IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

THE ACCELERATOR-BREEDER, AN APPLICATION OF HIGH-ENERGY ACCELERATORS TO SOLVING OUR ENERGY PROBLEMS*

P. Grand, K. Batchelor, J.R. Powell
M. Steinberg

Department of Applied Science
Brookhaven National Laboratory
Upton, N.Y. 11973

Summary

The rising costs of U235 and other fossil fuels, and the schedule for implementing the breeder reactor have renewed interest in the utilization of accelerators for breeding U233 or Pu239. This paper discusses some of the basic accelerator parameters and choices to be made in order to meet the technical and economic requirements of such a facility.

Introduction

The idea of converting fertile materials into fissile fuels (e.g. Th232 into U233, or U238 into Pu239) utilizing spallation neutrons produced by a high energy (e.g. 1-2 GeV) proton or deuteron accelerator and an appropriate target is not new. The first application of the concept was the MTA[1] (Materials Testing Accelerator) at Lawrence-Livermore Laboratory (1949-1954). This machine was a prototype for a full scale production facility to produce Pu239 for the nuclear weapons program. This project was abandoned when it was decided to use the Savannah River Reactor to produce the needed plutonium. However, the MTA did operate successfully and demonstrated the viability of the concept. In 1952 W.B. Lewis[2] in Canada considered the idea for power production.

The lack of interest in the accelerator breeder in the intervening years was not therefore due to the technical difficulties to be faced, but rather to the simple fact that, up to now, the cost of producing fissile fuels in this fashion was prohibitive. Even now, the economics of the accelerator-breeder are unclear. However, the rapidly rising cost of U235 due to increasing demand and depletion of high grade uranium ore reserves have rekindled the interest in this technollogy [3,4]. At today's price of $40/lb for U_3O_8, the cost of U235 is approximately $30/g, or about 5 mills/kwh. Very preliminary cost estimates for accelerator-bred fuel indicate costs of $100 to $200/g which is not competitive. However, depending on assumptions made on future costs, the accelerator-breeder can be shown to be either very desirable or completely uneconomical.

In addition to the economic argument, the accelerator-breeder is being considered as one possible option amongst others in the continuing review process of our whole nuclear energy policy. Under consideration are such things as: non-proliferation and safeguard aspects, safety, scheduling and viability of the upcoming LMFBR (Liquid Metal Fast Breeder Reactor), future fueling needs of LWR etc. It is even being suggested that the scheme could be utilized as a subcritical, driven reactor-breeder instead of a pure fuel factory. This is an attractive option when considering the safety and safeguard aspects.

The Accelerator-Breeder Concept

Figure 1 shows schematically the basic processes in accelerator breeding. One accelerates a proton (or deuteron) to a high energy (e.g. 1000 MeV) and directs it onto an appropriate target. Interactions with target nuclei produce many secondary particles in a cascade with ultimate production of anywhere from 40 to 60 neutrons. The available data on spallation neutron production indicates that the proton energy should be 1 GeV or greater to achieve efficient neutron production. When we consider a target/blanket of Th232 or U238, most of the neutrons are captured producing U233 or Pu239. The presence of this fissile material and fast fission of U238 lead to an additional neutron multiplication in the blanket. The net fuel so produced is therefore given by the breeding capture less the fission of bred fuel.

Thus, an accelerator-breeder designed for a 1 GeV, 300 mA proton beam directed onto a thorium or depleted uranium target would produce more than 1000 kg/year of U233 or Pu239 fuel. This would provide enough fuel for the support of 3000 to 6000 MW electric conventional reactor capacity depending on fuel cycle and reactor type chosen.

In addition to fuel production, the primary proton beam power of, for this case, 300 MW is converted in the target into heat. This, plus the heat produced by the cascade neutrons is estimated at about 1200 MW thermal and is available for recovery to produce electric power which in turn can be fed back to power the accelerator. Thus, it is estimated that if the accelerator efficiency approaches 50% the net power deficit to operate the facility can be made acceptably small. It is even possible that a different target design with higher gain might produce a net power surplus.

Figure 2 shows schematically a typical accelerator-breeder facility including the entire nuclear fuel cycle. Other nuclear fuel cycles options are available. A final choice for the system will depend on the optimization and choice of many parameters. In all cases, however, the accelerator-breeder centers around the ability to produce a relatively high energy (~1 GeV) very powerful and efficient accelerator to produce the hundreds of megawatts of beam required.

Accelerated Beam Parameters

Figure 3 shows the neutron yield for protons and deuterons for different particle energies. This data is not definitive, however it is good enough for the discussion that follows:

It is quite evident, from the above data, that if we chose a given neutron yield parameter or total neutron yield for a given target,we have a certain freedom of choice for the accelerator. The kind of choices available are trade-offs between types of particles (protons or deuterons), energy and beam currents. For example, taking as a base design a 1 GeV, 300 mA proton accelerator, we find that in terms of neutron production the following machines are equivalent:

800 MeV, 400 mA protons
2 GeV, 140 mA protons
800 GeV, 300 mA deuterons
1 GeV, 230 mA deuterons
1.5 GeV, 160 mA deuterons

These few examples chosen around practical linear accelerator parameters are not exhaustive, it is possible theoretically to visualize lower energies at very high

*Work performed under the auspices of the U.S. Energy Research and Development Administration.

currents or to the other extreme, very high energies at low current. It has even been suggested that the 1000 GeV Fermilab Energy Doubler be utilized for that purpose.[5]

At this time, the linear accelerator seems to be the most practical approach to producing the energetic particle beam required for the process. However, the choice of particles currents and energies mentioned above is as yet unclear and will be the result of optimizing and compromising on many factors.

The two principal factors which will dictate the accelerator parameters are the following:

1. Target Considerations

The target design is still an unknown quantity. The ongoing investigation indicates that radiation damage to materials and thermal effects will likely dictate the choice of accelerated beam parameters. For example, these problems could be solved by stopping the beam on a low-Z target (Be or Li) which may make the use of a deuteron beam desirable. Or, increasing the energy of the proton beam would correspondingly increase the particle range in the target lattice of a heavy material to make the thermal problem more amenable. In all cases, radiation damage caused by the primary beam may be the most important factor.

2. Economic Considerations

Assuming that the technical problems have been solved, then the most important consideration becomes that of economics, including both, capital investment and operating costs. Once the beam parameters have been chosen based on target design consideration, the study required to optimize the accelerator costs covers two broad areas:

a) As stated earlier, the overall efficiency of the accelerator (ratio of beam power to AC line power) has to be very high, at least 50%, in order to come anywhere near the breakeven point in the power balance for the entire facility. The resulting cost of fissile fuel produced in the accelerator-breeder is very sensitive to the accelerator efficiency. It is therefore, imperative that this efficiency be maximized by the proper choice and development of highly efficient components and AC-to-rf conversion equipment. This effort will have to concentrate especially on the production of extremely reliable and efficient klystrons and power amplifier tubes.

b) The overall efficiency of the accelerator is also sensitive to proper design choices for the machine. The energy lost in the accelerating structure will need to be minimized by optimizing shunt impedances and accelerating gradients. However, this optimization process involves such non-trivial problems as, beam loading, capital cost increments, physical accelerator length, etc.

Table I gives a flavor of various choices with resulting accelerator lengths and total rf power required. Each case is normalized to the total neutron yield produced by a 1 GeV, 300 mA proton linac. The method of calculation is an extrapolation on existing accelerators, as such it makes no claims of accuracy. A cost comparison between these different designs has not yet been made. It is not a straight forward procedure as it depends on many factors such as: accelerator structure frequency, rf efficiency, type of rf amplifiers used, plant factor, real estate etc.

Linac Design

The theory of linear accelerator design is now rather well understood.[6,7,8] No attempt is made here to delve on a detailed design. What is new however is the renewed interest in high currents, cw linacs. For the past three years, Brookhaven National Laboratory has had an ongoing study for an accelerator-based high-flux neutron source to be utilized for fusion reactor materials radiation damage.[9,10] In the course of this study we have analyzed in some detail the parameters, leading to an optimized design directly applicable to the accelerator-breeder.[11]

Figure 4 shows the maximum beam current allowable (derated by ~50%) vs. initial accelerating structure frequency for beams matched in both transverse and longitudinal phase spaces, an injection energy of 0.75 MeV and a maximum quadrupole pole-tip field of 10 KG. These curves were calculated for a given set of conditions, they vary to some extent with different choices of beam emittances, injection energy, accelerating gradients and other parameters. The sets of frequencies shown in Table II were taken from Fig. 4. In all cases the initial frequency is increased by a factor of three at $\beta \approx 0.5$ to take advantage of longitudinal beam bunch compression produced by adiabatic phase damping.

It is evident from the foregoing discussion, that the accelerator design will require an in-depth study of all parameters to achieve the kind of optimization required for such a facility. Special emphasis will have to bear on overall efficiency, capital and operating costs, reliability to maximize the plant factor, control of beam losses to insure "hands-on" maintenance and repairs, etc.

Conclusion

The accelerator-breeder concept is a practical method to convert fertile material to fissile fuel. The design and construction of the required linear accelerator, although not a trivial task, is possible with present day, state-of-the-art, technology. The target also does not seem to present any fundamental limitations. Whether such a facility will ever be built will then depend on political and economic considerations. These can only be assessed after a thorough study of the system.

References

1. Atomic Shield, "A History of the USAEC", WASH 1215, Vol. II, p. 425, 1969.
2. W.B. Lewis, "The Significance of the Yield of Neutrons from Heavy Nuclei Excited to High Energies". AECL Int. Report 968, 1952.
3. M. Steinberg et al., "Linear Accelerator-Breeder", Brookhaven National Laboratory Report, BNL-50592, Nov. 1976.
4. C.M. Van Atta, J.D. Lee, W. Heckrotte, "The Electronuclear Conversion of Fertile to Fissile Material", Lawrence-Livermore Lab., UCRL-52144, Oct. 1976.
5. R.R. Wilson, "Very Big Accelerators as Energy Producers", Fermilab Internal Report, FN-298, 0102.000, August 1976.
6. L. Smith, "Encyclopedia of Physics", Vol. 44, pp. 341-389, Springer, 1959.

References (continued)

7. M.S. Livingston and J.P. Blewett, Particle Accelerators, Chapter 10, McGraw-Hill, 1962.

8. P. Lapostolle and A.L. Septier, "Linear Accelerators", North Holland Co., 1970.

9. P. Grand et al., "A Proposal for an Accelerator-based Neutron Generator", Brookhaven National Laboratory Report, BNL-20159, July 1975 and BNL-20840, January 1976.

10. P. Grand et al., "An Intense Neutron Source Based Upon the Deuteron Stripping Reaction", Nuclear Instruments and Methods, (to be published)

11. K. Batchelor, "Choice of Initial Operating Parameters for High Average Current Linear Accelerators", Proceedings 1976 Proton Linear Accelerator Conf., p. 160, Sept. 1976, Chalk River, Canada.

Table I Typical Set of Parameter Trade-offs for a Linear Accelerator

HIGH GRADIENT* ACCELERATOR

E.MAX (MeV)	I (mA)	ION	FREQ (MHz)	BEAM (MW)	EXCIT (MW)	TOTAL (MW)	LENGTH (m)
800	395	p	100-300	316	126	442	440
1000	300	p	150-450	300	126	426	550
2000	136	p	300-900	273	170	443	1100
800	300	d	50-150	240	138	378	586
1000	230	d	75-225	230	140	370	734
1500	163	d	100-300	244	178	422	1100

LOW GRADIENT* ACCELERATOR

E.MAX (MeV)	I (mA)	ION	FREQ (MHz)	BEAM (MW)	EXCIT (MW)	TOTAL (MW)	LENGTH (m)
800	395	p	100-300	316	63	379	440
1000	300	p	150-450	300	63	363	1100
2000	136	p	300-900	273	85	358	2200
800	300	d	50-150	240	69	309	1173
1000	230	d	75-225	230	70	300	1466
1500	163	d	100-300	244	89	333	2200

*FOR THE SAKE OF DISCUSSION, HIGH GRADIENT HAS BEEN CHOSEN AS TYPICAL MAX. GRADIENT USED IN EXISTING LINACS ADJUSTED TO THE APPROPRIATE FREQUENCY. THE LOW GRADIENT CASE IS A FACTOR OF TWO LOWER.

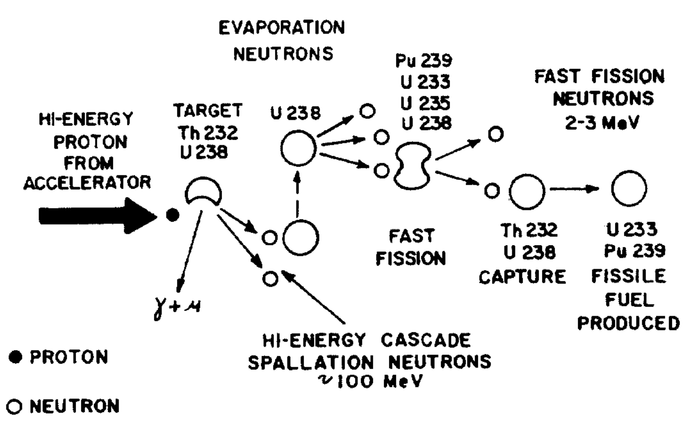

Fig. 1 Nuclear Reactions Produced by the Accelerator Breeder

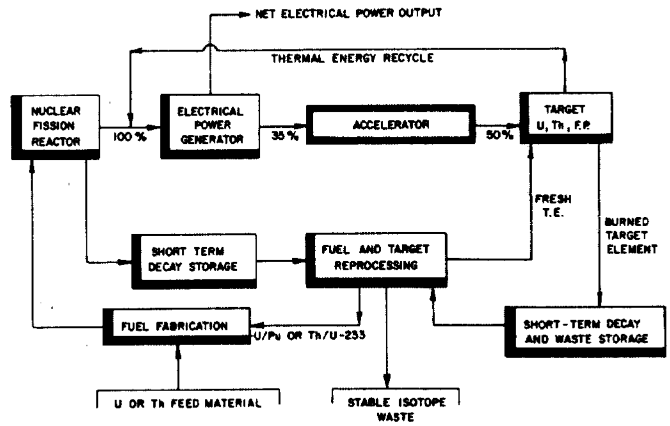

Fig. 2 Accelerator Breeder, LWR Power System with Fuel Reprocessing and Waste Management

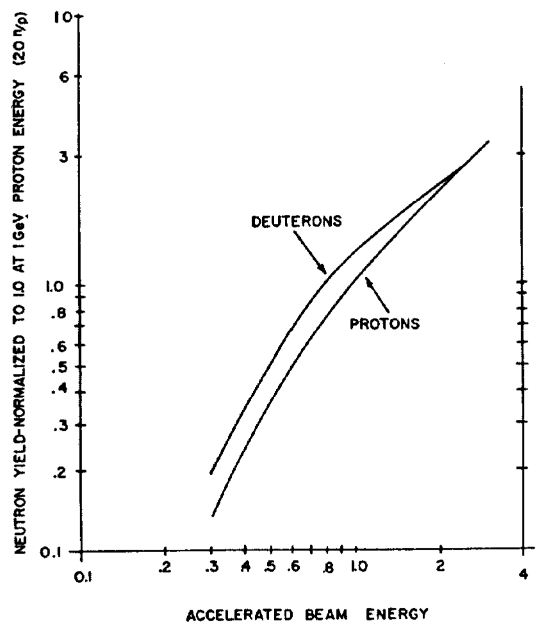

Fig. 3 Neutron Yield vs. Proton and Deuteron Beam Energy

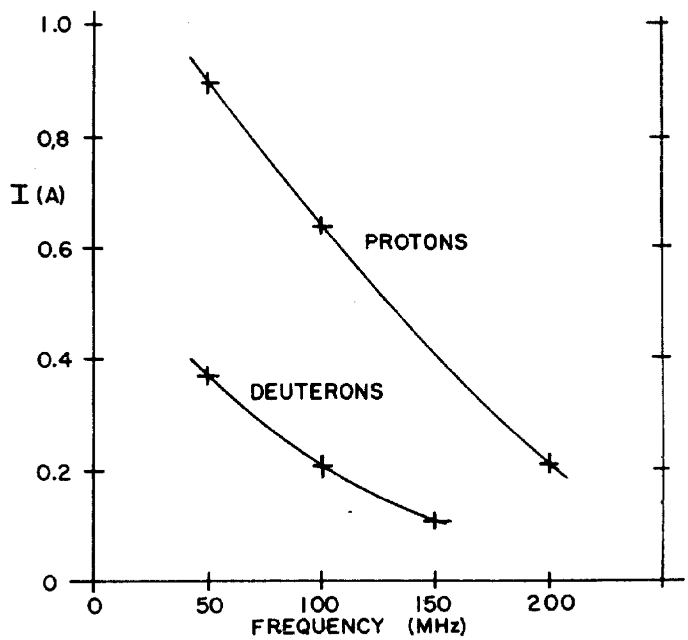

Fig. 4 Maximum Allowable Beam Current vs. Linear Accelerator Frequency