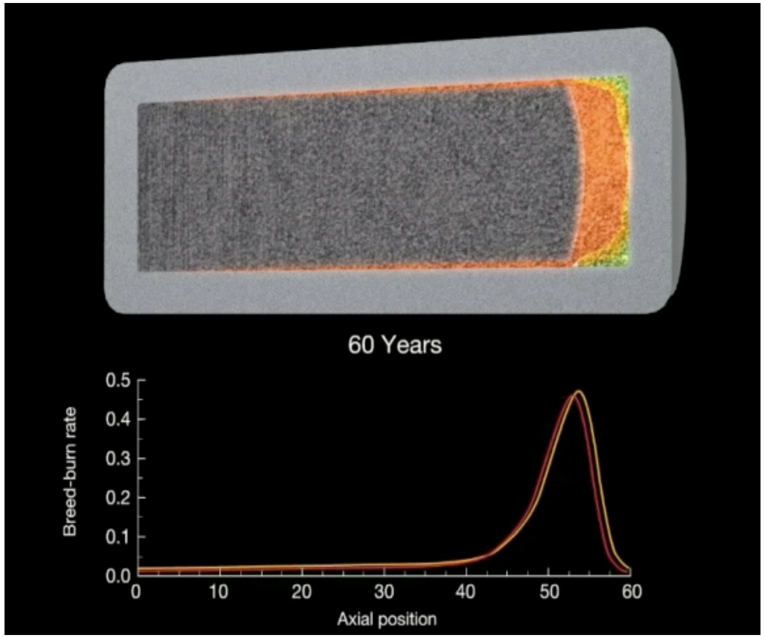
60 Years
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Axial position

Of course, like any reactor, it needs to have effective heat transport, and I believe that this one plans to use metal fuel and molten sodium coolant in a pool-type configuration.

For a large utility reactor with 60-year 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 depleted uranium--DU. It would therefore generate 3 GWt for 60 years from 380 t of heavy metal, for a burnup of 173 GWd/t, or 173/790 = 22% of the uranium.

This compares with a typical LWR burnup of 40-50 GWd/t and is quite comparable with other planned fast reactors at 150 GWd/t.

It is claimed that the spent fuel can simply be melted but not otherwise reprocessed, and refabricated in this way to be used again, indefinitely. This would be so if there were reasonable separation of the residual uranium and actinides from the metallic fission products, and I have no reason to doubt that it is adequate. Of course any fuel handling and fabrication other than the initial fuel must and should be done in a completely automated fashion. I think that the thermal recycle programs made a great mistake in going to manual activities for producing MOX fuel. It seems to me that if one is to avoid the use of enrichment to start a successor TWR, the TW should be stopped while it is still viable, and that section of the old reactor fuel used as the beginning section of the replacement reactor.

Although the entire core will remain at operating temperature for 60 years, intense neutron bombardment of any portion of the core is limited to a few years as the breed-burn wave moves over it. Core-life experiments do not need to be carried out over the 60-year period, except to assure oneself that both the fresh core and the spent core tolerate the temperature and contact with sodium over that period.

Dr. Wood says that for $800 one can buy the MCPNX-CINDER90 code and for another $2000 the PC to run it on, in order to carry out or verify the neutronics and burn calculations. He does not imply that this is adequate for the thermo hydraulic analysis.

Of course, in illustrating the use of these TWR plants to supply all humanity at the current consumption rate of U.S. residents, one is faced with the task of starting these reactors. First, how many reactors would be required? Well, 104 reactors produce about 20% of U.S. electricity, so it would take about 500 such to supply all of U.S. electrical needs. Since the U.S. population of 0.3 B is about 3% of the world population, we are looking at 15,000 full-size reactors, whether of the TWR or the LWR type.

If one requires 9 t of U-235 to start each of these reactors, that is, as is usually the case with any breeder scheme, accompanied by so much U-238 (1800 t or more) that one has hundreds of years of burning in that or a successor breeder. To put this in perspective, imagine that there exist some 3000 t of HEU and military plutonium. This would suffice, then, for some 330 TWRs out of the needed 15,000. Just as I indicated in my 1977 paper[7], "The Proper Role of the Breeder Reactor," there is no alternative to using natural uranium and enrichment technology to jump start the large breeder system. At nearly 200 SWU per kg of U-235 contained in the starter fuel, this is 0.2 M SWU per ton and about 1.8 M SWU per reactor. To start 15,000 reactors would take

[7] "The Proper Role of the Breeder Reactor,"

27,000 M SWU, which is a major investment, even if one did it over a 10 or 20-year life of the enrichment plants, so that one would get the cost down to a typical $100/kg-SWU. This is an enrichment cost of $2.7 trillion—comparable with the enrichment cost for fueling 15,000 LWRs for the first eight years of life, during which each consumes 8 tons of U-235 as 5% LEU. It is notable that at 9 t U-235 per reactor (1800 t of raw uranium) one needs to mine/extract and enrich 27 million tons of raw uranium to obtain the requisite U-235 (less if one has tails fraction < 0.2%.

It is said that the TWR has such good neutron economy that it can double the amount of plutonium in just a couple of years. Of course, that is not this particular power reactor. That refers to a breeder optimized for breeding and not for power. In any case, it is a massive task to build this nuclear capability or any other.

Lowell Wood supports obtaining uranium from seawater and points out that the rivers of the world replenish the uranium in the oceans and that we have enough uranium in the oceans to run 15,000 TWRs forever. And he also rightly says that no matter how you get your uranium, a breeder reactor uses the uranium so efficiently that the cost of uranium is negligible.

If the TWR operates for almost 60 years, the still vital part of the core at the right end could be placed at the left end of a new core fabricated without U-235, without reprocessing, just as one can light a cigarette from a butt of a spent cigarette. In this mode of operation, there can be no expansion of the population of TWR unless new ones are started with enriched uranium. The entire core would need to be disposed of as waste, for which metallic fuel is not well suited. And only 22% of the mined uranium will have been fissioned after 1800 years—still a lot better that the 0.5% for an LWR.

But the spent cylindrical fuel is almost critical and it would be irresistible and appropriate to reprocess the fuel to extract Pu and to use the more concentrated Pu to start several new TWR cores. On the assumption that a total of 5 new TWRs could be started from a single spent TWR, after a delay of 5 years, the autogenous annual expansion rate of TWRs would be 2.5%, thus reinforcing the conclusion that an expanding population of breeders will need to be fueled initially with newly enriched uranium, after the existing stocks of excess weapon HEU and Pu are exhausted.

[My understanding is that at an update presentation in February, 2010, the Terrapower team reports that a different arrangement is desirable or even necessary, with the enriched uranium starter fuel arranged on the axis, with the wave propagating radially. This has many disadvantages over the earlier concept, and the extrapolation of this progress is unclear.]

CHINA'S FBR PROGRAM

The aggressive aims of this program are set forth in a December, 2009 Kyoto presentation by Xu Mi[8]. We will be able to learn more in a few minutes as he describes the program here; the cost of the reactor is of considerable interest because the FBR is often stated as much more costly than the LWR, despite the fact that the sodium pool needs no forged steel pressure vessel. The Chinese program is built on liquid sodium as heat transfer fluid, pool-type geometry, GWe-class installations that are frankly breeders with a breeding ratio of 1.1, ultimately metal fuel, and an on-site closed fuel cycle. China plans to have about 202 GWe of FBR capacity in 2050 (as compared

[8] http://www-pub.iaea.org/mtcd/meetings/PDFplus/2009/cn176/cn176_Presentations/plenary_session_1/FRP-01.Xu.pdf

with 48 GWe of PWRs, and by 2100 to have FBRs replace most of fossil fuel use (for electricity generation). The large FBR capacity will also be able to accept spent fuel stocks from PWRs into the FBR cycle, thus eliminating the Pu and minor actinides from the waste stream from the LWR to the repository. Apparently, the Chinese program will avoid the resource loss and high early cost of recycle of plutonium into LWRs

CREATE A WORLD BREEDER REACTOR LABORATORY

Despite the forward-looking Chinese program, I recommend the equivalent of a world breeder reactor laboratory, with the purpose of working on three quite specific choices of breeder reactor, including their fuel form and fuel cycle. This laboratory would develop and use an advanced and evolving state-of-the-art suite of computer simulation tools, with the purpose of providing reliable simulation and modeling of the performance of each of the reactor types, its fuel, and the fuel cycle. If, after 10 or 20 years, the effort yielded a proposed system that was demonstrated in credible simulation to be as safe as existing light-water reactors and economically competitive with them, then a prototype could be built to verify the simulations. Considering the dismal record of national breeder programs in the past, I believe that this is the way to make progress most rapidly in this important sector, but it is, obviously, only one of the approaches that we could have been following all these years, and it won't help much for 20 years or more. The world breeder lab would also study vulnerabilities of reactors and their fuel cycles against terrorist attacks. I expect that China would play an important role in this collaboration, as suggested in the December 2009 presentation by Xu Mi,

CHINA INSTITUTE OF ATOMIC ENERGY

6. Summary

China needs a huge nuclear power capacity in future. Her first phase of nuclear energy application is rather quick for development with PWRs from now, the second phase, i.e. fast reactor development is still at its experimental stage. China has taken part in the INPRO ,GIF and GNEP, and is willing to have more cooperation with IAEA and other countries to share each other the experiences, and to speed up the national nuclear power development.