

## R&D Priorities for GNEP

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(Testimony of April 6, 2006 for the House Science Committee)

I provide here a narrative form of discussion of elements of the proposed GNEP, in order that the Committee should understand better my recommendations.

Most important is to understand that 103 reactors in the United States provide some 17% of U.S. electricity needs now with high reliability and that dry cask storage of spent nuclear fuel from these reactors is a safe, low-cost approach to covering any further delays in the availability of the mined geologic repository at Yucca Mountain.

I begin by answering the four questions in the invitation from the Chairman.

1. How realistic are the goals, timelines and budgets being proposed under the Global Nuclear Energy Partnership (GNEP)?

Garwin Reply: The goals and timelines advanced under the major portion of GNEP are unrealistic. Such a long-term program should not be considered without consideration of the long-term budgets rather than the near-year expenditures.

2. What does the Department of Energy (DOE) need to do to develop a robust program to meet its goal of an advanced nuclear fuel cycle-- one that includes both recycling and transmutation - while sufficiently addressing non-proliferation and waste management needs?

Garwin reply: DOE needs to step back from its dirigiste/gigantesque (in English, government-directed) approach in GNEP to one that more modestly and realistically addresses the primary goal-- a reduction in repository requirement, while highlighting the cost of alternative approaches that include expanding Yucca Mountain, taking the initiative toward international commercial competitive mined geologic repositories, and greatly expanding the spectrum of reactors to be considered for burning the TRU waste.

3. What significant research and development (R&D) questions, both science and engineering, exist for UREX+? Sodium-cooled fast reactors? Mixed-actinide fuels? In your view, how well do the GNEP R&D priorities coincide with these research needs?

Garwin reply: GNEP R&D priorities hardly match the needs for decision-- whether the burner reactors will be sodium or lead cooled, or whether they will indeed be thermal high-temperature encapsulated fuel reactors. Whether the fuel for the fast-neutron reactor will be metallic, carbide, nitride, or based on an inert matrix for one of these forms. GNEP assumes the answer and would launch us into a costly

program that would surely cost more to do the job less well than would a program at a more measured pace guided by a more open process.

4. DOE is in the process of developing the tools to carry out a cradle-to-grave systems analysis of the advanced fuel cycle. What questions should that systems analysis be able to answer?

Garwin reply: The GNEP program must await either good human leadership or the promised cradle-to-grave systems analysis of the advanced fuel cycle. In particular, the questions should include:

- a. Cost and availability of competitive commercial mined geologic repositories for the direct disposal option.
- b. Costs and performance (including safety and nonproliferation measures) for reactors suitable for burning TRUs separated from LWR fuel.
- c. The spectrum of fuels for such burner reactors, understanding that reactor type, fuel choice, and reprocessing approach are coupled, and that not only fast-neutron reactors but some thermal reactors can achieve reductions in transuranics that would expand capacity of a given repository at least several fold.
- d. The benefit associated with government-funded resource estimation for amount of uranium available as a function of price. This needs to include research and demonstration on obtaining uranium from seawater, where there is at least 2000 million tons readily available, but at a price that is very uncertain. Yet the exploration of seawater uranium at costs up to \$1000/kg is vital for decision-making in this field and is long overdue.

There are important points to be made beyond the answers to these specific questions.

There is wide agreement that the ABRs cannot operate economically as power producers in competition with LWRs. Yet there is no estimate of the government subsidy that would be required for private operation or the cost of government operation of these plants. All the more reason for a combined technical and economic effort to provide the least-cost solution for this vision, in competition with evaluating the straightforward approach of commissioning more mined geologic repositories.

As emphasized in my book with Georges Charpak<sup>1</sup> and in the September 2005 book with Charpak and Venance Journé<sup>2</sup> we believe that the expansion of nuclear power can best be helped now by the United States and other nuclear states taking the lead in changing the rules to permit and encourage competitive, commercial, mined geologic repositories. These would be approved by the IAEA, and would accept only spent fuel forms and packages (and vitrified fission-product forms and packages) approved by IAEA.

Commercial firms operating the repositories would provide employment and benefits to the local communities, and rather than seeing a repository as a burden, it would be seen by many as a commercial opportunity. Russia, China, the United States, Australia, and even Sweden might be locations for such repositories.

The other urgent matter for the U.S. and other governments is to determine the cost to obtain vastly more uranium. It is essential to know whether half of the 4000 million tons of uranium in seawater can be extracted at a cost of \$300/kg, as is tentatively suggested by the Redbook. Or whether the GEN-IV

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<sup>1</sup> Book by R.L. Garwin and G. Charpak, "Megawatts and Megatons: The Future of Nuclear Power and Nuclear Weapons," The University of Chicago Press, January 2003.

<sup>2</sup> French publication of book by G. Charpak, R.L. Garwin, and V. Journé, "De Tchernobyl en tchernobyls," Odile Jacob, September 2005.

working group approach that leads to an estimate of 170 million tons of uranium from terrestrial deposits at an extraction price less than \$260/kg is valid.

So in general I admire the goal of GNEP, but visions that ignore technical reality have often led to disasters, since they preclude more conventional and incremental approaches.

Aside from important elements such as the assured fuel supply-- provision of enriched fuel and take back of spent fuel-- and the supply of cartridge reactors (in competition with other nuclear supplier countries, no doubt) GNEP embodies a major vision for the United States and for the world.

#### THE GNEP VISION.

This is to handle in the intermediate term (on the order of 100 years) the spent fuel from existing nuclear reactors by separating the plutonium and other actinides so that they can be burned in fast-neutron reactors. This is quite different from the reprocessing and recycle that has been practiced in France and that is going to take place in Japan as well, where the plutonium is fabricated into MOX fuel and burned in LWRs. This recycle in LWRs does not in any way solve the actinide problem, nor does it help with repository space, because the spent MOX fuel element has at least four times the long-term heat output of a spent UOX fuel element, and so does not diminish the repository space required. Reprocessing as practiced in France, Britain, and about to begin in Japan has been a costly way to delay putting spent fuel into the repository that all agree is necessary; far cheaper would have been the straightforward approach of dry cask storage for whatever delay was desired.

The GNEP vision, however, would have most of the fission products extracted from the spent LWR fuel, together with most of the uranium, so that a fuel form that might be 15-20% actinides mixed with some of the initial uranium would provide fuel for a generation of fast-neutron Advanced Burner Reactors-- ABRs, which are essentially breeder reactors without the uranium "blanket." All of the actinides can be fissioned with fast neutrons, so they do not accumulate to the extent that curium does, for instance, in multiple recycle into LWRs. However, since one obtains only about 25% burnup of fuel in a fast reactor, that fuel needs to be reprocessed and recycled many times before the LWR actinides are substantially destroyed. In addition, if the actinides are mixed with uranium, the ABR is likely to have a "conversion ratio" on the order of at least 0.50, so that half of the actinides destroyed are replaced by Pu-239 that will need to be burned in the ABR and thus reduce the rate at which LWR actinides are destroyed, for a given thermal output power of the ABR. The question for the GNEP vision is how big a repository is needed for U.S. commercial fuel (and for possible U.S. reprocessing of foreign fuel) and at what cost for the repository and for the measures to reduce the necessary size. All indications are that the cost of direct disposal of spent LWR fuel is much less than the cost of the reprocessing and ABRs that are intended to reduce repository size.

There are major questions as to the fuel form for the generation of ABRs. Will it be metallic fuel, carbide fuel, nitride fuel, or oxide fuel? Will it be normal "mixed fuel" with uranium, that gives rise to more Pu-239, or will it be a "sterile fuel"-- so-called inert matrix fuel (IMF)-- rather than uranium-based. What will be the delayed neutron fraction in that reactor, and how will a safe operating margin be achieved?

Will the ABRs be cooled with liquid sodium or with molten lead? There are good arguments on both sides, but GNEP and its supporters appear to assume that the cooling will be liquid sodium, in order to be able to build the first "demonstration" ABR rapidly. This haste and ill-defined purpose recall the Clinch River sodium-cooled reactor project, terminated in 1977 and against which I testified, which would simply have demonstrated the high cost of fast-reactor power in comparison with LWRs. If the

purpose is to have a "demonstration/test reactor which would be used to effect qualification of advanced burner reactor fuel to consume transuranic elements (TRU) from spent light water reactor fuel and spent fast reactor fuel", why not use existing fast reactors in Russia and France for this purpose, thus saving years of delay? Simply building another sodium-cooled fast reactor to show that it can be done in the U.S. is not likely to advance the acquisition of knowledge necessary to the coupled choice of reactor type, fuel, and approach for the really difficult job of reprocessing ABR fuel with process losses of 0.1% or less.

The reprocessing for the ABR is a more important choice than the reprocessing for the LWR, since it needs to be done multiple times, and will also set the basis for a later breeder economy. So why is \$155 M of the \$250 M first-year budget sought for GNEP to go to the demonstration of UREX+ reprocessing for LWR fuel? Contrary to the 99.9% efficiency (0.1% loss) sought for each of the many reprocessing cycles for ABR fuel, 90% efficiency for the one-time reprocessing of PWR fuel would obtain most of the benefit. The proposed UREX+ ESD plant for PWR fuel is excessively large and has technical goals totally unnecessary for this task.

That fuel for the ABR will need to be available only when we have the first-generation ABR coming on-line, and it is an economic waste to reprocess the LWR fuel prematurely. The discounted present value (cost) of reprocessing is much less if reprocessing is delayed by a further 20 years, for instance.

It seems that one ought to have multiple design competitions for fast-neutron ABRs, and when the best two ABR designs have been chosen after the detailed technical evaluation that such a momentous step warrants, two separate engineering designs should be commissioned for each, in order to have some confidence of being able to choose the better.

One of the chief concerns with the ABR, as indicated, is its fuel composition, and the ABR reprocessing choice needs to be made in conjunction with the choice of fuel composition.

My major concern with the GNEP program as it has been presented is that it has the priorities all wrong-- with premature initiation of an engineering scale demonstration-- ESD-- of UREX+ for LWR fuel, when what we need is to move rapidly to see whether it is technically and economically feasible at all to deploy the vast numbers of ABRs that are required. This is an old dream, and if it is not feasible, the reprocessed LWR fuel will be a security and economic nightmare and an impediment to the expansion of nuclear energy supply. Furthermore, the technical goals of the program are set far higher than is needed to obtain the benefits of reprocessing of PWR fuel.

The goal of "proliferation resistance" is not met in any case, because the UREX process itself separates essentially all of the uranium. To obtain 10 kg of plutonium from ordinary PWR spent fuel containing 1% Pu, a terrorist would need to acquire and reprocess 1000 kg of highly radioactive material. Once the uranium and the fission products have been removed in any of the UREX processes, the plutonium will be contaminated only with a modest amount of transuranics (TRU) so that the terrorist would need to reprocess a mere 11 kg of material, and according to recent DOE studies, this would have only about 1/2000 of the penetrating radiation that would count as "self protecting." In fact, Pu metal contaminated with minor actinides could perfectly well be used in an implosion bomb. So UREX really offers no significant benefit over PUREX so far as resistance to proliferation or terrorist acquisition of weapon-usable materials. Of course, radioactivity could be left with or the Pu (actinide) fraction and removed after shipment from the PWR reprocessing plant to the ABR complex, but the likely contaminant, lanthanides, offer relatively little protection and, in any case, does not change the fact that only 1% as much material needs to be diverted and processed as in the case of spent LWR fuel itself.

The relatively minor goal of reducing uranium requirement comes at an extremely high price. Recycle of all of the TRU can reduce uranium requirements by about 20% (unless one has a breeder reactor that then does not eliminate the plutonium but preserves or expands its supply). Sound, recent studies show that this uranium saved comes at an equivalent cost of \$130-1000/kg of natural uranium that would otherwise need to be bought. At a time when 2 million tons of uranium can be mined at costs below \$40/kg, this is far from a good investment!

The main benefit claimed for the UREX+ teamed with the deployment of large numbers of ABRs is the reduced requirement for space in a mined geologic repository. Here we are greatly aided by an April 2006 paper from the Argonne National Laboratory<sup>3</sup>. The authors refer, and appropriately so, to a "recent review by the National Academy of Sciences, where the potential benefits regarding dose rate, decay heat load, and nonproliferation were discussed and estimated, at least qualitatively."<sup>4</sup> Strangely, the 1996 report is hardly referenced in the DOE literature on GNEP, but it is a monumental study that should be understood by all involved. It concluded:

"The excess cost for an S&T disposal system over once-through disposal for the 62,000 tons of LWR spent fuel is uncertain but is likely to be no less than \$50 billion and easily could be over \$100 billion if adopted by the United States."

This is equivalent to \$800-1600/kg of fuel (undiscounted), or roughly 2-4 mill/kWh.

A current EPRI-INL paper provides a sobering assessment both of the prospects for the reprocessing approach and of its necessity:<sup>5</sup>

"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 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.

"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

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<sup>3</sup> "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).

<sup>4</sup> "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).

<sup>5</sup> "The Nuclear Energy Development Agenda: A Consensus Strategy for U.S. Government and Industry."

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.”

The Wigeland, et al, paper arrives at conclusions that are summarized, for instance, in its Fig. 7, which I reproduce here.

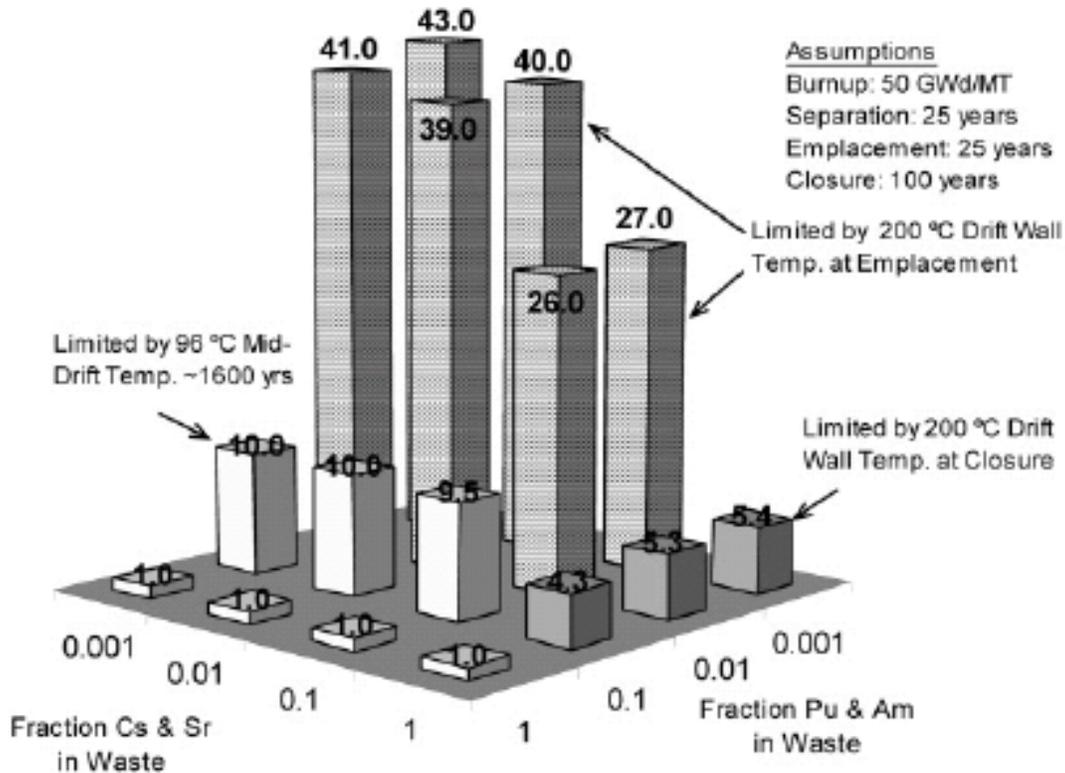


Fig. 7. Potential repository drift loading increase as a function of separation efficiency for plutonium, americium, cesium, and strontium.

This bar chart shows the increase in repository capacity that can be achieved by separating out plutonium, americium, cesium, and strontium, for various assumed fractions remaining in the waste. Note that the removal of the uranium does nothing to increase the capacity of the repository, which is limited by the decay heat of the radioactive materials. With no removal of these materials, the repository is planned for a reference value of initial 1.1 metric ton of heavy metal of spent PWR fuel per meter of "drift" space-- 1.1 MTIHM/m of the mined drift. If 90% of the Pu and Am are removed from the PWR waste, while all the Cs and Sr are retained, the repository capacity would be increased by a factor 4.3. But repository space is also required for the reprocessing waste from the ABR recycle process.

The paper notes that separation and recycle of Pu into LWRs cannot achieve this increase in repository performance, because the spent fuel from this recycle has as much TRU heat in a single fuel element as in the four or five UOX fuel elements that were reprocessed to make it. The fast-neutron ABR, however,

is able to fission the minor actinides so that they do not contribute to the decay heat, thus enabling the increase in repository capacity shown in Fig. 7.

Removing 90% of the Cs and Sr results in the bar labeled "9.5" for the factor by which the spent fuel loading in the repository could be increased. Note that this could be achieved either by chemical separation or by holding the waste for an additional 100 years, which gives a further factor 10 decay of the amount of Cs and Sr in the waste.

The 1996 STAP report used a 2% process loss estimate, and the Wigeland paper begins with a 1% process loss, as illustrated in its Fig. 6.

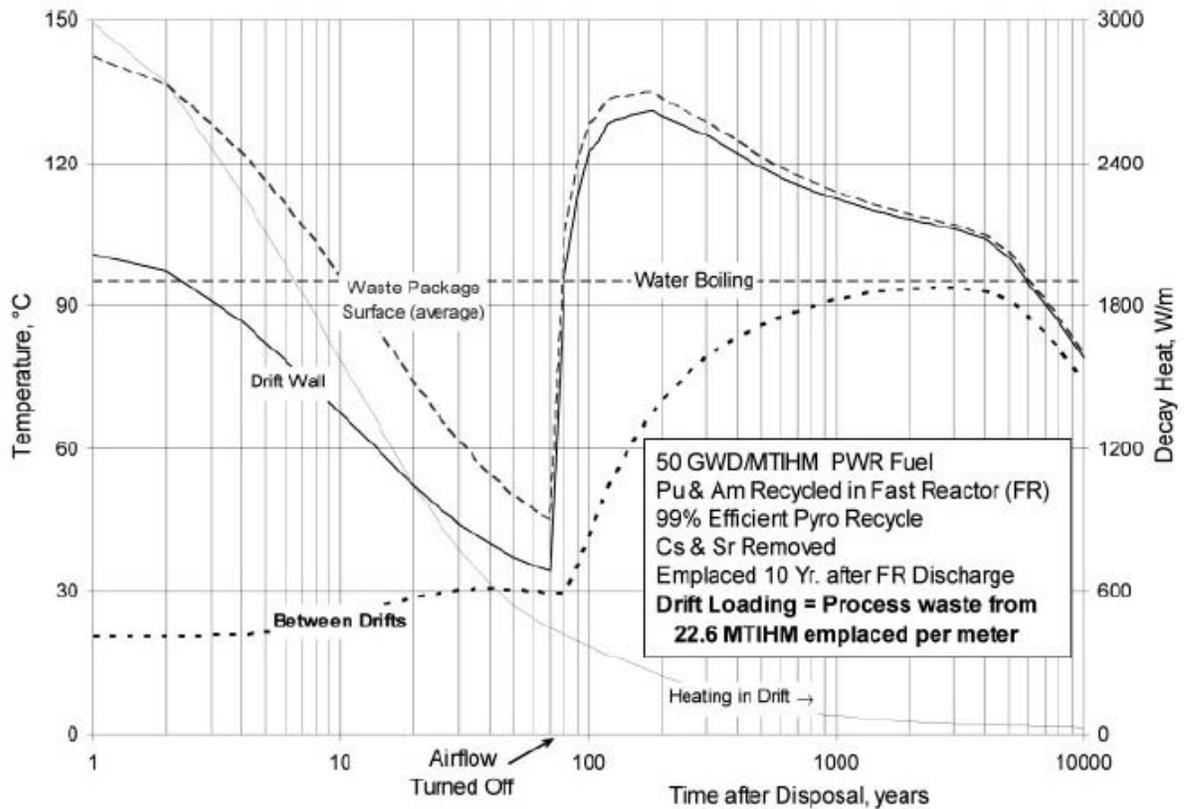


Fig. 6. Transient thermal response of a repository at Yucca Mountain with removal of plutonium, americium, cesium, and strontium from spent PWR fuel, recycling plutonium and americium in a fast reactor, with increased drift loading.

In Fig. 6 of Wigeland, et al, the FR fuel was burned to 80 GWD/MTHM, with about 4 tons of fuel in the FR. Assumed separation efficiency for the PWR fuel was 99.9%.<sup>6</sup>

The arguments for GNEP assert that 99.9% might be achieved, and a big part of the UREX+ ESD demonstration is to go from demonstrated 99% removal efficiency to 99.9% in the case of LWR fuel! But this effort is misguided; it is the ABR reprocessing that would benefit from efficiencies above 99%--not the PWR UREX+ process.

No rational business person or economist looking at Fig. 7 would want to do the UREX+ ESD program at the level requested.

<sup>6</sup> Personal communication from R. Wigeland, April 5, 2006.

What is happening here is that one has a cost structure that includes the cost of separation and transmutation (the "chemical plant" and the ABRs) and also the cost of the repository, presumably reduced by a factor comparable with the increased loading that can be achieved. A factor 10 improvement in repository capacity is sufficient to reduce the already low cost of the repository (estimated at 0.1 cents per kWh) to a much lower value. One could perfectly well leave further reduction in repository costs and increase in permitted loading to the much longer term future rather than expending vast sums and time up front to demonstrate on a large scale unnecessarily efficient processes.

Therefore, a reasonable goal for the performance of the chemical plant on PWR fuel is 90% removal of Pu and Am, and similar 90% removal of Cs and Sr, if that is economically achievable. Note that even substantially less removal of Cs and Sr would not much diminish the factor 9.5 increase in repository capacity. Performance already demonstrated far exceeds that required for PWR spent fuel separations. This minimal requirement for separation efficiency for the one-time PWR fuel separation contrasts strikingly with the 99+% that is needed for repeated separation and recycle in the ABR, just because of the multiple recycles required in the case of the ABR fuel.

These specific points reinforce my global point that the uncertainty is what kind of burner reactor can be built to operate 30 or 50 years hence, that will be safe and as close as possible to economically competitive with the LWR or other thermal reactor for the production of electrical power. This is the critical question and is linked to the type of fuel to be burned and hence to the separations technology that must be achieved in ABR fuel recycle.

Since a major element of cost and performance in this "waste reduction" program is the subsidy that would be required for the ABRs, it is of interest to note that there is a very different technology under development that would also modestly reduce repository needs. This is the thermal neutron reactor championed and developed by General Atomics that had deployed two plants-- one at Peach Bottom and the other at Fort St. Vrain, that relies on millimeter-size pressure vessels of carbon and silicon carbide to contain the fissile fuel and the resulting fission products. In the form of a modular high temperature gas turbine reactor-- (MHTGTR)-- such systems could be deployed in a "deep burn" mode, without reprocessing of this fuel, so as to achieve the modest benefits to the repository that could compete with or supplement expanding the repository capacity.

The American Physical Society Nuclear Energy Study Group<sup>7</sup> in its May 2005 report concluded,

"Any decision to reprocess spent fuel in the United States must balance the potential benefits against the proliferation risks. Fortunately, there is no near-term urgency to make a decision on implementing reprocessing in the United States. No foreseeable expansion of nuclear power in the US will make a qualitative change in the need for spent fuel storage over the next few decades. Even though Yucca Mountain may be delayed considerably, interim storage of spent fuel in dry casks, either at current reactor sites, or a few regional facilities, or at a single national facility, is safe and affordable for a period of at least 50 years."

The "GNEP Program" needs to be disaggregated and the technical priorities set appropriately-- the design of the ABR or other waste-burning reactor to be as safe and inexpensive as possible, and the choice of the nature of that reactor together with its fuel. As for the role of GNEP in assured supply of

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<sup>7</sup> Its membership included the Chairman of the Advanced Nuclear Transformation Technology Subcommittee of DOE's Nuclear Energy Research Advisory Committee.

enriched uranium and take back of fuel from much of the world, those policy problems must be addressed, as to whether the United States wishes alone to dispose of radioactive wastes from the rest of the world, or whether it wishes to take the lead in a process that is commercially viable and environmentally acceptable to have internationally approved repositories storing internationally approved waste forms in appropriate areas of the world.

As noted, the other urgent matter for the U.S. and other governments is to determine the cost to obtain vastly more uranium. It is essential to know whether half of the 4000 million tons of uranium in seawater can be extracted at a cost of \$300/kg, as is tentatively suggested by the Redbook. Or whether the GEN-IV working group approach that leads to an estimate of 170 million tons of uranium from terrestrial deposits at an extraction price less than \$260/kg is valid.

So in general I admire the goal of GNEP, but visions that ignore technical reality have often led to disasters, since they preclude more conventional and incremental approaches. The reprocessing and transmutation aspect of GNEP must be seen as a gamble, and an optional—not a necessary—gamble. It is presented as an alternative to expansion of the approved repository capacity, but is linked to the momentous decision to deploy highly subsidized fast reactors in numbers that would generate about 1/3 as much power as the light-water reactors with which they would coexist. And it blithely assumes above-ground storage for hundreds of years of separated cesium and strontium waste, as well as the operation of reprocessing plants, all a high-cost, technically risky, and proliferation-prone approach to saving a low-cost resource—space in a mined geological repository and the auxiliary interim dry-cask storage.

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Brief Biography of Richard L. Garwin

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See "Garwin Archive" at <http://www.fas.org/RLG/>

Richard L. Garwin was born in Cleveland, Ohio, in 1928. He received the B.S. in Physics from Case Institute of Technology, Cleveland, in 1947, and the Ph.D. in Physics from the University of Chicago in 1949.

He is IBM Fellow Emeritus at the Thomas J. Watson Research Center, Yorktown Heights, New York. After three years on the faculty of the University of Chicago, he joined IBM Corporation in 1952, and was until June 1993 IBM Fellow at the Thomas J. Watson Research Center, Yorktown Heights, New York; Adjunct Research Fellow in the Kennedy School of Government, Harvard University; and Adjunct Professor of Physics at Columbia University. In addition, he is a consultant to the U.S. government on matters of military technology, arms control, etc. He has been Director of the IBM Watson Laboratory, Director of Applied Research at the IBM Thomas J. Watson Research Center, and a member of the IBM Corporate Technical Committee. He has also been Professor of Public Policy in the Kennedy School of Government, Harvard University. From 1994 to 2004 he was Philip D. Reed Senior Fellow for Science and Technology at the Council on Foreign Relations, New York.

He has made contributions in the design of nuclear weapons, in instruments and electronics for research in nuclear and low-temperature physics, in the establishment of the nonconservation of parity and the demonstration of some of its striking consequences, in computer elements and systems, including superconducting devices, in communication systems, in the behavior of solid helium, in the detection of gravitational radiation, and in military technology. He has published more than 500 papers and been granted 45 U.S. patents. He has testified to many Congressional committees on matters involving national security, transportation, energy policy and technology, and the like. He is coauthor of many books, among them *Nuclear Weapons and World Politics* (1977), *Nuclear Power Issues and Choices* (1977), *Energy: The Next Twenty Years* (1979), *Science Advice to the President* (1980), *Managing the Plutonium Surplus: Applications and Technical Options* (1994), *Feux Follets et Champignons Nucleaires* (1997) (in French with Georges Charpak), and *Megawatts and Megatons: A Turning Point in the Nuclear Age?* (2001) (with Georges Charpak).

He was a member of the President's Science Advisory Committee 1962-65 and 1969-72, and of the Defense Science Board 1966-69. He is a Fellow of the American Physical Society, of the IEEE, and of the American Academy of Arts and Sciences; and a member of the National Academy of Sciences, the Institute of Medicine, the National Academy of Engineering, the Council on Foreign Relations, and the American Philosophical Society. In 2002 he was elected again to the Council of the National Academy of Sciences.

The citation accompanying his 1978 election to the U.S. National Academy of Engineering reads "Contributions applying the latest scientific discoveries to innovative practical engineering applications contributing to national security and economic growth." He received the 1983 Wright Prize for interdisciplinary scientific achievement, the 1988 AAAS Scientific Freedom and Responsibility Award, the 1991 Erice "Science for Peace" Prize, and from the U.S. Government the 1996 R.V. Jones Foreign Intelligence Award and the 1996 Enrico Fermi Award. In 2003 he received from the President the National Medal of Science.

From 1977 to 1985 he was on the Council of the Institute for Strategic Studies (London), and during 1978 was Chairman of the Panel on Public Affairs of the American Physical Society. He is a long-time member of Pugwash and has served on the Pugwash Council.

His work for the government has included studies on antisubmarine warfare, new technologies in health care, sensor systems, military and civil aircraft, and satellite and strategic systems, from the point of view of improving such systems as well as assessing existing capabilities. For example, he contributed to the first U.S. photographic reconnaissance satellite program, CORONA, that returned 3 million feet of film from almost 100 successful flights 1960-1972.

He has been a member of the Scientific Advisory Group to the Joint Strategic Target Planning Staff and was in 1998 a Commissioner on the 9-person "Rumsfeld" Commission to Assess the Ballistic Missile Threat to the United States. From 1993 to August 2001, he chaired the Arms Control and Nonproliferation Advisory Board of the Department of State. On the 40th anniversary of the founding of the National Reconnaissance Office (NRO) he was recognized as one of the ten Founders of National Reconnaissance. In June, 2002, he was awarded la Grande Medaille de l'Academie des Sciences (France)-2002.