00/00/79 "The Role of the Breeder Reactor," a chapter for the book, <u>Nuclear Energy and Nuclear Weapon Proliferation,</u> ed. F. Barnaby, et al., pp. 141-153. Publisher: Taylor and Francis, Ltd., London 1979. (000079.RBR)

Nuclear Energy and Nuclear Weapon Proliferation

sipri

Stockholm International Peace Research Institute

Taylor & Francis Ltd
London
1979

000079.RBR

Paper 9. The role of the breeder reactor

R. GARWIN

Square-bracketed numbers, thus [1], *refer to the list of references on page 153.*

I. 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 Non-Proliferation Treaty (NPT) and other efforts to control the spread of nuclear weapons) that world security (and especially regional and local security) is likely to be imperilled if nuclear weapons spread to many more nations.

II. Types of nuclear weapon proliferation

We have already distinguished between (*a*) national, and (*b*) non-national possession of nuclear weapons. In addition we should also distinguish between (*a*) one weapon versus many, and (*b*) optimized nuclear weapons versus terror weapons. Furthermore, one can have (*a*) overt possession of nuclear weapons; (*b*) covert possession of nuclear weapons; (*c*) possession of separated plutonium or other fissile material in metallic form, under international safeguards which would warn of diversion; (*d*) possession of fissile material in less immediately usable form; (*e*) possession of spent fuel rods, together with fuel reprocessing facilities; and (*f*) possession of fresh breeder fuel without reprocessing capability.

Even this familiar but incomplete list reminds us of the complexity of the proliferation problem. Other considerations are the sizeable effort required to design, build and test the non-nuclear portions of the weapon, and the political incentives or disincentives to proliferation.

III. Breeder fundamentals

The production of nuclear power in the light water reactor (LWR) is possible only because the typical fission event produces more than one neutron. On average, precisely one neutron from each fission goes on to cause another fission.

The fission rate and hence the reactor power (200 million electron volts (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 per cent of the neutrons from fission are delayed one 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 two neutrons per neutron absorbed. Thus, from the earliest days of fission, the possibility of a breeder reactor, in which one neutron per fission would continue the fission chain reaction in the reactor and another neutron per fission would be captured in U-238 eventually to give another fissile atom of Pu-239 has been recognized. Neutron energies above about 0.4 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 entire 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'—that is, 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. On the other hand, a nation engaged in long-range planning, especially one with internal pressure groups both in favour of and against getting 'closer to a nuclear weapon capability', could well opt for breeder reactors prematurely simply because of their proliferation potential. Without exhaustive discussion of all cases, we note that while for the LWR, fuel reprocessing and recycling are optional (and at present probably uneconomical), they are essential for the breeder. Furthermore, recycled 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 stock (as well as its net production) must be purified and recycled if the breeder is to do its job. From the points of view both of scale of operations required and of protection against penetrating radiation, it would be more convenient to extract the 15 per cent Pu content from breeder fuel than the 0.6 per cent Pu from LWR spent fuel.

Nuclear power benefits

My own judgement, expressed in *Nuclear Power Issues and Choices* [1], is that electrical energy from LWRs is competitive with electrical energy from fossil fuel (coal) in large countries with a strong electricity 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 hazards of LWRs can be managed (primarily by delaying reprocessing and recycling 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 20 or 30 years. However, by the year 2100, the known reserves of high-quality coal might 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 effects 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 less national dependence on external 'sources of energy'. Recent prototype large breeder reactor (PLBR) 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 economies were achieved in LWR operation. One economy in the present fuel cycle that is likely within the next 10 years is a reduction in the cost of isotope enrichment from the present $80–100/kg SWU to around $20/kg SWU.

But perhaps a nation should buy one or more breeder reactors in order to be independent of a continued supply of low-enriched uranium (LEU)—about 3 per cent 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 10 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.

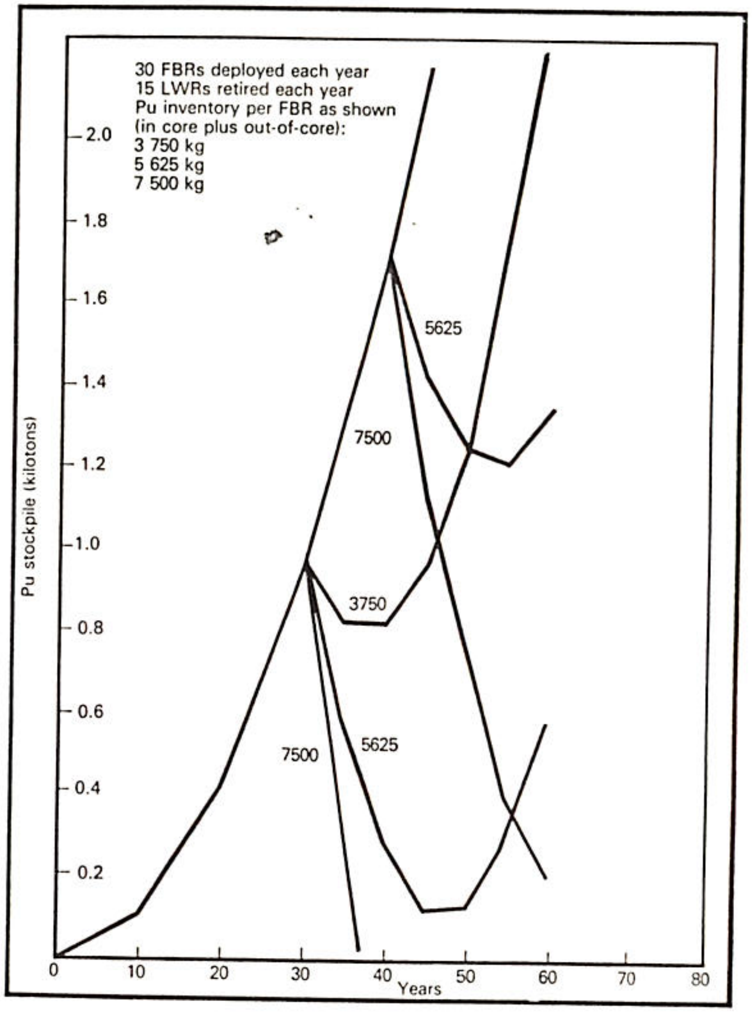
On the other side of the balance, possession of an operating LMFBR or other breeder reactor in no way guarantees energy independence. For example, the majority of countries operating LMFBRs will probably not have reprocessing and refabricating plants on their territories. Breeder reactor economics are 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 eight-year stockpile of LEU (at an 8 per cent annual interest rate) would only double the LEU-associated portions of the energy costs (raising the busbar cost of electricity by 20 per cent). An LMFBR, on the other hand, is estimated to have a fuel inventory out-of-core ranging between 150 per cent and 50 per cent 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 4 500-kg and 7 500-kg Pu. If one required a similar independence of eight 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 on the cost of electricity but on the feasibility of deployment of breeder reactors. Figure 9.1 shows for the United States the plutonium stockpile 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 cent 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 deployment begins.

Clearly, there is an economic incentive for a nation operating breeder reactors to have indigenous reprocessing capacity, but this would forgo 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.

Figure 9.1. US civilian plutonium stockpile versus year of FBR introduction



Note: The year of introduction of the FBR is taken as 2000 or 2010, with three assumptions about the required Pu inventory of each FBR. This figure was given to the author by the Director of Energy Research (DoE), 20 June 1978. Note that while NASAP assumes "a 3 750-kg FBR", a memorandum of 7 July 1978 to the Director of Energy Research (DoE) from the acting Director, Office of Fuel Cycle Evaluation (DoE) notes only that "it is reasonable to assume that lower inventory FBRs, such as the 5 625 kg/GW(e) design shown in your curves, could be available if required".

IV. The proper role of the breeder reactor

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, or 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 several 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 which produces most nuclear power uses uranium enriched to about 3 per cent U-235 from its normal isotopic abundance of 0.7 per cent. With an enrichment plant leaving 0.25 per cent 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 per cent of the time, consumes in its nominal 30-year life 6 970 tons of uranium ore.[1] Thus only about 502 1 000-MW(e) reactors could be fuelled 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 currently 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 (*a*) find and mine considerably more uranium at an economically and environmentally acceptable cost; (*b*) develop and deploy nuclear power plants with a substantially smaller appetite for uranium; or (*c*) provide an alternative source of fissile material to the simple extraction and enrichment route.

Start-up on LWR plutonium

A substantial fraction of neutrons even in an LWR are captured in U-238 to produce additional fissile Pu—typically about 60 per cent—some of which is later fissioned. In fact, 44 years of operation (of a 1 000-MW(e) LWR at 80 per cent capacity factor, assuming that the LWR operates to recycle its uranium) together with 8 536 short tons of U_3O_8 are required to produce the net 7 500 kg of fissile plutonium needed to start one 1-MW(e) LMFBR. Had the Pu also been recycled in the LWR, 1 530 tons of U_3O_8 would have been saved, together with 1 020 MgSWU,[2] but, of course, no Pu would then have been available for investment in a breeder.

The two extremes for fuelling 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 use it to fuel one LMFBR. The product plutonium would be idle for an average of 22 years (alternatively, the discounted present value of the 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 assumed 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.

V. What to do?

The Report of the Nuclear Energy Policy Study Group, *Nuclear Power Issues and Choices*, discussed, among other things, the role of nuclear power in the US economy. It notes:

> 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. [1a]

---

[1] A 'ton of uranium ore', as used in this paper, means a short ton of yellowcake (U_3O_8) 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 (769 kg) of uranium metal. Except as noted, all data dealing with alternative nuclear fuel cycles are taken from reference [2].

[2] 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 [2] assumes a cost of $75 000 per Mg SWU—approximately that charged now by the 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 reduction in cost by a factor of four and a substantially greater reduction in energy requirements.

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 programme.

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—that is, available for the replacement cores while the first core is being reprocessed) of U-235 as 20 per cent 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 would be less valuable. This would be a minor requirement to incorporate into the reprocessing plant.

At 0.25 per cent tail concentration of U-235, the assumed amount and concentration of U-235 would be obtained from 3 110 short tons of U_3O_8. 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 per cent capacity factor even if there were no excess plutonium production in the mature LMFBR. Thus, instead of fuelling 500 LWRs for thirty years, an assumed uranium resource of 3.5 million short tons of U_3O_8 would fuel 1 077 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 greater 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 above, would take a long time. Scenarios exist which show a transition from LWRs to LMFBRs within the limitation of available plutonium; these show a 30-year 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 new LWR construction by LMFBRs, by virtue of the flexibility of U-235 investment, as needed, of LMFBRs.

Table 9.1. Economic penalty of starting 1 000 MW fast breeders with enriched U-235

	Water reactor plutonium	20 per cent U-235 in uranium (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 ($/kg fissile)[a]	19 900	31 000
Total cost of fissile material ($mn)	149	349
Loss of breeding-gain fissile production		
(kg fissile Pu)	0	1 700
($mn)	0	34
Contribution to fuel cycle cost levelized over 30-year breeder plant life[b]		
Purchase of fissile material for start-up (mill/kWh)	2.2	5.3
Loss of breeding-gain fissile production (mill/kWh)	0	0.3
Relative total (mill/kWh)[c]	2.2	5.6
Levelized fuel cycle cost (mill/kWh)[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/year.

[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/kWh [2a].

Cost of LMFBR start-up 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 fuelling 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 9.1 assumes that water-reactor plutonium is bought at the price which would be paid for it for recycle into water reactors. (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 9.1 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 reduction by a factor of four 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 will probably 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 smaller amount of Pu for conventional equilibrium LMFBRs). But substantial cost reductions are 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 costs are incurred in order to obtain the net breeding excess of 8.4 per cent (net annual fissile plutonium production divided by fissile *core* inventory) which results in the 3.3 per cent 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 start-up of 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 ratios such as might be obtained with modified Canadian heavy water (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: (*a*) an arbitrary deployment rate (independent of LWR or breeder history); (*b*) lower-cost, greater safety potential, possible 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 higher conversion ratio; (*c*) earlier availability of a useful breeder; and (*d*) potentially increased benefits from lower-cost advanced isotope separation techniques and from lower inventory breeder/converters. The costs 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 breeders with U-235 instead of Pu has some modest anti-proliferation effect in comparison with the normal view of the fast breeder reactors.

1. Initial fabricated cores would require isotope enrichment to yield weapon-usable fissile material, as is the case with LWR fuel or natural uranium.
2. Pu recovery from irradiated LWR fuel could and should be deferred until a large number of U-235 invested fast breeder reactors 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.
3. Such a system is amenable to so-called 'Civex-type' fuel reprocessing (if the Civex concept could be developed as a practical, economical process), which, by reducing the reprocessing delay, could also reduce the out-of-core fissile requirement and thus the U-235 cost.

Implications for the US breeder R&D programme

Already mentioned is the possible benefit of redesign of the LMFBR core to minimize U-235 inventory and thus reduce costs. Additional analysis and some experimentation should be done on this possibility. The likely scale of these benefits is not known (or if known, is not published).

New interest might focus on the molten-salt breeder (MSBR) 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 start-up. 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 U_3O_8 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 cent 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 a far higher cost for the small amount of uranium needed to continue operation of these breeders than it can for the large amounts of U_3O_8 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.

VI. *Conclusion*

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 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. 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 will encourage the broadening of the present breeder R&D programme 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 reduction by a factor of four 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 electro-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.

Deployment of breeder reactors

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 short 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 described above, is to deploy breeder reactors of low total inventory, with initial cores of medium-enriched uranium (MEU). We have a technology to do this now; we could do it now and we should do it 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 could 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 9.1. 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 coming into being about the time of breeder introduction. Spending delayed is almost as good as spending avoided.

References

1. Keeny, S. M. *et al.*, ed., *Nuclear Power Issues and Choices* (Ballinger Press, Cambridge, Mass., 1977).
   (a) —, 'Energy and the economic future', chapter 1, p. 68.
2. Hebel, L. C., 'Report to the APS by the Study Group on Nuclear Cycles and Waste Management', *Reviews of Modern Physics*, Vol. 50, No. 1, Part II, January 1978.
   (a) —, p. 7.