HIGH CURRENT PROTON LINEAR ACCELERATORS AND NUCLEAR POWER

P.R. Tunnicliffe, B.G. Chidley and J.S. Fraser
Atomic Energy of Canada Limited
Physics Division, Chalk River Nuclear Laboratories
Chalk River, Ontario, Canada K0J 1J0

Summary

This paper outlines a possible role that high-current proton linear accelerators might play as "electrical breeders" in the forthcoming nuclear-power economy. A high-power beam of intermediate energy protons delivered to an actinide-element target surrounded by a blanket of fertile material may produce fissile material at a competitive cost. Criteria for technical performance and, in a Canadian context, for costs are given and the major problem areas outlined not only for the accelerator and its associated rf power source but also for the target assembly.

Introduction

In this paper we draw attention to an important potential application of linear accelerator technology - its role in one of the largest industries - energy. To do this we first try to give some appreciation of the fission power industry, its potential fuel resources and how they may be used. We then try to establish qualitatively criteria to be met and physical problems that must be solved if linear accelerators are to contribute to this industry. The problems seem relatively modest compared with those that must be solved by the fusion power community.

Nuclear Fuel Resources

The amount of the fissionable elements, uranium and thorium, within 1.6 km (1 mile) of the surface of earth's continents is sufficient to meet all world energy requirements for 10^8 years even if the present annual consumption increased 50-fold. It is unlikely that fission reactors need be short of fuel recoverable at acceptable cost for a very long time[1].

The key to burning this fuel and assuring the world of a cheap supply of energy for the indefinite future lies in the so-called "breeding fuel cycles" as exemplified in the familiar Fast Breeder Reactor which uses the ^{238}U-^{239}Pu fuel cycle. Thorium can also be burned by using a ^{232}Th-^{233}U fuel cycle.

"Neutron economy" is the key to these fuel cycles and its role is illustrated in Fig. 1[2]. The upper curve shows η, the number of neutrons produced per neutron absorbed, in the three pertinent fissile isotopes as a function of neutron energy; below are neutron spectra characteristic of thermal and fast reactors and of primary fission neutrons. Of the primary fission neutrons, one is required to produce a new fissile atom from fertile material, one to continue the chain reaction and about 0.2 to allow for neutron losses by leakage and parasitic absorption in structural materials and fission products. Thus an effective threshold of η = 2.2 is required to sustain a breeding fuel cycle.

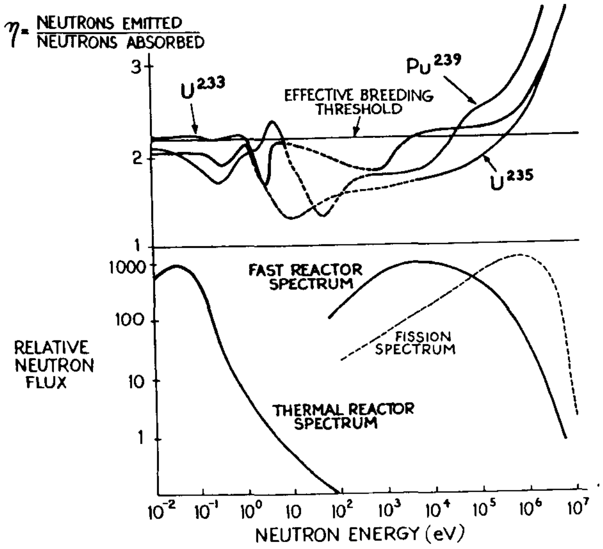

Fig. 1 The variation of η with neutron energy and typical neutron spectra in two reactor types for the three common fissile nuclides.

The motives for developing the fast reactor, in which the neutron spectrum is maintained as energetic as possible, and the choice of the ^{238}U-^{239}Pu fuel cycle, become evident when effective values for η are derived for the neutron spectra characteristic of the two reactor types. The results[2], given in Table 1, show that only ^{233}U exceeds the effective breeding threshold for thermal reactors, while for fast reactors ^{239}Pu exceeds the threshold substantially.

Table 1

Typical Values of $\eta = \frac{\text{Neutrons Emitted}}{\text{Neutron Absorbed}}$

Isotope	Thermal Reactor	Fast Reactor
^{235}U	2.01	1.93
^{233}U	2.25	2.31
^{239}Pu	1.88	2.49

Practical Threshold for Breeding η = 2.2

^{233}U will support a breeding cycle in both thermal and fast reactors. It is the ^{232}Th-^{233}U fuel cycle that has captured our attention in Canada because of the good neutron economy of the CANDU* heavy-water moderated thermal reactors. This type of reactor, which has reached industrial maturity using natural uranium fuel, can be readily adapted to ^{232}Th-^{233}U fueling - all that is needed is a fuel recycling plant.

There is no breeding precursor of mass 234 in appreciable abundance for a ^{235}U cycle - in any case η for ^{235}U would not support a breeding cycle. However the natural occurrence of this isotope is fortunate - it can provide us with the fissile inventory to initiate breeding cycles - indeed, its supply will be crucial in the next 50 years because even the most optimistic do not foresee the fast breeder providing the necessary inventory from surplus production for anticipated expansion requirements. The deficit is seen as being provided by ^{235}U isotope separation plants or "convertor" reactors[a]; both options require a supply of ^{235}U as natural uranium.

Electrical Breeding

It is evident then that neutrons are the essential ingredient in both establishing and maintaining a nuclear power system based on heavy-element fission. ^{235}U may be considered a neutron source that can be acquired by mining natural uranium and separating the ^{235}U. Are there any energetically and financially economic alternatives for the production of neutrons on the appropriate scale? There appear to be only two:-

a) a DD- or DT-fueled fusion system not necessarily achieving energy breakeven

and b) accelerator-based production via the spallation process.

At present the latter seems the only known industrially practical route and the rest of this paper is devoted to this option; fusion-fission systems have been discussed elsewhere[3].

The idea of accelerator-produced neutrons for fissile material production is not new. An extensive development program on the "Materials Testing Accelerator" was undertaken in the U.S.A. in the early 1950's[4] but never came to fruition. A 500 MeV, 320 mA, 50 MHz deuteron accelerator, bombarding a primary beryllium target surrounded by a secondary depleted uranium target, was expected to produce about 500 kg of plutonium a year at \$124/g (∿\$250/g, 1974\$[b]).

The concept of bombarding a heavy element target directly appears to have been first recognized by Lewis[5] who made some remarkably foresighted comments on the role accelerators might play in a nuclear energy system.

The spallation process occurs when high-Z targets are bombarded with energetic nucleons, for example protons of ∿ 1 GeV. Primary nuclear interactions cause a cascade of energetic nucleons to be ejected from struck nuclei with characteristic energies of about 100 MeV. Each nucleus is left highly excited and boils off several "evaporation neutrons" with a characteristic temperature of 3.5 MeV, somewhat more energetic than, but similar in spectral distribution to, fission neutrons. The target nucleus will occasionally "spall off" larger fragments, or will even fission. The "evaporation" neutrons and cascade nucleons induce further secondary processes, particularly (n,xn) and (n,f) reactions which are significant in uranium not only because of neutron yield enhancement but also because of the energy release from fast fission. Figure 2 shows some unpublished calculations and measurements on a 20 cm diameter target of uranium bombarded with protons[6]. We estimate that in a sufficiently large target of ^{238}U. a 1 GeV proton might produce 50 neutrons and up to 4 GeV of heat.

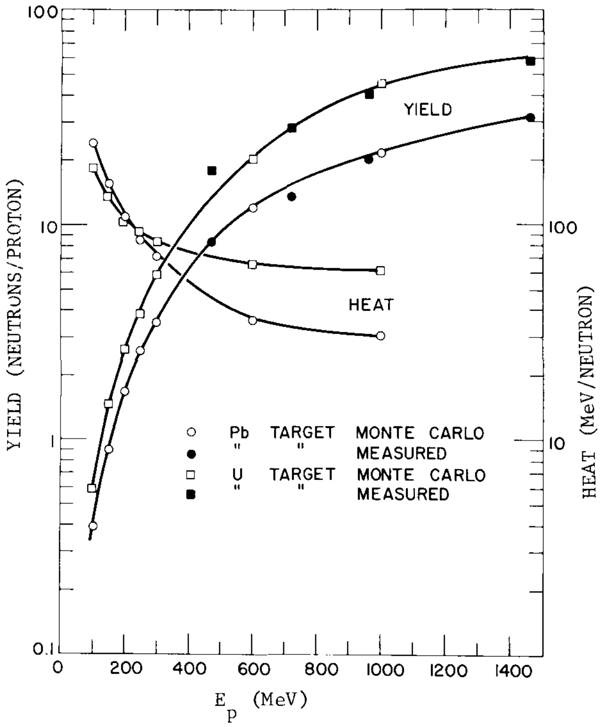

Fig. 2 Measured and calculated neutron yields and calculated heat production vs. proton energy for 20 cm diameter lead and fully depleted uranium targets.

---

[a] Any reactor fueled with natural or "enriched" uranium will have plutonium in its spent fuel which can be extracted by chemical processing. Conversion ratios i.e. plutonium atoms produced per ^{235}U atom destroyed, can range from 0.5 to 0.9.

[b] In present inflationary conditions and because of differing economic systems, cost comparisons can be misleading. We have chosen to correct the estimates of others by only the general inflation factor to 1974. Our own estimates are based on public financing conditions of about that time as used typically by Ontario Hydro and are for "constant 1974 dollars".

* CANDU - Canada Deuterium Uranium.

Yields for thorium are estimated to be lower[7], Deuterons, at 1 GeV, produce about 10% more neutrons[8] but because of accelerator problems the extra yield is probably not worthwhile.

It is expected that nearly every neutron produced will yield one fissile atom; thus 300 mA of 1 GeV protons on uranium could yield ∿ 1 metric tonne/year of fissile material - sufficient to provide fuel inventory for 1 GWe/year of increased capacity or topping enrichment for ∿ 10 GWe of reactors with a conversion ratio of 0.93. The necessary accelerator, with a beam power of 300 MW, would support a substantial utility network of the size of the present Ontario Hydro system.

We noted that each GeV proton would produce ∿ 4 GeV of energy in a uranium target so that a 300 MW beam would produce 1200 MW of heat in the target; a large fraction of this heat arises from direct fast fission of ^{238}U. The target will of necessity resemble a fast reactor of substantial size, and the heat can be of high grade and convertible to electricity for operation of the accelerator. If the net conversion efficiency of this heat to proton kinetic energy exceeds 25%, the accelerator-target breeding system will be self-sustaining in energy[c] and be driven by direct fission of ^{238}U. Because the system will need little or no external energy supply it will produce one gram of fissile material for about two grams of fertile material consumed. By contrast, a uranium separation plant or a convertor reactor would use ∿ 200 g per gram of fissile material produced.

The CANDU thermal reactor is an efficient convertor, indeed it can operate on a self sufficient ^{232}Th-^{233}U cycle if the fuel is reprocessed to remove fission product poisons sufficiently often. Fuel reprocessing costs money so that given a sufficiently cheap external supply of fissile material, cheaper energy can be delivered by less frequent reprocessing. This is illustrated in Fig. 3[9] which has been derived for a "plutonium topping" cycle. The "Total Unit Energy Cost" in this example is a minimum at a conversion ratio of ∿ 0.9 and at a fuel burn-up per pass about three times that for a self sustaining cycle. The plutonium topping price assumed corresponds to $24/g fissile in 1974 $'s[d]. It must be noted that the unit energy cost of the self-sustaining cycle is only 25% greater than the present one for single-pass natural uranium fuel (at present uranium prices) so that such a fuel cycle, given the initial fuel inventory, is economically viable.

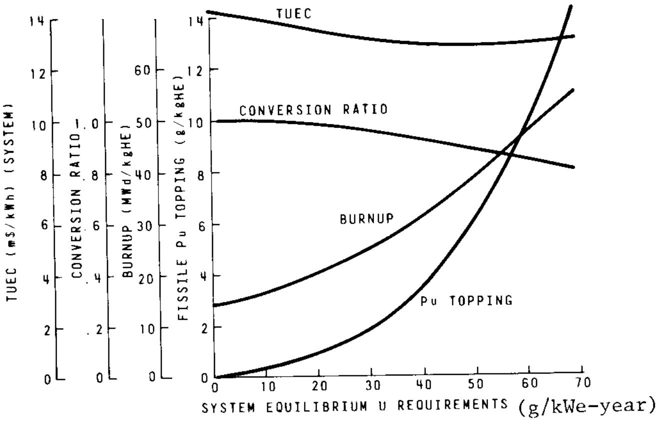

Fig. 3 Thorium cycle characteristics as a function of equilibrium uranium requirements in a CANDU reactor system. To increase burnup per fuel-pass before reprocessing, plutonium derived from CANDU convertor reactors is added as "topping"; the corresponding effects on the "total unit energy cost" (TUEC) and conversion ratio are shown (HE means heavy element i.e. fuel).

Because nuclear system capacity in North America alone may approach 1000 GWe with an expansion rate of 10's of GWe per year by the end of this century there seems to be scope for a considerable role for accelerators by then. They could supply fissile material both for initial inventory and for topping of near-breeding fuel cycles. The availability of fissile material could place serious limitations on essential growth of nuclear energy particularly because it seems unlikely that the Fast Breeder Reactor will be able to supply the inventory necessary for anticipated expansion; the uranium available (for convertor reactors or ^{235}U-separation plants) to provide fissile material may also place limits on growth. The ability of the accelerator-based spallation breeder to stretch uranium resources may be the determining factor in its deployment.

Uranium resources greatly depend on price, primarily set by demand; in this sense the spallation breeder is in competition economically with uranium. Nevertheless other factors could be determinant; failure of the Fast Breeder to achieve satisfactory capacity in time being one.

Thus we conclude that the role for accelerator-based spallation breeders in nuclear power systems is sufficiently important that the technical and economical feasibility should be studied.

Technical and Economic Feasibility

We have indicated that a 300 mA 1 GeV proton accelerator would be appropriate in size. We are not aware of any accelerator type, other than a linear accelerator, that is likely to reach industrial maturity in the time scale that seems necessary. The feasibility of a linear accelerator is discussed in more detail in the latter half of this paper; in this section we note briefly that an accelerator similar to that proposed in the Intense Neutron

---

[c] This is not a necessary criterion.

[d] "g fissile" refers to fissile isotope content only i.e. ^{239}Pu + ^{241}Pu.

Generator study[10] with 300 mA of beam is considered feasible for reasons to be given. At that beam current it would be 90% beam-loaded. The 330 MW radiofrequency power supply would use klystrons as the main power amplifiers. We expect these amplifiers to approach 80% efficiency so that, if the target heat can be converted to electrical power at 35% efficiency[e], such an accelerator-target combination would approach energy breakeven.

The target/breeding assembly will have many features of the Fast Breeder Reactor and benefit greatly from the latter's technology; its ultimate feasibility remains to be established. It has, as yet, received little neutronics and virtually zero engineering attention. Only basic cascade and multigroup neutron transport calculations together with spot verification measurements have been made on neutron production, absorption and leakage in targets of simple cylindrical geometry. A start has been made on measurements with more complex assemblies at TRIUMF[11]. Little attention has been given to necessary structural materials and coolants except to note that low-Z materials should be minimized and that there is no a priori reason for high-power densities; 0.5 MW/litre characteristic of fast reactor cores seems reasonable.

Realistic design concepts which take into account heat transport, radiation damage and materials compatibility need to be developed before accurate prediction of yields and ultimate fate of the neutrons can be predicted. The uranium target[f] could be surrounded by thorium and produce ^{233}U suitable for a CANDU thorium fuel cycle but inevitably (and perhaps by design) some plutonium will be produced in the uranium core; if the plutonium can be left long enough, it will ultimately fission and transfer the neutrons outward (with some gain) into the thorium. Whether "reactor-ready" fuel elements (or pins) could be produced is an intriguing possibility needing examination; if a ^{233}U concentration of 1% or more can be achieved, and this is possible in a hard enough spectrum, then the material may be usable directly as feed fuel in CANDU reactors. If the thorium has to be processed to extract the ^{233}U, then a processing charge will have to be added to the product costs.

Cost estimates are uncertain because of the limited development of the necessary technology, lack of detailed target design concepts and unstable and differing financial conditions. However we will attempt to demonstrate that the economic prospects for accelerator-based breeding technology are not unreasonable for our example.

The system is assumed to operate at energy breakeven and may be considered in four major parts:-

a) the target-electrical generating system
b) the component of the rf power supply assigned to the beam power
c) the accelerating structure plus associated rf power, shielded tunnel and other components needed to achieve the 1 GeV proton energy
d) other items which do not enter into minimizing the cost of c), for example the injector system and the beam transport system to the target.

Taking these items one by one -

(a) A simple way to bypass consideration of details of this system, and of costs and details of financing, is to regard the target and its associated electrical generating equipment as a nuclear power station. We then effectively account for its costs by charging power to the accelerator at the going nuclear-power station bus-bar rates. The Pickering 2000 MWe station in mature operation produced power at 7m\$/kWh in 1974[12] corresponding to \$61/kWe•year. Our accelerator at 70% efficiency and producing 1 metric tonne of fissile material per year would use $300 \times 10^3 \times 8760/0.7$ kWh to produce 10^6 g yielding a unit cost contribution = \$26.1/g for the target system.

(b) 300 MW of the rf power is required to provide the beam power. A recent estimate[13] of the cost of a 9 MW cw rf system using 18 klystrons was about \$500/kW (1975\$'s). In our opinion, allowing for scale, optimization of dc power supplies and inflation, this indicates a 300 MW system might cost ∿ \$350/kW. Allowing an annual interest and depreciation charge of 10%, this would contribute $0.1 \times 350 \times 300 \times 10^3/10^6$ = \$10.5/g for capital costs of beam-associated rf power.

(c) From earlier estimates[10] and allowing for improvements in design, the accelerator structure, the incremental rf power of ∿ 30 MW, shielding and services would cost about \$40 M. The contribution to product cost would be $0.1 \times 40 \times 10^6/10^6$ = \$4.0/g.

(d) Within the uncertainties of the estimates of the previous items this is considered negligible.

The total unit cost is then ∿ \$40/g of fissile element. The major contribution to this cost is the target system, the next largest item is the rf power supply needed for the beam load, the accelerator structure itself being a relatively modest contribution. This estimate is discussed further later in the paper.

Estimates of ^{235}U enrichment costs published in 1974[14] indicate a separation cost of \$15/g of ^{235}U at 93% concentration and at "0.2% tails" (i.e. 1 kg natural uranium yields 5 g ^{235}U). The uranium

---

[e] The target heat might be used in conjunction with the thermal cycle of a major nuclear power station in a superheat or reheat cycle and thus significantly increase the effective conversion efficiency to electricity.

[f] Nuclear systematics suggest that waste plutonium and higher-Z actinides would be even better target material.

competition then would be

$$\$15 + \frac{\$/\text{kg of natural U}}{5}$$

i.e. prices would be comparable at ≃ $130/kg uranium. While this comparison is no more than a guideline it does indicate that accelerator breeding costs may be competitive soon - uranium prices are rising rapidly - particularly by the year 2000.

Until accelerator and especially target concepts are developed further, more accurate cost estimates cannot be made. It should be noted however that the postulated system is probably approaching asymptotic unit costs within ∿ 20%; ^{235}U separa- plants have to be one to two orders of magnitude larger to obtain similar benefits from scale and require a correspondingly larger nuclear power system to justify their construction.

The Accelerator

Having attempted to provide an appropriate perspective and set of objectives, what are the problems that face us in accelerator design and engineering?

The foundations of the necessary accelerator technology have been laid in the design and construction of the Los Alamos Meson Physics Facility (800 MeV, 20 mA, 12% duty factor)[15]. That concept provided the basis for the study which led to the final version of the proposed Intense Neutron Generator accelerator (1 GeV, 65 mA, 100% duty factor) in 1967[10]. Pulsed currents of > 200 mA have been achieved in the CERN 3 MeV experimental linac[16]. Rf power tubes of MW capacity have been built and efficiencies of 75% achieved[17,18].

Other developments in accelerator technology and concepts as yet promise no more economical if indeed feasible conceptual designs. To achieve a significant industrial capacity within the next few decades, we believe attention must be concentrated on the linear accelerator. Such an accelerator, ∿ 1 km long, would consist of a dc injection section to about 1 MeV, an Alvarez section to about 100 MeV and the remainder, a coupled-cavity section to the final energy. The Alvarez section would operate at some submultiple of the frequency of the coupled-cavity section. The current that can be accelerated will primarily be determined by the Alvarez section, particularly the first few MeV, and by the performance of the dc injector; the coupled-cavity section will be dominant in determining efficiency and costs.

Current capability, efficiency and costs are not the only factors that must be considered; reliability and maintainability are also important factors in selection of machine design concepts and parameters discussed below.

Operating Frequency

The radiofrequency power supplies will dominate the cost and efficiency. Three technologies are available, gridded tubes, crossed field devices and linear beam devices. While all three are potentially capable of operating within plausible frequency and power requirements, our experience, like that at LAMPF, indicates that the klystron is likely the only satisfactory device for a multi-tank accelerator. Gridded tubes have low gain at high frequencies and the rf amplifier chain tends to be complicated[19] and expensive costing about $1/watt[20]. We have found crossed field devices, operating as oscillators (magnetrons), capable of operating at high efficiencies and with potential for > 100 kW cw[21]; amplifiers have operated up to 500 kW cw with good efficiencies[22]. However these devices, as amplifiers, have low gain, are difficult to control and have some unpleasant application problems.

High power cw klystrons with good efficiency have been built and operated over a wide frequency range[18]. Because the gain is high, typically 50 db, the device can be driven with low power cheap sources and amplitude and phase control is straightforward[23]. Frequencies between 200 MHz and 3 GHz seem feasible but klystrons would probably become unmanageably large both in physical size and in rating at much lower frequencies. Application of modern accelerator physics and computational techniques to klystron design will almost certainly raise efficiencies into the 80% region.

The allowable beam diameter is inversely proportional to frequency so that space charge limitations favour low frequencies for high current accelerators. This is exemplified by recent proposals for CTR materials testing facilities which use 50 MHz[20]. This frequency is chosen to hold activation caused by beam spill within acceptable limits. We would expect a breeder accelerator to exploit several different design features to reduce the beam spill (or the effects of the spilled beam) and allow use of a more economical higher frequency. These include increasing the admittance by using a high injection energy, improved focusing, making the structure more tolerant to beam loss at low energy by accelerating protons instead of deuterons, choosing the accelerator material to reduce activation, and reducing the current requirement by increasing the output energy to say 2 GeV and possibly by simultaneous acceleration of H$^+$ and H$^-$ beams[24].

A 200-600 MHz operating combination is probably optimal.

Duty Factor, Gradient and Energy

Because the accelerator will be designed close to the space-charge limit, 100% duty factor operation is essential to achieve the needed current. To those more familiar with machines for research applications, the associated average dissipation losses of 10's of MW's may seem very large; in our application they are relatively modest. Avoiding pulsed operation has some other important advantages as well. In particular it has a major effect on the cost of the radiofrequency supply - probably approaching an order of magnitude. Another advantage is that regulating systems do not need to respond as fast and hence are cheaper and simpler[23].

The choice of accelerating gradient will depend on the relative values for length-dependent costs and incremental unit costs for rf power. The ING study yielded a relatively modest gradient, < 1 MeV/m, but our present predictions suggest a higher gradient may be more economical. Until better unit cost estimates are available we cannot predict if thermal dissipation in the accelerating structures will be a problem, certainly at the ING design gradients we have established that it is not[25,26]. Improved performance of simpler coupled-cavity standing-wave structures with on-axis couplers[27,28] promise reduction in length dependent costs but we suspect that there will still be economic pressure to use somewhat higher gradients.

The choice of output energy, current and gradient is not only dependent on unit costs of accelerator components but also on neutron yield in the target and on its cost. We have constructed a computer optimization code which can give results quickly for whatever scenario one might wish to select. At present it only ascribes "global" length dependent costs to the accelerator but more sophistication to account for transitions in accelerating structure and other cost factors will be added. Figure 4 is an illustration of the output for one particular set of assumptions. The results indicate the advantages of scale and, on the larger scale, the relative independence of accelerator output energy. As there will undoubtedly be a cost factor associated with current in overcoming space charge effects the optimum may indeed move towards the 2 GeV region. This case also illustrates that a drastic increase in accelerator unit-length costs is not very important; the simple analysis given earlier in this paper corresponded to about $17k/m, this case, $60k/m.

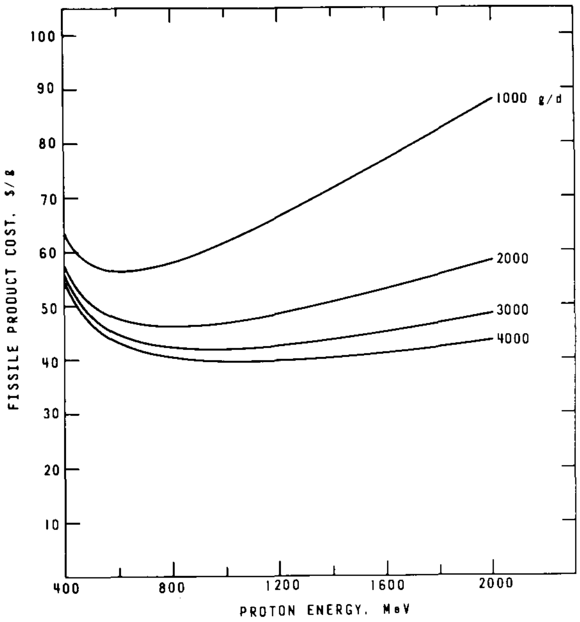

Fig. 4. Calculated unit fissile product costs for production rates 1000 to 4000 grams per day vs. proton energy. The principal assumptions are: electrical power costs, $0.007/kWh; target costs included in the electrical power costs; interest and depreciation, 10% per year; rf equipment capital $350/kW; accelerator unit length cost, $60,000/m; maximum peak accelerating field, 2 MV/m, averaged over the accelerator length.

Reliability, Maintainability and Beam Spill

The amount of beam spill that can be tolerated is determined by two effects, heating and activation. Except for the first few Alvarez "cells", the latter is the most important consideration. Below a few MeV the nuclear activation that can be induced by protons can be minimized by materials choice and need not seriously impede access for repairs. Above this energy many radioactive nuclides can be produced and, as the energy increases, spallation activation becomes the important factor. To a first approximation the activation will be proportional to the power of the spilt beam but it also depends on the materials involved - lower mass nuclides are generally least activated, at least during the first 10^3-10^4 hours after irradiation[10].

Tolerable beam spill estimated during the ING study[10] was $\sim$ 2 GeV.nA/m; Murin and Fedotov suggest the order of 10^{-10} A/m at high energy[29]. These estimates are not inconsistent - different assumptions of acceptable radiation fields were used, the latter have taken 2.8 mrad/h (28 μGy/h) at one metre from the accelerator centreline. More spill can almost certainly be tolerated if materials for the accelerator and beam transport structures and for the machine tunnel lining are properly chosen. The ING concept anticipated provisions for a shielded cab that could traverse the machine tunnel. Remote handling tools and techniques, successfully used in repairs to nuclear reactors, could be used - we have made numerous in-core repairs to the research reactors here at CRNL and replaced the main reactor vessels twice in one high-flux reactor and once in another - large and highly radioactive objects can be handled safely without undue difficulty.

Nevertheless simplicity of equipment located in the machine tunnel, use of passive components such as permanent magnet quadrupoles and radiation-hardened components will minimize maintenance problems. Electrical and mechanical tolerances must be carefully determined and met and, if possible, provision made for continued operation with faults. For example, if the rf unit size is not too large it should be possible to continue to operate, with appropriate regulation adjustment to subsequent accelerator modules, if one rf unit fails - detuning of the accelerator section it drives would be essential. Unpublished work at Chalk River has suggested that the transverse focusing system might be designed so that particles losing synchronism early (but not too early) can be transported to the end of the machine.

Injection and Initial Acceleration

To achieve high current at high frequency, high injection energy is required to raise the space-charge limit sufficiently. Table 2 lists this limit estimated for the conditions proposed in the ING study[10] namely with the Alvarez section operating at 268 MHz, 75 T/m (7.5 kG/cm) maximum quadrupole gradient and injector normalized emittance 0.4 π mm.mrad.

Table 2

Space-charge Limit vs Injection Energy

E_{inj} (MeV)	I_{max} (mA)
0.75	65
1.035	110
1.503	260

Because of the high power that must be delivered by the injector, air-insulated systems seem desirable but by using SF_6 at near atmospheric pressure, 1.5 MV is probably reasonable. Given H^+ and H^- injection it should be possible to achieve 500 mA at 200 MHz without too much difficulty; beyond this point it will probably be preferable to increase the machine output energy if a larger production capacity in one unit is desired.

Improvements in focusing in the Alvarez structure such as a combination of alternating phase[30] and conventional quadrupole focusing may significantly increase the achievable current.

Low beam spill and high capture efficiency require a low emittance from the injector. High-gradient dc accelerating columns have been used to minimize space-charge induced emittance growth; Ungrin et al[31] have found that these designs have led to serious limitations from current-induced breakdowns. CTR injector technology[32] suggests sufficient current can readily be achieved - unfortunately there is no guidance yet on beam quality obtained using those techniques.

Given sufficient current, buncher performance may not be crucial. Provided sufficient current can be captured, beam spill allowable near injection is primarily determined by heat removal problems. However, use of a multi-cavity buncher system and possibly a chopper, to remove uncaptured beam, may be desirable.

The emittance of the beam at a few MeV will influence beam spill in the high energy parts of the machine. Emittance "filtration"[29] must not discard too large a fraction of the current or our goal of operation at higher frequencies will be defeated. A detailed understanding of space-charge induced emittance growth in the injector, buncher system and during initial rf acceleration, which conforms to observed behaviour, is essential.

Conclusions

Electrical breeding of fissile material via the spallation process offers a technically feasible route in competition with or complementary to the Fast Breeder Reactor for extending the world's fissionable fuel resources into the indefinite future. The proton linear accelerator operating at 100% duty factor appears to be a well-developed technology that could be brought to industrial fruition within a few decades, the time scale required. Engineering problems with accelerator-based breeding appear much less formidable than with any hybrid-CTR device.

No fundamental problems are foreseen in designing 300 mA, 1 GeV linear accelerators but a great deal of development work is still required. Existing research accelerators will provide valuable guidance in solving problems.

The cost of fissile material produced by this route will probably be in the range \$40-\$100 g (1974 \$'s). While this cost is not competitive now, shortages of uranium will likely alter the situation within the time scale needed for achieving industrial capacity. Indeed, such fissile material may prove crucial in providing inventory for expansion of nuclear power at the rate necessary during the next 50 years.

References

1. See for example A.J. Mooradian and O.J.C. Runnalls, CANDU - Economic Alternative to Fast Breeders, Atomic Energy of Canada Limited Report No. AECL-4916 (1974).
2. C.H. Millar, private communication.
3. L.M. Lidsky, Fission-Fusion Systems: Hybrid, Symbiotic and Augean, Nucl. Fusion 15, 151 (1975).
4. Livermore Research Laboratory, Status of the MTA Process, Livermore Research Laboratory Report LRL-102 (Del) (1954).
5. W.B. Lewis, The Significance of the Yield of Neutrons from Heavy Elements Excited to High Energies, Atomic Energy of Canada Limited Report No. AECL-968 (1952).
6. J.S. Fraser et al., Neutron Production in Thick Targets Bombarded by High Energy Protons, Physics in Canada 21, 17 (1965) and J.C.D. Milton, private communication.
7. J.C.D. Milton and J.S. Fraser, A Monte Carlo Calculation of Neutron Production in Heavy Element Targets by Protons in the Range 0.3 to 1 BeV, Atomic Energy of Canada Limited Report No. AECL-2259 (1965).
8. D. West and E. Wood, Neutron Yield from Protons and Deuterons of Momenta Between 0.85 and 1.7 GeV/c Totally Absorbed in Lead, Can. J. Phys. 15, 2061 (1971).
9. E. Critoph et al., Prospects for Self Sufficient Equilibrium Thorium Cycles in CANDU Reactors, Atomic Energy of Canada Limited Report No. AECL-5501 (1976).
10. ING Status Report July 1967, T.G. Church, ed., Atomic Energy of Canada Limited Report No. AECL-2750 (1967).

11. Progress Report, Physics Division, Jan. 1 - March 31, 1975, Atomic Energy of Canada Limited Report No. AECL-4916, p.125 (1975).

12. J.S. Foster, The Canadian Nuclear Power Program, Atomic Energy of Canada Limited Report No. AECL-5534 (1976).

13. PEP Conceptual Design Report, Lawrence Berkeley Laboratory Report No. LBL-4288 (1976).

14. AEC Calculates Public vs. Private Enrichment Costs, Nucleonics Week, Special Issue - August 6, 1973, p.3.

15. A Proposal for a High-Flux Meson Facility, Los Alamos Scientific Laboratory, September 1964, pp.358-363.

16. D.J. Warner, Accelerator Development with the CERN 3 MeV Linac, Proc. 1972 Proton Linear Accelerator Conf., p.33, LA-5115 (1972).

17. E.L. Lien, High-Efficiency Klystron Amplifiers, Proc. 8th Int. Conf. on Microwave & Optical Generation, Sept. 7-11, 1970, p.11-21.

18. R.H. Giebeler, High Power Microwave Generation, J. Microwave Power 4, 79 (1969).

19. J.C. Brown and B.G. Chidley, A High Power rf Source for the Chalk River 100% Duty Factor Alvarez Linac, Proceedings of this Conference.

20. See for example, P. Grand, Ed., A Proposal for an Accelerator Based Neutron Generator, Brookhaven National Laboratory Report No. BNL-20159 (1975) and BNL-20840 (1976).

21. C.B. Bigham and M. Viant, High Power Industrial Heating Magnetron Development, J. Microwave Power 10, 233 (1975).

22. J.F. Skowron, W.C. Brown and G.H. McMaster, The Super Power Amplitron, Microwave J. 7, (10), 65 (1974).

23. See for example, J. McKeown, J.S. Fraser and G.E. McMichael, Field Control in a Standing Wave Structure at High Average Beam Power, Proceedings of this Conference.

24. C.H. Westcott, Simultaneous Acceleration of Two Beams in a Linear Accelerator, Acta Physica Polonica A38, 515 (1970).

25. J.S. Fraser et al., Operation of the Graded-β Electron Test Accelerator, Proceedings of this Conference.

26. B.G. Chidley et al., The Chalk River High Current Test Facility, Proc. 1972 Proton Linear Accelerator Conf., p. 218, Los Alamos Scientific Laboratory Report No. LA-5115 (1972).

27. S.O. Schriber et al., Beam Tests with S-band Standing Wave Accelerators using On-axis Couplers, ibid p. 140.

28. S.O. Schriber and L.W. Funk, ZT^2 Comparison between S-band Standing Wave Accelerators with On-axis and Off-axis Couplers, Proceedings of this Conference.

29. B.P. Murin and A.P. Fedotov, Radiation Cleaness and Economics of Modern High Current Linear Accelerators of Protons and Heavy Ions, Atomnaya Energiya 38, 146 (1975).

30. D.A. Swenson, Alternating Phase Focused Linacs, Particle Accelerators 7, 2 (1976).

31. J. Ungrin et al., Chalk River Experience in the Operation of High-Current 100% Duty Factor Accelerating Columns, Proceedings of this Conference.

32. J. Kim and O.B. Morgan, An Intense Neutron Source using a Spherical Drive-in Target, Proc. of Int. Conf. on Radiation Test Facilities for the CTR Surface and Materials Program, p.250, ANL/CTR-75-4 (1975).

DISCUSSION

D.C. Hagerman, LASL: How fast does the cost of the end product go up with the overall conversion efficiency; you're dealing with a design efficiency of around 70% - what happens if it is 35%?

Tunnicliffe: Roughly doubles it. I think you could see from my breakdown that it's the electrical energy power supply that is contributing about 70% of the cost of the product.

J.E. Vetter, Karlsruhe: What is the total amount of neutrons produced on the target and what is the power density in the target?

Tunnicliffe: The yield of neutrons at 1 GeV on the uranium target would approach ∿ 50 neutrons per proton. I think we would expect to design the target in the region of 1/2 MW/litre. This is characteristic of a fast reactor system. There is no "a priori" reason why that density should be much larger.

G. Dome, CERN: I understood you favoured operation around 600 MHz. What is the cw klystron power you are considering for operation per klystron?

Tunnicliffe: I would expect one would be looking at units of the order of a megawatt or more in size. Varian have built an X-band klystron cw at 1 MW and that is not a hard job. I saw the tube a while ago. I believe it was a military communications tube.

E.A. Knapp, LASL: It would seem to us that there is a tremendous break in the feasibility or infeasibility of this whole project if the beam loss gets to be above the level at which the remote maintenance is required or not required. That is, if the beam loss can be kept low enough so that hands on maintenance is possible on the machine, the costs are much, much less than if remote equipment is required. Have you any program here to look at exotic beam loss mechanisms such as beam halo growth and so on, or is that just starting in your program?

Tunnicliffe: The amount of effort we have had to devote to the problem is quite small. We haven't really tackled it adequately yet. We haven't developed our understanding much further than we had a few years ago. I think Bruce Chidley will agree with that. I recognize the point that you are making but I think I tried to indicate that if you double the accelerator costs it doesn't perturb the result appreciably. I think that having been associated with the reactor business I am not quite so scared of handling highly radioactive objects as the accelerator community may be. We have replaced the vessels of our two research reactors here 3 times and these vessels are the order of 3 metres in dimension. You have to plan it well. You have to use remote handling techniques but its not by any means such an impossible job as you might think at first sight and we have made many repairs in the cores with remote handling tools. I think that one would expect to have to provide for access to the machine by something like a shielded cab to run the length of the tunnel. This means the tunnel has to be rather larger than you would otherwise need it but I don't think that would add too much to the cost in the terms of the final product cost.