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FISSION BREEDER REACTOR

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THE PROPER ROLE FOR THE BREEDER REACTOR

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Let me first explain why this is a little different from the way I had planned it. My proposed background reading on the breeder reactor was a paper which I had drafted over the last two years, and finally perfected last August for a SIPRI symposium, so instead of referring to it for background, I sent a copy for reproduction and distribution. I expected to examine you on your having read it, but I gather you don't have it. I have been assured that it will be available on the table afterwards, but my repared presentation did not allow for your not having read it. So I have to back up a little. Fortunately I brought some foils, and perhaps we can have an introduction to the subject.

Well, why do we need a breeder reactor or want a breeder reactor? Because it's not clear right now what we will be doing for energy in the next century. There are many things that we might do for energy. Some of them are intolerable environmentally. Some of them are too expensive compared with other approaches and so intolerable economically.

There is only one approach to the manufacture of economic electric power which we know how to do now more or less, which we'll know how to do better in the 21st Century and which can take over for several hundred years to supply the current demand for total energy, and that's the breeder reactor.

Now, that makes me a breeder fan, but that doesn't mean that I'm about to build breeder reactors now or even to define which breeder reactor to build later. In my opinion, it would be foolish to do that, because we have an even better way to make electrical power right now -- better perfected, cheaper, more widely available, with less hazards so far as we know, and that's the light-water reactor; so what we ought to do is to continue using light-water reactors until the breeder reactor itself becomes economical, that is, becomes cheaper. It will become cheaper either because somebody will have a new idea as to how to make better breeders (and that means <u>cheaper</u> breeders), or it will become cheaper than the light water reactor because the cost of uranium will rise to the point where the light-water-reactor fuel cycle is more costly than the annualized increased capital cost of the breeder reactor.

So that's the punch line. The bottom line after the punch line is besides, you don't have to get to work now accumulating and separating your plutonium stores to run breeder reactors because you can wait as long as you like and then have as many breeder reactors as you want all of a sudden, provided that you're willing to pay the capital cost (which is necessary anyhow). The rest of my talk will introduce the paper that you were to have read and which will constitute the bulk of my contribution to the Symposium Proceedings.

The story on U.S. energy resources is familiar. In quads (10^{15} BTU and just as a baseline the U.S. consumption is about 75 quads per year, of which something like 15 or 17 goes into electrical generation producing in this chart 5 or 6 quads of electrical energy per year), we have not very much oil in this country, 600 quads more or less. Of course, there will be more oil as the price goes up and one drills. These are resources, not reserves, except as indicated. The difference is that reserves are thoroughly delineated, you know where they are, you know what they cost, you can produce them at current prices and so on.

In some cases, the resource base is not very well known and it's very important to find out what it is in order to plan ahead, because otherwise you may plan for a very high cost technolody which will never come in economically because conventional fuels may become available early on at an economical price. But there is the <u>coal</u> of the order of 9,000 quads underground and surface, and that's a hundred years of total energy supply for the United States. There's more coal than that; we don't know how much more.

Oil, only ten years. Uranium at $30 per pound (forward cost in 1975 dollars) is probably around $45,00 per pound so far as 1979 dollars are concerned. These are costs and not prices, but in an efficient market, the cost and the prices are very similar, although forward costs are by definition somewhat less.

Economists will tell you that it doesn't matter if somebody charges you too high a price for the fuel; what counts is the resource cost in getting it out. If you don't like to pay that high a price, very much over the cost, then you ought to expect rapidly decreasing costs as competition enters the supply market (or if no competition arises, attend to antitrust provisions and so on to get the price down to reflect the cost).

But this 3.5 million tons in more-or-less agreed-on uranium resources, is only 2,000 quads in light water reactors and would supply only about 30 years of energy. In the breeder, 3.5 million tons would produce 100,000 quads, because one can burn not the 0.7% of the uranium, which is U^{235}, but as we shall see, 50% of the uranium as U^{238}.

Geothermal energy is a big resource, even bigger than the breeder-burned uranium. You have to go after geothermal energy by mining it. It doesn't come out. You have to exhaust it. It was stored there over billions of years and we would use it up in the hundreds or thousands of years. Solar input, of course, is continuous and one can get something like 40,000 quads per year. It's truly inexhaustible.

As for fusion, so much fuel is available that it's totally unlimited as a resource except in the capital cost of producing it. Technically, in fact, we don't know how to do it right now, except in the form of hydrogen bombs.

Here was electrical production and remember electricity was only about 20 percent of the primary energy and if you were going to use the electrical output for heating instead of as heat pumps or driving motors or electric lights, it was considerably less, only about six percent, seven percent of the input.

So we had in 1974 these numbers of thousand megawatt nominal power plants--about 200 coal, 60 oil, 70 gas, 24 nuclear, 63 hydro. That's why we should be interested in the breeder.

Now, what is a breeder reactor? At this point I incorporate my August 15, 1978, paper, "The Role of the Breeder Reactor."

ABSTRACT

Proliferation hazard of the breeder can best be restrained by delay in breeder deployment until it is economically advantageous. The breeder reactor should be regarded as a means for converting a given investment of uranium ore into electrical energy. Because of the 0.7% U^{235} content of natural uranium, even a breeding gain of zero will allow a 1000 Mw(e) LMFBR to be fueld initially with 11,250 kg of U^{235} as 20% in U^{238} and then to operate for 2,000 years on the 3,100 short tons of U308 from which that U^{235} was extracted. An assumed resource base of 3.5 million tons of U308 would thus start and operat 1,100 such simplified LMFBRs for 2,000 years, as compared with 500 LWRs for only thirty years. Redesign of the LMFBR can reduce the $200 million initial penalty per reactor which would be incurred in this use of U^{235} if LWR plutonium were available. If a molten salt breeder reactor is practical with a 2,500 kg U^{235} inventory, some 5,000 could be started and operated for 500 years from the assumed resource base. After the exhaustion of low-cost uranium, a breeder population could be maintained (but not started) on uranium costing $5,000/lb without significant increase in electrical energy costs. Although plutonium will have to be recycled in Pu-breeders started with U^{235} (and to the extent it is available should be used to fuel Pu breeders), the route of U^{235} investment will allow a large, rapid deployment of breeders when they are economically desirable without the necessity of premature commercial breeder operation or plutonium separation.

BACKGROUND

There is near-universal consensus that world security would not be benefited by nuclear weapons in the hands of terrorists or other non-national groups. There is also wide agreement (reflected in the NPT and other efforts to control the spread of nuclear weapons) that world security (and especially regional and local security) is likely to be imperiled if nuclear weapons spread to many more nations.

TYPES OF NUCLEAR WEAPON PROLIFERATION

We have already distinguished

- national vs. non-national possession of nuclear weapons.

We should also distinguish

- one weapon vs. many, and
- optimized nuclear weapons vs. terror weapons.

Furthermore, one can have

- overt possession of nuclear weapons,
- covert possession of nuclear weapons,
- possession of separated plutonium or other fissile material in metallic form, under international safeguards which would warn of diversion,
- possession of fissile material in less immediately usable form,
- possession of spent fuel rods, together with fuel reprocessing facilities, and
- possession of fresh breeder fuel without reprocessing capability.

Even this familiar but incomplete list reminds us of the complexity of the proliferation problem. Unmentioned has been the sizable effort required to design, build, and test the non-nuclear portions of the weapon, and the political incentives or disincentives to proliferation.

BREEDER FUNDAMENTALS

In the breeder reactor, the fission chain reaction which is responsible for the production of nuclear power in the LWR is possible only because the typical fission event produces more than one neutron. On the average, from each fission precisely one neutron goes on to cause another fission.

> The fission rate and hence the reactor power (200 MeV of energy from each fission event) is maintained constant by the very slow motion of "control rods" changing the parasitic absorption of neutrons, or by thermal expansion or other means for changing neutron leakage, or in other ways; slow motions suffice because 1% of the neutrons from each fission are delayed 1 second or more and thus allow plenty of time for control. But fission not only produces more than the one neutron required to continue the chain reaction; fast fission in any of the fissile isotopes (Pu^{239}, U^{233}, U^{235}) gives considerably more than <u>two</u> neutrons per neutron absorbed. Thus, from the earliest days of fission there has been recognized the possibility of a <u>breeder</u> reactor, in which one neutron per fission would continue the fission chain reaction in the reactor and <u>another</u> neutron per fission would be captured in U^{238} eventually to give another fissile atom of Pu^{239}. Neutron energies above about 0.4 million electron volts (MeV) will yield more than two neutrons per neutron absorbed in U^{235}; neutron energies above about 0.04 MeV will do the same in Pu^{239}. In addition, Pu^{239} has substantially higher neutron excess (over 2.00) per incident neutron above 1 MeV than does either U^{235} or U^{233} (but U^{233} gives somewhat more than two neutrons over the <u>entire</u> energy range, extending to the slow neutrons used in water-moderated reactors). Neither Pu^{239} nor U^{235} yields enough neutrons per neutron absorbed in the thermal and intermediate energy range to allow a "thermal breeder"-- i.e., one in which the fission neutrons are slowed before being captured.

BREEDER PROLIFERATION HAZARDS IN PERSPECTIVE

It is clear that a nation desiring a few nuclear weapons early would not undertake the construction or purchase of a breeder reactor but would instead build or buy a research reactor to produce plutonium at a rate of about 1 g/megawatt-day of operation. An alternative would be the construction of a centrifuge plant to produce high-enrichment U^{235}.

But a nation engaged in long-range planning, especially a nation with internal pressure groups both in favor of and against getting "closer to nuclear weapon capability," could well opt for breeder reactors prematurely simply <u>because</u> of their proliferation hazard. Without exhaustive discussion of all cases, we note that while for the LWR, fuel reprocessing and recycle is optional (and at present probably uneconomical), for the breeder, reprocessing and recycle is <u>mandatory</u>.

Furthermore, recycle fuel for the breeder reactor contains large amounts of chemically separable fissile material, protected by a relatively small amount of penetrating radiation.

Thus while one can argue whether a given breeder produces more or less net plutonium annually than a given LWR, the breeder Pu <u>stock</u> (as well as its net production) must be purified and recycled if the breeder is to do its job.

Both from the point of view of scale of operations required and protection against penetrating radiation, it would be more convenient to mine breeder fuel of its 15% Pu content than LWR spent fuel of its 0.6% Pu.

NUCLEAR POWER BENEFITS

My own judgment (expressed in the book,

Nuclear Power Issues and Choices) is that electrical energy from LWR is competitive with electrical energy from fossil fuel (coal) in large countries with a strong electrical grid. Because of the smaller size of an economical unit of fossil electrical capacity, electrical energy from the combustion of coal is much more economical than nuclear power in small countries, even if the coal has to be imported and stockpiled. Thus, although I believe the proliferation hazard of LWR can be managed (primarily by delaying reprocessing and recycle of LWR fuel until it is clearly and demonstrably profitable), there would be insignificant impairment of the world's economic well-being if for some reason nuclear power did not exist for the next twenty or thirty years. However, by the year 2100 the known reserves of high-quality coal might be near exhaustion, and the known reserves of fissile uranium would be an insignificant supplement. Furthermore, it may be important to be able to reduce substantially the input of carbon dioxide into the atmosphere, in order to avoid injurious effect on the world's climate. Two energy resources can serve from the mid-to-long run-- solar energy and the breeder reactor. Of the two, paradoxically, the breeder is far more certain to be able to provide electrical energy at near-current costs.

Two advantages have been claimed for the breeder reactor-- reduced cost and a lesser national dependence on external "sources of energy." Recent PLBR (prototype large breeder reactor) studies in the United States estimated the capital cost of a breeder reactor to be at least $600 million more than that of an LWR. Present uranium costs of some $30/lb would have to rise to some $130/lb before such a breeder could compete with the LWR, even if no economics were achieved in LWR operation. Among these latter which I feel will come surely and within the next ten years are a reduction in the cost of isotope enrichment from the present $80-$100/kg-SWU to something on the order of $20/kg-SWU.

But perhaps a nation should buy one or more breeder reactors in order to be independent of a continued supply of LEU (low-enriched uranium-- about 3% U^{235} in U^{238})? In my opinion, a nation would serve its citizens better by deploying LWRs and buying ahead a stockpile of either fuel rods or LEU material from which to fabricate reactor cores for the next ten years or so. The small size and inert nature of either the LEU material or the fuel rods means negligible physical space and cost required for such stockpiling. The relatively low fraction of the nuclear energy cycle represented by LEU investment means that it is economical to buy fuel five or ten years in advance. Further economies could be realized by stockpiling only natural uranium, depending upon one or another competitive suppliers of enrichment services to enrich and to fabricate fuel a few years in advance.

On the other side of the balance, possession of an operating LMFBR or other breeder reactor in no way guarantees energy independence. For example, the majority of countries operating LMFBRs will probably not have reprocessing and refabricating plants on their territories. Breeder reactor economics are seriously impaired by delay in reprocessing (or, alternatively, by a security requirement to maintain several years' core load in order to cope with interruption of supply of reprocessing/refabrication services).

In the case of LWR fuel, buying an 8-year stockpile of LEU (at an 8% annual interest rate) would only double the LEU-associated portion of the energy costs (raising the busbar cost of electricity by 20%). An LMFBR on the other hand, is estimated to have a fuel inventory out-of-core ranging between 150% and 50% of the in-core inventory. For a 3,000 kg Pu LMFBR core, this would correspond under normal reprocessing assumptions to a total inventory between 4500 kg and 7500 kg Pu. If one required a similar independence of 8-years' replacement of half the core annually, the Pu inventory would be increased by something like 12,000 kg.

The most significant effect of the increased inventory would not be in the cost of electricity but on the feasibility of deployment of breeder reactors. Figure 1 shows for the United States the plutonium inventory as a function of time for different assumed Pu inventories for an LMFBR deployed at a very nominal rate of 15 Gw(e) per year net increase in nuclear power capacity, beginning in the year 2000. This corresponds to about 3.5% per year net increase in the nuclear component, without major replacement of fossil fuel generating capacity by nuclear fuel, and without significant transition from direct heat to electricity. Even under these very modest assumptions, only those LMFBR designs significantly more advanced than those now available will avoid a plutonium inventory limitation on their deployment rate. Furthermore, although the plutonium may exist in spent LWR fuel, there may also be a shortage of reprocessing capacity, since there will be no market for the LWR plutonium until the breeder

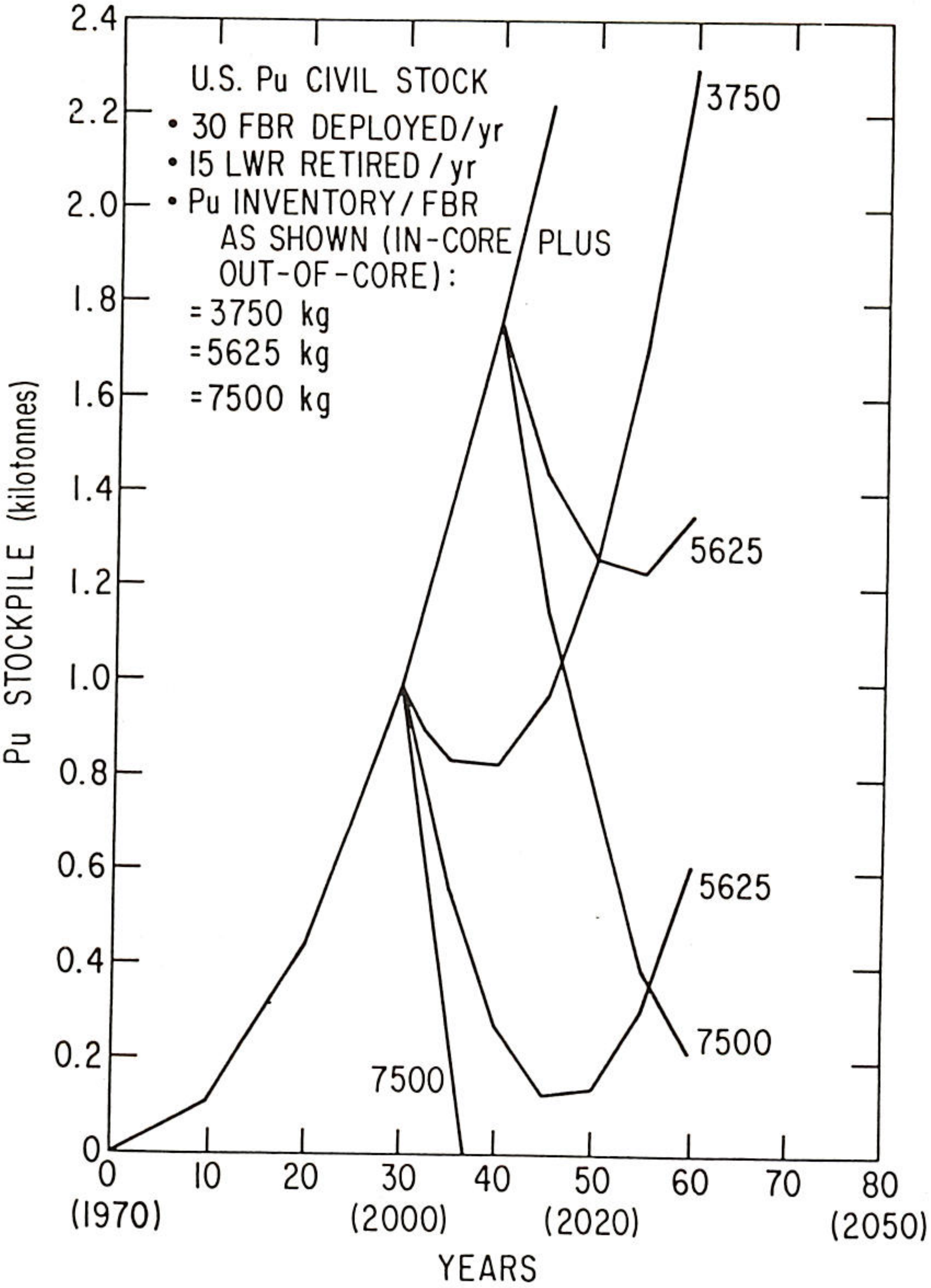

Figure 1. U. S. civil plutonium stockpile vs. year of introduction of the FBR (year 2000 or 2010), with 3 assumptions as to required Pu inventory of each FBR. This figure was provided to the author by the Director of Energy Research (DoE) June 20, 1978. Note that while the NASAP assumes a "3750 kg FBR", a memo of July 7, 1978 to the Director of Energy Research (DoE) from the Acting Director, Office of Fuel Cycle Evaluation (DoE) notes that "it is reasonable to assume that lower inventory FBRs, such as the 5625 kg/GWe design shown in your curves, could be available if required."

deployment begins.

Clearly, there is an economic incentive for a nation operating breeder reactors to have indigenous reprocessing capacity, but this would forego economies of scale and would further increase the cost of the breeder reactor and delay the date at which it could compete with the LWR.

In my opinion, the LWR as a producer of commercial electricity has a relatively minor but useful role to play for a short time. The breeder reactor, on the other hand, is an important insurance policy-- against a carbon dioxide catastrophe, against having to pay possibly relatively high costs for solar heat and electricity. It may be important to be able to deploy breeder reactors rapidly, and to provide a considerable portion of the world's energy needs for a time on the order of centuries.

INTRODUCTION

LIMITED URANIUM RESOURCES. The technical achievement of producing commercial electrical power from nuclear fission may have limited economic and social benefits in view of the limited resources of high-grade uranium ore. The light-water reactor (LWR) which now produces most nuclear power uses uranium enriched to about 3% U^{235} from its normal isotopic abundance of 0.71%. With an enrichment plant leaving 0.25% concentration of U^{235} in the "tails," a conventional pressurized water reactor (PWR) of 1 million kW peak electrical output (1,000 MW(e)) and operating at full capacity 80% of the time, consumes in its nominal 30-year life 6,970 tons of uranium ore.*

Thus only about 502 1,000-MW(e) reactors could be fueled for their 30-year lives by the presently considered uranium resources of the United States.

In view of the present low rate of deployment of nuclear power reactors, there is no possibility that the low-cost uranium will be exhausted by the year 2000, but there is also no considerable opinion that the presently contemplated reserves will last to the year 2100. Therefore, nuclear power in the United States would be a brief and minority contributor to electrical power supply unless some way could be found to

- find and mine a lot more uranium at an economically and environmentally acceptable cost, or
- develop and deploy nuclear power plants with a substantially smaller appetite for uranium, or
- provide an alternative source of fissile material to the simple extraction and enrichment route.

Startup on LWR plutonium. However, a substantial fraction of neutrons even in an LWR are captured in U^{238} to produce additional fissile Pu-- typically about 60%-- some of which is later fissioned. In fact, 44 years of operation (of a 1,000-MW(e) LWR at 80% capacity facotr, assuming that the LWR operates to recycle its uranium) together with 8,536 short tons of U308 are required to produce the net 7,500 kg of Fissile plutonium needed to start one 1000 MW(e) liquid-metal-cooled fast breeder reactor (LMFBR). Had the Pu also been recycled in the LWR, 1530 tons of U308 would have been saved, together with 1,020 Mg SWU**, but, of course, no Pu would then have been available for investment in a breeder.

The two extremes for fueling first-generation breeders from LWR plutonium are equally improbable-- the first being to accumulate a stock of plutonium from an individual LWR and also from its successor (44 years of operation) and then to invest one LMFBR. The product plutonium would be idle for an average of 22 years (alternatively, the discounted present value of the

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* As used in this paper, a "ton of uranium ore" means a short ton of yellowcake (U308) of which domestic US resources (known, probable, possible, and speculative) may be 3.5 million tons at a cost of production below $30/lb. A ton of yellowcake contains 1,700 pounds of uranium metal or 769 kilograms U. Except as noted, all data dealing with alternative nuclear fuel cycles are taken from the "Report to the APS (American Physical Society) by the Study Group on Nuclear Fuel Cycles and Waste Management," L. C. Hebel, Chairman, Reviews of Modern Physics 50, 1, Part II (January 1978).

** A megagram SWU is a "separative work unit" which for many kinds of isotope separation, (including gaseous diffusion and centrifuge) is directly related to cost. The APS Study assumes a cost of $75,000 per Mg SWU-- approximately that charged now by Department of Energy. Note, however, the existence of substantial private and government efforts in the United States and elsewhere to reduce the cost of isotope separation by the use of lasers (laser isotope separation-- "LIS") which might result in a factor 4 reduction in cost and a substantially greater reduction in energy requirements.

energy produced by the LMFBR would be much reduced by the delay). The other extreme is to collect all Pu produced by the entire population of LWRs and "immediately" to invest it in new LMFBRs. This assumes no delay in reprocessing, in fuel fabrication, and in scheduling the start of new LMFBRs. The APS Study assumes process times allowing for about two years between the discharge of fuel from an LWR and the incorporation of that Pu-bearing fuel in an LMFBR. Thus one might imagine a new LMFBR to be spawned every two years by each set of 22 operating LWRs, and one every two years by each set of 16 operating LMFBRs, but with a two-year delay in both cases.

Under these assumptions, the growth rate for breeder reactor power is clearly inadequate for nuclear electric generation to take over rapidly from fossil fuels, much less to replace non-electric uses of fossil fuel.

WHAT TO DO?

The Report of the Nuclear Energy Policy Study Group, Nuclear Power Issues and Choices (March 1977), in Chapter One, "Energy and the Economic Future", discusses the role of nuclear power in the US economy. It notes (p. 68):

> "One feature of our analysis, which is particularly important from the standpoint of policy, is the assumption that an 'advanced technology' will be available around 2020. This advanced technology could be an advanced breeder or it could be solar or fusion, advanced coal production and use, or some combination. The prospects of these advanced technologies and the nature and timing of the U.S. breeder program are discussed in some detail in Chapters 4 and 12. For the perspective of this broad economic analysis, the precise costs of these advanced technologies are not important. It is important, however, that one or more of these technologies be available within the next fifty to seventy years to provide assured energy supplies and keep energy prices from increasing rapidly."

The main point of this note is to put some flesh on the "delayed breeder or alternative" and to suggest a useful way to think about the importance of the breeder reactor. Such an application also has important implications for the US breeder research and development program.

PROPOSAL. The conservative proposal is simply to fuel "normal" first-generation LMFBRs with 11,250 kg (4,500 kg in-core and 6,750 kg out-of-core-- i.e., available for the replacement cores while the first core is being reprocessed--) of U^{235} as 20% in U^{238}. The LMFBR would be operated at the same power level as usual, and the fuel would be reprocessed and recycled in the normal manner, feeding the LMFBR annually with 1,200 kg of depleted or natural U. We assume that the breeder core portion of the fuel rods will for the most part be reprocessed into the next core, to avoid putting the enriched U^{235} into the blanket where it will be less valuable. This would be a minor requirement to incorporate into the reprocessing plant.

At 0.25% tail concentration of U^{235}, the assumed amount and concentration of U^{235} would be obtained from 3,110 short tons of U308. The uranium mined and stripped of U^{235} to fuel the LMFBR would then suffice to sustain it (or its successors) for more than 2,000 years of operation at 1,000 MW(e) and 80% capacity factor even if there were no excess plutonium production in the mature LMFBR. Thus, instead of fueling 500 LWRs for thirty years, an assumed uranium resource of 3.5 million short tons of U308 would fuel 1077 LMFBRs for more than 2,000 years even if their breeding performance were far worse than has already been demonstrated.

There is nothing new about starting LMFBRs with enriched U^{235}; most LMFBRs in the world have in fact been started in this way because of the lower cost of fabricating fuel with enriched uranium than with plutonium, and because of the limited availability of LWR plutonium. This possibility gives great flexibility for deployment of additional, enduring nuclear power. In particular, one does not need to recycle Pu now (or to avoid recycling Pu now) in LWRs with a view to the LMFBR future; one need not deploy first-generation LMFBRs now, in order to (very slowly!) breed the LMFBR population to an appreciable level-- which, from the foregoing, would take a long time. There exist scenarios which show a transition from LWR to LMFBR within the limitation of available plutonium; these show a 30-yr period of low growth of the nuclear power sector for precisely the reasons I have given. I consider it unlikely that such a long transition (with simultaneous building of LMFBR and new LWR capacity) would be economically desirable. It should be cheering to observe that success in designing an economically superior breeder could result in total displacement of

From TABLE AV-2 of Ref. 1

Economic Penalty to Start 1000 Mw Fast Breeder with Enriched U^{235}

	Water-reactor Plutonium	20% U^{235} in Uranium (with separate core reprocessing and recycle)
Fissile amount required from external source for start-up and replacement loadings, kg.	7,500	11,250
Value of fissile material, $/kg fissile (a)	19,900	31,000
Total cost of fissile material, $million	149	349
Loss of breeding-gain fissile production:		
kg fissile Pu	0	1,700
$million	0	34
Contribution to fuel cycle cost levelized over 30-year breeder plant life (b)		
Purchase of fissile material for start-up mill/kwhr	2.2	5.3
loss of breeding-gain fissile production mill/kwhr	0	0.3
Relative total, mill/kwhr (c)	2.2	5.6
Levelized fuel cycle cost, mill/kwhr (c)	2.0	5.4

(a) Plutonium value is calculated for alternative use as a water-reactor fuel.

(b) Calculated from time schedule of fissile purchases and sale, using utility discount factor of 0.0755/yr.

(c) The relative total not the total fuel cycle cost. Later credits from breeding gain fissile production and cost of fabrication and reprocessing result in an estimated LMFBR levelized total fuel cycle cost of about 2.0 mill/kwhr (Stauffer et al, 1975).

new LWR construction by LMFBRs, by virtue of the flexibility of U^{235} investment, as needed, of LMFBRs.

COST OF LMFBR STARTUP ON ENRICHED URANIUM. The APS Study Group has compared the cost of starting a 1 000-MW(e) LMFBR with enriched U^{235} with the cost for fueling it with water-reactor plutonium. Such a comparison has validity only if the desired deployment rate of LMFBRs can be accommodated by the stock of LWR plutonium--otherwise the choice is between having electrical power from breeders invested with U^{235} or not having it from breeders at all.

Table AV-2 assumes that water reactor plutonium is bought at the price which would be paid for it for recycle into water reactor. (Actually, there is no guarantee that it could be produced for this price, in which case it might not be available at all or could be more costly.) According to the assumptions of Table AV-2, there would be approximately a $200 million penalty for starting an LMFBR with U^{235}. Taking the estimate at face value, there is an expected penalty of about 3.4 mills/kwh in starting an LMFBR with enriched uranium instead of LWR plutonium when the latter is available. (It should be noted that a factor 4 reduction in cost of isotope separation should reduce this penalty to about $75 million-- some 1.1 mill/kwh.)

OTHER ALTERNATIVES. I have already noted that LWR plutonium probably will not be available in sufficient quantity when one wants to build LMFBRs. I further note (as commented by the APS Study Group) that an LMFBR core could be reoptimized to require less U^{235} (the calculations were done for U^{235} loading of a core optimized for steady-state plutonium operation); if the cost incurred per reactor in changing core configuration after two years or thereabouts is considerably less than the value of the U^{235} saved, then one clearly would want to change the configuration (or use a more complicated interactive system in which some specialized LMFBRs processed enriched U^{235} into a lesser amount of Pu for conventional equilibrium LMFBRs). But there are substantial cost reductions possible simply from relaxing the requirement for a breeder with a conversion ratio exceeding 1.00. In the conventional LMFBR with as high a breeding ratio as possible, considerable constraints and cost are incurred in order to obtain the net breeding excess of 8.4% (net annual fissile plutonium production divided by fissile core inventory) which results in the 3.3% maximum LMFBR population growth rate when one considers out-of-core Pu as well. If one relaxes the requirement that the LMFBR produce more Pu than it consumes (because one plans to invest each LMFBR in the future with its own core of U^{235}) one can use wider coolant channels, thicker fuel cladding, and in general do things which will reduce the capital cost of the LMFBR (which is four or five times the $200 million "penalty" from startup on U^{235}). Part of this new-found flexibility can be traded off in increased (or more assurance of) safety.

In fact, no magic attaches to a conversion ratio of 1.00. A conversion ratio of 0.99 is almost as good, and even significantly lower conversion ratio such as might be obtained with modified CANDU reactors would be of benefit, if only to give more time for the achievement of conversion ratios of 1.00 or better.

BENEFITS. In all, the potential for starting LMFBRs with U^{235} allows:

- an arbitrary deployment rate (independent of LWR or breeder history),
- lower-cost, greater safety potential, possibly higher efficiency because of the absence of a constraint of high conversion ratio. A conversion ratio of 1.00 is fine, although one would not reject a breeder with a conversion ratio exceeding 1.00,
- earlier availability of a useful breeder,
- potentially increased benefits from lower-cost advanced isotope separation techniques and from lower-inventory breeder/converters.

The cost for these benefits cannot exceed and may be less than the 3.4 mill/kWh which is computed for LMFBR deployment conditions ideally suited to the Pu-based LWR-LMFBR transition.

NON-PROLIFERATION CHARACTERISTICS OF THE PROPOSAL. Investing LMFBR or other breeder with U^{235} instead of Pu has some modest anti-proliferation effect in comparison with the normal view of the FBR:

- initial fabricated cores would require isotope enrichment to yield weapons-usable fissile material, as is the case with LWR fuel or natural uranium,
- Pu recovery from irradiated LWR fuel could and should be deferred until a large population of U^{235} invested FBR were in operation, thus reducing the early availability of large amounts of Pu. Spent LWR fuel should be kept in interim or recoverable storage until the breeder era.
- Such a system is amenable to so-called "CIVEX-type" fuel reprocessing (if the

CIVEX concept were developable as a practical, economical process), which could indeed by reducing the reprocessing delay also reduce the out-of-core fissile requirement and thus the U^{235} cost.

IMPLICATION FOR U.S. BREEDER R&D PROGRAM

Already mentioned is the potential benefit of redesign of the LMFBR core to minimize U^{235} inventory and thus reduce cost. Additional analysis and some experimentation should be done on this possibility. The potential benefit is not known (or if known is not published).

New interest might focus on the molten-salt "breeder" with continuous reprocessing and no out-of-core inventory. Aside from the corrosion problems of the MSBR (which have not been solved to the degree necessary for a viable commercial technology) the system may be ideally suited to the non-breeding role envisaged for U^{235} startup. This benefit would arise from the low in-core U^{235} inventory of about 2,500 kg (and the absence of out-of-core fissile material), which would allow the previously assumed 3.5 million short tons of U308 to fuel 5,000 MSBRs for more than 500 years (even if during all that time no one had a better idea as to how to make a breeder with a conversion ratio significantly exceeding 1).

It should be noted that on such multi-century time scales even a growth rate of 1% per year (of "breeder" reactors) would provide a substantial increase in electrical power availability (if population growth can be held to zero). In any case, humanity can afford to pay far higher cost for the small amount of uranium needed to continue operation of these "breeders" than it can for the large amounts of U308 necessary to fuel LWRs or to start breeder reactors. Thus, sustaining breeder operation on uranium costing $5,000/lb would contribute about as much to the cost of breeder electricity as the present $30/lb uranium contributes to the cost of electricity from LWRs.

CONCLUSION

I am persuaded by the considerations discussed here that it is most important to look at the breeder reactor as a means of using most of the fuel value in our uranium resources, but that we should not ignore the existence of U^{235} in this uranium which makes possible deployment of an arbitrarily expanding breeder population. It is not important that the conversion ratio exceed 1, and certainly not that it be much bigger than one. Abandoning the requirement to start breeders from LWR plutonium or to produce Pu from breeders to fuel other breeders allows one to modify the design of the LMFBR in order to reduce the cost of breeder electricity, to improve safety, and to further reduce the uranium investment required to fuel a new LMFBR.

Furthermore, this approach impels the broadening of the present breeder R&D program to emphasize rapid acquisition of knowledge about breeders and near-breeders of low capital cost and low fissile inventory. It is possible that such a reactor will turn out to be cheaper than LWRs for the production of electrical power; it is not important, however, to have a cheaper source of electricity or to hasten the deployment of a more expensive source of electricity which uses less of our uranium resources. What is important is to have the knowledge so that we can plan for the eventual transition from inefficient consumption of U^{235} to the more efficient consumption of U^{238} as the cost of producing uranium rises.

It seems to me that this view of breeders (and even an eventual factor 4 reduction in enrichment costs by the use of laser isotope separation) is much more plausible and thus worth much more emphasis than other means of expanding fuel supply such as electroc-nuclear "breeding," the "fusion hybrid," or the obtaining of energy from pure fusion. This does not imply that we should retard the acquisition of knowledge about the potential feasibility of these alternatives--simply that we should not prematurely go beyond the test-bed stage into much more costly and uneconomic subsidized prototypes.

HOW MANAGE THE BREEDER REACTOR?

Were there no potential contribution of the breeder reactor to the proliferation of nuclear weapons, there would still be important questions regarding the introduction of the breeder. Enthusiasts for a new technology like the commercial supersonic transport (or, for that matter, those opposing the introduction of a new technology) may propose courses of action which imply the commitment of society to expenditures per marginal unit of product many times larger than the alternative, thereby making society poorer as a whole.

Premature introduction of an early breeder will have just this effect, since its electricity will be more costly than that from an LWR. It is difficult to see a highly competitive supply of breeder reactors, so one might expect only a slow improvement in the technology and slow reduction in cost of the breeder. It would be far better, in my opinion, to support work on breeder concepts, experimental work on breeder fuels, research into economical reprocessing and refabrication, and to delay the deployment of the breeder reactor until private suppliers (or in the case of non-market economies, generally accepted and not-too-distorted economic analyses) showed a substantial benefit of the breeder over LWR or fossil plants in the near term.

Also tending in several ways to increase the cost of the breeder is the general argument that breeders must be deployed early in order to gain experience and in order that their (not very great) breeding rate provide the plutonium stock to support exponential growth of the breeder economy. The preferable alternative, as I have described above, is to deploy breeder reactors of low total inventory, with initial cores of MEU (medium-enriched uranium). We have a technology to do this now; we could do this now; we should do this when the resource cost of uranium supply to an LWR becomes high enough to outweigh the greater capital costs of the breeder.

Note that additional flexibility is available in this way. For instance, if an economical module of breeder fuel reprocessing plant would handle the continuing needs of 50 breeders, approximately two such plants would have to be built every three years to handle the 30 LMFBRs deployed per year under the assumptions of Figure 1. But the construction and actual operation of these reprocessing plants might economically be delayed several years in view of the fact that the early breeders could be supplied for several years with fresh MEU cores, building a stock of spent breeder fuel which could be economically processed by the plants which will come into being about the time of breeder introduction. Spending delayed is almost as good as spending avoided.

Dr. MILLS: The meeting is open for questions.

QUESTION: Your thesis, if I follow it, is to go ahead with light-water reactors, there's no rush to develop the breeder until we can come up with better ideas, and somehow after all the laboratory work and studies, we'll come up with something that's commercial that will compete with light water reactors, and then we'll be off and running.

What is your scenario from that small-scale laboratory work to commercial deployment without going through a demonstration scale of engineering technology, which is really what the Clinch River Plant is all about?

DR. GARWIN: That's not my position. My position is that even if there is no improvement of breeder reactors, we have the knowledge now to go through 30 years of engineering development and prototypes and early use, starting in the year 2000 or so, so that in the year 2030, 2040, we can have a very large breeder industry. So I don't need to do anything in the meantime.

But I do think it's a terrible waste of these 30 years time not to look for better concepts so that when we do deploy breeders we can deploy the best breeder. I certainly don't say we need something better than the sodium-cooled fast breeder. We just can't use it now; to deploy it now would increase the cost of electricity, without corresponding benefits.

QUESTION: Where do you bring the talent and the technical capability out of the woodwork by the year 2000?

DR. GARWIN: Well, may I remind you, there wasn't any nuclear industry until 1942, and we had a very considerable nuclear industry in a country which was not nearly so technologically advanced by the year 1960, 18 years.

QUESTION: Well, it wasn't until 1970; we took over 30 years.

DR. GARWIN: But that's starting from nothing, acquiring knowledge. That knowledge now exists. The idea that we have to keep the particular aircraft companies, the particular manufacturers going in this long interim in order to preserve the knowledgeable people, I reject. You can do it later on. You build the capability as you need it.

We'll be building light water reactors during that period. People won't forget -- either nuclear physics or neutronics, and when we need the sodium technology, we will have been working on it -- not just in the laboratory at bench scale, but in engineering test facilities. We have a very major, separated-function test program, which other countries really don't have, and I think that's the right way to do it.

But why should you hasten the day of high cost electricity by deploying before you need the thing? My position is not that we need to have a better reactor; my position is that we ought to delay before we deploy a higher cost technology, and we can use that time for product improvement. If you don't want to use the time for product improvement, be my guest.

QUESTION: Mike McCormack last night came up with a date of 1990, based on certain sets of arithmetic. Were you there last night?

DR. GARWIN: No. I couldn't be here.

QUESTION: All right, the arithmetic very simply, was that we would have perhaps 400 light water reactors by the end of the century. Each reactor uses about 6,000 tons of uranium, and looking at the resource level, we would have to be in a position where we ought to be able to afford a breeder by year 2000 because there won't be enough uranium to supply lifetime fuel requirements for reactors built after that time. Could you comment on his selection of that date? How do you feel about it?

DR. GARWIN: I think it's early.

QUESTION: Well, why?

DR. GARWIN: It's early because he hasn't included any of the improvements in light-water reactor fuel usage. It's early because he's assumed that one runs every one of those LWR's to completion, which is madness.

If the cost of uranium increases, eventually, then you shut down a reactor, not because it's outlived its useful life of 30 or 40 years, but because fuel has gotten more expensive -- just as you shut down a gas-burning plant or an oil-burning plant, because you can't afford the fuel any more.

And if you look at the discounted present value of the last ten years of operation of an LWR, you don't lose very much by shutting it down early. That's of course, what determines the 30-year useful life. You shut it off, although the day before you shut it off, it's working fine. You shut it off. Why? Because it's economical to do so. The maintenance costs will be higher, the inspection costs -- we will have better technology. It's just a matter of economics in the utility industry.

So I don't need it at that time. If we do need it, then we can work a little faster.

QUESTION: But the Nuclear Regulatory Commission requires a 30-year fuel commitment before approving reactor construction.

DR. GARWIN: Well, that's a totally arbitrary rule. You can build a fossil-fuel-fired plant without having a lifetime supply of fuel. And there's nothing in the public safety which says that you have to have a lifetime supply of uranium.

Furthermore, you don't have to have a contract for enrichment. If you did, it's not clear that your supplier would provide. You know, these contracts where you buy from Westinghouse and you don't get it.

So, these things can be changed; they can even be changed by the Nuclear Regulatory Commission, they can be changed by the Congress.

QUESTION: They have generally, in the past few years, tended to go towards minimizing the environmental risk which means that if you're going to have to have a plant which demands a certain amount of front-end fuel cycle, get as much as you can out of it in terms of economic benefit. And I think that's the basic judgment for that rule. Now I agree -- they might very well change it.

DR. GARWIN: Yes, they might go back to the reason why they ruled and modify the rules.

QUESTION: But I would hate to base current policy on a proposed change in rules in 1990. If you're going to change the rules, try to change them now.

DR. GARWIN: I agree with that. We have a <u>N</u>ational <u>U</u>ranium <u>R</u>esource <u>E</u>valuation program ("NURE") which hasn't been doing its job, in my opinion. And one of the important benefits of that is not to find the uranium -- but to see how much uranium there is, and so to determine when one has to deploy the breeder, because it tells you when you will run out of economical uranium.

So I am very much in favor of that, but I think we ought also look at the arbitrary rules which delay the construction of light water reactors (or breeders), which take so long to license. We ought to do a better job on licensing other technologies, too.

QUESTION: Suppose the uranium estimates are seriously in error, how could we then respond?

DR. GARWIN: I don't think it's a mistake to rely on the market. I think that each individual utility can look at the supply of uranium, can look at the future availability of breeder reactors. If the cost of uranium gets high, then, sure, they'll turn in perfectly good plants as they're going to turn in perfectly good oil plants, and that is all included in the lowest expected cost of electricity.

You don't get the cheapest electricity on the average, and the best growth rate in the country, by choosing the safest route. But you want to choose a route that is not disastrous -- and someplace in between is probably the best business and social decision.

QUESTION: You've been discussing more efficient uses of uranium in converter reactors. What kind of factor do you think that can improve our use of uranium by now, or in the next decade?

DR. GARWIN: Well, they are very different. On the isotope separation, one produces a product which is just like the present low-enriched uranium, 3.5% U^{235} in U^{238}, and instead of going from 0.71% down to 9.25% tails, one might go to 0.05%, at reduced cost.

That would be about a 40% or 50% increase in uranium supply. That's useful. More important for the scheme that I propose here is that the cost of isotope separation is probably going to come down by a factor of 4 or 5. (You don't have to count on it; it's affordable, anyhow.) And that will come about from deployment of laser isotope separation processes.

Now, improved fuel economy for light water reactors. There are schemes proposed for deploying novel kinds of reactors. I don't favor those. I think it's just impractical to license those new things; to build up a whole manufacturing capacity for them; to run them in a special mode, to fragment the industry, and so on.

But I think there are things that can be done to improve fuel utilization in the light water reactors, and that might be 30% or so improvement.

QUESTION: You emphasized the fuel side of the ledger, but what about the capital costs projection?

DR. GARWIN: Well, capital cost is the very great uncertainty in breeder reactors, and I said that in the prototype large breeder study, the capital cost differential was some $600 million between a light water reactor and a fast breeder.

QUESTION: What are the absolute values?

DR. GARWIN: Well, I think it was about $800 million for the LWR, and $1400 million -- there were three or four studies, and they differed. But they weren't all that disparate. Nobody said that the fast breeder was going to be cheaper, although there is no fundamental reason why fast breeders couldn't eventually be cheaper somehow than light water reactors. They dont' have pressure vessels, a lot of other things on them are different.

The old AEC program, in my opinion, was really misdirected in trying to eke out a couple of percentage points greater thermal efficiency, and so they got into what was also, in my opinion, a high risk program of thermal creep in the core, which could have been avoided by backing down in temperature by fifty degrees or so.

But they insisted on doing this, and I think it made the development program most costly, the reactors more costly -- and the whole process less certain.

QUESTION: If we can relax, as it were, until the year 2000, how is it that the Europeans are going full tilt? The French, British ...

DR. GARWIN: Well, that's because nobody over there who knows anything about the industry is outside the industry. It's the British and the French who built the Concorde supersonic transport, and they built it by cheating their governments, by tieing themselves together in a transnational consortium so that the British, when they wanted to back out, could not; the French told them, "You could back out, but you still have to pay" -- and you have these monsters now which didn't cost $300 million for development, which was the prediction -- but $3 or $4 billion, and on which the British Airways and Air France lose I think about $50 million per year each.

Now that's the sort of thing that you get from those societies where everybody who knows anything about the technology is either in the industry, or not in the government -- and opposing the government entirely.

In the United States, there is a lot of support for the government by people who might be in the industry, or who were in the industry and tried to help make decisions.

So the British and French are wrong, in my opinion -- but I'm glad they're doing it, because when they develop fast breeders, they will be anxious to sell them to us, and we may need to buy them. It's a good thing to have the French building the Super Phenix.