AECL-7260

ATOMIC ENERGY
OF CANADA LIMITED

L'ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

A REVIEW OF PROSPECTS FOR AN ACCELERATOR BREEDER

Possibilités de l'accélérateur surgénérateur

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Chalk River, Ontario

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Résumé

On passe en revue la faisabilité scientifique, la praticabilité technologique et les perspectives économiques d'un accélérateur surgénérateur. La faisabilité scientifique de composants d'accélérateur à haute puissance repose sur une base solide par suite des progrès techniques réalisés au cours des récentes années mais il est nécessaire de combiner tous les composants dans un modèle de démonstration fonctionnant dans des conditions réalistes. La praticabilité technologique des composants d'un accélérateur surgénérateur doit être mise à l'essai dans un développement gradué aboutissant à une installation de démonstration grandeur nature. L'évaluation économique dépendra du calcul des dépenses en capital estimées et permises pour un accélérateur surgénérateur destiné à la filière CANDU fonctionnant sur un cycle de combustible au thorium-uranium. Les résultats montrent que le rapport des dépenses en capital entre celles estimées à celles permises est environ 3.5 pour un surgénérateur ayant une couche fertile d'uranium métal enrichi à 2% et pour de l'U235 séparé évalué à 48$/g.

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ABSTRACT

The scientific feasibility, engineering practicability and economic prospects for an Accelerator Breeder are reviewed. The scientific feasibility of high power accelerator components rests on a firm basis as a result of technical advances made in recent years but there is a need to combine all components in a demonstration model working under realistic conditions. The engineering practicability of Accelerator Breeder components should be tested in a staged development culminating in a full-scale demonstration plant. The economic assessment depends on calculations of allowed and estimated capital costs of an Accelerator Breeder for a CANDU system operating on the Th-U fuel cycle. The results indicate that the ratio of estimated to allowed capital cost is approximately 3.5 for a breeder with a 2% enriched uranium metal blanket and for separated U235 valued at 48 $/g.

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I INTRODUCTION

The present study is designed to provide a current basis (1981) for long range planning of advanced systems research within AECL. The ultimate goal of an Accelerator Breeder (AB) has stimulated a number of research programs and design studies from the early 1950's[1], through the Intense Neutron Generator (ING) study of the 1960's[2,3] and the advanced systems research[4-8] of the 1970's to the present. Experiments directed towards the technical feasibility of the accelerator and the target of an AB[4-8] formed the backbone of the long range program of the Accelerator Physics Branch in the 1970's. In 1978 an AB program study[9] outlined a tentative plan of research and development that would lead to an AB demonstration. The study also summarized the economic outlook for an AB.

The primary objective of the present study is to re-assess the prospects and potential for an AB as an adjunct to the CANDU reactor system. This study and a companion study on Fusion Breeding of Fissile Fuel[10] were undertaken to provide a basis for selecting AECL's program in advanced systems in the 1980's and beyond.

The present AB review is confined to three areas: scientific feasibility, engineering practicability and economic prospects. Questions of scientific feasibility are much closer to being answered today than they were a decade ago as a result of the technical advances made in accelerator design and operation. Thus the study is on reasonably firm ground in making projections from a rapidly advancing state-of-the-art technology. Engineering feasibility of AB components is based in part on practicable accelerator concepts and in part on fast-reactor-like concepts of the breeding target/blanket.

Economic assessment of the AB follows a procedure used by Critoph in an earlier study of laser fusion systems[11]. To be consistent with assumptions used in the companion study[10], an AB fuel production capacity of 1 Mg/a is used. This production rate would service approximately six 2000 MWe CANDU stations using a thorium fuel cycle with a 0.9 conversion efficiency factor and operated at 80% availability.

II SCIENTIFIC FEASIBILITY

System Description

Main components of an Accelerator Breeder as currently envisioned are shown in Fig. 1. The injector, consisting of an ion source and extraction column, delivers a dc beam of up to 375 mA of protons to a low-energy, focusing, bunching and accelerating structure known as a "radio-frequency quadrupole" (RFQ) that transmits 80% of the input beam. The 300 mA beam from the RFQ is accelerated in a "drift-tube linac" (DTL) from 2 MeV to about 200 MeV, at which point the beam is transferred to a more efficient structure for accelerating intermediate energy particles called a "coupled-cavity linac" (CCL). Finally, the beam impinges on a target at an energy of 1000 MeV. The target absorbs most of the beam energy and is surrounded by a blanket of fertile material. The two regions of the target blanket assembly would most likely be cooled by liquid metals.

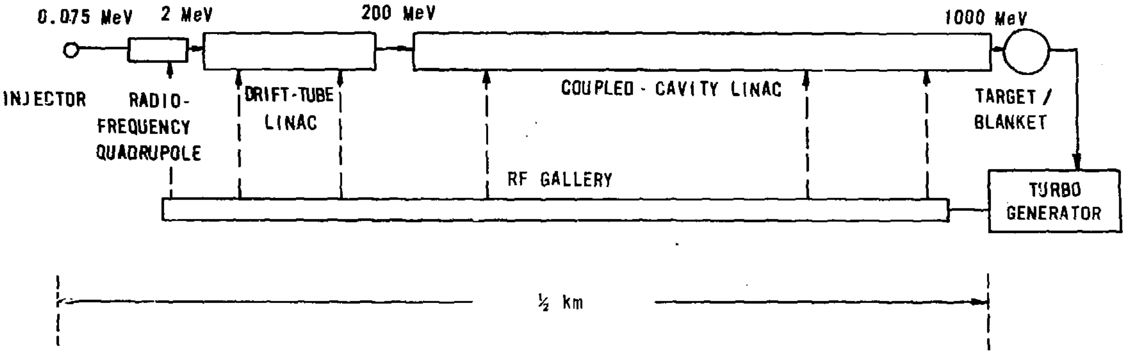


Fig. 1 Main components of an Accelerator Breeder.

Energy deposited and generated in the target/blanket is removed through heat exchangers to raise steam that drives a turbo-generator. The electric power so generated is used to drive the AB complex.

Requirements

The essential requirements of an AB can be stated as follows[7]. A proton beam of about 300 MW beam power must be produced in a reliable manner. The energy of the proton beam delivered by the accelerator should be in the range 1 to 2 GeV with corresponding beam currents of 300 to 150 mA. The ion source must be capable of delivering 750 mA dc of unanalyzed hydrogen ion beam at an energy of about 75 keV. All accelerating structures must be capable of sustaining the maximum continuous beam current of 300 mA and must make efficient use of radio-frequency (rf) energy. This implies that the power delivered to the beam should be a large fraction ($\gtrsim$ 80%) of the power fed to the linac. The rf generator must use ac mains power efficiently. Finally, the target/blanket assembly must use the particle beam energy efficiently in the production of fissile material.

State of the Art

Demonstration of scientific feasibility for most of the component parts of the AB is well advanced.

Development of the duoPIGatron ion source has reached the level at which scientific feasibility is assured. A 42 keV, 500 mA mixed hydrogen beam was recently achieved[12]. Earlier measurements of the mass distribution in such beams showed that at least 350 mA of protons would be available to inject into a linac structure. Some improvements are required to increase the current above 375 mA. The operation of 75 kV dc extraction columns has been shown to be sufficiently reliable for use in the AB.

The initial accelerating structure, the RFQ, has been demonstrated[14] in a pulsed mode with acceleration of 38 mA of protons from 100 keV to 600 keV at a frequency of 425 MHz. Theoretical analysis of the RFQ including disruptive effects of space-charge forces indicates that the acceleration of 300 mA of protons is achievable at a structure frequency of 108 MHz.

Experience with drift-tube linacs is now very extensive. With the advent of the RFQ, the injection energy to a DTL can be increased to over 2 MeV. At this injection energy and operated at 216 MHz the matched current acceptance of a DTL exceeds 500 mA[14].

Beyond the entrance to the CCL, i.e., above a beam energy of about 200 MeV, there is little doubt of scientific feasibility. Experience at LAMPF[15] has shown that beam spill in the intermediate energy region of an accelerator will be acceptable in an industrial accelerator environment.

The efficiency of each step in the power cycle - ac to dc, dc to rf and rf to beam - must be maximized. The ING study[16] showed that ac-to-dc conversion is optimized in a module size of 18 MW, a result still valid today. Presently, klystron power amplifiers are the most suitable, efficient converters of dc power to rf power; efficiencies of 74% have been achieved in a 100% duty factor, 50 kW klystron at 2940 MHz[17]. For the 353 MHz PEP storage ring, 500 kW klystrons are being developed[18] with an efficiency approaching 70%. Extension of tested design principles[17] would yield efficiencies above 70%. With the well-established efficiency of 95% for ac-dc conversion the overall efficiency of ac-rf conversion can exceed 70% using recognized techniques.

Beam-loading factors of over 80% have been demonstrated[19]. Although continuous beam currents up to 300 mA have not been demonstrated in the laboratory, a high beam loading factor has been achieved at 15 mA with no unexpected results.

Finally, experimental and theoretical work on simple target assemblies bombarded by 500-800 MeV protons provides an adequate understanding of the physics of production processes in fissile materials on which to base target/blanket designs.

III ENGINEERING PRACTICABILITY

The transformation of an Accelerator Breeder from a conceptual design of demonstrated scientific feasibility to a practicable, engineered production plant is a challenging task. The demonstration can be accomplished in a series of stages in which the investment in hardware and manpower is gradually increased. The first step would be acceleration to a modest energy of the full design current. A number of test rigs are under construction or planned at CRNL from which design data will be obtained for this step. The device, called ZEBRA (for Zero Energy BReeder Accelerator), would accelerate a 300 mA proton beam to 10 MeV. It is widely believed that above this energy no appreciable deterioration of beam quality will result from the large space charge forces that are serious problems at lower energies.

The ZEBRA project will bring to the fore many of the engineering problems associated with high beam current acceleration. A project in the U.S.A., the Fusion Materials Irradiation Test Facility (FMIT)[20], will deal with some of the same engineering problems. In FMIT the final beam delivered to the target is not more than 100 mA at 35 MeV whereas ZEBRA would be a prototype of the front end of a very long accelerator in which superior beam quality and higher beam current would be essential.

Full-current, low-energy acceleration at full power-density levels will provide realistic testing for all of the essential components of the front end of an AB. A second stage of development, with the beam energy raised to about 200 MeV but current no greater than 70 mA, called Electronuclear Materials Test Facility (EMTF), could provide an intense neutron source of 6 x 10^{17}/s for a variety of interests including condensed matter physics, nuclear physics, fusion and AB materials damage studies, and liquid metal technology[21]. This would be a project of somewhat larger scale than FMIT and would address a larger spectrum of uses. Successful operation of EMTF would demonstrate the engineering practicability of the accelerator part of an AB.

A realistic start on the target/blanket engineering problems could only be made when a higher beam energy than that provided by EMTF is available. A target/blanket engineering facility with a 70 mA beam at 1000 MeV could provide the means to investigate these problems. Preliminary studies have shown that the principal problem to be tackled arises from the high power density and the attendant high temperature gradient in the vicinity of the beam impingement area. Unlike a fast breeder reactor in which power density is roughly sinusoidal across a core diameter, an AB blanket would have a steep power density gradient that decreases from the beam impact zone. In a similar manner the production rate of fissile material would have a steep gradient. These conditions might be alleviated, however, by using graded enrichment accomplished by an appropriate fuel management scheme. A suitable blanket design would have a maximum power density not exceeding that in a liquid metal fast breeder reactor.

Materials problems in the harsh environment of the primary target and surrounding blanket would have to be addressed. Experimental and theoretical work on radiation damage could commence using the strong neutron sources available with ZEBRA and, especially, EMTF test facilities. Similarly the technology of liquid metal coolant and primary target system could be developed in a progressive manner as the size and complexity of the facilities grew.

The final stage to develop and demonstrate engineering practicability would be a full scale test facility - a demonstration AB. Only at this stage would the crucial operating parameters be realized in the target/blanket assembly.

IV TARGET/BLANKET MODEL STUDIES

A plausible model of a target/blanket assembly suitable for an initial neutronics calculation is a liquid-metal-cooled fast breeder reactor (LMFBR) lattice with the proton beam impinging on a central liquid lead/bismuth target. Preliminary NMTC/MORSE calculations have been completed for this design, a design based on a 1977 ORNL study[22]. In the neutronics calculation, charged particles and neutrons with energy greater than 14.92 MeV are transported using the NMTC[23] code. Neutrons with energies less than 14.92 MeV are transported using the MORSE[24] code with a 23-group neutron cross-section library based on ENDF/B-IV data.

The target for this study consisted of a liquid lead cylinder, 50 cm long x 16 cm outer diameter, surrounded by a breeder blanket in a simulated LMFBR lattice arrangement. The lattice was represented by a homogeneous mixture of 50% oxide fuel, 25% stainless steel sheathing (Fe assumed in the calculations) and 25% sodium coolant. Plutonium-239-enriched UO_2 and uranium-233-enriched ThO_2 fuels were investigated.

A characteristic result for this target/blanket design is a very steep power gradient in the vicinity of the primary target. The peak power density approaches 5 MW/ℓ, a value considerably larger than the power density of 0.3 MW/ℓ in an LMFBR.

High peak power densities and gradients ca.. be alleviated by introducing a cavity between the liquid metal target and the blanket. Figure 2 shows a modified ORNL design with the blanket pushed away from the target to reduce the neutron flux density crossing the blanket boundary. The fertile fuels used in the modified model were uranium and thorium metal and uranium and thorium carbide. It was found that the harder spectrum, resulting from the removal of oxygen, significantly increased the number of reactions per incident proton and also increased the variation in fissile production rate with enrichment.

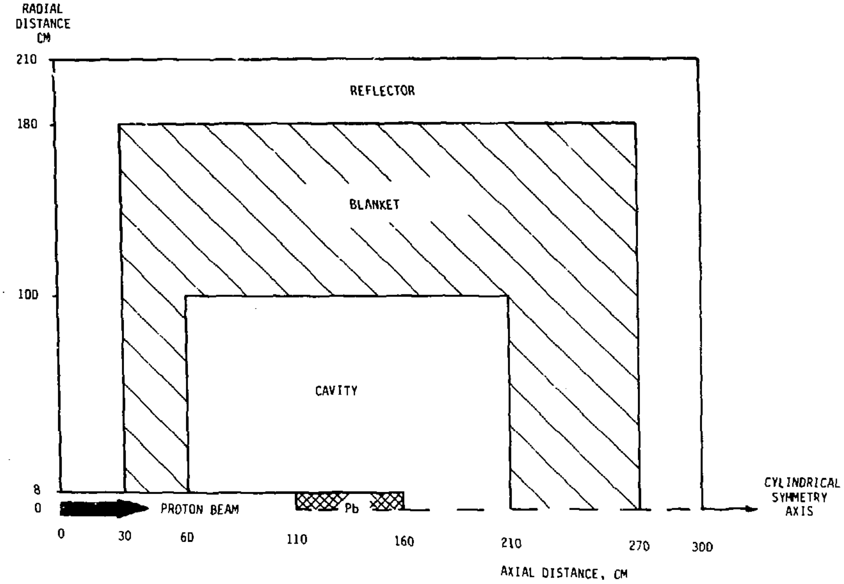


Fig. 2 Accelerator Breeder target and blanket geometry used for scoping studies.

Results for the UO_2-fuelled cases are compared in Table 1 with results for uranium metal fuel with and without the cavity. Peak power density values quoted are located in the radial direction 1 m from the target axis at the inner blanket surface. Peak powers in the axial direction are not given due to poor statistical accuracy. The axial peak is higher than the radial value because the blanket is 50 cm closer to the target in the axial direction. However, the axial peak can be reduced with little change in neutronic efficiency by extending the cavity region further back from the target in the axial direction. Introduction of the cavity has only a small effect on the neutronics but gives a large reduction in peak power densities. This indicates that practical power densities can be achieved by suitable cavity dimensions.

Table 2 gives results for a thorium-metal-fuelled blanket for an assembly containing the cavity and compares them with the ThO_2 results. In this case, the effects of oxygen removal are not as significant as in the uranium case. Table 3 summarizes the results for all blanket compositions studied in assemblies incorporating a cavity. Results for all the blankets calculated in the present study are shown in Figs. 3 and 4. Carbide fuel results lie between the oxide and metal cases with a tendency to lie closer to the metal results. Carbide fuel is likely to be a more practical proposition than metal fuel and is being considered as an advanced fuel for LMFBR's.

These results indicate that a carbide-fuelled assembly, incorporating a cavity to reduce power densities, could form the basis of a conceptual AB target/blanket design meriting further study.

V CALCULATION OF ALLOWED CAPITAL COST

The procedure for estimating AB allowed capital cost is described and results are given for uranium and thorium blankets with various levels of fissile enrichment. The allowed cost was determined by comparing a thorium cycle CANDU reactor power station using U235 as makeup fuel

TABLE 1

Comparison between original ORNL conceptual assembly with a uranium oxide fuel blanket (1), uranium metal fuel blanket (2) and with the metal fuel and cavity (3)

% Pu239	0			2			4		
Assembly	1	2	3	1	2	3	1	2	3
Neutrons abs/p	41	56	54	57	111	102	88	263	273
Fissions/p	4.1	7.6	7.5	11	28	26	23	89	93
Peak Fiss. Pow. Dens. (MW/ℓ)	4.6	9.8	0.2	6.7	15.8	0.4	8.8	22.6	1.1
Blanket Fiss. Pow. (MW)	252	461	454	651	1688	1550	1380	5415	5626
Fissile Prod. Rate (kg/d)	2.21	2.99	2.90	2.32	4.00	3.62	2.56	5.87	6.04

TABLE 2

Comparison between original ORNL conceptual assembly with a thorium oxide fuel blanket (1) and with a thorium metal fuel and cavity (2)

% U233	0		2		4		6	
Assembly	1	2	1	2	1	2	1	2
Neutrons abs/p	32	33	44	55	67	99	105	194
Fissions/p	0.5	0.6	6.0	9.5	15.8	28.0	34	72
Peak Fiss. Pow. Dens. (MW/ℓ)	0.9	0.03	2.9	0.12	5.3	0.26	8.2	0.90
Blanket Fiss. Pow. (MW)	32	39	366	579	960	1701	2050	4364
Fissile Prod. Rate (kg/d)	1.89	1.93	1.86	2.12	1.92	2.32	1.82	2.33

TABLE 3

Results for different blanket compositions for Pb target inside cavity

Fissile Enrichment %	0	2	4	6	8
50% (Pu239/U) metal, 25% Na, 25% Fe					
Blanket Power (MW)	454	1550	5626		
Peak Power Density (MW/ℓ)	0.18	0.43	1.05		
kg/d Pu239	2.90	3.62	6.04		
50% (Pu239/U)C, 25% Na, 25% Fe					
Blanket Power (MW)	409	1301	3746		
Peak Power Density (MW/ℓ)	0.18	0.28	0.54		
kg/d Pu239	2.62	3.12	4.24		
50% (Pu239/U)C, 25% Void, 25% Fe					
Blanket Power (MW)	416	1429	4265		
Peak Power Density (MW/ℓ)	0.19	0.31	0.68		
kg/d Pu239	2.50	3.19	4.51		
50% (U233/Th) metal, 25% Na, 25% Fe					
Blanket Power (MW)	39	579	1701	4364	
Peak Power Density (MW/ℓ)	0.03	0.12	0.26	0.90	
kg/d U233	1.93	2.12	2.32	2.33	
50% (U233/Th)C, 25% Na, 25% Fe					
Blanket Power (MW)	36	459	1341	3334	6384
Peak Power Density (MW/ℓ)	0.02	0.09	0.23	0.42	0.75
kg/d U233	1.93	2.01	2.23	2.39	1.43
50% (U233/Th)C, 25% Void, 25% Fe					
Blanket Power (MW)	42	488	1372	3362	7625
Peak Power Density (MW/ℓ)	0.02	0.09	0.23	0.43	0.86
kg/d U233	1.91	2.03	2.21	2.16	1.55

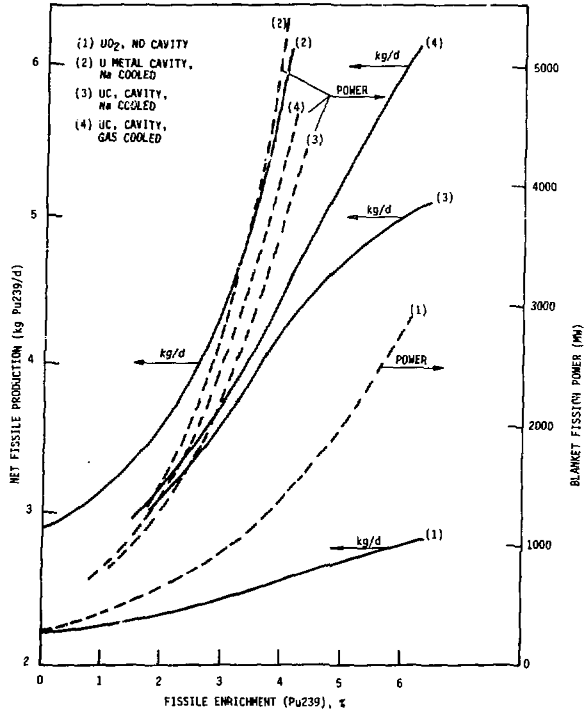


Fig. 3 Fissile and blanket power production with uranium-fuelled blankets.

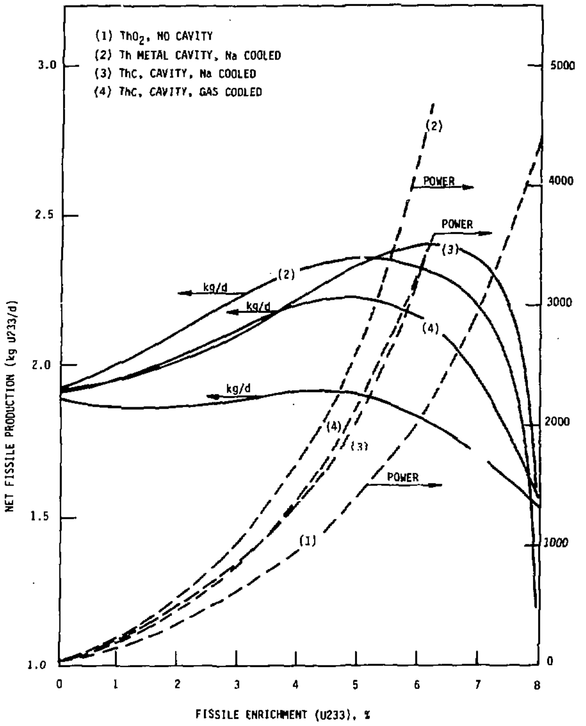


Fig. 4 Fissile and blanket power production with thorium-fuelled blankets.

(system 1) with a similar station using AB-produced fissile material to replace the U235 feed (system 2) - see Fig. 5. The net electrical outputs of both systems, as well as electricity costs, were kept equal. Costs for operation and maintenance, fuel fabrication and reprocessing, and charges on capital were included. The cost calculation was similar to that used in reference 10 and was basically the same as that in the 1973 Laser Fusion Working Party Study[11], but with the following changes:

1. The laser fusion device was replaced by an AB consisting of an accelerator and a target/blanket assembly in which neutrons were produced via the spallation process and fissile fuel was bred.
2. Tritium breeding was not considered because it was unnecessary for spallation.

All costs are in 1981 Canadian dollars. Definitions of the symbols used in the calculation are contained in the glossary on p. 17.

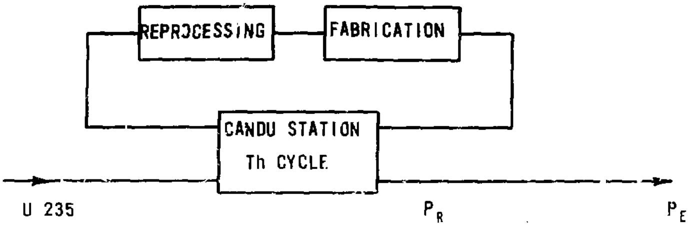
Reactor-breeder Model

Figure 5 gives a block diagram of the two systems compared. System 1 is a CANDU station operating on a thorium cycle with spent fuel recycled and with 35% thermal conversion efficiency. The U235 makeup feed rate (93% enriched) was assumed to be $f = 0.1\ \mathrm{g/(MW_{th}\cdot d)}$. It was further assumed that station capital cost C_{R1} could be represented by

$$C_{R1} = A + BP_R, \quad \mathrm{M\$}$$

where A and B are constants and P_R is net electrical output power in MW. Values used for these constants were A = 180 M$ and B = 0.96 $\mathrm{M\$/MW_e}$[25,26]. Fuel reprocessing and fabrication charges were $S_{f1} = 1.9$ mills/(kW·h)[27,28].

SYSTEM 1



SYSTEM 2

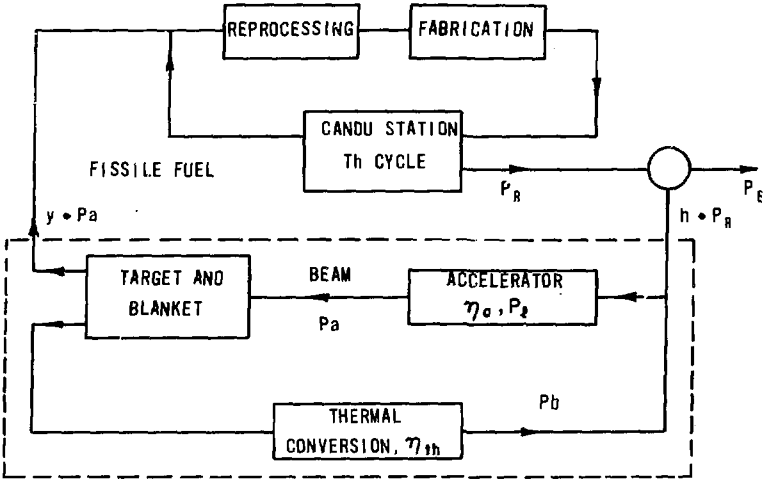


Fig. 5 Schematic diagram for costing two CANDU reactor systems: system 1 produces net electrical power P_E from a thorium fuel cycle reactor using U235 fissile makeup and system 2 is similar except the fissile makeup is supplied by an Accelerator Breeder.

Glossary

a_1	net U233 atoms bred per incident proton
a_2	net Pu239 atoms bred per incident proton
C	total capital cost for AB
C_{R1}	reactor capital cost in system 1
C_{R2}	reactor capital cost in system 2
D	amortization rate
f	fissile fuel makeup rate
F	ratio of AB operation and maintenance cost to capital cost
h	fraction of station 2 electric power fed to or from the AB
i	annual interest rate
ℓ	system capacity factor
N	amortization period in years
P_a	accelerator beam power
P_b	electrical power generated by the AB
P_E	net electrical power output from system
P_ℓ	accelerator rf power loss
P_R	net electrical output power from reactor
S_{f1}	fuel reprocessing and fabrication charge in system 1
S_{f2}	fuel reprocessing and fabrication charge in system 2
S_{fb}	AB fuel reprocessing and refabrication cost
S_u	contribution to power cost from U235 makeup fuel in mills/(kW·h)
U	unit cost of U235 in \$/g
y	AB equivalent fissile yield
η_a	efficiency of conversion of mains ac power to rf power
η_{th}	thermal conversion efficiency

The CANDU station in system 2 is similar to that of system 1, but makeup fuel is generated by the AB. For convenience the AB was divided into three major parts:

1. An accelerator, with rf power loss P_ℓ and efficiency η_a (mains power to rf), produces a beam of 1 GeV protons (output beam power P_a) that impinges on a lead target.
2. A target/blanket assembly in which spallation reactions generate neutrons. The blanket becomes enriched in fissile material with an attendant enhancement of energy production.
3. A turbo/alternator in which the target/blanket thermal energy is converted with an efficiency $\eta_{th} = 0.35$ into electricity.

To close the AB energy loop, a fraction h of station 2 electrical power was fed to or from the AB. If the AB generated power, P_b, that did not match its own requirements, a fraction h of the CANDU station power was either fed to or drawn from the AB. In all cases the output P_E from system 2 equalled the output from system 1. CANDU stations in system 2 were assumed, as in system 1, to have capital cost C_{R2} given by

$$C_{R2} = A + B\ P_R$$

where P_R is the net electrical output in MW from the station fission reactors. Fuel reprocessing and fabrication costs were assumed to be proportional to station output, $S_{f2} = 1.9\ P_R/P_E$ mills/(kW·h). The cost of AB operation and maintenance was assumed to be a fraction F = 1/3 of the AB annual capital charge. Operating and maintenance costs for CANDU stations in both systems were assumed to be equal. The cost of reprocessing and refabricating AB fissile material was S_{fb} mills/(kW·h). Two values were used in the calculations: $S_{fb} = 0$ and $S_{fb} = 0.1\ S_{f2}$. The latter value was consistent with the AB supplying one tenth of the station fissile material (a fertile-to-fissile conversion factor of 0.9) and with fissile concentrations in station spent fuel and AB fissile blanket output being equal. Concentrations in the AB blanket might be higher, which would presumably decrease S_{fb}.

The capital cost difference between stations in systems 1 and 2 is

$$C_{R1} - C_{R2} = +0.96\ P_E \frac{h}{1+h}, \qquad \text{M\$}$$

where station power $P_R = P_E/(1+h)$. The difference in fuel reprocessing and fabrication terms is

$$S_{f1} - S_{f2} = +1.9 \frac{h}{1+h}, \qquad \text{mills/(kW·h)}$$

Total allowed capital cost C for the AB is found by equating electricity costs for systems 1 and 2. The resulting expression is

$$C = \frac{P_E\ L}{D(1+F)} [S_U + S_{f1} - S_{f2} - S_{fb}] + \frac{1}{(1+F)} [C_{R1} - C_{R2}], \qquad \text{M\$}$$

where $L = \ell \times 24 \times 365 \times 10^{-6}$,

ℓ is the capacity factor or availability,

$D = \frac{i(1+i)^N}{(1+i)^N - 1}$, amortization rate at annual interest i over N years,

$S = fU/24\eta_{th} = 0.0119\ U$ mills/(kW·h), the contribution to power cost from U235 makeup fuel and

U = cost of U235 in \$/g.

Values assigned to ℓ, i and N were

$\ell = 0.8$

$i = 0.1$

and $N = 30$ years.

The AB was sized to manufacture fissile material at a rate $y \cdot P_a$ equivalent to a feed rate $f \cdot P_R/0.35$ of enriched U235. Thermal-to-electric conversion efficiency for the CANDU station was assumed to be 0.35 and y was the AB fissile yield in grams equivalent of U235 (93% enriched) per megawatt day of accumulated beam energy. This match of AB to CANDU station required a beam power

$$P_a = \frac{f}{y} \frac{P_E}{0.35} \frac{1}{1+h}, \quad \mathrm{MW}$$

The power balance for the AB determined the value of h,

$$h = \frac{f}{\eta_{th}} \frac{1}{y\,P_a} [P_b - \frac{1}{\eta_a} (P_a + P_\ell)]$$

The expression in square brackets is the net electrical power generated by the breeder.

The AB "equivalent" fissile yield y is given by

$$y = \frac{0.272\ a_1}{0.210\ a_2} \quad \mathrm{g/(MW{\cdot}d)}$$

where a_1 and a_2 are net fissile fuel breeding parameters (atoms bred per proton) for U233 and Pu239, respectively. The coefficients were based on the assumptions that 0.77 g of U233 or 1.02 g of Pu239 is equivalent to 1.0 g of uranium, 93% enriched in U235.

The cost U of separated U235 was determined from the assumptions that U_3O_8 costs $120/kg, that a separative work unit (SWU) costs $120 and that 200 SWU are required to yield 1 kg of 93% enriched U235 and 0.2% tailings. The resultant U = 48 $/g has about equal contributions from material and separative work.

After substitution of appropriate values, the expression for allowed capital cost C of the breeder is

$$C = 0.1734\ y{\cdot}P_a[0.0119\ U - 0.19\ \alpha + (0.0119\ U + 16.4)h], \quad \mathrm{M\$}$$

where $\alpha = 0$ when $S_{fb} = 0$ and $\alpha = 1$ when $S_{fb} = 0.1\ S_{f2}$. Once the equivalent fissile yield $y \cdot P_a$ and the net electrical output power $(P_b - (P_a + P_\ell)/\eta_a)$ for an AB are known, the AB allowed capital cost can be determined for the coupled CANDU reactor breeder system of Fig. 5. The yield $y \cdot P_a$ establishes the fission reactor power P_R.

Results

Results are presented for sodium-cooled uranium and thorium breeder blankets with the fertile material in either metal or carbide form. In all cases, a cavity separates the blanket and lead target (Fig. 2). A 300 mA reference beam of 1 GeV protons, from an accelerator with $\eta_a = 0.703$ and $P_\ell = 73.2$ MW (Fig. 9), impinges on the target.

Table 4 gives typical values of breeding parameters a_1 a, a_2 as a function of blanket enrichment. Blankets breeding Pu239 have superior equivalent fissile yields (y) to those breeding U233.

TABLE 4

Net fissile fuel breeding parameters a_1 and a_2 (atoms/proton) for U233 and Pu239, respectively, bred in Na-cooled blankets of metal or carbide fuel, as a function of enrichment

Enrichment	a_1		a_2	
%	Metal	Carbide	Metal	Carbide
0	30.8	30.8	45.2	40.8
2	33.9	32.1	56.4	48.6
4	37.1	35.6	94.0	66.0
6	37.2	38.2		
8		22.8		

Figures 6 and 7 give curves of allowed AB capital cost versus enrichment for uranium and thorium blankets, with the cost U of separated U235 as a parameter. Curves for $S_{fb} = 0$ and $S_{fb} = 0.1\ S_{f2}$ define upper and lower limits of a "band" of allowed capital cost for each value of U. Also indicated are enrichment values required for energy breakeven operation of the AB (h=0). Using the average value in a "band", the allowed AB capital costs at U = 48 \$/g and h = 0 vary from 250-280 M\$ for the uranium blankets down to 200-250 M\$ for the thorium blankets. These values increase substantially when fissile enrichment is increased to give h > 0. For example, at 2% enrichment in the uranium metal blanket the allowed capital cost (average) becomes ∿ 400 M\$, which is ∿ 3.5 times less than the estimated capital cost. Too high an enrichment is not acceptable because blanket power increases quickly as shown in Figs. 3 and 4 (above 4% and 6% for U and Th blankets, respectively). Figure 8 gives the power fraction h as a function of enrichment for the different blankets. Energy breakeven operation occurs at less than 2% enrichment for the uranium blankets and at more than 3% for the thorium blankets.

The cost of the primary product of the fission reactor-accelerator breeder system, electrical energy, is rather insensitive to the cost of fissile makeup fuel. Based on the costing model used, the increase in the cost of electricity is only about 1 mill/(kW·h) if the cost U rises from 48 to 144 \$/g (caused, for example, by an increase in U_3O_8 cost).

Table 5 summarizes the results of Figs. 6 and 7 for the energy breakeven case (h=0) and lists data for a system sized to service a CANDU reactor-breeder system of 12000 MW_e total output. Accelerator beam power is slightly larger than the reference case value of P_a = 300 MW. If beam power was restricted to 300 MW then at h=0 such a breeder could, for example, service 11600 MW_e with a uranium metal blanket or 9900 MW_e with a thorium carbide blanket.

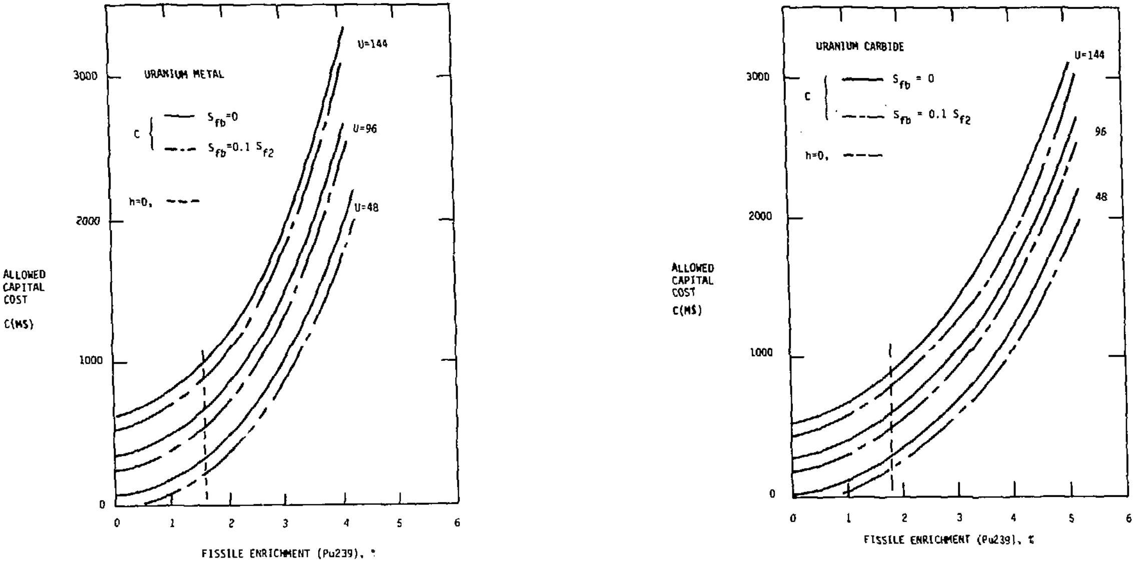


Fig. 6 Allowed capital cost C versus fissile enrichment for uranium metal (a) and uranium carbide (b) blankets.

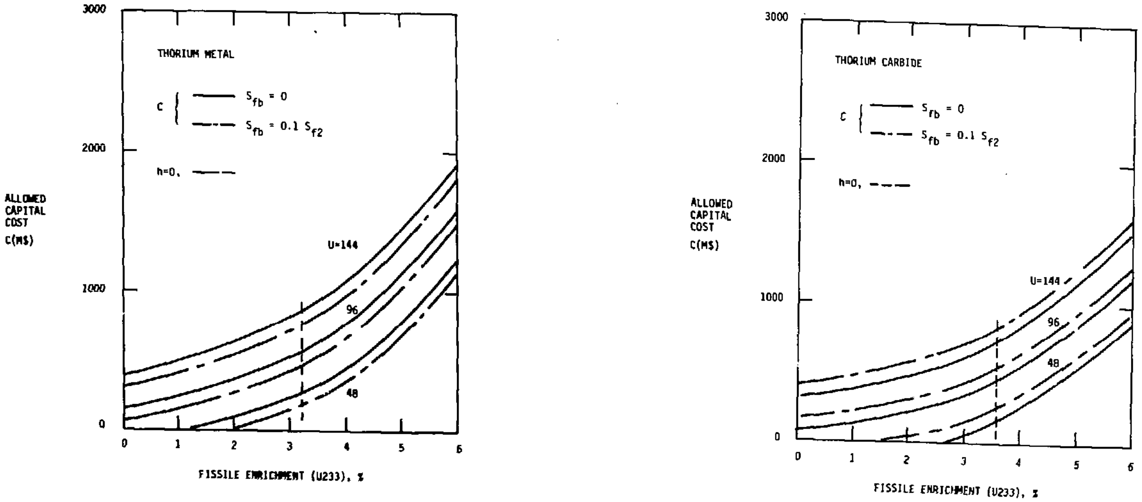


Fig. 7 Allowed capital cost versus fissile enrichment for thorium metal (a) and thorium carbide (b) blankets.

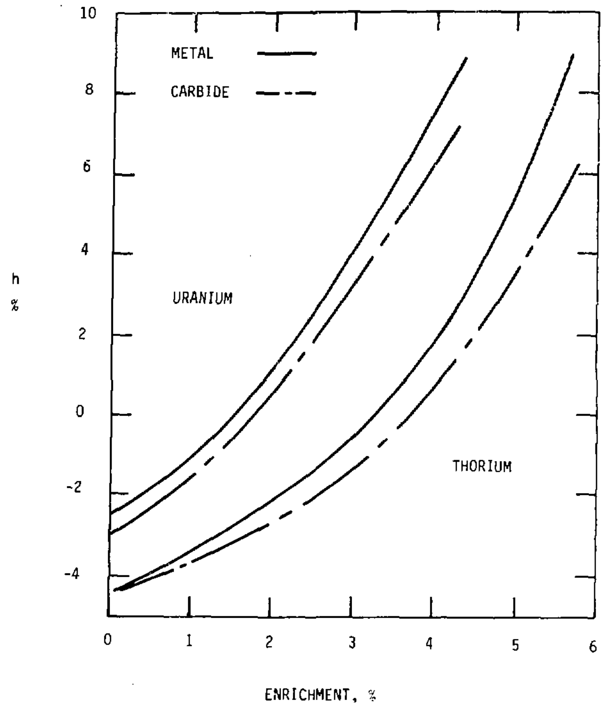


Fig. 8 Power fraction h versus fissile enrichment for uranium and thorium breeding blankets having the fertile material in metal or carbide form. These blankets contain 50% fertile/fissile material, 25% Na, 25% Fe (volume %).

TABLE 5

Data for an Accelerator Breeder at energy breakeven (h=0) that services a CANDU reactor-AB system of 12000 MW_e output

U = 48 \$/g

	Fissile				Allowed Capital Cost					
Blanket	Enrichment	P_a	P_b	Fissile Yield	$S_{fb} = 0.1\ S_{f2}$			$S_{fb} = 0.0$		
	%	MW	MW_e	Mg/year	M\$	M\$/Mg/year	\$/W_e	M\$	M\$/Mg/year	\$/W_e
U metal	1.6	309	543	1.02 Pu239	227	223	0.43	340	333	0.64
U carbide	1.8	343	591	1.02 Pu239	227	223	0.39	340	333	0.58
Th metal	3.2	349	600	0.77 U233	227	295	0.39	340	442	0.59
Th carbide	3.7	360	616	0.77 U233	227	295	0.38	340	442	0.57

VI ESTIMATE OF ACCELERATOR BREEDER COST

Costs in 1981 dollars for producing Pu239 or U233 from an electronuclear breeder based on a 100% duty cycle linear accelerator have been determined for different energies of output proton beams impinging on a lead target. Energies from 1/2 GeV to 10 GeV were used in the calculations with three different output beam powers (150 MW, 300 MW and 600 MW) in an attempt to determine beam power and energy relationships. Funneling schemes (combining or coalescing of two or more beams at a position between changes in structure rf frequency), different operating frequencies and different beam apertures were considered to accommodate the range of beam currents necessary for the energy and power region studied. Proton beam currents varied from 1.5 A at 1/2 GeV to 15 mA at 10 GeV.

The linac configuration studied consisted of the components shown in Fig. 1. Different rf structures were selected for optimum rf efficiency and beam dynamics reasons in three beam energy ranges. The accelerating gradient in the DTL and CCL sections was determined by an optimization procedure that set linac length costs (including the structure, cooling, services, instrumentation and building costs) equal to the cost of the rf power necessary to establish the accelerating fields in the accelerating structure. The designs were checked to ensure that rf beam loading was not excessive, that ample stored energy was available in the beam region for accelerating the beam and that surface electric fields did not lead to excessive breakdown. Much detailed work remains to be done on particle beam dynamics in the accelerator to determine the feasibility of the scheme chosen and its limitations and tolerances.

The lead target was surrounded by a blanket of fertile material. Data from the calculations of Sec. IV on the target/blanket assembly were fitted by a least squares method to determine net fissile production rate as a function of fissile fuel enrichment and fissile fuel enrichment as a function of blanket fission power. Fuel costs were determined for a steady-state system of linac and target/blanket that was energy self-sufficient (i.e., the h of Sec. V equalled zero). The equilibrium fuel enrichment was determined from the blanket power necessary to achieve energy breakeven. This enrichment then yielded a fissile fuel production rate. Using the capital costs of the facility and a specific charge rate, the cost for producing the fuel was determined.

Assumptions used in determining capital cost, structure optimization and fuel costs are given in Table 6 for a 300 mA, 1 GeV linac. The 2.1 MeV/m average accelerating gradient yields a linac 480 m in length that is ∿ 80% beam loaded and requires ∿ 375 MW of rf power. The output beam aperture from the CCL is 6 cm in diameter. Rf efficiencies, structure parameters and component costs in 1981 Canadian dollars were based on current technology and what could be expected in the near future. The 11% capital charge rate included operating and maintenance charges that were assumed to be 10% of the charge rate. Control and monitoring costs for the linac and rf system were based on a percentage (∿ 10%) of the total capital cost for the linac and rf system. Reprocessing charges were assumed to be $17/g.

Figure 9 shows a schematic of the 1 GeV AB that is energy self-sufficient. Rf power at frequencies higher than 250 MHz are supplied by klystrons that are more efficient and have a longer life than the gridded tubes necessary at lower frequencies. Frequencies chosen were based on available frequency regimes for the rf sources and beam dynamics constraints.

Fuel costs for Pu239 and U233 are shown in Fig. 10 as a function of the proton output energy for three beam powers. Production rate of fissile fuel is listed on the figure for each beam power. Production of Pu239 is estimated to be cheaper than U233. A minimum in costs is achieved for proton beam energies ∿ 1 GeV. There is a slight penalty for higher energy

TABLE 6

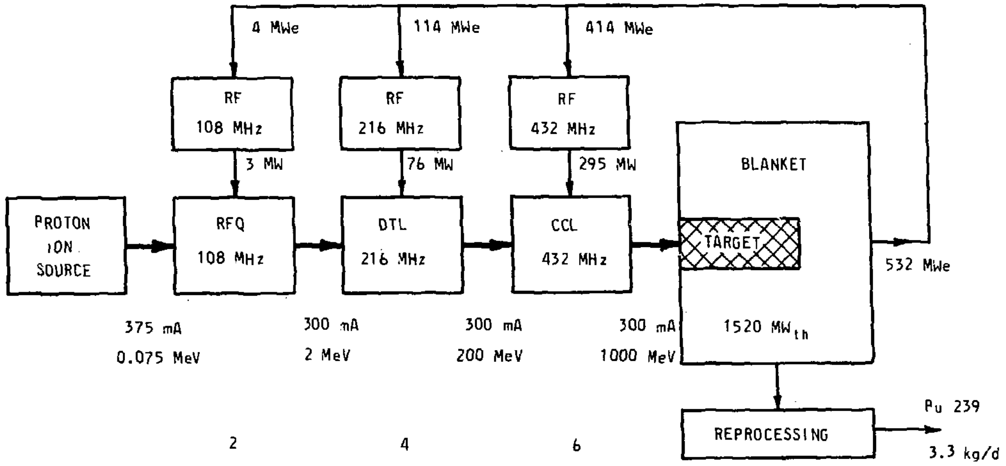
Assumptions and costing formulae for an AB based on a 300 mA 1 GeV linac

Accelerator Sections
50 kV injector
108 MHz RFQ to 2 MeV with 2 cm diameter beam aperture
216 MHz DTL to 200 MeV with 4 cm diameter beam aperture
432 MHz CCL to 1000 MeV with 6 cm diameter beam aperture

Accelerator Parameters (Efficiency ac to dc - 95%,
Accelerating Gradient - 2.1 MeV/m)

	Stable Phase (degrees)	Average Theoretical ZT^2 (MΩ/m)	Fraction of ZT^2 Achievable	Efficiency dc to rf	Rf Total (MW)	Length (m)	% Beam Loading
RFQ	variable	-	-	70%	2.8	4.0	22%
DTL	26	39.2	80%	70%	75.7	94.9	78%
CCL	26	44.5	85%	75%	294.7	383.2	81%
				Totals	373.2	482.1	

Costing
Accelerator Structure Length Costs - $\$[1.212/\sqrt{f(\text{MHz})} + 0.015] \times 10^6/\text{m}$
Length Costs for Cooling, Services, Instrumentation
and Building - $\$0.044 \times 10^6/\text{m}$
Rf Costs including dc, Socket, Tube and Associated
Components - \$0.7/W
Target/Blanket Complex - 1.5 M\$/MWe
Charge Rate - 0.11 (Operating and Maintenance are 10%
of charge rate and included)
Control and Monitoring - 10% of Total Linac and Rf Costs
Efficiency - thermal to ac - 35%
Reprocessing Charges - \$17/g
Engineering and Management Charges - 20% of all items
except 10% of cooling, instrumentation, controls
and monitoring
Contingency - 20%
Availability - 80%



BORE DIA. (cm)		2	4	6	
LENGTH (m)		4	95	383	
SHUNT IMPEDANCE (MΩ/m)			31.3	37.8	
GRADIENT (MeV/m)			2.09	2.09	
COST	$0.8 M	$0.5M	$21M	$73.5M	$797 M(TARGET/BLANKET)
RF COST		$2.0M	$53M	$206 M	

$357M

Fig. 9 Schematic of an Accelerator Breeder that is energy self-sufficient.

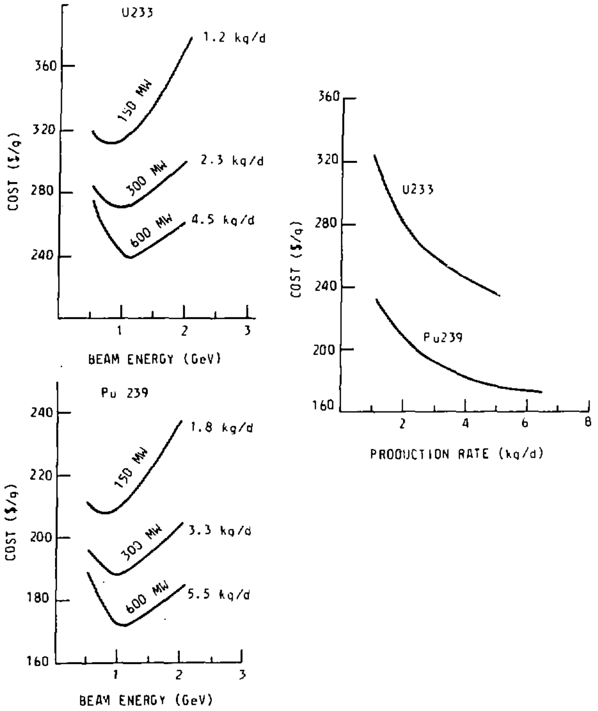


Fig. 10 Summary of accelerator-bred fuel costs.

(for instance 300 MW at 2 GeV is 11% more expensive than at 1 GeV) but the higher energy does offer advantages of lower proton current and more penetration in the lead target. Note that lower current at higher energy relaxes constraints on the accelerator design and accelerator operation, and reduces beam spill that will activate the accelerating structure and beam handling components. Fuel costs are shown as a function of the production rate. Estimated costs level off for high production rates. Doubling Pu239 production for 1 GeV protons from 2.5 to 5 kg/d reduces fuel costs by only 9%.

The most difficult parts of the linac to engineer are the low-energy components associated with launching the beam and with the first frequency increase at the RFQ/DTL interface. Therefore a 300 mA, 10 MeV proton linac would provide an excellent test facility to determine engineering and physical constraints of an AB. It would also be an excellent system for studying emittance growth, beam spill rate, multi-tank control, beam startup and high beam loading, all associated with operating conditions required by an AB.

Table 7 gives a summary of fissile fuel production and costs in 1981 dollars for a 1 GeV AB with an 80% facility availability. The target/blanket and rf systems account for the major capital outlay and are the most significant contributor to fuel costs.

The dependency of costs and linac length in percent per percent change in a system parameter are given in Table 8. In each case the system was re-optimized to accommodate the changed variables. As expected, rf costs, rf efficiency, target/blanket costs and the capital charge rate yield the most significant changes in fuel costs. The table can be used to determine the effects of improvements without recalculating and re-optimizing the entire system.

TABLE 7

300 mA, 1 GeV AB summary

Target/Blanket Thermal Power	1520 MW_{th}
AC Power Generation	532 MW_e

	Blanket Enrichment (%)	Production Rate (kg/d)	Fuel Costs ($/g)
Pu239	1.6	3.4	183
U233	3.2	2.3	261

Pu239 Costs

	Cost ($M)	Relative Fuel Cost (%)
Target/Blanket Capital	797	57
Rf Capital	261	19
Linac Capital	60	4
Controls and Monitoring Capital	36	3
Capital	1154	
Engineering, Management plus 20% contingency	298	
Total Capital	1452	
Operating and Maintenance		8
Reprocessing		9

80% facility availability

TABLE 8

Pu239 fuel cost, total capital and total length dependency
(% per % change in parameter for reoptimized systems)

Parameter	Fuel Cost	Total Capital	Total Linac Length
CCL Linac Length Costs	0.07	0.09	-0.35
CCL Rf Costs	0.21	0.23	0.38
CCL AC/Rf Efficiency*	-0.25	-0.41	-
CCL ZT^2	-0.07	-0.09	-0.37
DTL Linac Length Costs	0.02	0.03	-0.09
DTL Rf Costs	0.05	0.06	0.09
DTL AC/Rf Efficiency*	-0.07	-0.11	0
DTL ZT^2	-0.02	-0.02	-0.06
Reprocessing	0.15	-	-
Thermal/AC Efficiency*	0.15	-	-
Target/Blanket Costs	0.52	0.59	-
Charge Rate	0.87	-	-

* Less fuel produced at lower enrichment when efficiency improved for energy breakeven system.

VII SUMMARY AND CONCLUSIONS

While the performance of major components of the accelerator has been demonstrated separately in research accelerator applications and in development laboratories, there is a need to demonstrate performance under realistic AB conditions. The preferred route to such a demonstration is through a staged development program beginning with a low energy but full current linac. Successful completion of this step would establish the engineering practicability of the front end of an AB. A second stage of development, with a beam energy of 200 MeV and a current of 70 mA, could provide an intense neutron source for a variety of interests, the most important of which is materials damage studies relevant to AB target/blanket assemblies. A third stage, raising the beam energy to 1 GeV with 70 mA current, would provide a realistic environment in which to develop AB target/blanket assemblies. The fourth and final stage, a demonstration AB, would be attained by raising the 1 GeV beam current to its full 300 mA value.

The target/blanket assembly has been subject to less development than the accelerator part of an AB. Although the basic neutron physics of conceptual target/blanket designs can be calculated with reasonable confidence using existing neutron transport codes, much work remains to be done on heat density, corrosion and materials damage problems. In parallel with a staged accelerator development, engineering of appropriate target systems would be required at each stage. Separate liquid metal test loops would be built to facilitate development of coolant systems with the necessary degree of corrosion resistance. The large power density ratios revealed by neutron transport calculations show that a workable target/blanket assembly will have to depart from simple compact cylindrical geometries. Some form of multiple liquid metal jets or a modified molten salt breeder reactor core might be required as a primary target.

The economic assessment of the AB shows that beam power must be at least 300 MW. This implies a range of possible combinations of beam energy and current from 1 GeV, 300 mA to about 2 GeV, 150 mA. The estimated capital cost of an energy self-sufficient AB is approximately 1500 M$ (1981). The AB would contribute only about 2 mills/(kW·h) to the overall cost of electricity based on the estimated \$183/g cost of Pu239 fuel. Model calculations, based on an energy self-sufficient mode of operation and with the current value of U235 (assumed to be \$48/g), show that the allowed capital cost falls short of the estimated capital cost by a factor of 3.5. However, the dependence of allowed capital cost for the cavity blanket design on the degree of enrichment is large, so that if the enrichment is raised and, as a result, h is increased to the 2 to 4% range the economics become more favorable. Moreover, if the cost of U235 was to rise above the current \$48/g by a factor of at least two, then the allowed capital cost would enhance the justification for building an AB.

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