GNEP: Leap before looking

(The Global Nuclear Energy Partnership as proposed will facilitate proliferation and the fast-neutron reactors are premature)

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ABSTRACT

President Bush's proposed Global Nuclear Energy Partnership--GNEP--proposes to permit expansion of nuclear power plants worldwide by introducing the assured leasing of low-enriched-uranium fuel and the take-back of spent fuel. This is an important initiative and the US government should lead the drive to reverse law and custom in all nations to permit the transfer of spent fuel rather than its required disposal in the country in which it is produced. But the major part of GNEP is a proposal immediately to build a spent-fuel reprocessing plant to treat the entire 2500 metric ton per year output of the 103 operating US power reactors to obtain fuel for scores of new fast-neutron advanced burner reactors that in turn will require multiple reprocessing cycles. The reprocessed product, whether it is

50% uranium or not, is far more readily stolen and transported than is the current spent fuel and is suitable for fabricating nuclear weapons. The reprocessing aspect of GNEP is really a back-handed approach to deploying scores of breeder reactors. I favor the breeder approach, but only after competitive technical studies make a persuasive case that the breeders are cheaper than the current light-water reactors with direct disposal of spent fuel. The US should take the lead in encouraging the creation worldwide of competitive, commercial mined geologic repositories, with routine above-ground dry-cask storage of spent fuel for 100 years or more. These storage and disposal sites should be under international regulation, as should the spent fuel or processed high-level waste that would be disposed in them.

The Global Nuclear Energy Partnership-- GNEP-- announced by President Bush in February 2006, promises to remove a barrier to the expansion of nuclear power by making a fixed repository capacity (at Yucca Mountain, for instance) serve for disposal of waste from 10 or even 100 times as much nuclear power production as the current legislated limit of 63,000 tons of civilian spent fuel. In this vision, the United States would immediately begin reprocessing all of the spent fuel emerging from the 103 domestic nuclear power reactors that currently produce 20% of U.S. electrical power and each yields about 20 tons of spent fuel per year containing about one ton per reactor-

year of fission products and 250 kg of plutonium and other higher actinides.

The ACS meeting at Chicago is an excellent venue for this discussion, in view of the fact that the fission chain reaction was first achieved December 2, 1942 at the University of Chicago by Enrico Fermi and his team. The graphite reactor in there was limited to a power of about 2 watts, in view of the lack of shielding and the dense population in the neighborhood. The next step in the wartime program for the production of plutonium was the 250 MWt reactor at Hanford, WA, to which Fermi and others in the Metallurgical Laboratory at Chicago contributed mightily. There, too, was worked

out the chemical processes that would take the highly radioactive uranium fuel from the Hanford reactor and would separate exquisitely pure Pu from the witches' brew of radioactivity of the fission products. That PUREX process is used, with refinements, to this day and leaves less than one part in ten million of the fission products with the plutonium. In this way the resulting plutonium oxide, sealed now into stainless steel containers looking like soup cans each containing 2 kg of Pu, can be handled with the bare hands without undue exposure to radiation from any residual gamma-ray emitting fission products.

Shortly after the war, Fermi was my sponsor for the Ph.D. in the University of Chicago Physics Department, and I was fortunate to count among my good friends such superb radiochemists as Anthony Turkevich and Nathan Sugarman.

Argonne National Laboratory is outstanding among the centers of excellence in matters concerning spent fuel and chemical separation, so my remarks, though highly critical of the DOE GNEP program, should not be taken as a lack of esteem for the quality of some of the people who are involved in such activities at present.

GNEP also envisions the U.S. supplying "cartridge reactors", pre-fueled and delivered to produce electrical power at foreign sites for 30 years or more before being returned for de-fueling and disposition or refurbishment. Many foreign operators, though, are expected to take advantage of the GNEP model of the "secure fuel cycle," in which the U.S. and other supplier countries would provide a reliable supply of low-enriched uranium (typically 4-5% U-235 in U-238) and would take back the spent fuel for ultimate disposal after its typical sojourn of four years in the power reactor and another couple of years cooling in a deep pool of pure water. At present, countries are responsible for the disposition within their borders of all of the spent fuel

produced in the nuclear power sector, except for some U.S.-supplied fuel that was delivered with a commitment on the two sides to send it back. Russia has recently begun accepting spent fuel, for a fee, which it intends eventually to reprocess and to feed the plutonium into its power reactor economy.

Still, national and international regulations and customs need to be changed in order to permit spent fuel to be transferred from one country to another for ultimate disposition, either by direct entombment in a mined geologic repository or by reprocessing followed by entombment in a repository. The secure fuel cycle makes good sense economically from the point of view

of the using country, and for the world from the point of view of limiting facilities capable of providing weapon-usable materials: enrichment plants and reprocessing plants that, respectively, produce enriched uranium (and could produce highly enriched uranium), and the reprocessing plant that produces plutonium, even if it is mixed with 50% uranium in some of the recent proposals. The proposal to lease and take back reactor fuel was published long ago by Harold M. Agnew, then Director of the Los Alamos Scientific Laboratory, in the Bulletin of the Atomic Scientists (May 1976, page 23), as "Atoms for lease: An alternative to assured nuclear proliferation."

States that express concern about the reliability of future fuel supply under potentially tense international conditions could well buy a stockpile of LEU fuel for 10 years of operation of their reactors; fortunately, LEU fuel is safe and cheap to store and cheap to buy, in comparison with fossil fuels.

The United States practices the so-called "open fuel cycle" or, "direct disposal" of the spent fuel, without reprocessing. This was set as a policy by President Gerald Ford following India's 1974 nuclear test and continued by President Jimmy Carter. Although the national inhibition on reprocessing was reversed by

President Reagan in 1981, no commercial reprocessing exists because it is clearly more expensive than is the direct disposal into a mined geological repository, although that has had great delays in opening. As this audience well knows, the radioactivity of the products of the fission essential to the production of nuclear heat, and the radioactivity of the higher actinides produced by neutron capture in U-238 and by further capture in the resulting products, requires the isolation of the spent fuel from the biosphere for periods of 100,000 or even millions of years. Technically one works with "dilution factors" but the liberation of the specific chemical moieties from the spent fuel in a rather uncertain geologic environment and the transport of the

radioactive materials through ground water or otherwise is not easy to estimate reliably. Furthermore, over these periods that are relatively short on a geologic scale, climate can change many times, in a few thousand years going from an ice sheet kilometers deep to a temperate or desert environment.

The *spent fuel* elements removed from the reactor in the refueling operation are highly radioactive. Even after 100 years they are regarded as *self protecting* in that a single fuel element would irradiate a person at one meter distance with more than a dose of 1 *sievert* (1 Sv) in 1 hour. Delivered in an instant, a lethal dose of 4Sv would raise the body temperature only about 0.001ºC.

Within the operating reactor, each kg of fuel generates about 30kW of heat. A week after reactor shutdown, fuel elements transferred to the spent-fuel pond still generate about 100W/kg, from the decay of the radioactive fission products. If the water were lost, the spent fuel would heat within hours to the melting temperature of the fuel-rod sheath; the zirconium alloy would burn in air. After 10 years, spent fuel still creates 2W/kg, little enough that the fuel can be stored in massive casks to protect people from the gamma radiation of the fission products; the casks are cooled by natural air convection.

In contrast, for decades France has been *reprocessing* spent fuel from its 58 LWRs, using the PUREX process to separate about 16 tons per year of plutonium from about 1600 tons of spent fuel. Much of the spent fuel was of German or Japanese origin, and the separated Pu and *vitrified* fission products were by law and contract to be returned to the country of origin. France has used its own Pu to fabricate mixed-oxide—*MOX*—ceramic fuel pellets that displace LEU fuel elements—*UOX*—and thus reduce the uranium demand by about 20%.

This saving of uranium comes at a very high price. Assuming a reprocessing cost of $1000/kg of spent fuel, and noting that 5 kg of spent fuel must be reprocessed

for each kg of MOX fuel produced (that is, 5 spent fuel elements for each fresh MOX fuel element), it is a simple matter to calculate the cost per kg of uranium saved. Each kg of fresh fuel element (5% U-235) requires 9 kg of natural of uranium, although less NU would be required if the tails concentration from the enrichment plant were reduced, as would naturally follow from the higher price of uranium. Nevertheless, at 9kg of NU per kg of LEU, the break-even cost of uranium as contrasted with reprocessing would be $5000/9 = $555/kg of NU. In reality, the fabrication of a MOX fuel element, given the MOX material is far more expensive (by about $1000/kg) than is the fabrication of a UOX fuel element. So the break-even

cost of NU that would make reprocessing and recycle in LWRs a wash is thus about $555 + $1000/9 = $666/kg of natural uranium. For comparison, I show the historical cost of uranium.

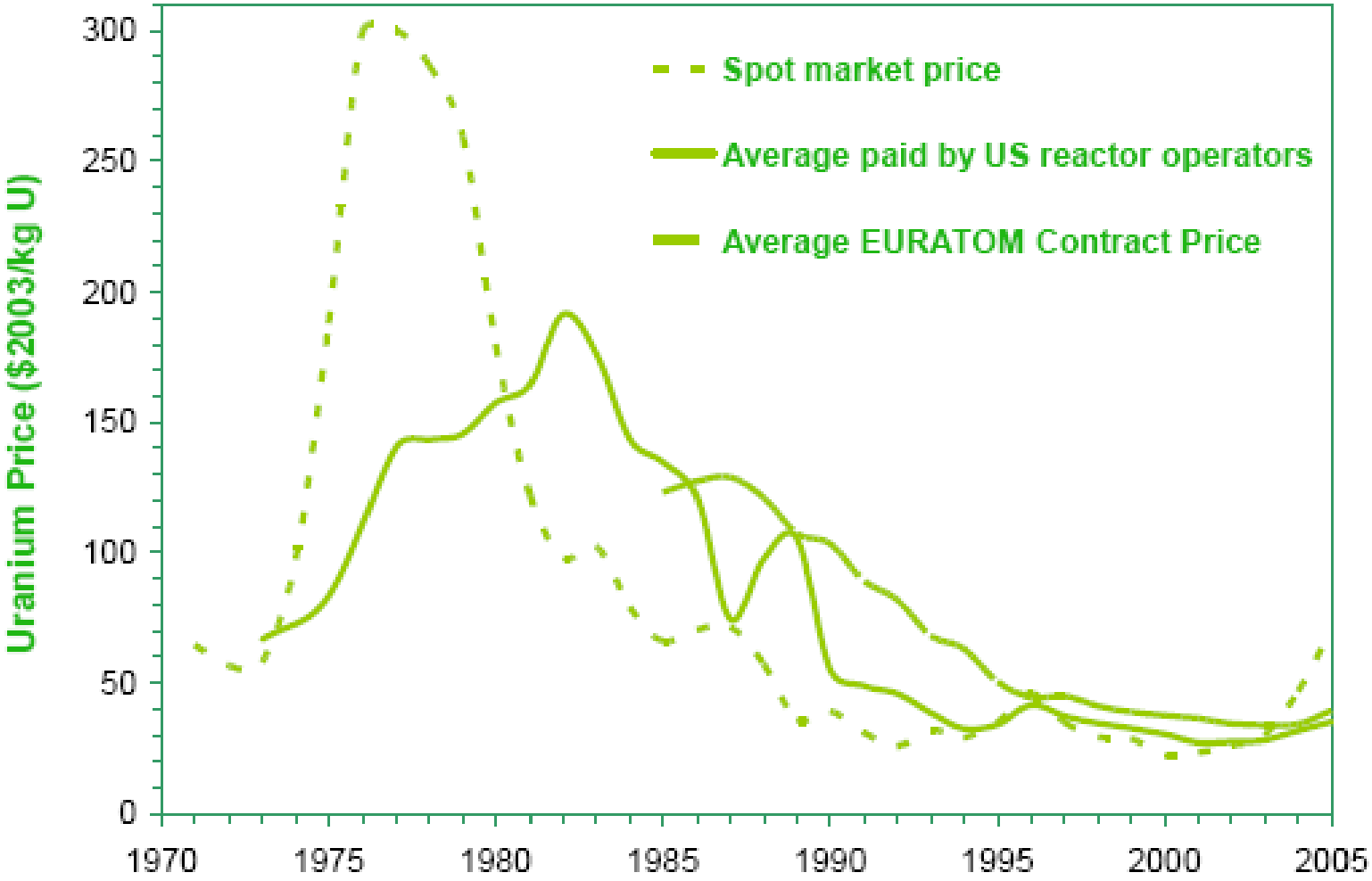

Figure 3. Average and spot uranium prices in constant 2003 dollars, 1971-2005.[18]

Fig. 5. Average and spot uranium prices in 2003 dollars[2]

[2] Frank von Hippel, "Managing Spent Fuel in the United States: The Illogic of Reprocessing" Research Report No. 3, International Panel on Fissile Materials, January 2007 (at www.fissilematerials.org

Now, it may be that 50 years ago with less knowledge about the availability it might have seemed a good bet to reprocess. But that bet has failed, and it has made no sense for Rokkasho to be built and it makes even less sense from the point of view of saving money and uranium for the U.S. to go into reprocessing.

It has always been the dream to dispose of the noxious radioactive materials in a short time by nuclear transmutation, especially by the use of the most effective projectiles for nuclear transmutation-- slow or fast neutrons. Because the innocuous components of spent fuel also have an appetite for neutrons,

technically the approach is known as "separation and transmutation—S&T" with each type of hazardous material being subject to an optimum exposure.

The problem, of course, is the cost and the neutron economy of such an S&T system. If nuclear power is to play a major role in competition with fossil fuels and expendable sources of power, S&T must not add exorbitantly to the cost of power. And if this operation is to be carried out in a nuclear reactor that also produces power, only a modest fraction of the neutrons is available for transmutation, as opposed to causing fission or, in the case of a breeder reactor, to causing

fission and providing another fissionable nucleus to restore the fissile fuel used.

Thus in a thermal reactor using LEU and producing about 2.5 fission-energy neutrons per fission process, the requirement is that one of these 2.5 go on to cause another fission. Since there is also non-fission capture in U-235 and in U-238, and in the structure of the reactor, and there is leakage from the reactor and capture in the coolant or heat-transport material, it is not a trivial matter even to ensure that one neutron of the 2.5 goes on to cause another fission. And this must be true not only with the fresh load of fuel, but after much of the initial fissile material has been exhausted.

In a breeder reactor, to maintain the fission chain reaction one of the approximately 3.5 neutrons per fission of Pu-239 must go on to cause another fission reaction, but another one must be captured in U-238 to form (after two beta decays over a few days) Pu-239. This can happen practically only in a reactor that does not use water as the heat-transport fluid ("coolant")—hence the choice of molten sodium or lead or molten salt or even helium gas for heat transport.

GNEP envisages that each of the million-kWe light-water reactors used for power be associated with a fraction of a million-kWe fast-neutron reactor that has a

low Conversion Ratio—CR—so that for each of the nuclei of Pu or minor actinides fissioned in the reactor, there would be only a small fraction newly created by capture in U-238.

Since for each fission in the LWR there is downloaded about 0.25 transuranics that need ultimately to be fissioned, and since each fission yields approximately the same excess energy, the heat developed in a fast neutron reactor that fissioned each of the TRU atoms fed to it would be 25% that of the LWR it was scavenging. The electrical output would be greater because non-water-coolant reactors can run at a higher temperature and hence better Carnot efficiency.

However, stability of fast reactors arises in good part from the Doppler coefficient provided by the neutron-capture resonances of U-238 that is the usual diluent for normal fast reactor fuel. It is very difficult to transfer the heat from pure TRU in a reactor in which there is a high flux and hence a good destruction rate of TRU. By its very nature, these neutron-capture resonances capture neutrons, thus producing Pu in the fast reactor. In the breeder reactor, CR > 1.0, in which case the fast reactor would do nothing to consume the LWR TRU fed to it. A massive study published in 1996 by the National Academy of Sciences on contract to DOE[3]

[3] "NUCLEAR WASTES, Technologies for Separations and Transmutation, National Academy Press, 1996 (http://books.nap.edu/openbook.php?record_id=4912)

quotes GE to the effect that a fast reactor designs with CR = 0.65 is the minimum practical. At that CR, the average fission in the ABR would destroy only 0.35 of a TRU atom fed to the Advanced Burner Reactor—ABR; on balance, 0.65 of the fissioned nuclei being replaced by the Pu-product of the ABR. To fission the 250kg of actinides downloaded each year from a reactor powered by 1000kg of fission, the fast reactor population would need to be have a thermal output of 0.25 multiplied by 1/(1-CR). For CR = 0.65, this is 0.25/0.35 = 71% that of the thermal reactor, and an electrical output about 80% as large.

Taking seriously the GNEP proposal for burning TRU so as to increase repository capacity by a large factor, the capital cost of the ABR would be extremely important to the economy of such a fuel system. In addition, of course, there are costs associated with the reprocessing of the ABR fuel, which must be done more often than the LWR fuel. In particular, LWR fuel needs to be reprocessed once, and the TRU prepared for feeding to the ABRs, presumably as MOX fuel.

The fission products are to be removed and put within a short time into the repository, except for the 30-yr half-life Cs-137 and Sr-90, which are intended to be maintained in above-ground storage for 200-300 years,

according to the scant GNEP literature. Of course, long-lived Cs-135 (2.5 million year half life, and 45% as abundant as Cs-137 in spent fuel) would also be chemically extracted into this component.

In contrast, the ABR fuel burned to perhaps twice the heat output per kg of heavy metal—100GWd/tHM in contrast with 50GWd/tHM for LWR fuel—corresponds to a destruction of only about 25% of the fuel load. For CR = 0, this would mean that four reprocessings would be required of the ABR fuel to get the initial TRU atoms down by a factor *e*, or nine reprocessings to reduce it by a factor ten. But many of the fissions in the ABR must be devoted to burning the Pu made by the

ABR itself. In any case, even with an ABR fed only with TRU from the LWR reprocessing, 25% of the fuel fed each year is fissioned over the course of a typical 7-yr ABR cycle, but an ABR with a CR = 0.65 would mean that there was only a (1-CR)*25% = 8.8% reduction in TRU in 7 years, or about 1.3% per year. With a CR = 0.50, the destruction rate under these assumptions would be 12.5% in 7 years or about 1.7% per year.

The point is that much more TRU passes through the reprocessing plant for the ABR than for the LWR, which is the initial purpose of the GNEP program. Thus a proper GNEP program must be focused on

lowering the cost and reducing the leakage to waste of the ABR reprocessing—a point emphasized in the 1996 STAP report never mentioned by DOE in the context of GNEP.

The idea of keeping the most radioactive and toxic fission products in above-ground storage for 300 years raises serious concerns. In my visit to the reprocessing plant at Sellafield, I saw many heavily shielded large tanks full of cesium, each with a triply redundant cooling system. Were the cooling system to fail, the contents of the tank would superheat, evaporate the water, and eventually spew the sublimed dry contents of the tank into the atmosphere. This would be

analogous to the "Kyshtym Disaster" of 1959 in the Urals. So passive storage will be considered, with the problem that the Cs-Sr component has most of the decay heat of the spent fuel, so it presumably would be cooled in a similar fashion to spent fuel, in dry-cask storage.

Many suggest that a start can be made on GNEP-like goals by the use of limited recycle as practiced in France. Such a proposal was presented by Dr. Alan Hanson on behalf of AREVA NC Inc. on March 19, 2007 at a public meeting in Washington. This proposal includes reprocessing such as is practiced at La Hague and recycle into light-water reactors with the storage

and ultimate disposal of used MOX fuel. According to AREVA, "about 30% of the initial fissile Pu atoms have been destroyed" and "used MOX fuel is more self-protecting than used UOX fuel." Fact. But the disposal of MOX fuel provides a very serious problem for the repository because it produces far more heat than spent UOX fuel. According to highly authoritative publications (and public presentation by Phillip J. Finck),[4] this limited recycle might save about 10% of the repository capacity at Yucca Mountain.

[4] Philip J. Finck, February 17, 2007 presentation at AAAS symposium, San Francisco, CA

The French approach to the *closed fuel cycle* has been demonstrated by French government analyses to be more costly than the open fuel cycle.

Table 2. Spent-fuel disposal costs in four scenarios for the French Fuel Cycle[61]
(Billions of 2006 $, 58,000 tons of spent fuel)

	Percentage of Spent LEU Fuel Reprocessed			
	100% (Derived scenario)	**67%**	**27%** (Reprocessing ends in 2010)	**No Reprocessing**
Back end costs	84	74	61	41
Front end cost savings from plutonium recycle	-10	-8	-2	0
Net costs	74	66	59	41

Fig. 2. Spent-fuel disposal costs in $billion per 58,000 tons of spent fuel[5]

[5] Frank von Hippel, *op cit.*

Despite persistent claims that this approach to plutonium recycle has substantial benefits in reducing the burden on the repository, there has been recent awareness that the capacity of the repository is not limited by the bulk of the spent fuel but by the continuing heat evolution from the fission products and the *transuranics*—that is, plutonium, americium, neptunium, and curium. This is clear from two highly authoritative books by Robert Dautray, former high commissioner of the French Commisariat à l'Energie Atomique—CEA.

Finck introduces a clear conclusion that limited recycle constitutes a "delay line" that eliminates the need to think about a repository for 15-20 years, while the reprocessing is taking place. In fact, the radioactivity residing in the spent fuel and which in the once-through process would be transferred after a few years in the pool storage to dry-cask storage and then to the repository, instead is mobilized in the processing to be far more available, before it is separated (fission products and minor actinides) into vitrified waste and the plutonium recycled into the reactor to become spent MOX fuel. As indicated, the single spent MOX fuel element has about as much spent heat in the long run (and radioactivity) as the five spent UOX fuel elements

from which it was made, and puts the same burden on the repository. All that has been accomplished by limited recycle is to move all the radioactivity from the reactor sites to the reprocessing site, at great cost for reprocessing.

A less costly and better "delay line" with far more potential is to store the spent fuel itself in dry casks, either at the reactor, as shown in the illustration of Yankee, or, if more convenient, to a centralized dry-cask storage site. There is general agreement, even among those most critical of nuclear power, that dry-cask storage is safe and economical for 50-100 years.

Even if I were going to reprocess, I would thus delay the expenditure for 100 years in order to reduce the discounted present value of the cost stream.

The rather complicated considerations of benefit of minor-actinide removal and Cs-Sr removal on repository capacity, to remain below the boiling point of water in the “dry environment” of Yucca Mountain, are shown in the figure.

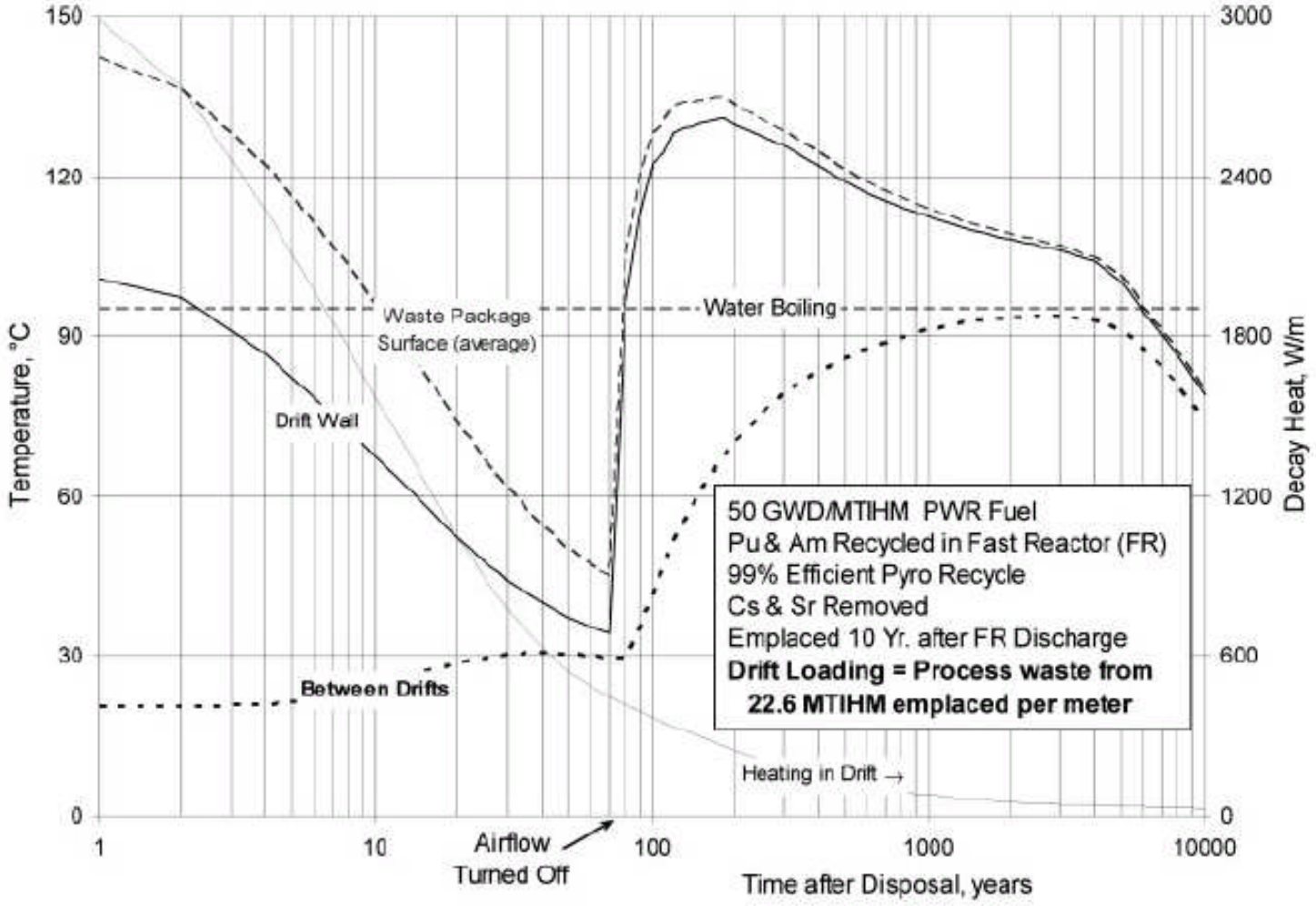

Fig. 6. Transient thermal response of a repository at Yucca Mountain with removal of plutonium, americium, cesium, and strontium from spent PWR fuel, recycling plutonium and americium in a fast reactor, with increased drift loading.

Fig. 6. Transient thermal response of YM repository[6]

[6] "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).

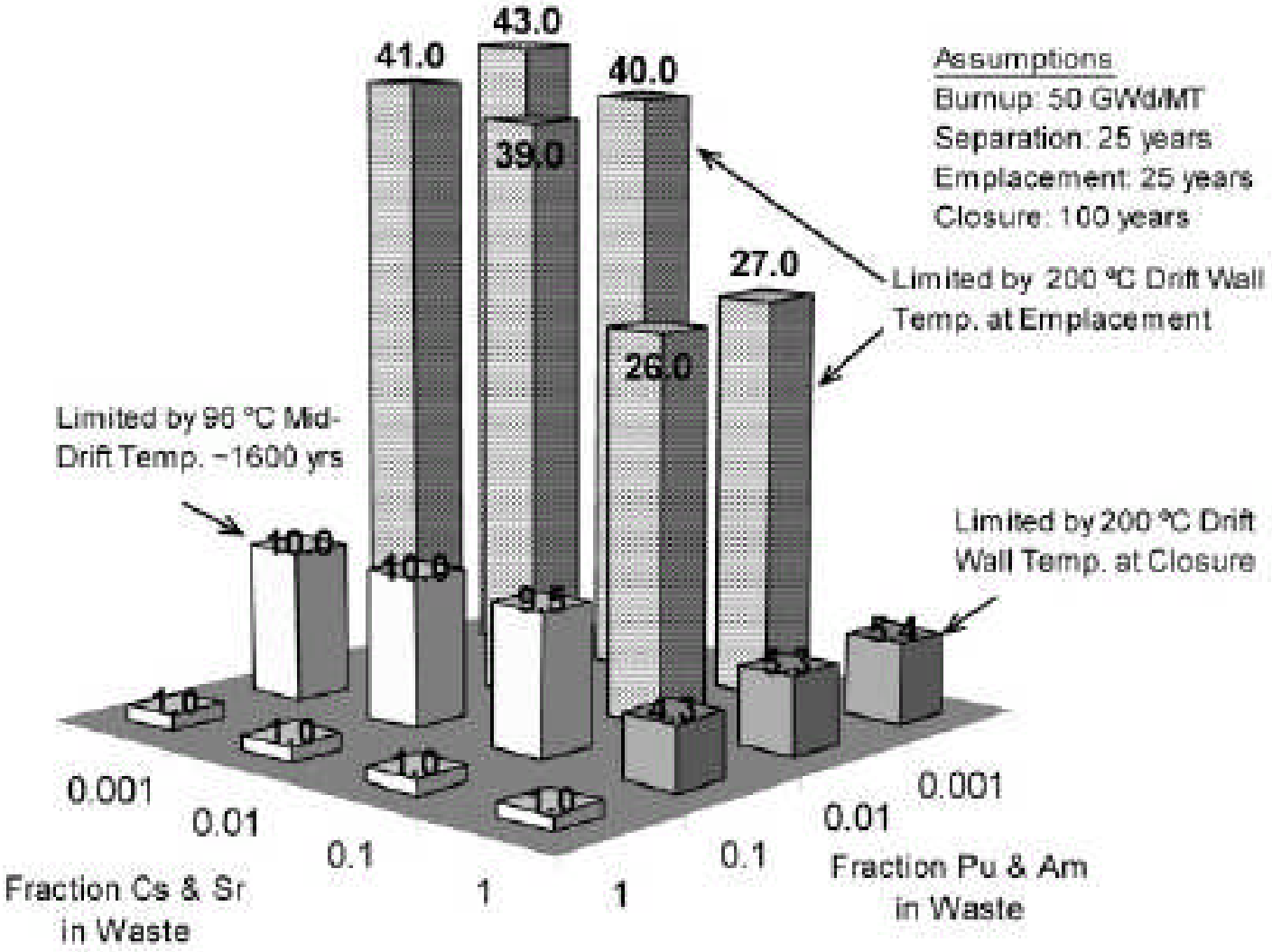

Fig. 7. Potential repository drift loading increase as a function of separation efficiency for plutonium, americium, cesium, and strontium.

Fig. 7. Potential repository drift loading increase.[7]

[7] R.A. Wigeland *et al*, *op cit.*

The reprocessing world adds additional potential hazards. The THORP plant at Sellafield was shut down in April 2005 with the discovery that 25 tons of spent fuel (a full reactor-year's worth) dissolved in 83 cubic meters of acid had leaked over a period of months into a stainless-steel-lined concrete enclosure. THORP will have been closed for at least two years, sacrificing an income stream that at 750 tons per year of spent fuel and an estimated $1000/kg reprocessing fee would amount to some $1.5 billion.

A current EPRI-INL paper provides a sobering assessment both of the prospects for the reprocessing approach and of its necessity:[8]

> "In addition, reprocessing plants are expensive and not attractive to commercial financing in the context of the U.S. economy. Thus, the cost increment for reprocessing (i.e., the incremental cost above the cost of repository disposal) will be subsidized initially by the federal government. Although the estimate above does not include repository costs, it is expected that reprocessing will remain more

[8] "The Nuclear Energy Development Agenda: A Consensus Strategy for U.S. Government and Industry."

expensive than storage (centralized above-ground plus geologic repository) for the foreseeable future. Projections of major savings in Yucca Mountain repository costs as a result of reprocessing are highly speculative at best. On the other hand, the increased revenues to the Nuclear Waste Fund from an expanding fleet of new reactors will eventually help defray the costs of operating closed fuel cycle facilities.

I add here also material from the EPRI report: of May 2006, "Program on Technology Innovation: Room at the Mountain – Analysis of the Maximum Disposal Capacity for Commercial Spent Nuclear

Fuel in a Yucca Mountain Repository. EPRI, Palo Alto, CA: 2006. 1013523." There we read, "EPRI is confident that at least four times this legislative limit (~260,000 MTU) can be emplaced in the Yucca Mountain system..." And EPRI believes that with additional site characterization this minimum factor of 4 could well be a factor 9.

"It is important to note that despite the extended timetable for introducing reprocessing in the U.S. (due to R&D prerequisites to satisfy cost and nonproliferation objectives, policy considerations, etc.), that a single expanded-capacity spent fuel repository at Yucca Mountain is adequate to meet

U.S. needs, and that construction of a second repository is not required under this timetable.

"If, however, reprocessing is implemented on an accelerated schedule before it is economic to do so based on fuel costs, then the federal government will need to bear a much larger cost. As discussed in Appendices B and D, the optimum scenarios for transitioning nuclear energy to a closed fuel cycle in the U.S. context requires us to focus the R&D on those technologies that would enable a transition to cost-effective and proliferation resistant "full actinide recycle" mode with fast reactors that would eventually replace light water reactors. This path is

preferred over one that maintains for decades a "thermal recycle" mode using MOX fuel in light water reactors, because the high costs and extra waste streams associated with this latter path do not provide commensurate benefits in terms of either non-proliferation or spent fuel management costs."

In what world does the drive for reprocessing make sense? In the long-sought world of fast-neutron breeder reactors which differ from the fast-neutron ABRs in that the breeders produce at least one plutonium atom for each transuranic atom destroyed—a conversion ratio—*CR*—of 1.0 or more; in contrast, that ABR is desired that has a CR of 0.0, which could only be

achieved with fuel containing no uranium. The CR goal for ABR is 0.25, although previous analyses for a very comprehensive 1996 National Academy study[9] quotes a General Electric judgment that a CR of 0.65 is the minimum practical. The difference is that the number of million-kWe ABRs to burn up the plutonium from 100 LWRs is proportional to (1/(1-CR)), which is more than doubled with the reactor of CR=0.65. Since the fast-neutron reactor is expected to be more costly than the LWR, this has serious cost implications for the GNEP approach.

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[9] Nuclear Wastes: Technologies for Separations and Transmutation," by the Committee on Separations Technology and Transmutation Systems, ("STAP" for short), National Research Council, National Academy Press, Washington, DC (1996). (http://books.nap.edu//books/0309052262/html)

It is clear that some GNEP supporters have mixed feelings about the central pillar of GNEP—the ABR fleet. For instance, at an October 17, 2006 meeting, in presenting his very detailed technical paper, "Technologies for Advanced Fuel Cycles," Finck commented that he did not favor the Compact Core sodium-cooled fast reactor (pp.17-18)

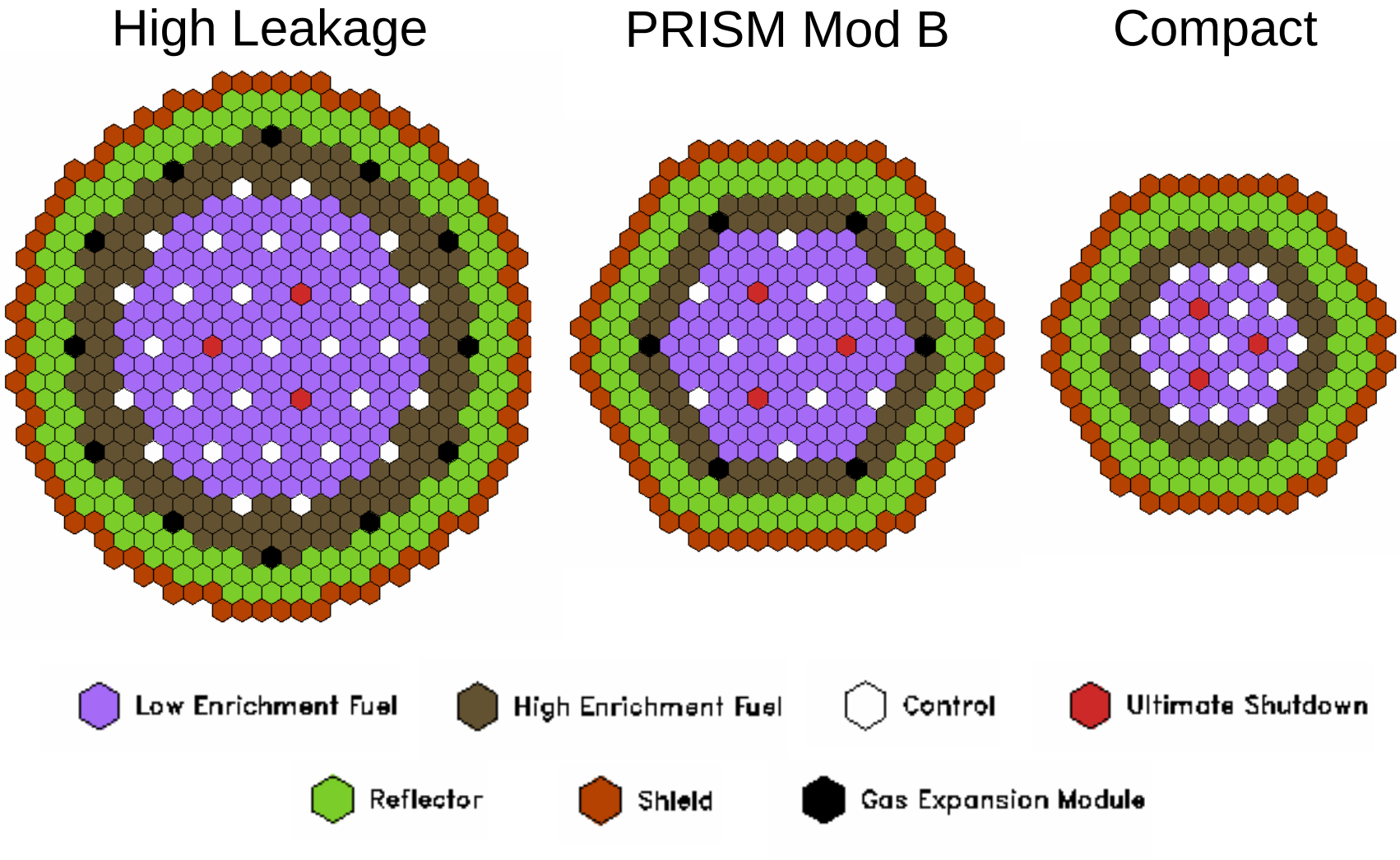

Fig. 8. Core configurations for several ABR candidates[10]

[10] Phillip J. Finck, *op cit.*.

	PRISM Mod B	High Leakage		Compact Core	
Conversion Ratio	**0.8**	**0.5**	**0.0**	**0.5**	**0.0**
Capacity Factor	**0.86**	**0.83**	**0.83**	**0.82**	**0.82**
Annual Generation (TWh/yr)	**14.07**	**13.60**	**13.60**	**13.47**	**13.47**
Total Capital Cost ($/kWe)	**1,554**	**1,626**	**1,626**	**1,536**	**1,541**
Total Levelized Cost (mills/kWhr)	**40.4**	**47.7**	**47.7**	**39.6**	**39.7**
Capital	20.0	21.7	21.7	20.7	20.7
O&M	7.0	7.3	7.3	7.5	7.5
Fuel	12.4	17.7	17.7	10.4	10.4
Decommission	1.0	1.1	1.1	1.0	1.0

- Compact low conversion design COE is similar to reference system
  - High leakage configuration increases cost by 20%
- Fuel cost differences are the most significant discriminator
- Capacity factor penalizes Capital and O&M components for burners
- Details are given in the AFCI report ANL-AFCI-118

with a CR=0.5 and an electricity production cost of 39.7 mills/kWh (a mill is 0.1 cent) over a “high-leakage” reactor with the same CR and a Total Levelized Cost of 47.7 mills/kWh. Finck’s reason is that the compact-core fast reactor could not be readily converted to a breeder reactor by replacing the inert (steel) “blanket” by depleted-uranium fuel elements. Given that the cost paid by US reactor operators for waste disposal is 1mill/kwh, to accept one fast reactor design over another at 10 times the non-reprocessing waste disposal cost is a phenomenal penalty to be paid for a contingency never discussed in the GNEP

literature—that we should deploy sodium-cooled fast reactors that can readily be converted into breeder reactors under the guise of reactors that burn up as much plutonium as possible rather then regenerating it.

What should be done with GNEP? It is profoundly misguided in wanting to reprocess LWR fuel early, for later feeding to the ABR. All believe that ABRs will be more expensive than LWRs, some hope that eventually some design or production economy may reduce the cost to be comparable with that of an LWR. There is no reason that I can see to preclude this happening, since liquid-metal cooled reactors don't operate at high pressure like that in an LWR. We have already noted

that the spent fuel from an LWR needs to be reprocessed multiple times, and so the leakage of fission product to the waste streams (or of transuranics to the waste stream) is a much more critical question than for the single reprocessing of LWR fuel. In addition, just because of this multiple reprocessing, the form of ABR fuel, the ABR, and the reprocessing itself must be developed together.

Among the ABR fuel choices are MOX (oxide), mixed carbide, or metal fuel. And if one is seeking low conversion ratio, there is the possibility of precluding U-238 and using a material such as Zr or its compounds to dilute the TRU that is the fuel for the ABR. In

excluding U-238 from the reactor, one would sacrifice the stabilizing Doppler effect of the capture resonances.

If one were serious about the GNEP goal of expanding repository capacity by the use of an ABR, it would be useful to begin a competitive design of, say, three ABRs, together with their individual fuel form and reprocessing cycles, to the point at which there could be an analysis of their cost. It makes no sense to build a test ABR at present, because it will be just another sodium-cooled fast-neutron reactor. Calls for an early fast reactor in the United States to test ABR fuel ignore the fact that the Russian BN-600 can fill this function very well, as can the Japanese reactors, Joya and Monju.

Only when the design shows economics and safety as good as that for an LWR should a demonstration ABR or breeder reactor go forward.

Note that the great enhancement of repository capacity claimed for the GNEP ABR approach is based on never putting any TRU into the repository, except for the assumed 0.1% that leaks from the separations process into the long-lived fission product stream and is to be vitrified and entombed. If solar energy, nuclear fusion, or some other source were developed to become more economical and satisfactory than fission energy for electrical power, all the TRU in the cycle, including

that in the ABRs and LWRs would need to be entombed in the repository, and it would be irresponsible not to have a repository large enough to handle either success or failure—either of which would require space in the repository for the entombment of all of the fuel, reprocessed or not. With the illustration of this paper, that would mean space for 60-80 years or more of LWR fuel output that had been fed to the ABRs.

In a journal article of January 200711 Robert Dautray, who built the first French fast reactor and was head of the CEA[12], writes,

Together with the important launching of EPR[13] reactors (and of considerable importance for safety and radioprotection), the next two decades should in priority finalize the back end of the fuel cycle of the thermal neutron power reactors, …, with a final disposal into a underground geological repository (for the radioactive products generated in the past and future nuclear activity of this country). It is an ***illusion*** *to count on a notable reduction of the fission products by using* ***fast neutron reactors****: to face the long term world requirements,* ***their essential task****, necessary before the end of the century,* ***will be to***

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[11] R. Dautray and J. Friedel, "Energy: towards nuclear breeder installations before the end of this century?" C. R. Mecanique 335 (2007) 61–74.

[12] Commissariat à l'énergie atomique

[13] Evolutionary Power Reactor (formerly the European Pressurized Reactor).

make energy from fission competitive with that of coal *or eventually with other types of energy from fusion.[emphasis added]*

Dautray specifically rejects the concept of the Advanced Burner Reactor, but urges the disposal of fission products and spent fuel into the mined geologic repository and the development of fast-neutron breeders that (if they) can be cheaper than coal.

As for myself, I favor the deployment of breeder reactors and their mandatory reprocessing and recycle of plutonium, but only when the cost and safety of the fast reactor system is demonstrably better than that of reactors with the once-through cycle. In the future, once-through is not limited to LWRs but could include the micro-encapsulated fuel pioneered by General Atomics and now under development in a joint program with Russia as a modular high-temperature gas turbine reactor, and in South Africa as a *pebble-bed* reactor. In 1982 I testified against the Clinch-River breeder reactor program because it had no chance of demonstrating

anything other than that the concept was a high-cost approach.

Similarly I testified in 1970 against the US Government-funded commercial supersonic transport program—*SST*—and was vilified by program supporters, including the US airlines which had had their arms twisted to provide moral support for the SST program. The USG had testified that if the US did not develop the Mach-3 SST to compete with the British-French Concorde Mach-2 SST, US airlines would end up buying 500 Concorde aircraft. In fact, only 16 Concorde aircraft were built and transferred to the national airlines, of which only 9 ever flew in

commercial service. Ten years later, the SST contractors, Boeing and General Electric, thanked me for helping to terminate the program in its early stages.

The DOE *process* for obtaining approval for GNEP is defective; DOE does not have the systems analysis tools to design and judge such a program, despite its commitment to the Congress to develop them. Nor does it freely provide information for independent analysis. I have long urged my DOE colleagues, including Vic Reis, a moving spirit of the program, to create a DOE website where government-financed papers would be posted, as I and Frank von Hippel post our own analyses. The response has been that the

existing technical website operated by Sandia National Laboratories and available only to government and selected contractors cannot be influenced by DOE headquarters.

Einstein’s words, "The right to search for truth implies also a duty; one must not conceal any part of what one has recognized to be true" are engraved in stone on the Keck Center of The National Academies in Washington, DC. It would be helpful if the DOE took them to heart. Failing to do so is likely to inflict serious damage on the US nuclear industry.

CONCLUSIONS RE GNEP

- "Proliferation resistant" reprocessing seems to be anything that the US decides to do, and thus will increase rather than reduce proliferation hazards worldwide.
- A US sodium-cooled fast reactor is another me-too; we should use foreign fast reactors—especially the BN-600—for testing of fuels.
- GNEP is unresponsive and secretive. They ignore technical facts and provide none of their own.
- Cartridge reactors and secure fuel cycle will be a competition unless the US strongly subsidizes the

world's nuclear power program, which is undesirable and unacceptable under the WTO.

- Missing from the DOE program is an urgent effort to determine the "uranium supply curve"—cost per kg of uranium (both from terrestrial resources and from ocean uranium) vs. millions of tons of uranium extracted.
- Missing also is leadership in an initiative to permit competitive, commercial, mined geologic repositories to accept spent fuel from any source, or packaged nuclear waste, with repositories and waste forms alike, in the US and abroad, regulated by IAEA.

- With its focus on reprocessing of US reactor fuel GNEP is so flawed that it should be terminated
  - The international *policy* aspects of the secure fuel cycle (without committing to reprocessing) should be handled by State and DOE.
  - Other aspects should be handled by AFCI—the Advanced Fuel Cycle Initiative.
  - I personally favor a major exploration of a fast breeder reactor and accompanying fuel form and reprocessing of the breeder fuel, deployed *when and only when* it can be responsibly shown to be safer, cheaper, and as proliferation resistant as current US power reactors.