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THE ACCELERATOR BREEDER, A VIABLE OPTION FOR THE PRODUCTION OF NUCLEAR FUELS*†

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Introduction

Despite the growing pains of the US nuclear power industry, our dependence on nuclear energy for the production of electricity and possibly process heat is likely to increase dramatically over the next few decades. This statement dismisses fusion as being entirely too speculative to be practical within that time frame.

Presently, Light-Water nuclear Reactors (*LWR's*) burning fissile U-235 supply ~12% of our electric power generation. These reactors are inefficient as they utilize only about 1% of the energy available in uranium. Although fertile material (U-238) is plentiful, the amount of economically available and naturally occurring fissile material (U-235) is limited. The Fast Breeder Reactor (FBR) will, however, change that. When developed and implemented, the FBR will allow for essentially the full utilization of the energy available in U-238, thus assuring our electrical energy needs for centuries to come. The FBR does, however, require an initial fissile inventory of ~4 tons (Pu-239 or U-235). During its operating life, it will then consume converted fertile U-238 and, possibly, achieve a net Pu-239 surplus production of ~200 kg/yr (this assumes a 20-year doubling time).

We will not attempt, here, to speculate about the future growth of our nuclear electrical power generation capacity, nor about the estimated uranium reserves in the U.S. Suffice it to say that there is general agreement that sometime, between the years 2000 and 2050, fissile material will be in short supply whether it is to fuel existing LWR's or to provide initial fuel inventory for FBR's.(1) The accelerator breeder could produce the fuel shortfall predicted to occur during the first half of the 21st century.

The accelerator breeder offers the only practical means today of producing, or breeding, large quantities of fissile fuel from fertile materials, albeit at high cost. Studies performed over the last few years at Chalk River Laboratory(2,3) and at Brookhaven National Laboratory(4,5) have demonstrated that the accelerator breeder is practical, technically feasible with state-of-the-art technology, and is economically competitive with any other proposed synthetic means of fissile fuel production.

This paper gives the parameters of a nearly optimized accelerator-breeder system, then discusses the development needs, and the economics and institutional problems that this breeding concept faces.

Accelerator-Breeder Parameters

As seen on schematic Fig. 1, the accelerator breeder facility consists of three main components: a) the accelerator, b) the target, and c) the Balance Of Plant (BOP) including the steam generators, turbines and alternators, etc.

Basic parameters of the accelerator breeder are shown in Table 1. These parameters were chosen conservatively, and are self-explanatory. Some numbers invite comments however.

The choice of accelerator final energy is quite arbitrary. It was chosen as a maximum consistent with rastering magnet design. However, this number can be changed to suit material production goals. Above ~1000 MeV, Pu-239 production varies linearly with beam power at a rate of about 4.5 kg/MW/yr, this assumes a 70% plant factor. This reference design, at 450 MW beam power, will produce 2000 kg Pu-239/year. Target design considerations indicate that proton beam energies, 1000 MeV<E<2500 MeV, are practical.

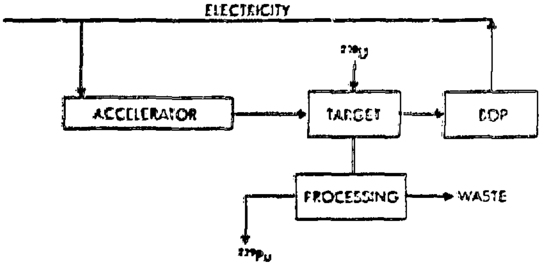

Figure 1. Schematic Accelerator-Breeder System

TABLE 1
ACCELERATOR BREEDER REFERENCE CONCEPT PARAMETERS
2000 kg PLUTONIUM-239 PRODUCTION CAPABILITY
70% PLANT FACTOR

Accelerator (Proton Linac)	
Final Energy	1500 MeV
Beam Current	300 mA
Duty Factor	100 %
Efficiency (Beam Power to ac Power)	50 %
Injection System	
Bucket-Type Ion Source, dc Accel.	100 keV
75 MHz RFQ Accel.	0.1-1.5 MeV
150 MHz Alvarez Accel.	1.5-150 MeV
450 MHz Coupled Cavity Accel.	150-1500 MeV
Average Gradients	~2 MeV/m
Total Accelerator Length	~1200 m
Target (H_2O Cooled UO_2)	
Power Generated	3000 MW(th)
Size (x,y,z)	5x3x2 m
316 SS Pressure Tubes	800x0.15 m diam
Coolant/Fuel Volume Ratio	0.5/1
Fuel Inventory	400 tonnes
Max. Coolant Temperature	300°C
Max. Coolant Pressure	2000 psi
Peak/Average Power Ratio	1.5/1
Peak-Power Density	180 W/cm^3

The accelerator proton beam current of 300 mA cw was chosen as the maximum current we think can be accelerated, without excessive beam loss, in a well designed state-of-the-art linac. This current is far from theoretical space charge limits. At chosen frequencies of 150 and 450 MHz and injection energy of ~2 MeV, theoretical current limits are >1 A for 50% aperture filling factor. The major question of beam loss control has been analyzed. Operation of a 300-mA, cw-proton linac with hands-on maintenance requires continuous losses to be kept <1 nA/m. This will be accomplished by long drift sections (10 to 20 m) at several locations down the length of the linac. Those drift sections will be equipped with heavily shielded, remotely handled, collimators. Those particles, which otherwise would be lost along the accelerator, will be scraped at these discrete points. Beam rebunching will be required after each drift space.

Electrical efficiency of the accelerator breeder is defined as the ratio of beam power on target to ac

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electrical power feeding the system. We have estimated this efficiency to be 50% for a 300 mA linac assuming rf power amplifier (klystron) efficiency of 70%. The accelerator breeder is designed as a break-even system, namely the thermal power generated in the target will be sufficient to produce the electricity required to power the accelerator and all auxiliary equipment. It is of interest to note that efficiency is primarily a question of economics as reflected by capital investment. It turns out that 75% of the total facility cost is generated by the power conversion and conditioning system, that is, going from target thermal power to rf power. Thus, any increase in power conversion and conditioning efficiency is highly desirable.

Other accelerator parameters have been discussed earlier.(5) Although this accelerator design presents challenging opportunities for qualitative improvement and new ideas, the system put forward for this application is conventional. The large scale of the project and its application to energy production will, however, provide a real incentive for substantial engineering development to optimize cost, efficiency, and reliability.

The target deserves a more detailed description as it poses the greatest challenge to the technical feasibility of an accelerator breeder system. The target design must satisfy all the requirements of a power reactor while being subjected at the same time to an external, nonuniform, anisotropic proton-beam-induced neutron source. An optimized target design will then provide for a maximum material production rate, while satisfying limitations imposed by allowed peak-power densities, radiation damage to structural materials, cooling rates, etc. The target design developed at Brookhaven offers the only approach to near optimization of all major requirements. The concept is shown in Fig. 2. The target consists of an assembly of many pressure tubes (~800) containing fertile material pins and coolant, of a design very similar to that of the Canadian CANDU reactor. As a matter of fact, it utilizes the same technology allowing for on-line refueling and fuel shuffling.

The target face (pressure tube assembly) measures 3x5 m, and is 2 m deep. The entire assembly is contained in a "Hohlraum" triangular-shaped vacuum vessel lined with additional fuel material and reflector to minimize overall neutron leakage.

To minimize peak-power density and radiation damage, the 450 MW proton beam is first defocused into a thin ellipse (height of pressure tube assembly), then rastered across the target face at ~1 kHz, as shown in Fig. 3. Thermal effects due to rastering are acceptable. The proton beam does not traverse any window before striking the pressure tubes themselves. At this point, we have achieved a nearly uniform power deposition on the front face of the target with proton, current density of the order of $2\ \mu A/cm^2$.

The thermal power generated in the target has three main sources: proton beam ionization losses, U-238 fast fission energy, and energy produced by Pu-239 thermal fission (burning) of the material being produced. The first two sources of thermal energy are fixed with maximum power produced near the front of the target; this amounts to about one-third (~1500 MW(th)) of total power. The remaining power (~1500 MW(th)) is produced by judicious choice of fuel enrichment gradients with respect to target depth designed to achieve uniform power generation. The accelerator-breeder target can thus be viewed as a subcritical, driven power reactor with total power output tailored to match the input power requirements to the accelerator.

The Balance Of Plant comprising the steam generators, turbines and alternators, and heat rejection system, will, for all practical purposes, be identical to that of equivalent capacity power plants.

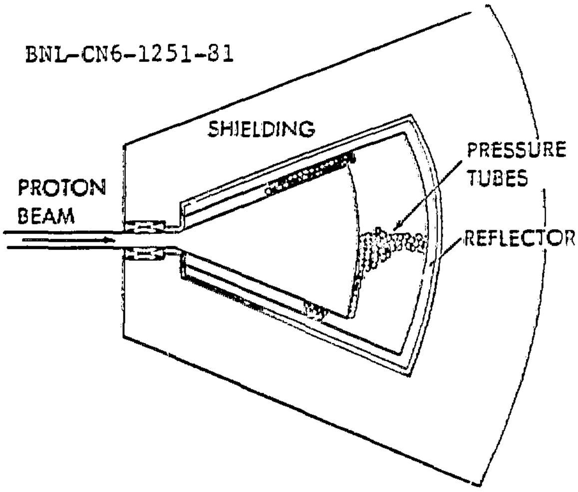

Figure 2. Schematic A-B Target Cross Section

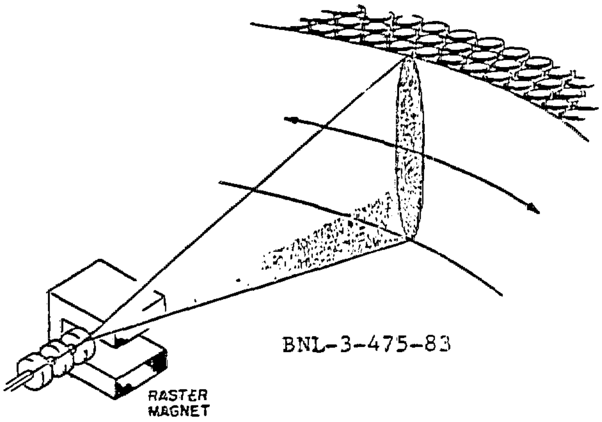

Figure 3. Schematic Beam Rastering System

Development Needs

The entire accelerator breeder concept design presented here, including the target, utilizes existing, state-of-the-art technology. This means that given support, a demonstration facility could be built with low technical risk, within a period of ten years, and commercialization could start effectively within twenty years. That is not saying that research and development are unnecessary. On the contrary, high efficiency and reliability required to guarantee 70% plant factor and economical operation, and the large scale of a production facility requiring >500 MW cw rf power are strong incentives for technology advances. Figure 4 outlines what is deemed the necessary, phased engineering development program culminating with the operation of a demonstration facility. It is a ten-year program estimated to cost MS ~1000 (1983). This must viewed against the cost of a 2000 kg/yr production facility at MS ~2500 (1983). Beside structure development, the major R&D program for the accelerator should be directed toward highly-efficient, cost-effective conversion of ac/rf power. Any increase in efficiency and reliability promises a large payoff in capital investment and operations costs.

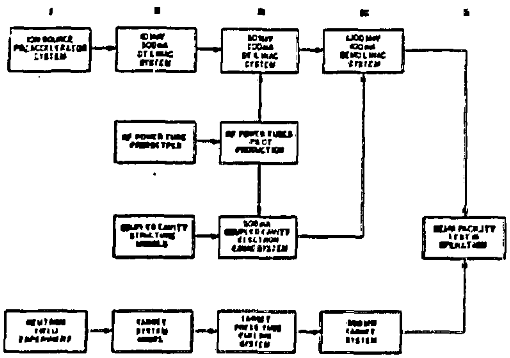

Figure 4. A-B Development Program Steps

Economics

A realistic cost estimate for the construction of a commercial accelerator-breeder facility (1.5 GeV, 300 mA, 2000 kg Pu-239/yr) has been performed by United Engineers and Constructors. The capital investment price tag is M$ 2500 (1983). This is high, it is about the same cost as that of a Liquid Metal Fast Breeder Reactor (LMFBR), or about twice that of a LWR. In addition, operation of the plant is estimated at about M$ 50 (1983) yearly.

Using 10% depreciation charge and adding the cost of operation bring the cost of Pu-239 production by accelerator breeding to ~$150/g. This number does not include accrued interest charges during construction. This is expensive! The present cost of enriched fuel is about $30/g U-235.

Obviously, the accelerator breeder will only become competitive when scarcity of U-235 forces us to a breeder economy. When this will happen, it is unclear. As mentioned earlier, it is expected to occur sometime during the first half of next century. An absolute economic comparison cannot be made at this time, as there are too many imponderables. We can, however, make an objective relative economic evaluation based purely on capital investment requirements, since it is the driving factor in the cost of nuclear generation of electricity. Table 2 shows the relative incremental cost of electricity at the power plant for breeders-burners systems in 1983 value normalized to existing once-through LWR's.

TABLE 2
RELATIVE ECONOMIC COMPARISON
INCREMENTAL ELECTRICITY GENERATION COST OF BREEDER

SYSTEM	ONCE-THRU LWR	5 LWR + 1 AB	2 FBR + 1 LWR	1 HFB + 10 LWR
Conversion Ratio	0.6	0.6 —	1.05 0.6	— 0.6
Power MW(e)	1000	5x1000 —	2x1000+1000	1000+10x1000
Cost (1983) M$	1250	5x1250+2500	2x2000+1250	5000+10x1250
Cost/1000 MW(e) M$	1250	1750	1750	1750
Fuel Cost	0	0	0	0
Normalized Cost	1	1.40	1.40	1.27

This comparative evaluation assumes that additional fuel costs will be zero since all systems require the same processing and fabrication facilities. The only exception would be the once-through LWR which must obtain its fuel at enrichment plants at a cost of $30/g U-235. Thus, the cost of fissile material will have to increase by a factor of five, before the accelerator breeder can compete with the once-through fuel cycle. The comparison is made for the in-place plutonium fuel cycle economy and burner reactor conversion ratios of 0.6 requiring 400 kg Pu-239 fuel/yr. A similar comparision can be made for the thorium-fuel cycle with somewhat different results. Unit cost for the various systems come from U.E.&C.

The results indicate that on a relative basis, and present day economics, electricity produced with accelerator-bred fuel would cost 40% more than the once-through cycle, whereas fusion hybrid may be somewhat lower, 27%. Actually, the incremental electricity cost to the consumer could be lower depending on the fraction of total costs due to other factors, e.g., uranium mining and enrichment, wheeling charges, etc. In addition, improvements in burner reactor efficiency could have an added strong influence in lowering these increments by as much as 40%. for a conversion ratio of 0.8.

It is interesting to note that FBR produced electricity is in the same ballpark as the accelerator-breeder-LWR combination. It is, however, different in that it is not truly a fuel producer. It is also clear that, if and when fusion becomes commercial reality, it will be the leading contender for large-scale fissile fuel production.

Institutional Problems

It is clear that accelerator breeding is not at this time. an economical source of nuclear fuel for energy production. Will it be in the future? This must be viewed from two angles.

Accelerator breeding, like other nuclear competitors, is a high-technology, capital-intensive approach to energy production. The long-lead times required to build these plants in the present inflationary climate add so much financing costs that these energy systems are not cost-effective anymore. This is not being helped by the country's attitude toward nuclear power. If this argument holds true for thermal reactors and accelerator breeders, it is even more applicable to the higher technology of the breeder reactor and fusion devices. Under this assumption, there is no future for our nuclear industry, it will be cheaper to burn oil at $300/barrel or coal at $1000/ton.

On the other hand, if for some unimaginable reason we manage to set our nuclear house in order, the accelerator breeder must be viewed as competing against fusion-hybrid as a fuel producer for fission reactors which appears cheaper, but speculative, both in terms of costs and implementation. However, the accelerator breeder future must be viewed in the light of vested interests in this country of the breeder reactor and of the fusion reactor program. Both parties view accelerator breeding as potential competition for finite development funds. Thus, the climate to pursue development of this technology is not very favorable.

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