MASTER

LINEAR ACCELERATOR-BREEDER (LAB)

A PRELIMINARY ANALYSIS AND PROPOSAL

Presented to the
DIVISIONS OF PHYSICAL RESEARCH AND NUCLEAR ENERGY
UNITED STATES ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
WASHINGTON, D.C. 20545

on
NOVEMBER 10, 1976

BROOKHAVEN NATIONAL LABORATORY
ASSOCIATED UNIVERSITIES, INC.

UNDER CONTRACT NO. EY-76-C-02-0016 WITH THE
UNITED STATES ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

LINEAR ACCELERATOR-BREEDER (LAB)

A PRELIMINARY ANALYSIS AND PROPOSAL

Contributors:

Meyer Steinberg	Thomas V. Sheehan
James R. Powell	Hans Ludewig
Kenneth Batchelor	Vi Duong Dang
Hiroshi Takahashi	Pierre Grand
John Blewett	Otto Lazareth

Herbert J.C. Kouts

Presented to the
DIVISIONS OF PHYSICAL RESEARCH AND NUCLEAR ENERGY
UNITED STATES ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
WASHINGTON, D.C. 20545
on
NOVEMBER 10, 1976

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy \$5.00; Microfiche 3.00.

January 1977

260 copies

TABLE OF CONTENTS

	<u>pages</u>
<u>Summary</u>	v
1. Introduction	1
2. Background	2
3. Other Interesting Linear Accelerator-Breeder Applications	5
4. Linear Accelerator-Breeder Design	6
5. System Studies	7
6. Cost Estimates and Benefits	8
7. Cost of Development Program	9
<u>Exhibits</u>	
1. Chronology	12-28
2. Neutron Yield vs. Proton Energy	
3. Linear Accelerator-Breeder Nuclear Reactions	
4. Neutron Yields vs. p, d, and t Energy	
5. Neutron Yield and Heat Production in Pb and U Targets	
6. BNL Estimates of Neutron and Energy Yields for LAB	
7. Linear Accelerator-Breeder Concepts	
8. Linear Accelerator-Breeder with Reprocessing and Transmutation	
9. Linear Accelerator Breeder - LWCR Power System without Reprocessing	
10. Overall Plan View of the Linear Accelerator-Breeder	
11. Target Reactor Design	
12. Estimates of Fuel Production for Supporting Power Reactor Systems	
13. Capital and Operating Cost Estimate	
14. Benefits and Main Development Needs	
15. Proposed Development Program and Costs	
16. Proposed Development Program Schedule	
Literature	29

TABLE OF CONTENTS (continued)

<u>Appendices</u>	<u>pages</u>
1. LINAC Design	30-39
2. Neutron Yield by Interaction of High Energy Particle Beam and Uranium Target	40-52
3. Preliminary Calculation of the Neutronic Behavior of an Linear Accelerator-Breeder	53-61
4. Target Reactor Design	62-73

LINEAR ACCELERATOR-BREEDER
(LAB)
A Preliminary Analysis and Proposal

Department of Applied Science
Brookhaven National Laboratory
Upton, New York 11973

November 1976

Summary

The development and demonstration of a Linear Accelerator-Breeder (LAB) is proposed. This would be a machine which would use a powerful linear accelerator to produce an intense beam of protons or deuterons impinging on a target of a heavy element, to produce spallation neutrons. These neutrons would in turn be absorbed in fertile ^{238}U or ^{232}Th to produce fissile ^{239}Pu or ^{233}U .

Though a Linear Accelerator-Breeder is not visualized as competitive to a fast breeder such as the LMFBR, it would offer definite benefits in improved flexibility of options, and it could probably be developed more rapidly than the LMFBR if fuel cycle problems made this desirable.

It is estimated that at a beam power of 300 MW a Linear Accelerator-Breeder could produce about 1100 kg/year of fissile ^{239}Pu or ^{233}U , which would be adequate to fuel from 2650 to 15,000 MW(e) of fission reactor capacity depending on the fuel cycle used. One reasonable system based on producing ^{233}U in a Th-U fuel clad with zircaloy in light water cooled reactors could support about 6,100 MW(e) of fission reactor capacity. In addition, subject to the ability to solve metallurgical problems associated with the cladding of fuel, the concept offers the possibility that fuel might be recycled

directly between a Linear Accelerator-Breeder and a Light Water Reactor without the need for intervening chemical reprocessing.

The technology required for a Linear Accelerator-Breeder is currently available. The yield of protons from spallation in heavy targets is known and is ample. The features required of the accelerator are essentially incorporated in existing machines. Several options are available in target lattices that would also incorporate well-known features. These lead to the belief that a Linear Accelerator-Breeder could be built with only a relatively small requirement for prior development.

Cost estimates have been made for a conceptual industrial design of an industrial stage device. The estimated capital cost of the accelerator and the target of fertile material is 880 million dollars. Reprocessing facilities to accommodate the estimated throughput of 600 ton/yr of target fuel would cost about 350 million dollars. Operating costs and amortization of capital costs would lead to an estimated value of fissile material produced of between \$70/gm and \$195/gm, depending on operating strategy.

A proposed 2-year program to cost an estimated 2 million dollars would narrow the design possibilities and establish the regions of optimal design choices. It is estimated that a 4-6 year program of engineering and design could develop detailed Title II design of a full-sized demonstration plant for an estimated 119 million dollars. The demonstration plant itself would cost an estimated one billion dollars, and would be available by 1988.

The two-year study period would also be used to evaluate variations of design directed at such possibilities of spinoff as ultimate radwaste disposal by means of neutron-induced transmutation, and dual purpose machines to produce both fissile material and marketable electric power.

The concept of the Linear Accelerator-Breeder is not new, having been the basis for a major AEC project (MTA) a number of years ago. It has also been pursued in Canada starting from the proposal for an Intense Neutron Generator (ING) several years ago. The technical basis for a reasonable design has only recently been achieved. It is our view that the concept offers an opportunity to fill an important gap that may develop between the short-term and long-term energy options for energy security of the nation.

LINEAR ACCELERATOR-BREEDER
(LAB)
A Preliminary Analysis and Proposal

Department of Applied Science
Brookhaven National Laboratory
Upton, New York 11973

November 1976

1. Introduction

It has been recognized for many years that in addition to breeding fissile fuel in a reactor, it is possible to convert fertile nuclei to fissile nuclei by means of neutrons produced by bombarding a heavy metal target with high energy protons from an accelerator. Indeed a linear accelerator called the MTA designed and partially built at Livermore in 1952 provided an early indication of feasibility of the process. However, the accelerator technology, especially of the vacuum system, the RF system, and the drift tubes, were not well developed, so that the cost turned out to be high compared to producing fissile material in fission reactors. For this reason, further development of the MTA was abandoned in favor of construction of the Savannah River reactors to produce plutonium for AEC programs.

Almost 25 years later, the technology of constructing linear accelerators has improved considerably, and there is presently a high degree of confidence in the ability to construct linear accelerators which offer high beam power and high efficiency at a reasonable cost. Our proposal, therefore, is to use modern linear accelerator technology in combination with reactor target technology to convert fertile material to fissile material for the US nuclear fueled light water reactor economy.

The Linear Accelerator-Breeder does not displace or compete with the LMFBR, which is recognized to be essential to the long-term nuclear

fuel cycle. Instead, the Linear Accelerator-Breeder (LAB) offers an independent capacity to produce fissile fuel, which can be used as backup, should there be an unforeseen short-fall in the natural supply of fissile material or a delay in the development of the LMFBR. Viewed in this way, the actual cost of fuel produced in an Accelerator-Breeder is of secondary importance. This promise of added options for the nuclear fuel economy and further insurance of energy security of the country is in many respects no different from the original purpose of the MTA, when it was initially viewed as an alternative means of producing fissile material for the military security of the country.

The Linear Accelerator-Breeder has in the past been referred to by such other names as the Electronuclear Breeder and more recently the Clean Breeder Machine. An important reason for pursuing the concept at BNL is the strong linear accelerator development group at Brookhaven. In fact, modern linear accelerator development had its origin in the Accelerator Development Department at Brookhaven, in support of the construction of accelerators for high energy physics research. Another important reason is the large concentration of reactor analysts at Brookhaven, who mainly work in reactor safety. Thus Brookhaven provides a unique concentration of the strengths needed for this project.

2. Background

Exhibit 1 shows a chronology of the developments which have led to proposing a Linear Accelerator-Breeder for the nuclear power economy. It is seen that there has been a steady progress in machine capability since the early days of MTA design. For purposes of reference, it should be noted that the accelerator for purposes of breeding should produce a beam of typically 1 GeV protons, at a beam current of 300 ma steady state.

The linear accelerator at the LASL Meson Factory is to produce a 1 ma beam (average) at 800 MeV. However, proton ion sources of up to 500 ma CW have been produced elsewhere. Peak currents of up to 250 ma to an energy of 200 MeV have been accomplished. The accelerator requirements can be met within current technology.

A number of experiments have been conducted to measure the yield of neutrons from spallation in a heavy metal target. Exhibit 2 shows the results of experiments conducted a number of years ago by a joint BNL-ORNL group. These indicate that for a uranium target the yield is about 40 neutrons/GeV of proton energy. These and related experiments constitute the basic information from which beam power requirements may be estimated.

Exhibit 3 shows schematically the progression starting from neutron spallation-evaporation reactions when a high energy proton hits a heavy metal target through the subsequent fission and absorption reactions which multiply the neutrons and convert fertile ^{238}U or ^{232}Th to fissile ^{239}Pu or ^{233}U .

Results of calculations of neutron and energy yield from impingement of high energy deuterons or tritons on heavy metal targets indicate that some advantage could be gained from use of a deuteron beam or a triton beam rather than a proton beam. This point is brought out in Appendix 2. Exhibit 4 shows the normalized neutron yield per particle versus the particle energy for proton (p), deuteron (d), and triton (t) beams. Although the specific yields from d and t beams are 25 and 40% greater, respectively, than for p beams, the tentative conclusion is that technical difficulties and expense of producing and using tritium would probably not warrant exploiting its advantages at the outset. On the other hand, the use of deuterons looks interesting.

Exhibit 5 shows experimental and computed neutron and energy release data gathered by the Canadians which confirm the values up to 1.5 GeV of proton energy.

Before leaving the subject of neutron yield from spallation, we might point out the existence of some discrepant data. Exhibit 3 lists and compares data from various sources. The Russian data are high compared to the others. The high Russian values may result from overestimating the yield of spallation neutrons, though this requires more attention. The other estimates differ in the distribution of the neutron yield in terms of their origins (i.e., spallation, evaporation, or fission), though they agree on total yield of neutrons.

A considerable contribution would be made by neutrons from the fission process as fissile material builds up in the target. Neutron transport calculations have been made for a finite target reactor configuration containing varying initial amounts of fissile ^{239}Pu . Results of these calculations are presented in Appendix 3. From these estimates, which have been made starting from a fairly realistic target-reactor situation, we have estimated the actual neutron and energy yields. The results are summarized in Exhibit 6. Note that the net neutron yield would be significantly increased by the addition of fissile material which, in any case would begin to build up in any real target assembly. The rate of heat generation in the target would also increase. Thus the target can produce significant amounts of energy that could be used for recycling power to the accelerator. It is interesting to consider the circumstances required for the heat generated in the target to be so big that when converted to electricity it would supply all the needs of the accelerator. Exhibit 6 shows that this condition would be met by a target containing approximately 6% Pu^{239} in uranium, generating 58 neutrons per incident 1 GeV proton, and releasing 5.1 GeV of heat in the target. For a 300 MW

beam, at 50% efficiency (electricity input to beam power output) and 40% power cycle efficiency, the LAB would become self-sufficient in that no external source of power would be needed for operation of the accelerator.

3. Other Interesting Linear Accelerator-Breeder Applications

It is interesting to speculate on other uses to which the Linear Accelerator-Breeder might possibly be put. Exhibit 7 is directed at this question. The first use listed is the basic one prompting this study, which is production of fissile material with subsequent reprocessing. This fissile fuel could be used in any type of reactor. For the US nuclear economy, this mainly means LWR's. A second use would involve the initial breeding of Pu^{239} in depleted or natural uranium, or U^{233} in natural thorium fuel in the LAB target reactor and subsequent use of the bred element in the LWR without intervening reprocessing. After burning down the fissile material in the LWR's, the fuel pins could be taken out and rejuvenated in the target reactor to boost their fissile concentration again to values required for criticality in the LWR's. This use could either be for the conventional LWR or the near-breeder being developed in the Naval Reactors Program. There are numerous technical problems to this scheme, but at first consideration, the problems seem less difficult than those confronting the LWR - HWR cycle of burning that has been proposed by the Arms Control and Disarmament Agency (ACDA) to avoid reprocessing.

The third possible application would be that of using spallation reactions for transmuting transuranics and long-lived fission products, especially Cs, Sr, and Kr. Interest in ultimate radwaste disposal by transmutation has existed at BNL since 1964.

Exhibit 8 and Exhibit 9 are the process flow diagrams which outline the three possible applications described above.

4. Linear Accelerator-Breeder Design

Exhibit 10 depicts a conceptual layout of the LAB showing the injector, the LINAC accelerator tube, and the target reactor assembly. The target reactor design is analyzed in Appendix 4. Exhibit 11 shows a plan view of a target reactor consisting of a UO_2/PuO_2 core with a ThO_2/UO_2 blanket surrounded by a graphite reflector within a prestressed concrete pressure vessel. This design, of course, calls on HTGR technology. The steam generators and gas circulators are located inside the PCRV as in gas-cooled reactor designs. Helium is used to cool the target reactor. The stopping range of a 1 GeV proton in a UO_2 target reactor is estimated to be about 5 ft. A cavity in the center of the target assembly serves as a hohlraum to conserve the neutrons generated in the target. A thin water-cooled titanium window would be required to withstand the internal 1000 psi pressure while not absorbing too much of the beam energy. Development of a window to meet requirements must be undertaken, but studies indicate no great difficulty in achieving a satisfactory solution. Cooling and radiation damage of the window must be considered. Safety measures including quick acting valves would be needed to isolate the accelerator beam transport system (which is under vacuum) from the reactor in the event a window failure were to occur.

The average power density of about 0.7 MW/ft^3 and peak power density of about 6 MW/ft^3 would be less than in that in a gas cooled fast breeder reactor (GCFBR), and would be somewhat greater than in an LWR.

Major efforts will have to be undertaken to develop the neutronics of the target and to test fuel and cladding materials performance under conditions of exposure in the accelerator target reactor in combination with the LWR convertor reactors. A goal of 100,000 MWD/ton in a Th-U oxide fuel clad with zircaloy would increase the utilization

of fuel from 0.5% to 10.0% making available 20 times the present supply of fissile material and this would eliminate the need for enrichment and reprocessing.

5. System Studies

Estimates have been made of the amount of nuclear fuel produced and the number of fission reactors that can be supported by a 300 MW Linear Accelerator-Breeder. Calculations, derived from data given above, are summarized in Exhibit 12. The following conclusions can be drawn envisaging a 300 MW, 1 GeV proton beam accelerator to produce between 1 and 2 tonnes of fissile material per year.

1. For light water reactors of the type now used in the US, with a U/Pu/Zr-LWR fuel cycle, enough fissile material can be produced in a Linear Accelerator-Breeder to support between 2650 and 5250 MW(e) of power continuously. At the lower value, 120 MW(e) of power would be needed by the accelerator, so that the electrical breeding ratio (EBR) would be $2650/120$ or 22. At the higher power level, enough heat would be generated in the target for the device to become a net power producer.

2. For present Canadian-type heavy water convertor reactors on a Th/U/Zr-HWR fuel cycle, enough fuel could be generated in a 300 MW Linear Accelerator-Breeder to support between 10,500 and 15,000 MW(e) of power continuously. The former level indicates an electrical breeding ratio of 88, and at the latter the Linear Accelerator-Breeder would become a net power producer.

3. A 300-MW(e) LAB could supply enough Th/U/Zr fuel to support between 5,200 and 10,500 MW(e) of modern water reactors. At the lower value the EBR would be 44. At the higher value, the device would be a net supplier of electricity.

4. Another case would be an LWR on a Th/U fuel cycle with 94% U - 6% Pu ²³⁹ in a core and Th/U in a blanket. The fuel pins would be shuffled between core and blanket in the target-reactor and the core of the burner and convertor LWR's. It might be possible to achieve 100,000 MWD/T burnup without reprocessing. This is the minimum goal for the LMFBR fuel burnup. In this case, the 300 MW LAB could support 6100 MW(e), extending the fuel supply at least 20 times without the need for enrichment facilities. This case has also been designed as a self-sustaining linear accelerator-breeder requiring no input power and no net power to be fed to the grid.

Exhibit 12 also gives a comparison of the consumption and production of fissile fuel for the pertinent power reactor systems. The LWR consumes a net of 180 to 360 Kg/yr of fissile material while the Linear Accelerator-Breeder would produce between 1000 and 2000 Kg/yr of ²³⁹Pu (the reference design mentioned in 4 above produces 1100 Kg/yr). It is interesting to note that 1000 MW(e) LMFBR on a 30 yr doubling time would produce only about 25 Kg/yr enough to sustain an extra 150 MW(e).

6. Cost Estimates and Benefits

Exhibit 13 gives an estimate of capital and operating expenses for a Linear Accelerator-Breeder in 1976 dollars. The accelerator costs are taken from the Memorandum attached as Appendix 1. The target and turbo-generator are estimated to cost about \$520/KW, so that the capital cost of a LAB would be about \$880 million without reprocessing facilities. With reprocessing, the total cost could be about \$1,230 million. The reprocessing cost estimates are believed to be generous in comparison to present estimates of cost of other remotely maintained reprocessing plants, since only about 600 tons would require processing per year. If a 15%

depreciation rate is assumed and it is recalled that the LAB system is designed to require no net power consumption and if operating and maintenance costs are added, the cost of fissile fuel produced can be as low as \$70/gm (without reprocessing) to as high as \$195/gm (with reprocessing). This range of values indicates that production with a LAB would compete with enrichment based on natural U costs of \$40 to \$200/lb. But it must be borne in mind that enrichment plants offer a utilization of only 0.5% of the fertile nuclear material resource whereas the LAB (like the LMFBR) can theoretically convert almost 100% of the available fertile material to fissile fuel, thus markedly increasing the natural energy resource in the world and allowing the realization of the full potential of the nuclear resource.

Exhibit 14 summarizes the main benefits of a Linear Accelerator-Breeder which include among other items (1) provision for flexibility in the nuclear fuel cycle, (2) energy security in the country, (3) the dependence on existing technology, (4) the possibility of improving safeguards through lower requirements for fuel reprocessing and enrichment, and (5) the possibility of ultimate waste disposal through transmutation. The main development needs are (1) the demonstration of a high current linear accelerator and (2) the demonstration of a target reactor. Some of the problems to be solved are also listed at the end of Exhibit 14.

7. Cost of Development Program

Exhibit 15 shows a first view of the cost of a development program.

Phase I consists of a Feasibility Study lasting no more than 2 years, with a cost of \$2 million. A prime task for the feasibility study is an experimental verification of the neutron and energy yields for high energy protons, deuterons, and (possibly) tritons on UO_2 and ThO_2 targets

containing varying amounts of fissile oxide. Phase II involves Engineering, Design, and Development for a demonstration experiment. This phase would last no more than 6 years. The accelerator hardware development would cost \$26 million. The estimated cost of target-reactor design and development and component testing is less certain but should be no more than about \$93 million because a great deal of information is available on the U/Pu/Zr and Th/U/Zr fuel cycle and materials. Substantial programs will be needed in neutronics and safety analysis, and in neutron damage of materials. The total development cost is estimated at about \$121 million. This would be so laid out that by 1982 construction of a Phase III demonstration and production plant can be started for completion by 1988. It is estimated that this plant would cost about \$1 billion. Components developed in Phase II could be used in Phase III to reduce time and cost. If the reprocessing is needed, the total cost through development and demonstration might be \$1.5 billion. Relative to the LMFBR demonstration program, which runs about \$0.5 billion per year and which will eventually run to \$10 billion, an insurance of no more than 15% in the form of the Linear Accelerator-Breeder appears not to be too high a price to pay for acquiring a national nuclear energy security policy.

Exhibit 16 gives a more detailed estimate of the cost and schedule of the development program. The annual cost builds up to a high of about \$27 million per year, with the program completed by 1984. Once again, this is not unreasonable for the promising payoff.

The Linear Accelerator-Breeder appears to be a necessary link in the short and long term nuclear energy security chain in the US today and we thus urge its early development, demonstration, and implementation.

EXHIBITS

Exhibit 1

LINEAR ACCELERATOR-BREEDER

Chronology

- 1947-1952 Material Testing Accelerator (MTA) constructed at Livermore
- Large, costly, inefficient, but demonstrated operability
 - Technology was advancing
 - BNL developed strong focusing principle
- 1956-1960 Development of modern accelerator designs.
- 50 MeV LINAC developed and constructed at RNL.
- 1958-1962 Definitive data on spallation reactions become available
- Yield of n/p up to 1.5 GeV protons
 - Theoretical estimates of neutron yields and energy deposition
- 1962-1964 Design studies by Chalk River (AECL) on intense Neutron Generator (ING)
- Research Proton ING - 60 ma and 1 GeV
 - Production of fissile material considered
- 1964-1971 Large linear accelerators constructed and operated
- BNL 200 MeV LINAC injector to AGS
 - Fermilab 200 MeV LINAC injector
 - Los Alamos LAMPF - 800 MeV
- 1964-present AECL continues to study accelerator breeding
- 1975-present Revived BNL interest in Linear Accelerator Breeding
- Improved technology and efficiency of proton accelerators makes concept feasible
 - Backup to LMFBR
 - Insurance for a national nuclear energy program

Exhibit 2. Yield of neutrons by bombardment of a heavy metal target with high energy protons.

EXHIBIT 3
LINEAR ACCELERATOR - BREEDER NUCLEAR REACTIONS

NEUTRON YIELD FOR 1 GeV PROTONS ON A ^{238}U TARGET (~ 35% less for ^{232}Th TARGET)

Estimates	Spall., Evap., H.E. Fission	Fast Fission n	Total n	Energy Release in Target, GeV/p GeV
Canadian Infinite Medium	20	30	50	4
Russian Infinite Medium	40	60	100	7
BNL Estimate Finite Medium	27	16	43	3.5
BNL Estimate Finite Target with 6% Pu in U	27	31	58	5.1

Exhibit 4. Neutron yield vs. energy for proton, triton, deuteron, and neutron particles.

Exhibit 5. Accelerator breeder. Neutron yield and heat production in 20 cm Pb and U targets.

Exhibit 6

LINEAR ACCELERATOR-BREEDER
ESTIMATES OF NEUTRON AND ENERGY YIELD

Neutron Yield					
No. of Neutrons per 1 GeV Proton					
Cubic Target - 390 cm on a side with Cavity ⁽¹⁾					
% Pu ²³⁹ in U ²³⁸ Target at start	0%	2%	4%	6%	-
Spallation and Evaporation	20	20	20	20	
Hi-Energy Fission	7	7	7	7	
Fast Fission	16	20	25	31	
Total	43	47	52	58	

Heat Release				
GeV in Target per 1 GeV Proton in Beam				
Spallation and Evaporation	1.0	1.0	1.0	1.0
Hi-Energy Fission	0.8	0.8	0.8	0.8
Fast Fission	1.7	2.1	2.6	3.3
Total	3.5	3.9	4.4	5.1

For a 300 MW proton beam total heat in target = $5.1 \times 300 = 1530 \text{ MW}(t)$

Electrical Power Produced = 40% eff $\times 1530 = 612 \text{ MW}(e)$

Accelerator can be self-sustained.

¹⁾ See Appendix 3.

Exhibit 7

LINEAR ACCELERATOR-BREEDER APPLICATIONS

I. Breeding Fuel with Reprocessing

- U-Pu Cycle
- Th-U Cycle
- Combination

II. Initial Breeding and Topping of LWR Fuel

Without Reprocessing

- U-Pu Cycle
- Th-U Cycle
- Combination Seed and Blanket

III. Transmutation of Waste

- Long-Lived Fission and Spallation Products (FP's and SP's)
- Transuranics (TU's)

Exhibit 8. Linear accelerator-breeder - LWR power system with fuel reprocessing and waste management.

Exhibit 9. Accelerator-breeder - LWCR power system fuel topping - without reprocessing.

Exhibit 1G. Accelerator breeder, general layout.

Exhibit 11. Target reactor design. Plan section on ϕ beam tube.

Exhibit 12

LINEAR ACCELERATOR-BREEDER

Estimates of Fuel Production in Support of Various Power Reactor System

Accelerator Proton Beam - 1 GeV - 300 ma - 300 MW
 Power to Accelerator = 600 MW(e) - 50% Efficient
 Gas Cooled Power Cycle Efficiency from Target = 40%
 Water Cooled Power Cycle Efficiency = 35%

Neutron Yield n/p for 1 GeV Protons	Thermal Energy in Target Kwh(t)	Fuel Cycle and Reactor Type	Conversion Ratio	Net Fuel Production Kg/yr ⁽³⁾	Net Power to Accelerator MW(e) ⁽¹⁾	Total Reactor Power Supported by Accelerator- Breeder MW(e)
50	1200	U/Pu/Zr-LWR	0.6	1000	120	2,650
100	2100	U/Pu/Zr-LWR	0.6	2000	-240	5,250
50	1200	Th/U/Zr-HWR	0.9	1000	120	10,500
100	2100 ⁽²⁾	Th/U/Zr-HWR	0.93	2000	-410	15,000
50	1200	Th/U/Zr-LWR	0.8	1000	120	5,250
100	2100	Th/U/Zr-LWR	0.8	2000	-240	10,500
BNL Est. with 94% U-6% Pu ²³⁹ in Finite Target						
58	1500	Th/U/Zr LWR	0.8	1100	0	6,100
Comparison Consumption and Production in Reactors						
Present 1000 MW(e) LWR		U/Pu/Zr-LWR	0.6	-360	--	
Convertor 1000 MW(e) LWR		U/Th/Zr-LWR	0.8	-180	--	
Demonstration 1000 MW(e) LMFBR		U/Pu/SS-LM	1.033 ⁽⁴⁾	25	--	150

1) Negative sign means net power produced

2) Assumes max. 70% accelerator efficiency

3) At 82% capacity factor or 300 days/yr on line - neg. sign means fuel consumed.

4) 30 yr doubling time for LMFBR demonstration in 1985.

Exhibit 13

LINEAR ACCELERATOR-BREEDER

Capital and Operating Cost Estimate
(1976 Dollars)

Capital Investment

Accelerator - 300 MW (from Appendix 1)	$\$520 \times 10^6$
Target Reactor and power conversion equipment - $\$600/\text{KW(e)}$	$\underline{360 \times 10^6}$
Total without Reprocessing	$\$880 \times 10^6$
Fuel Reprocessing ~ 600 Ton/yr of fuel	$\underline{350 \times 10^6}$
Total Capital Cost Including Reprocessing	$\$1230 \times 10^6$

<u>Production Cost per Year</u>	<u>No Reprocessing</u>	<u>With Reprocessing</u>
Depreciation at 15%/yr	$\$132 \times 10^6$	$\$185 \times 10^6$
Operating and Maintenance	$\underline{8 \times 10^6}$	$\underline{10 \times 10^6}$
Total Operating Cost	$\$140 \times 10^6$	$\$195 \times 10^6$

Unit Production Cost Pu²³⁹ or U²³³ - $\$/\text{gm}$

For 1000 Kg/yr	$\$140/\text{gm}$	$\$195/\text{gm}$
For 2000 Kg/yr (makes available ~ 100% of nuclear resource)	$\$70/\text{gm}$	$\$98/\text{gm}$

Equivalent Electrical Energy Cost - mills/KW(e)

U/Pu-LWR 0.6 Conv. Ratio	3.5-7	10-20
Th/U-LWR 0.8 Conv. Ratio (makes available ~ 100% of nuclear resource)	1.8-3.5	5-10

Note: -

Unit Production Cost of U ²³⁵ by Enrichment for	
$\$100/\text{SWU}$ and $\$40/\text{lbU}_{308}$	$\$70/\text{gm}$
$\$100/\text{SWU}$ and $\$200/\text{lbU}_{308}$	$\$140/\text{gm}$
(makes available only 0.5% of nuclear resource)	

Exhibit 14

LINEAR ACCELERATOR BREEDER

Benefits

- Provides flexibility in the nuclear fuel cycle
 - Independent source of fissile material
 - Reduces enrichment requirements
 - May reduce reprocessing requirements
 - Allows access to Th-U cycle
 - Can make use of first cycle LWR fuel
 - Can make use of depleted Uranium
- Provides excellent support for the country's breeder program
 - Decreases pressure on LMFBR program
 - Can breed fissile material for LMFBR first core loading
 - Provides energy security in the present nuclear fuel economy due to possible shortage of Uranium reserves and enrichment facilities
- Provides fuel for LWR's
- Inventory of fissile material in accelerator reactor is low
- Target assembly is highly sub-critical
- Could improve safeguards by reducing fuel reprocessing requirements
- Fits well into nuclear parks concepts
- Uses mainly near term technology
- Possibility of breeding fuel within unburned and burned fuel rods - use of stored first cycle fuel elements and use of depleted U and Th
- Possibility of ultimate waste disposal through transmutation

Main Development Needs

- Demonstration of a high current linear accelerator
- Demonstration of a target reactor

Exhibit 14 (continued)

LINEAR ACCELERATOR BREEDER

Problems

Accelerator

- Increase system reliability
 - RF power amplifier life
- Beam loss control
- Maintainability
- High current CW injection system

Target-Reactor

- Design of a reliable window system for beam transport
- Emergency cooling of target reactor
- Quick shutoff of accelerator beam transport tube
- Integrity of target fuel element materials

Exhibit 15

LINEAR ACCELERATOR-BREEDER

Proposed Development Program and Costs

(1976 Dollars)

<u>Phase I</u>	<u>Feasibility Study (2 yrs)</u>	<u>Staff</u>	<u>Yrs</u>	<u>Cost in \$ million</u>
Task 1 -	Develop a feasible accelerator design Injector, Low and High RF System	3	2	\$0.5
Task 2 -	Develop a feasible target design			
	2.1 Experimentally confirm neutron and energy yield (LAMPF)	4	2	0.8
	2.2 Develop a target reactor design Target, window, and materials Thermohydraulics, reference design	4	2	0.5
	2.3 Systems Study and Planning Breeding, processing, no processing Transmutation, program planning	2	2	0.2
		<hr/>	<hr/>	<hr/>
		13	2	\$2.0
<u>Phase II</u>	<u>Engineering Design and Development Program (6 yrs)</u>			
Task 1 -	<u>Accelerator</u> -Develop, Construct, and Test Components			
	1.1 Injector system (ion source, hi volt low energy beam transport)			\$4.0
	1.2 Low frequency accelerator system			5.0
	1.3 150 MHZ RF System Tube Development			5.0
	1.4 Hi-frequency 450 MHZ RF system and 600 MHZ Klystron			5.0
	1.5 Hi-frequency accelerator system			5.0
	1.6 Construction, Planning and Design and Managoment			<hr/> 2.0
		<hr/> 20	<hr/> 4	<hr/> 26.0

	<u>Staff</u>	<u>Yrs</u>	<u>Cost</u> <u>\$ million</u>
Task 2 Target Reactor - Design, Development, and Component Test (utilizing as much LWR and GCR Technology is available)			
2.1 Continue neutronic and energy experiments			10
Detailed cross section and spectral distribution measurements, and calorimetry			
2.2 Code development and lattice measurements			20
2.3 Materials Development			22
Fuel elements - cladding and fuel damage window damage, reactor structure			
2.4 Engineering Development			30
Target-Reactor - thermohydraulics Neutronics and lattice analysis, PCR, window Structures			
2.5 Systems Studies			5.5
Optimization studies Develop reference design Advanced transmutation, SP, TU, and FP Disposal and reprocessing of fuel			
2.6 Construction, Planning, Design, and Management			5.5
		6	93.0
<u>Phase III. Construction of Demonstration and Production Plant</u>			
Task 1 Accelerator			600
Task 2 Reactor			400
Total Phase III			1,000
Total Phase I and Phase II			121
Total Without Reprocessing			1,121
Reprocessing Plant			350
Total With Reprocessing Plant			\$1,471

Exhibit 16

LINEAR ACCELERATOR-BREEDER

Proposed Development Program Schedule
(millions of 1976 dollars)

<u>Phase and Task</u>	<u>FY 77</u>	<u>78</u>	<u>79</u>	<u>80</u>	<u>81</u>	<u>82</u>	<u>83</u>	<u>84 → 88</u>
I. Feasibility Study	0.5	1.5						
1. Accelerator								
2. Target Reactor								
II. Eng. Des. & Dev.								
1. Accelerator			3	5	8	6	3	1
2. Target Reactor								
2.1 Neutronics			1	2	2	2	2	1
2.2 Code Dev. & Lattices			1	2	4	5	5	3
2.3 Materials			2	4	5	5	4	2
2.4 Eng'g. Dev.			1	2	4	7	8	8
2.5 Systems Studies			0.5	1	1	1	1	1
2.6 Adm. Planning & Des.			0.5	1	1	1	1	1
III. Const. Demo. and Prod. Plant						*		
1. Accelerator								600
2. Target Reactor								400
Totals	0.5	1.5	9	17	25	27	24	17
Total Expenditure								\$1,121

* Initiate Demo Construction

Literature

- (1) J. S. Fraser, R. E. Green, J. W. Hilbom, J. O. D. Milton, W. A. Gibson, E. E. Gross, and A. Zucker, "Neutron Production in Thick Targets Bombarded by High Energy Protons", Phys. in Canada 21, No. 1, 17 (1965).
- (2) D. West and E. Wood, "The Neutron Yield from Protons and Deuterons of Momenta Between 0.85 GeV/e and 1.7 GeV/e Totally Absorbed in Lead", Can. J. Phys. 49, 2061 (1971).
- (3) J. S. Fraser, C. R. J. Hoffmann, and P. R. Tunnicliffe, "The Role of Electrically Produced Neutrons in Nuclear Power Generation", AECL 4688, Chalk River, Ontario, Canada (October 1973).
- (4) J. D. Blewett, P. Grand, and K. Bachelor, et al. Private Communication, AGS Department, Brookhaven National Laboratory (1976).
- (5) M. Steinberg and G. Wotzak, "Neutron Burning of Long-Lived Fission Products for Waste Disposal", BNL 8558 (Sept. 1965).
- (6) M. V. Gregory and M. Steinberg, "A Nuclear Transformation System for Disposal of Long-Lived Fission Product Waste in an Expanding Nuclear Power Economy", BNL 11915 (November 1967).
- (7) W. C. Wolkenhauer, B. R. Leonard, Jr., and S. F. Gore, "Transmutation of High-Level Radioactive Waste with Controlled Thermonuclear Reactors", BNWL 1772 (September 1973).
- (8) K. Yasuda, "Report of Deactivation Treatment Working Groups" Tokyo (August 29, 1972).
- (9) P. Rose and S. Pearlstein, personal communication, National Neutron Cross Section Center, BNL (January 1976).
- (10) W. B. Lewis, et al. The AECL Symposium on the Generation of Intense Neutron Fluxes, AECL 2177, Chalk River, Ontario (April 1965).
- (11) Draft Proposal for "An Intense Pulsed Neutron Source", Edited by J. M. Carpenter, Argonne National Laboratory (October 1975).
- (12) Atomic Shield, A History of the U.S. Atomic Energy Commission, Vol. II, WASH. 1215, 1947/52, pp. 425-6 (1972).
- (13) Chart of the Nuclides, 11th Ed., Knolls Atomic Power Lab. Naval Reactors, USAEC (April 1972).

APPENDIX 1

LINAC DESIGN

BROOKHAVEN NATIONAL LABORATORY

MEMORANDUM

DATE: 10/27/76

APPENDIX 1

TO: Accelerator Breeder File
FROM: K. Batchelor, P. Grand, and
J. Blewett
SUBJECT: LINAC Design

1. Introduction

During the past ten years proton linear accelerators have been constructed and operated for peak output beam currents of up to 200 mA and average currents of up to 1 mA. There appears to be no technical reason why c.w. currents of 300 mA should not be achievable in a reasonable time scale (5-7 years) providing there is sufficient funding to carry out the necessary prototype work involved for such a machine. Here we will try to identify those areas in which we see the need for testing.

2. Injection

(a) Source and High Voltage Column. Duoplasmatron-type ion sources have been operated at long ($> 200 \mu\text{sec}$) pulse lengths up to 500 mA and c.w. sources have been run at up to 200 mA. In order to operate at the 400-500 mA c.w. level improved cooling arrangements are necessary and life tests are also required. Accelerations of the 20-30 KeV beam from such an ion source to the 500-750 KeV required for injection into the radiofrequency accelerator has not been proven for an operational machine, though a column has operated at 500 KV for c.w. H_2^+ currents of 300 mA. ⁽¹⁾ The beams produced in this example were not suitable for linear accelerator applications due to the large value of radial emittance.

Two identical pre-injection systems will be used each feeding a common Low Energy Beam Transport Line which utilizes a bending magnet, radio frequency bunchers, and focussing quadrupoles to match the beam to the radio frequency accelerator section (see Fig. 1). One of the injector systems would act as an operational spare in order to achieve high availability of beam to the main accelerator. The matching of the pre-injector beam to the main accelerator is one of the areas which requires careful study both in theory and practice. At the present time a maximum of 70% of the beam produced in the existing pre-injectors is within the acceptance of the existing drift-tube accelerator. The remaining 30% which is lost mainly due to longitudinal mismatch contributes to emittance growth in the early part of the accelerator and also to heating of the drift-tube bores by those lost particles which do not become radially unstable until they have passed through many cells of the accelerator. It may be necessary to provide special water-cooled apertures to skim off these unwanted particles from the beam in the case of a c.w. machine.

3. Drift-Tube LINAC Acceptance

A number of reports have been written (2-4) in which the matched beam parameters at injection have been calculated for various injection parameters. From these computations we arrive at a frequency and injection energy of 750 KeV and 150 MHZ for the first part of the accelerator. At this frequency a beam current of > 300 mA is readily accepted into the drift-tube accelerator for the expected value of radial emittance. In Figure 2 the maximum accepted beam current is plotted as a function of frequency for an injection energy of 750 KeV and a beam current of 300 mA. The maximum pole tip field in the first drift-tube quadrupole is also plotted. It can be seen that at 200 MHZ the pole tip field required is ~ 13.5 K Gauss which is above the practical limit. Cost considerations require the highest practical value of quadrupole gradient. In general cost considerations require the highest practical operating frequency since this reduces the cost of the building and radio frequency structure due to its reduced length and diameter. However, the available drift-tube aperture also reduces with frequency so the maximum acceptable beam current is also reduced. Thus 150 MHZ is the highest practical frequency for the first part of the accelerator for the chosen injection energy.

4. Drift-Tube Accelerator

The first part of the radio frequency accelerator will utilize the familiar Alvarez structure which is used for all modern proton linacs. Due to the 100% duty factor heat dissipation and temperature control become major factors in the cavity design. Furthermore, power economy suggests that the temperature rise in the cooling water be greater than the fraction of a degree found in pulsed machines, so a means of achieving constant phase between cavities over a temperature range of up to 20°C is required. Excessive beam loss in the accelerator could give rise to radiation damage to the d.c. quadrupoles which are needed to maintain a beam focus. Conventional mechanical fabrication techniques using copper clad steel to act as a combined radio frequency cavity and vacuum envelope will be used. Power will be coupled to the structure via water-cooled coupling loops. A water cooling jacket designed to maximize the surface area in contact with the cooling fluid and minimize temperature gradients will be welded to the tanks outer surface. For this reference design this structure is utilized for acceleration of protons up to 200 MeV, requiring a total cavity length of 200 m. Figure 3 is a photograph of the inside of cavity #1 of the 200 MeV Injector LINAC at Brookhaven and shows the type of accelerator that is proposed. At about the 200 MeV point it becomes practical to change the frequency of operation to a harmonic of 150 MHZ. At this point the phase width of the beam has damped to about $\pm 5.5^{\circ}$ of 150 MHZ phase making a shift in frequency possible without incurring beam loss due to longitudinal mismatch. A frequency of 450 MHZ has been chosen for this part of the accelerator which will have a total length of ~ 400 m. The structure will be of the type used at Los Alamos⁽⁵⁾ of that of the ING⁽⁶⁾ group in Chalk River, the choice being made on the basis of ease of fabrication and cooling. We believe that cooling will become a problem at frequencies much in excess of the value proposed though 600 MHZ may be considered.

5. R.F. System

The ultimate choice of frequencies may be influenced by the availability of radio frequency power at reasonable cost. To minimize operating costs, it is necessary to obtain the maximum plate efficiency in the necessary amplifier stages of the r.f. drive chain. At 150 MHz existing final amplifiers used in c.w. operation have efficiencies $\sim 50-60\%$ for power output of $\sim 300-400$ KW. A developmental tube for switching applications may be modified for c.w. operation to give up to 2 MW power output at efficiencies of $> 70\%$ but testing of such a tube on a prototype system would be a necessary criterion for its use. This tube has the additional advantage of utilizing high pressure steam cooling which may be usable as a heat source for aiding power generation. At 450 MHz Klystrons similar to those to be used for PEP⁽⁷⁾ would be utilized giving 500 KW c.w. power output at 70% efficiency.

In both applications the tubes would be de-rated $\sim 25\%$ with 4 tubes being used to power each cavity (see Figure 4). Thus if one tube failed, operation could continue with the remaining 3 tubes while the faulty tube is being serviced.

For this reference design a power output of 300 KW per tube is assumed with a total tube capability of up to 400 KW.

Table I lists the design parameters of this reference design.

6. References

1. O. B. Morgan, G. G. Kelley, and R. C. Davis, Rev. Sci. Instr., Vol. 38, No. 4, p. 467, April 1967.
2. R. Ahabman, "Proceedings of the 1968 Linear Accelerator Conference" Brookhaven BNL 50124, p. 372, 1968.
3. K. Batchelor, "Optimization of the Input Parameters for a high current c.w. deuteron linear accelerator". Brookhaven Report No. BNL 50515, April 1976.
4. K. Batchelor. "Choice of initial operating parameters for high average current linear accelerators" 1976 Proton Linear Accelerator Conference, Chalk River, Canada to be published.
5. E. A. Knapp, IEEE Transactions on Nuclear Science, Vol. NS-12, No. 3, p. 118, June 1965.
6. S. O. Schribes and L. W. Funk, 1976 Proton Science Accelerator Conference, Chalk River, Canada to be published.
7. Gerhard T. Konrad, IEEE Transactions on Nuclear Science, Vol. NS-22, No. 3, p. 1249, March 1975.

KB:amf

Attachments

TABLE I
DESIGN PARAMETERS FOR 1000 MeV PROTON LINAC

(a) PREINJECTOR

Injection Energy	750 KeV
Beam Current	500 mA
750 KeV Emittance (non-normalized)	$1.11\pi \times 10^{-4}$ m-rad

(b) ALVAREZ ACCELERATOR

Operating frequency	150 MHZ
Acceleration rate	1 MeV/m
Stable phase angle (40° at input)	30°
Total length	200 m
Total Cavity power	20 MW
Total Beam power	60 MW

(c) HIGH ENERGY STRUCTURE

Operating frequency	450 MHZ
Acceleration rate	2 MeV/m
Stable phase angle	30°
Total length	400 m
Total cavity power	60 MW
Total beam power	240 MW

6. Accelerator Costs

The cost figures presented are in 1976 dollars and are based on equipment which is available today. The reference design is in no way optimized so it is possible that some reduction in costs may be achieved in a final design.

Buildings (accelerator)	100 M\$
Injectors and Low Energy Beam Transport	3
Accelerator at \$100,000/m	60
RF System (80 MW at \$1.00/watt+300 MW at \$0.56/watt)	250
Services Beam Transport	2
Controls	5
Contingency ~25%	100
Total cost 1976 dollars	<u>520 M\$</u>

Figure 1. LINAC injection system.

TABLE II

PEP KLYSTRON SPECIFICATIONS, IEEE, June 1975, Vol. NS 22 #3

Klystron Interaction Space Parameters

f = 358.54 MHz	
Bandwidth 1 db points	= 0.5 %
Beam Voltage	= 62 KV
Beam Current	= 11.5A
Beam Power	= 713 KW
R.F. Output Power	= 500 KW
Drive Power	= 15 W
Saturation Gain	= 45 dB
Efficiency	= 70%
Load vs. W.R.	= 2.1 at any phase angle
Magnetic Focussing Field	= 150 E
Ratio of Beam/Drift-tube radii	= 0.7
# of Cavities	= 5
Overall Length	= 350 cm

Cavity #	R/Q	β	Gap Transit Angle	Gap Voltage @ 500 KW
1	85	1000	0.274 rad	1 KV
2	90	3000	0.726 rad	8.4 KV
3	74	2000	0.839 rad	4.5 KV
4	115	3000	1.232 rad	24
5	85	83	0.433 rad	90

RF System Costs/MW	
Low Level System	\$ 30,000
Filament Power Supply	30,000
Anode Power Supply	100,000
Protection System (crowbar)	30,000
Klystrons (2 off 500 KW)	100,000
14" Transmission Lines	30,000
14" Phase Shifters	30,000
Feed Loops	50,000
Dump Loads	10,000
Controls	20,000
Installation	100,000
T O T A L	\$530,000

\$0.55/watt at 450 MHz
cf. \$1.00/watt at 150 MHz

RF System cost at 150 MHz	= 80 x 1.00	= 80M\$
RF System cost at 450 MHz	= 300 x 0.55	= 165M\$
Total for 1000 MEV		= 245M\$

Figure 2. Maximum accepted proton beam current vs frequency.

$E_{Inj} = 750 \text{ KeV}$, $E_R = 3.7 \pi(Ib) \times 10^{-4} \text{ m-rad}$
 $K = 1.6 \text{ MeV/m}$ $E_\ell = 1.61 \pi \times 10^{-4} \text{ m-rad}$ at $f = 200 \text{ MHZ}$
 $K = 1.21 \text{ MeV/m}$ $E_\ell = 3.82 \pi \times 10^{-4} \text{ m-rad}$ at $f = 100 \text{ MHZ}$
 $K = 0.8 \text{ MeV}$ $E_\ell = 9.12 \pi \times 10^{-4} \text{ m-rad}$ at $f = 50 \text{ MHZ}$
 For $f = 150 \text{ MHZ}$; $B = 10.4 \text{ KG}$, $G = 3.47 \text{ KG/cm}$ for 3 cm
 aperture radius. $I_{max} \approx 650 \text{ mA}$, $\Lambda = 0.5$, $\mu_{SF} = \pi/2$

Figure 3. Cavity #1 of the 200 MeV
injector LINAC at BNL.

Figure 4. RF system for one LINAC cavity section.

APPENDIX 2

TOTAL NEUTRON YIELD DUE TO
INTERACTION BETWEEN HIGH ENERGY
PARTICLE BEAM AND A URANIUM TARGET

BROOKHAVEN NATIONAL LABORATORY

M E M O R A N D U M

APPENDIX 2

DATE: 10/22/76

TO: Accelerator Breeder Nuclear
Reactor File
FROM: Hiroshi Takahashi
SUBJECT: Total Neutron Yield Due to
Interaction between High
Energy Particle Beam and a
Uranium Block Target

In order to evaluate the accelerator breeder nuclear reactor,⁽¹⁾ it is very important to estimate the total yield of neutrons produced from the high energy particle beams injected into an uranium target.

The neutron yield varies as a function of particle energy and target material, as shown in Figure 1.⁽²⁾ In nuclei having a low fission threshold energy such as U^{238} , a significant contribution comes from fissions. A reasonable fit to the data of yield shown in Figure 1 is the function⁽³⁾

$$Y(E, A) = (E - 120)(A + 20) \times 10^{-4} \text{ n/p (except U)}$$

$$= 0.0516 (E - 120) \text{ n/p (U}^{238}\text{)}$$

where A is the atomic number and E is the proton energy in unit of MeV.

At 1 GeV proton, the neutron yield by uranium -238 and Pb targets are respectively calculated from the above formula as 45 and 20 per proton. In order to analyze the interaction between high energy proton and target materials, several codes have been developed after original intercascade Monte Carlo code by Metropolis⁽⁴⁾ and Destrofsky.⁽⁵⁾ These are Ranft's program,⁽⁶⁾ Barashenkov's program⁽⁷⁾ and NMTC program codes.⁽⁸⁾ The first Ranft's program is directed towards the calculation of the interaction of very high energy particles ($E = 10-10^3$ GeV) with large blocks of material, and this uses the very coarse approximation of particle-nucleus collisions.

The Barashenkov's program is suitable only for comparatively small energies ($E < 600-700$ MeV) where meson formation can still be neglected. The NMTC code is the abbreviation of nucleon meson transport code and simulates the propagation in matter of nucleons with energies $E < 3.5$ GeV (including low-energy neutron components) and of fluxes of π and μ meson with energies $E < 2.5$ GeV. Inelastic particle nucleus collisions are taken into account through the cascade-evaporation model of nuclear reactions described by Bertini.⁽⁹⁾ A deficiency of this program is the no fission competition in the evaporating process.

Table I shows the mean characteristics of the interaction of a beam of protons with energy E (normalized to one primary proton) with a block of natural uranium (cylinder $R = 60$ cm, $L = 90$ cm) calculated by Barashenkov. (7) In this table, N^t is the total number of elastic and inelastic collisions in the block of the particles from a cascade generated by one primary proton, N^{in} is the corresponding number of inelastic interactions, $N^{\gamma 8}$ and $N^{\gamma 5}$ were the number of radiative captures of neutrons by the nuclei ^{238}U and ^{235}U respectively. N_{esc}^{cap} is the number of neutrons escaped from the block, N is the total yield of neutrons, γ^8 and γ^5 are the number of fission events of the nuclei ^{238}U and ^{235}U , γ is the total number of fissions, and Q is the heat release in the block. Quantities which characterize the interactions of particles with energies $E < 10.5$ MeV and $E > 10.5$ MeV are presented separately. For $E = 660$ MeV the quantities associated with a block of pure ^{238}U are shown in parenthesis. The statistical error in the data presented is 5 to 10%. Fullwood, et al. (10) made extensive study for the neutron yield by using NMTC code, Figure 2 shows the radial and axial distribution of the production of evaporated neutrons in a 7.5 cm-radius, 30 cm long ^{238}U target with 800 MeV proton incident on axis. Figure 3 shows comparison of 4π neutron spectra for ^{238}U and Pb cylinders in the same size and the same proton energy as the above. The calculated value for the neutron yield 26 per proton with 800 MeV seems to be about 25% lower than the measured yield.

The neutron yield for the ^{238}U target, calculated from the fitted yield formula above is 35 n/p.

The difference between Fullwood's (10) calculated value and Barashenko's (7) value is partly due to the size of the target material. Furthermore, the high value of Barashenko's calculation compared with the Fullwood's one is due to the fact that the neglect of the meson production in the Barashenko's calculation overestimate the neutron yield, and the neglect of the fission process in the evaporation stage in the NMTC code underestimates the neutron yield. Thus, in order to estimate the neutron yield more accurately, we should include the fission capability in the evaporation stage in the NMTC code.

Frazer (11) in Chalk River estimated the total yield of neutron produced by 1 GeV proton injecting into the 10 cm diameter 60 cm long cylinder uranium-238. His evaluation of heat production per neutron produced and neutron yield vs incident proton energy for ^{238}U and Pb blocks is shown in Figure 4.

^{233}U System Using Thorium Block

Let us consider the case of producing ^{233}U fissionable material using a Th^{232} block instead of producing Pu^{239} using ^{238}U block. As shown in Figures 5 and 6 (12), the fission cross section of Th^{232} between 1 MeV and 15.0 MeV is about 1/4 of the fission cross section of ^{238}U . From the comparison between the total neutron yield due to ^{238}U block and Pb block, we can estimate that about half of the total neutron yield for the ^{238}U target; 25 neutrons are due to the fast fission of ^{238}U . Therefore, using Th^{232} target instead of ^{238}U , we can get only about $25 + 25/4 = 32$ neutrons per 1 GeV proton. The system of $^{233}\text{U} - \text{Th}^{232}$ is less suited

for this electronuclear reactor concept than the Pu²³⁹-U²³⁸ system.

Comparison among Proton, Deuteron, and Triton Beams

V. Barashenko⁽¹³⁾ indicated that the average number of neutrons produced from the high energy deuteron beams injected into the uranium target increases about 20% more than the case of using the same energy proton beams. We consider the case when the triton beam is used instead of proton beams, we get that the average number of neutron yield increases about 40% more than for the proton in the energy range between 1 GeV to 2 GeV, from his calculation. The detail of this can be found in the Memorandum⁽¹⁴⁾ dated October 15, 1976.

HT:amf

Attachments

Reference

1. Meyer Steinberg et al. The Clean Breeder Machine (CBM), Internal Report, Brookhaven National Laboratory (March 1976).
2. L. D. Stevens and A. J. Miller, "Radiation Studies at a Medium Energy Accelerator", UCRL-19386 (Lawrence Radiation Laboratory, 1969).
3. J. M. Carpenter (Edited) ZING Proposal (ANL), Draft Proposal for Intense Pulsed Neutron Source (October 1975).
4. N. Metropolis et al. Phys. Rev. 110, 185 and 204 (1958).
5. I. Dostrovsky et al. Phys. Rev. 111, 1659 (1958).
6. J. Ranft, CERN 64-67, Geneva (1964); Nucl. Instrum. Methods, 48, 133, 261 (1967).
7. V. S. Barashenkov et al. At. Energ. 35, No. 2, 163 (1973).
8. W. A. Coleman and T. W. Armstrong, "The Nucleon-Meson Transport Code, NMTC", Oak Ridge National Laboratory, ORNL 4606 (October 1970).
9. H. Bertini, ORNL-3383, Oak Ridge (1963); Phys. Rev., 188, 1711 (1969).
10. R. R. Fullwood, J. D. Cramer, R. A., Harman, R. P. Forrest, Jr., and R. G. Schrandt, "Neutron Production by Medium Energy Proton on Heavy Metal Target", I -4789 (1972).
11. J. S. Fraser, R. E. Green, J. W. Hilborn, J. C. D. Milton, W. A. Gibson, E. E. Gross, and A. Zucker, Phys. in Canada 21 (2), 17 (1965); and G. A. Bartholomew and P. R. Tunnicliffe (ed.) AF-CL-2600 p. VII. 12 (Chalk River) (1966).
12. D. I. Garber and R. R. Kinsey, Neutron Cross Sections (Vol.II) Curves. BNL 325 Third Edition, Volume II.
13. V. S. Barashenkov et al., Atomnaya Energiya 37, 480 (1974).
14. H. Takahashi, BNL Memorandum subject on "Interaction of high energy triton beams in matter" , October 15, 1976.

Table 1. Mean Characteristics of the Interaction of a Beam of Protons with Energy T (Normalized to one primary proton) with a Block of Natural Uranium

Characteristics	T, MeV			
	300	400	500	600
N^t	700	1290	1990	3030
$N^t (< 10,5)$	3,0	4,0	5,8	8,5
N^{in}	100	184	280	430
$N^{in} (< 10,5)$	1,7	2,1	3,1	4,6
N_{cap}^8	17	32	48	74(60)
N_{cap}^5	0,18	0,36	0,5	0,8 (--)
N_{esc}	1,1	2,5	3,3	5,4(4)
N	18	35	52	80(64)
$\nu (< 10,5)$	1,4	1,6	2,4	3,7(3,6)
$\nu (< 10,5)$	2,6	5,6	8,6	13,4(10,2)
$\nu (< 10,5)$	1,0	1,8	3,0	4,6(--)
ν	5,0	9,0	14,0	21,7(13,8)
Q, GeV	1,2	2,2	3,4	5,0(3,4)

Figure 1. Measured neutron yield vs proton energy for various targets.

Figure 2. Radial and axial distribution of the production of evaporation neutrons in a 7.5-cm-radius, 30-cm-long ^{238}U target with 800-MeV protons incident on axis.

Figure 3. Comparison of 4π neutron spectra for ^{238}U and Pb cylinders 15-cm diam, 30-cm long with 800-MeV protons incident on axis.

Figure 4. Heat production per neutron produced and neutron yield vs incident proton energy.

Figure 5. Fission cross section of ^{238}U .

Figure 6. Fission cross section of ^{232}Th .

BROOKHAVEN NATIONAL LABORATORY

MEMORANDUM

DATE: 10/19/76

APPENDIX 2a

TO: Accelerator-Breeder File

FROM: Hiroshi Takahashi

SUBJECT: Interaction of High Energy
Triton Beams in Matter

Recently V. S. Barashenko et al.⁽¹⁾ indicated that the average number of neutrons produced from high energy deuteron beams injected into the uranium target increases about 20% more than the case using the same energy proton beams. His conclusions are based on his Monte Carlo cascade calculation for the nuclear, meson, and nucleus interaction, and the average characteristics of the interaction of deuteron and proton beams in a block composed of a natural mixture of uranium isotopes is tabulated.

In the case of 1 GeV deuteron beams, the binding energy between neutron and proton which compose the deuteron nucleus is very small compared with their kinetic energy. Therefore, the deuteron beams can be treated as the two beams composed of proton and neutron each of which has 0.5 GeV energy.

Figure 1 shows the total neutron yield (normalized to 1.0 at 1 GeV proton beams) by interaction of high energy neutron beam with a very large (practically infinite) block of natural uranium calculated from the Barashenkov's paper. The calculation was done for 0.33 GeV, 0.5 GeV, and 1 GeV energies. Above the 1 GeV, the data is extrapolated so that the value energy for more than 2 GeV is the same as the ones of the proton beams. The total neutron yield by the triton beams with energy between 1 GeV-3 GeV is calculated from the obtained data.

The replacement of the proton beam by one of tritons leads to a considerable increase in the total neutron yield about 40%.

Reference

(1) V. S. Barashenko et al. Atomnaya Energiya 37, p. 480-83 (1974).

HT:amf

Attachment

Figure 1. Beam particle energy.

APPENDIX 3

PRELIMINARY CALCULATION OF THE
NEUTRON BEHAVIOR OF AN ACCELERATOR-BREEDER

BROOKHAVEN NATIONAL LABORATORY

M E M O R A N D U M

DATE: 10/13/76

APPENDIX 3

TO: Accelerator Breeder File

FROM: Hans Ludewig

SUBJECT: Preliminary Calculation of the
Neutronic Behavior of an Ac-
celerator-Breeder

In this memorandum the initial calculation of the fission distribution and neutron balance of an acceleration driven breeder are presented. The idea of generating an intense neutron source by impinging a high current of protons or deuterons on a heavy metal target is not new. In this memorandum only the BNL concept⁽¹⁾ will be considered, which relies on a 1 GeV proton beam impinging on an array of gas cooled rods containing fertile material. Neutron production in such a machine has two distinct steps, first a cascade step which results in relatively high energy neutrons and second an evaporation step which is due to the deexcitation of the nucleus. The latter step can be represented by a maxwellian distribution in energy an isotropic distribution in angle.

All the neutron transport calculations to be reported here were carried out using the DSN code TWO TRAN^(2,3), which was coupled to a 49-group cross section library. These cross sections were based on ENDF/B-IV. Due to limitations in the cross sections information available on the ENDF/B data files (primarily developed for the analysis of fission reactors) the maximum energy neutron which could be treated was 15 MeV. It was thus necessary to treat the resulting source neutron, described above, in an approximate manner. The approximate source was represented by a maxwellian in energy, isotropically in angle and the spatial distribution was based on experimentally measured results. The characteristic energy of the maxwellian was varied until one fission neutron was obtained for every source neutron in an infinite medium of ²³⁸U. Three series of calculations were carried out, first for an infinite medium (to determine the source), using this source a finite two dimensional cylinder was analyzed and finally a series of calculations were carried out for the proposed BNL breeder machine. These calculations will be treated separately below

a) For the infinite medium calculations the source was represented by

$$S(E, \bar{r}, \bar{\Omega}) = f(\bar{r}) f(\bar{\Omega}) \frac{E}{E_m^2} e^{-E/E_m} dE d\bar{r} d\bar{\Omega} \quad (1)$$

In this case $f(\bar{r})$ and $f(\bar{\Omega})$ are equal to unity. Results of these calculations are presented on Table 1 for various values of E_m . It is seen that $E_m = 7$ MeV corresponds to the desired multiplication.

October 13, 1976

b) Using the source distribution determined above a finite depleted uranium cylinder with a proton beam impinging on one face was analyzed. The spatial distribution of the source was given by ⁽⁴⁾

$$f(\bar{r}) = e^{-\bar{r}/12.3} \quad (2)$$

Results of these calculations for two values of E_m are shown on Table 2.

c) Finally the proposed BNL breeder machine was analyzed. In this case, the source has the same form as that given by Eq (1), except the spatial distribution is given by ⁽⁵⁾

$$f(\bar{r}) = e^{-z/44.12} \quad (3)$$

Fig. (1) shows the general layout of the machine as it was represented in the calculation. The composition of the target was primarily stainless steel and $^{238}\text{UO}_2$ for the base. Three additional cases were treated in which $^{239}\text{PuO}_2$ was added to a region immediately surrounding the area of impact of the beam. This was done to simulate this build of ^{239}Pu in this region. The neutron balance for all four cases is shown in Table 3. Axial (along A-A) and radial (along B-B) fission distribution are shown in Figs. 2 and 3 respectively.

HL:amf
Attachments

References

1. Meyer Steinberg et al. The Clean Breeder Machine (CBM), Internal Report, Brookhaven National Laboratory, March 1976.
2. K. D. Lathrop et al. TWOTRAN-II, An Interfaced Exportable Version of TWOTRAN code for Two-Dimensional Transport" LA-4868-MS (1973).
3. A. L. Aronson, "TWOTRAN-II" Memorandum to M. M. Levine, Brookhaven National Laboratory, (1975).
4. R. R. Fullwood et al., "Neutron Production by Medium Energy Protons on Heavy Metal Targets", LA-4789 (1972).
5. H. Takahashi, Private Communication (1976).

Table 1

Neutron Balance for Infinite Medium

E_{th} (MeV)	Fission	Source	Total
5.0	.917846	1.0	1.917846
7.0	1.092645	1.0	2.092645
10.0	1.240492	1.0	2.240492

Table 2

Neutron Balance for Finite Cylinder

	$E_m = 7.0 \text{ MeV}$	$E_m = 10. \text{ MeV}$
Source	1.0	1.0
Fission	.485151	.546608
Total (Fission and Source)	1.485151	1.546608
Absorption	.166329	.166635
Top leakage	.044820	.047132
Bottom leakage	.196316	.204466
Right leakage	1.077686	1.128375

Table 3

Neutron Balance for Brookhaven Breeder Machine

% of ^{239}Pu	0	2	4	6
Source	1.0	1.0	1.0	1.0
Fission	.578334	.727153	.904245	1.119544
Total (Fission & Source)	1.578334	1.727153	1.904245	2.119544
Absorption	1.339869	1.469232	1.623269	1.810631
Top leakage	.047425	.047569	.047738	.047941
Bottom leakage	.163163	.178548	.196657	.218443
Right leakage	.027877	.031804	.036581	.042529

Figure 1. Schematic representation of an accelerator driven breeder machine.

Figure 2. Accelerator-breeder.

Figure 3. Accelerator-breeder.

APPENDIX 4

TARGET REACTOR DESIGN

BROOKHAVEN NATIONAL LABORATORY

MEMORANDUM

DATE: 10/25/76

APPENDIX 4

TO: Accelerator-Breeder File
FROM: T. V. Sheehan, J. R. Powell, and
M. Steinberg
SUBJECT: Target-Reactor Design

I. General Concept

The concept of this device is to use a powerful proton accelerator, with energy of 1 GeV at a current of 300 ma, corresponding to 300 MW(e) of beam power to impinge on a target with resultant formation of an intense neutron field due to spallation, evaporation, and fission neutrons from $\text{UO}_2\text{-PuO}_2$ in the target. ThO_2 is incorporated in the outer regions of the target where fissile U^{233} will be bred.

An overall plan view of the device is shown in Figure 1; an overall flow diagram in Figure 2, a plan view of the target area in Figure 3, and a section through the beam tube in Figure 4.

The design has been postulated as a helium gas cooled reactor, containing fertile and fissile fuel material in fuel pins in square fuel element boxes of varying lengths. The beam crosses the elements transversely, the helium flows parallel. The 300 MW(e) beam power entering the target will cause the release of heat about 1500 MW(t) therein. This heat will be removed by a conventional helium cooling circuit, making use of a mechanical arrangement comprising a prestressed concrete pressure vessel with target, turbo machinery, steam boiler and reheater, and conventional fuel handling equipment housed therein. The cooling helium is orificed to each element in such a manner that a top temperature of 1000°F or less is attained. Operating pressure at the target is 1000 psia.

Net steam is produced at about 925°F, 1200 psia, resulting in a thermal efficiency of 40% and generation of 600 MW(e). Lower power conditions which would accommodate fuel materials integrity (i.e., U/Th/Zr clad) could also be obtained.

II. Target

In design of the target, a principal consideration is the range of the protons in the target material. The target must be capable of completely stopping the 1 BeV protons.

The range of protons of a given energy in a medium of density ρ is given by:

$$L = \frac{1}{\rho} [\rho(RE)]$$

October 25, 1976

Range, $L = \text{cm}$ Density, $\rho = \text{gms/cm}^3$ Stopping Power, $[\rho(\text{RE})] = 0.46 E(\text{MeV})$

In the case of the proposed target-reactor, the average density of the fuel pin assemblies including fissile or fertile material, cladding, structures, and helium is about 5 gm/cc. For a 1 GeV (10^3 MeV) = particle, therefore,

$$L \text{ (feet)} = \frac{1}{5} \times \frac{0.46 \times 10^3}{30.48} = 3.0$$

In our design, 5 feet has been used to insure complete stopping.

Figure 5 is a plan view on the centerline of the target and Figure 6 is an isometric view which shows the opening into which the beam is directed, the overall dimensions, and the types of fuel elements located in various regions. The cavity arrangement is to capture back scattered neutrons.

Note that a target vessel 25 ft or more in diameter 15 ft or more in height will be required. The proposed rectangular design of target is by no means intended to be final or optimum. Further study may result in a nearly circular target with horizontal elements that may be cooled by cross flow or longitudinal flow of gas coolant.

Referring again to Figure 5, note that the active region of the target which is first struck by the beam is packed with only 50% of elements. This is to minimize the severity of heating on the front face of the target. Those protons which go through the openings, or strike glancing blows on the front elements will be effectively stopped by the rear 5 ft of close packed elements. The elements at the very rear are blanket type, containing ThO_2 .

III. Power Densities

As shown in Figure 5 for the target section on center line, the average heat generation is less than 1 MW(t)/ft³. In a gas cooled reactor of, for instance, the fast breeder type, the average heat density in the core is about 7 MW(t)/ft³. Accordingly, one would expect mild conditions of service for cooling, even for very appreciable peak to average power relationships.

Assuming that 80% of the total power, 1200 MW(t) is released in the 5' x 5' x 10' core region (Fig. 5) of the target, the peak power density becomes $1200/187.50 = 6.40$. The average power density over the entire core and blanket = 0.77 MW(t)/ft^3 . This compares to a 3 MW(t)/ft^3 for the LWR and 7 MW(t)/ft^3 for GCFR. Accordingly, at worst, the cooling problem probably cannot be more severe than in a gas cooled reactor and is probably much less severe.

IV. The Window

In order to separate the high pressure helium gas in the target area from the high vacuum in the accelerator tube, a window is required. It appears that titanium would be an appropriate material, having good strength at moderate temperatures. However, the window material must be cooled; otherwise the heat deposition would cause it to melt. This design considers a multilayer window of titanium, spherical, 18 in. diameter, water cooled at high velocity between layers. Figure 7 will make clear the general concept.

About 1% of the beam power, or 3 MW(t) will be deposited in the window. If the beam is 15 in. in diam., and a 4 layer window is used there will be 6 wetted surfaces plus some extended surface that can probably be worked in. The area of the 15" diam. window spherical section is somewhat (say 10%) greater than a plain circular section. Thus total area for cooling will be about 8 ft². Power deposited in the window is about 10×10^6 Btu/hr, or the density 1.25×10^6 Btu/ft²/hr. This very high heat load will require a very high coefficient to keep film temperature difference to a manageable level in order to keep the window material cool and obviate the need for high pressure to suppress boiling. Assuming a coefficient h of 5000 Btu/ft²/hr/°F can be attained with water velocities of 35 to 50 ft/sec, Δt film will be 250°F. With a base water temperature of 150°F, the metal temperature will be 400°F, and the pressure required some 250 psi which appears feasible. Double quick acting valves are provided on each side of the window for safety purposes. Liquid metal cooling of the window could also be considered should pressure conditions become too severe.

Radiation damage to the window will be marked. Consideration has been given to a design containing multiple windows such that a new one could be quickly moved into place just before the operating window had reached its safe limit of damage.

Titanium Properties (for window)

Test Temperature = $\sim 600^\circ\text{F}$

Ultimate Strength = 66,000 psi

Yield Strength = 56,000 psi

Consider operating at a stress equal to 1/2 of the yield = 28,000 psi

Window = spherical 18 in. diam.

Max pressure = 1000 psi He + 250 psi H₂O

= 1250 psi

$$t = \frac{PR}{2S} = \frac{1250 \times 9}{56000} = 0.20''$$

October 25, 1976

It would appear that a total window thickness of 1/2 in. would be very conservative considering radiation damage. Depending on the number of layers, each layer could be 1/4 in., 1/3 in., 1/8 in., etc.

While the window design presented herein for a 1/2 in. thickness results in a deposition of 1% of the beam power, it is possible that a thinner window would be satisfactory and result in less severe cooling problems, but this would have to be balanced against radiation damage.

Table 1 summarizes the principal characteristics of the Accelerator-Breeder Reactor Design.

amf

Attachments

Table 1
Principal Characteristics of
LINEAR ACCELERATOR-BREEDER REACTOR

Beam	1 GeV - 300 ma
Beam Power	300 MW(e)
Input to Accelerator	600 MW(e)
Target Power Generation	1500 MW(t)
Length of Accelerator	2000 ft
Target Vessel	23 ft x 15 ft
Target Volume	1987 ft ³
Target Core Volume	187.5 ft ³
Target Density	5 gm/cc
Total Target Weight	50,000 Kg 110,000 lb
Target Core Weight	4,700 Kg
Prestressed Concrete Target Vessel	90 ft diam 75 ft high
Containment Vessel	~ 200 ft diam
Average Power Density in Target	0.77 MW(t)/ft ³
Max. Power Density in Core	6.4 MW(t)/ft ³

Figure 1. Accelerator breeder general layout.

Figure 2. Accelerator breeder target reactor overall flow diagram.

Figure 3. Target reactor design. Plan section on $\bar{C}$ beam tube.

Figure 4. Target reactor design vertical section on ϕ beam tube.

TYPICAL FUEL PIN
BOX-6" x 6"-256 PINS

AVG. POWER DENSITY IN TARGET = 0.77 MW/ft^3
AVG. POWER DENSITY IN CORE = 638 MW/ft^3

SEC XX ON
CL TARGET

(A) (B) (C) (D) TARGET REGIONS; (B) AND (C) ARE CALLED CORE

Figure 5. Accelerator breeder target design. Plan section on CL.

REGION A SHORT ELEMENTS 2'-6" LONG TOP AND BOTTOM - CLOSE PACKED
 REGION B SHORT ELEMENTS 2'-6" LONG TOP AND BOTTOM - CLOSE PACKED
 REGION B 5'-0" INTERMITTENT ELEMENTS OPPOSITE BEAM ENTRY HOLE
 REGION C 10'-0" LONG ELEMENTS, SOME PuO_2 UO_2 + SOME ThO_2
 REGION D 10'-0" LONG ELEMENTS
 UO_2 - PuO_2 IN ELEMENTS EXPOSED TO MOST INTENSE BEAM
 ThO_2 IN PERIPHERAL ELEMENTS

Figure 6. Accelerator breeder target layout.

FOR $\frac{1}{2}$ " TOTAL TITANIUM THICKNESS:
 4 LAYER WINDOW-EACH LAYER = $\frac{1}{8}$ "
 3 LAYER WINDOW-EACH LAYER = $\frac{1}{3}$ "

Figure 7. Window.