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Breeding Nuclear Fuels with Accelerators - Replacement for Breeder Reactors*

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1. Introduction

Low-energy particle accelerators have found a multitude of diverse industrial applications from medical diagnostic and therapy, to down-hole well logging, food preservation, and even sewage treatment. High energy particle accelerators on the other hand have not been so fortunate in finding justification for expansion of the technology outside their primary mission, namely high energy physics.

This does not mean that potential applications do not exist. A number have been identified and attempts made to develop them. Perhaps the one coming closest to realization has been pion therapy; the technique was being developed by groups at Stanford and Los Alamos.

One really tantalizing application of high energy particle accelerators has been, and still is, the production of nuclear fuel for the nuclear energy industry; tantalizing because it would create a whole new industry. This approach to producing fissile from fertile material was first considered in the early 1950's in the context of the nuclear weapons program. A considerable development effort was expended before discovery of uranium ore in New Mexico put an end to the project. Later, U.S. commitment to the Liquid Metal Fast Breeder Reactors (LMFBR) killed any further interest in pursuing accelerator breeder technology. Interest in the application of

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accelerators to breed nuclear fuels, and possibly "burn" nuclear wastes, revived in the late 1970's, when the LMFBR came under attack during the Carter administration. This period gave the opportunity to revisit the concept in view of the present state of the technology. This evaluation and the extensive calculational modeling of target designs that have been carried out are promising. In fact, a nuclear fuel cycle of Light Water Reactors and Accelerator Breeders is competitive to that of the LMFBR. At this time, however, the relative abundance of uranium reserves vs electricity demand and projected growth rate render this study purely academic. It will be for the next generation of accelerator builders to demonstrate the competitiveness of this technology versus that of other nuclear fuel cycles, such as LMFBR's or Fusion Hybrid systems.

2. The Basis for Accelerator Breeding

Breeding nuclear fuels with a high energy particle beam (protons or deuterons) is a two-step process requiring careful optimization. The first step is the creation of a copious source of neutrons with the proper energy spectrum and the second step is the capture of these neutrons in the fertile material to the maximum extent possible. These two processes are made more complex by the fact that energetic neutrons can fission as well as be captured, releasing the material's fission energy in the process.

Neutron multiplication in the accelerator breeder target relies on spallation and fast fission. The spallation process occurs when high-energy nucleons, E>500 MeV, interact with heavy nuclei. Fast (to several tens of MeV) protons and neutrons, as well as smaller numbers of cascade nucleons (to several hundreds of MeV) are produced. In a thick target, the high-energy nucleons go on to induce further spallation reactions. At the end of this prompt cascade, the nucleus is left in a highly excited state, typically several hundred MeV. It loses this energy primarily by the evaporation of neutrons, some protons and other charged particles. The evaporation neutrons have a spectral shape similar to that of the fission neutrons, but with a higher average energy. These neutrons can then produce fast fissions, and hence, additional neutrons in a heavy element fertile target. When all these effects are taken into account, calculations verified by earlier experiments(1) at the BNL Cosmotron indicate that in a sufficiently large target of depleted uranium, a 1-GeV proton will produce 60 fissile nuclei and about 4 GeV in heat.(2,3) Heat generation will vary greatly with enrichment. Similar but somewhat lower values would be obtained for a thorium target.

The fissile production rate is strongly dependent upon the neutron spectrum and the type of fertile isotope present in the target. A hard spectrum allows further multiplication by fast fission in the fertile isotopes. A ^{238}U target is also better than ^{232}Th due to its larger fast-fission cross section. Other elements present in the target will act as neutron absorbers and decrease the fissile production rate.

Neutron yield and fissile production rate calculations are carried out in two stages: first a high energy Monte Carlo calculation accounts for all nuclear reactions with excitation energies >15 MeV, and second, a neutron transport calculation deals with all reactions below 15 MeV.

The high energy calculation uses the NMTC/BFIS code. This version of the code includes fast fissions. Spatial and energy distributions for neutrons generated in the NMTC/BF1S analysis serve as input for the subsequent neutron transport calculation. The transport codes used at BNL are ANISN (1-dimensional) and TWO-TRAN (2-dimensional). Neutron group cross sections are obtained from collapse of the DLC-37 library based on the ENDF/B-IV file.

This computational procedure has been tested against experimental values.(4) Predictions of neutron yield for Vasil'kov's(5) and FERFICON(6,7) neutron yield experiments is compared with the experimental data in Table 1. Garvey's calculation substantially underestimates the yield because it does not include the contribution of fast fissions. This shows the importance of utilizing the fertile material directly in the primary target.

Calculational results for the BNL target geometry are given in Table 2. These give typical yields for nonoptimized target geometries. These results are consistent with work done at other laboratories.(8) It must be noted that these numbers do not account for leakage. However, parasitic absorptions are accounted for to the extent that these materials and appropriate cross sections are included in the calculation. Thus, fissile production in UO_2 is 30% lower than that in U metal, an important difference! The numbers shown in the table are normalized for 1-GeV protons. These yields scale approximately linearly with proton energy within a reasonable range of 700 MeV<E<2000 MeV. Although present designs are far from optimization, a ~30% drop can be expected in the production of ^{233}U as compared to ^{239}Pu due to the inherent cross section difference between the two fertile materials. Similarly, the total thermal energy generated in a thorium target will be much lower, less than 50% of the power generated in a ^{238}U target. This difference becomes even larger with increased fissile enrichment. Target power is an important design criterion; on the one hand, there is the need to limit maximum power densities and maximum to average power ratios, and on the other hand, there is the incentive to reach electrical breakeven for the operation of the accelerator breeder system. This requires generating about 6 GeV thermal per GeV proton. This requirement can be met in a ^{238}U target but is not likely in the thorium case.

3. A Reference System

Advances in accelerator technology and target design have provided a solid base on which to predict performance and optimize designs. As a result, the accelerator breeder concept has evolved over the years to a design which maximizes fissile production while relying on proven, existing technology. Thus, the reference design used for analysis is thought to be close to optimum, providing maximum fissile production rates at lowest cost and lowest technical risk.

An accelerator breeder facility consists of three main components: a) the accelerator, b) the target, and c) the balance-of-plant including steam generators, turbines and alternators, and heat rejection system. It should be noted that an accelerator breeder system is not complete without the required reprocessing plant and waste management facilities which are needed to complete the fuel cycle.

Table 3 shows the main parameters for the plutonium production mode of this reference concept. The parameters given are representative only.

The system is based on the successful development of a 1 to 2-GeV, 300-mA linear accelerator. It is state-of-the-art technology. The studies that have been carried out over the last few years at several laboratories indicate that it is mainly an engineering development project.(9-15) I am not implying here that such an accelerator can be designed and built at the drop of a hat. I am merely stating that the present state of accelerator knowledge and technology is adequate for the job.

The target system for this 1-to-2 GeV, 300-mA beam is another matter altogether. Beam power alone is 300 to 600 MW. This does not include the additional fission energy released, whether it is the fast fission inherent in the spallation process of uranium, or the thermal fission of fissile material present which will increase the power to be dissipated by a factor of 5 to 10.

The real interest of this paper is the work relating to the application of this powerful proton beam, namely the target design.

A number of target concepts have been investigated. Target concepts fall into two categories: Those that utilize a primary target (liquid metal) surrounded by a secondary target of fertile material (blanket),(16-19) and those that impinge the high-energy proton beam directly upon the fertile material combining neutron production and absorption in the same medium. The idea of a primary liquid metal target is attractive as it alleviates potential problems of primary beam power dissipation and radiation damage to structural materials. A target combining liquid metal and fertile material has also been proposed utilizing uranium-floride in molten salt (e.g., $LiF-BeF_2-UF_4$).(20)

Despite their obvious advantages, liquid metal targets have been abandoned in favor of direct fertile material bombardment for three reasons: a) the use of a nonfertile material (e.g., Pb-Bi) primary target reduces the neutron yield (fissile production) by a factor of about two, b) the use of liquid metal requires the development of a new technology unavailable at this time, and c) any liquid metal target (heavy elements are assumed) will undergo a high fission rate produced by the proton beam and consequent rapid buildup of fission product with no easy solution to containment and cleanup. These same arguments also hold to some extent for molten salt.

Thus, a solid fertile material target is preferred, providing the problems associated with peak power density and radiation damage can be solved.

The reference concept target design, shown in Fig. 1a, b, solves these problems by defocusing the proton beam in one direction and rastering the beam in the other, to achieve a nearly uniform, dilute power deposition on the inner front face of the target. The beam current density on the target is small ($\sim 2\ \mu A/cm^2$). Neutron leakage is minimized by proper design of the target geometry and use of reflector materials.

The target itself consists of pressure tubes containing fertile material in the form of cladded rods and necessary coolant (H_2O) of a design similar to that of CANDU reactors. The optimum lattice design must be a compromise between maximizing fuel production (this requires the practical elimination of moderators and parasitic absorbers), and the ability to remove the heat generated by the primary beam and all other processes including fission in the fertile and fissile material. A volume ratio (coolant-to-fuel) of 0.5/1 appears reasonable. Utilization of D_2O does not appear warranted.

Because of the inherently nonuniform irradiation of target material leading to a large peak-to-average power density distribution ratio, fuel shuffling is required on a carefully programmed basis. On-line fuel shuffling and fuel loading is a must to maximize the facility utilization factor.

The total heat generated in the target of an accelerator breeder can vary from a minimum of about 3X the proton beam power to a maximum determined by detailed target design dealing with parameters such as lattice geometry, structural materials, coolant, enrichment, etc., the integrated effect being equivalent to the k_{eff} of a reactor. Preliminary investigation of target designs indicates that the accelerator breeder can be made to breakeven in the plutonium production mode; the target will generate enough electrical power to run the accelerator. Thus for a 50% efficiency, 450 MW beam accelerator reference concept, the thermal power available in the target should be about 3000 MW.

The balance-of-plant (BOP) comprising the steam generators, turbines and alternators, and heat rejection system will, for all practical purposes, be identical to that of equivalent capacity power plants. The system should, therefore, not require any development efforts.

4. Economics

A realistic cost estimate for the construction of a commercial, plutonium, breakeven accelerator breeder facility (1.5-GeV, 300-mA, 2000-kg ^{239}Pu/yr) has been performed by United Engineers and Constructors (UE&C). The capital investment cost has been estimated at M$2500 (1983). This production plant includes thermal-to-electrical power conversion of 1000 MW(e).

The equivalent cost of a ^{233}U production facility (1.5 GeV, 300 mA, 1300 kg ^{233}U/yr) is estimated at M$3000 (1983). In this case, the accelerator breeder does not attempt to breakeven, BOP costs have been reduced and replaced by the larger increase required by a HTGR power plant of sufficient capacity to operate the facility.

Using a 10% depreciation charge and adding the cost of operating the accelerator breeder (~M$ 50 yearly) bring the cost of ^{239}Pu to ~$ 150/g. The equivalent cost of ^{233}U would be $280/g. This is expensive! The present cost of low-enriched fuel is about $30/g ^{235}U. It must be noted, however, that this cost is based on existing, depreciated facilities, and not on replacement costs. These would be much higher. Obviously, the accelerator breeder, like the LMFBR, will only become competitive when scarcity of ^{235}U forces its real cost to that same level. This is supposed to happen sometime during the next few decades. An absolute economic comparison, taking into account all relevant factors, cannot be made at this time as there are too many imponderables. We can, however, make an objective relative economic evaluation based purely on capital investment requirements, since it has become the driving factor in the cost of nuclear generation of electricity. Table 4 shows the relative cost of electricity at the power plant for breeder-burner systems in 1983 dollars, normalized to existing once-through LWR's. This comparative evaluation assumes that the fuel costs are the same for all systems; it assumes that the cost of reprocessing and remote fabrication of AB and LMFBR fuels will be equivalent to that of mining, refining, enriching, and fabricating LWR fuel. Obviously, this is an oversimplification, but even if wrong, the effect would be minor.

The comparison, in Table 4, is made for an in-place plutonium fuel cycle with burner reactor conversion ratios of 0.6 requiring 400 kg ^{239}Pu fuel/yr, and LMFBR conversion ratios of 1.05 (20 years doubling time) producing 200 kg ^{239}Pu net per year. Unit costs for the various systems come from UE&C.

The results indicate that on a relative basis and present day economics, electricity produced with accelerator-bred fuel would cost 40% more than the once-through cycle, whereas fusion hybrid may be somewhat lower at 27%. Actually, this incremental electricity cost could be lower depending on the fraction of total costs due to other factors, e.g., uranium mining and enrichment, etc. In addition, improvements in burner reactor efficiency could have an added strong influence in lowering these increments by as much as 50%, for a conversion ratio of 0.8.

Table 5 makes the same comparison for the HTGR fuel cycle with a conversion ratio of 0.9, again normalized to the once-through LWR fuel cycle cost. The unit cost of HTGR's has been developed at UE&C for Gas Cooled Reactor Associates (GCRA) on the basis of 800 MW reactors.(21) The number of reactors supported by the accelerator-breeder is based on a net fuel production rate of 1200 kg/yr. The hybrid fusion breeder parameters are based on a TRW/LLL study.(22) Its cost is estimated at M$6000 and ^{233}U production rate at 6000 kg/yr.

The results are surprising! The electricity costs of the AB-HTGR fuel cycle is the same as that of the equivalent LWR fuel cycle of Table 4 and in both cases they are competitive with the FBR. It must be noted that half the increase is due to the higher cost of the HTGR burner. In all cases, these costs are competitive with the LMFBR, with the exception of the Fusion Hybrid system which is cheaper.

The incremental cost of electricity shown in these tables, appears substantial. It must be remembered, however, that the normalized cost of electricity shown for the LWR is the generation cost only. It represents only about half of the total cost of electricity delivered to the customer. Thus, given the same delivery charges, the incremental cost to the customer would only go up by 20%, instead of 40% for the LMFBR or AB cases.

Why then should we consider the accelerator breeder at this time, or the fusion hybrid? Clearly, they compete with the fast breeder reactor for the future of the nuclear power industry. After all, we have now about 60 LWR's either operating or being constructed, and we have spent billions of dollars in LMFBR development. Can we, or should we, change course at this time? Should we do so when there is no apparent economic advantage to the accelerator breeder symbiotic systems over the LMFBR? The argument against hybrid fusion breeders is even stronger; how can we justify development of a very speculative technology for what appears to be a small return? Answers to these questions have to be found in the broader context of the institutional and political problems facing our nuclear power industry. These problems of safety, safeguard, and proliferation have no absolute answer. Even though we know the existing system is technically viable, we seem incapable of convincing the public and our political institutions that this is so. Is there an alternative option to the present state-of-affairs? There is--the HTGR-thorium cycle backed by accelerator breeders. This system offers an inherently safe, highly proliferation resistant, reasonable cost power producer. It will go a long way to increase public acceptance of nuclear power while providing energy self-sufficiency assurance for a long time to come.

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Figure Caption

1. Accelerator Breeder Target Plan View and Beam Rastering Concept Schematics

TABLE 1

ANALYSIS OF VASIL'KOV's EXPERIMENT FOR HIGH ENERGY PROTONS INCIDENT ON LARGE URANIUM BLOCK

	Proton Energy MeV	Vasil'kov's Experiment	BNL Calculation	Garvey's* Calculation
Capture ^{238}U	660	46.0 ± 4.0	42.6 ± 4.8	26.9 ± 1.6
Fission ^{238}U	660	14.6 ± 1.3	11.3 ± 1.2	5.2 ± 0.3
^{235}U	660	3.9 ± 0.4	2.44 ± 0.2	1.6 ± 0.1
Total	660	18.5 ± 1.7	13.74 ± 1.4	6.8 ± 0.4
Capture ^{238}U	400	22.1 ± 2.4	16.2 ± 2.0	10.9 ± 0.6
Fission ^{238}U	400	7.0 ± 0.8	4.5 ± 0.6	2.1 ± 0.1
^{235}U	400	1.9 ± 0.2	0.96 ± 0.1	0.7 ± 0.1
Total	400	8.9 ± 1.0	5.46 ± 0.7	2.8 ± 0.2

ANALYSIS OF FERFICON EXPERIMENT FOR HIGH-ENERGY PROTONS

Target**	Proton Energy MeV	Ferficon Experiment	BNL Calculation	Garvey's* Calculation
U-1	480	9.6 ± 0.7	12.0 ± 1.0	10.1 ± 0.4
U-7	480	14.1 ± 0.9	14.0 ± 0.9	10.9 ± 0.4
U-19	480	15.2 ± 1.0	14.1 ± 1.4	12.4 ± 0.4
U-37	480	17.1 ± 1.0	16.9 ± 1.0	12.3 ± 0.4

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* High energy fission is not included in the calculation.

** Target consists of bundles of 1, 7, 19, and 37 uranium rods, 30.5 cm long, 1.6 cm radius, and 0.26 wt% ^{235}U.

TABLE 2

CALCULATED FISSILE PRODUCTION RATE PER 1-GeV PROTONS

Fuel	Enrichment	Moderator	Neutron Yield >15 MeV Reaction	Net Fissile Element* Production Rate	Total** Energy
UO_2	0.3%	H_2O	51.23 ± 3.75	60.94 ± 4.46	3.6
		D_2O		59.48 ± 4.35	3.0
UO_2	3.0%	H_2O	51.15 ± 3.79	61.60 ± 4.40	6.1
UO_2	6.0%	H_2O	51.15 ± 3.79	60.90 ± 4.40	9.4
U	0.3%	H_2O	71.79 ± 3.59	93.58 ± 4.68	4.5
		D_2O		97.38 ± 4.87	4.6
Th	0%	H_2O	57.10 ± 3.03	59.06 ± 3.13	1.9
		D_2O		59.61 ± 3.16	1.9

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*Production of fissile element (e.g., ^{239}Pu) minus consumption of fissile element (^{235}U).

**Total fision and beam energy in target (includes endothermic energy requirements for beam-induced neutron release from target nuclei).

NOTE: 1) Volume fractions are fuel (0.64), moderator (0.27), and tube/clad (0.09).

2) NMTC/BFIS code does not differentiate between ^{238}U and ^{235}U.

TABLE 3

ACCELERATOR BREEDER REFERENCE CONCEPT PARAMETERS
2000 kg PLUTONIUM PRODUCTION CAPABILITY
70% PLANT FACTOR

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

TABLE 4

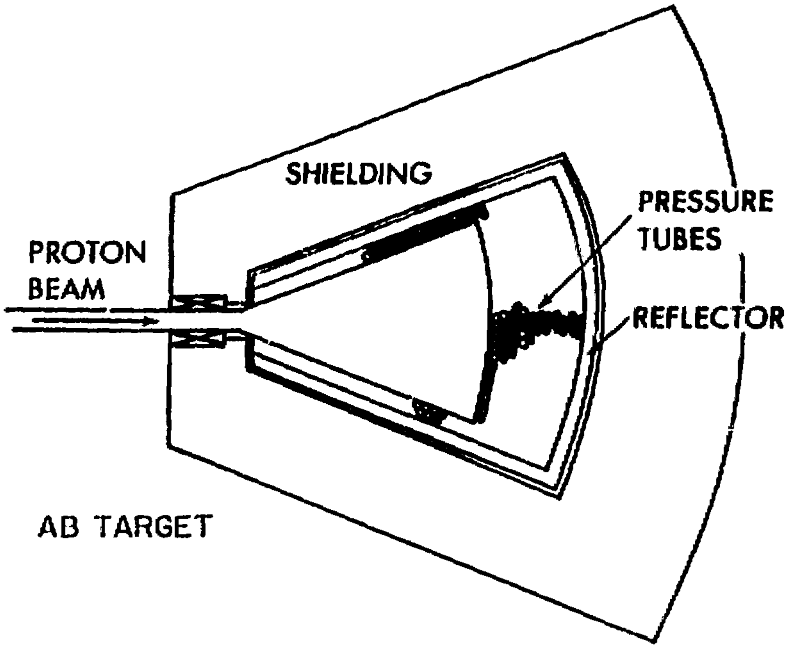
RELATIVE ECONOMIC COMPARISON
INCREMENTAL ELECTRICITY GENERATION COST OF ^{239}Pu BREEDERS

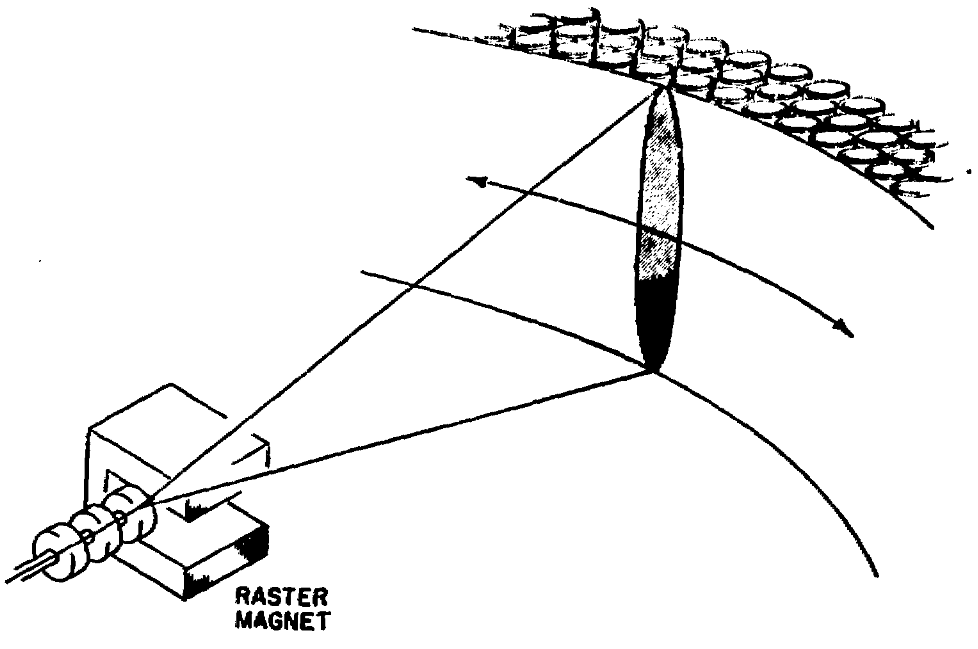
SYSTEM	ONCE-THRU LWR	5 1 LWR + AB	2 1 FBR + LWR	1 10 HFB + LWR
Conversion Ratio	0.6	0.6 ---	1.05 0.6	--- 0.6
Power MW(e)	1000	5x1000 --	2x1000+1000	1000+10x1000
Cost (1983) M$	1250	5x1250+2500	2x2000+1250	5000+10x1250
Cost/1000 MW(e) M$	1250	1750	1750	1590
Fuel Cost	0	0	0	0
Normalized Cost	1	1.40	1.40	1.27

TABLE 5

RELATIVE ECONOMIC COMPARISION INCREMENTAL ELECTRICITY GENERATION COST OF ^{233}U BREEDERS

	LWR ^{235}U ONCE-THROUGH	HTGR $^{235}U/^{233}U$ ONCE-THROUGH	AB+HTGR ^{233}U 1 + 15 AB + HTGR	HFB-HTGR ^{233}U 1 + 75 HFB + HTGR
Conversion ratio	0.6	0.6-0.9	— 0.9	— 0.9
Power, MW(e)	1000	800	— 15x 800	1000+75x 800
Unit cost (1983) USM$	1250	1200	3000+15x1200	6000+75x1200
Cost/1000 MW(e), (1983) USM$	1250	1500	1750	1570
Fuel cost	0	0	0	0
Normalized cost	1	1.20	1.40	1.26





ACCELERATOR BREEDER TARGET PLAN VIEW AND BEAM RASTERING CONCEPT SCHEMATICS

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