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PROPOSAL FOR AN

Accelerator - based NEUTRON GENERATOR

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Proposal For An

**Accelerator - based
NEUTRON GENERATOR**

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Accelerator - based NEUTRON GENERATOR

I. INTRODUCTION

1.1. Summary of the Proposal

The materials surrounding the plasma of a fusion reactor will be subjected to intense neutron bombardment. In all probability the first successful reactor will use the D-T reaction in which case the inner wall will be bombarded by about 10^{14} 14-MeV neutrons per square centimeter per second. Blanket materials and structural members will be subjected to bombardment of the same order of magnitude. Since the effects of such intense radiation applied over months and years to the materials of construction are not known, construction of adequate test facilities is essential.

Feasibility experiments on fusion reactors will be taking place early in the 1980's. In preparation for this it is important to start construction of intense neutron sources for materials testing. Using D-T reactions it seems difficult to produce 10^{14} neutrons per square centimeter per second over any appreciable volume. A deuteron stripping reaction on a light element can, however, provide beams of more than 10^{14} neutrons per square centimeter per second over appreciable volumes using easily attainable deuteron beams. If the deuterons have been preaccelerated to about 30 MeV, the neutron spectrum will be peaked at about 14 MeV.

In the present proposal we describe an Accelerator-based Neutron Generator consisting of a 30-MeV deuteron linear accelerator using a flowing liquid lithium target. With a continuous deuteron current of 100 milliamperes, a source intensity of more than 10^{16} neutrons per second will be produced. The neutrons will be emitted in a roughly collimated beam.

No new technology is required in this project. The linear accelerator is well within the state of the art; the liquid lithium target and its circulating system present no problems that have not been already solved in reactor cooling systems using flowing alkali metals.

Construction of the machine could be completed in about four years. If the start of construction were authorized for the beginning of FY 1977, the machine could come into operation early in FY 1981 at a total cost of \$43,000,000.

Like others of Brookhaven's major facilities, the Accelerator-based Neutron Generator would be a national facility to be used by qualified groups to obtain information about fast-neutron damage to materials.

The proposed facility can be divided into two areas: the 30-MeV linear accelerator and the multiple-target experimental area.

The 30-MeV accelerator will consist of eight rf accelerating cavities in a single vacuum tank, each cavity being powered by its own rf power amplifier operating at 50 MHz. To shield the beam bunches from the rf field when it is in the decelerating direction, 66 "drift tubes" will be included; the drift-tube structures will include quadrupole magnets which will keep the beam focused. The accelerator will produce a continuous beam of 100 milliamperes. Beam power will thus be 3.0 megawatts; total power including rf losses in the accelerating cavities will be 4.5 megawatts.

The injectors for the linear accelerator will be two 500-kV dc accelerators, one for injection of D^+ ions and the other for D^- ions. They can be used simultaneously or one can serve as a spare in case of breakdown or maintenance of the other.

The design of the accelerator has not yet been worked out in complete detail but its specifications lie well within the state of the art; no fundamental problems are anticipated during the detailed design phase. Experience with linear accelerators indicates that the machine can be run without appreciable beam loss during acceleration so that no problems are anticipated with residual radioactivity.

The target system will be separated from the accelerator by a distance of the order of 60 meters. In this distance the bunched beam will debunch and become a virtually continuous beam. The separation will serve also to isolate the high radiation levels in the experimental area from the accelerator.

The target area will include four target caves and a beam dump separated from an overhead staging area by 2.5 m of concrete. With D^+D^- operation, two targets can be operated simultaneously while experiments are being set up in the other two caves. The staging area will include hot cells and other necessary experimental services.

A typical target will consist of a liquid lithium jet, 1.5-cm thick and 12-cm wide, crossing the beam with a velocity of about 10 m/sec. Analysis of heat deposition in this jet indicates that the 3 megawatts of beam energy in the D^+ target can be dissipated without troublesome local heating to

unreasonable temperatures. A single liquid-lithium loop with the necessary pumps and heat exchangers will service the four targets.

The accelerator will be contained in a 150-ft-long shielded tunnel adjoining a light structure containing the rf equipment, assembly area and other services (14,000 sq.ft). The experimental staging area (5600 sq.ft) will be serviced by a 20-ton crane for shielding removal. An office and laboratory building (10,000 sq.ft), containing the central control room, will provide the laboratory and office space required for machine personnel and experimenters.

The frontispiece is an artist's conception of the building that will house the deuteron linac and its experimental areas. Figure I-1 is a map of the Brookhaven site showing the proposed location of the Brookhaven Accelerator-based Neutron Generator (BANG).

1.2. Design Choices

a) The Deuteron Stripping Reaction

Fast neutrons are necessary to simulate the neutron radiation environment of an operating thermonuclear reactor. The principal need for high-energy neutrons in meeting the needs of the CTR materials program is based on the importance of the nonelastic neutron-scattering events, including transmutations and nuclear reactions such as (n,α) , (n,p) and $(n,2n)$ in producing defects and impurities. The importance of helium production in determining the behavior of materials in fission reactors has been amply demonstrated; accordingly, the higher production rate expected in fusion reactors will have even more serious results. Impurity production by neutron-induced reactions can result in significant accumulation of undesired impurities during the life of a reactor and may produce serious deterioration of the materials of construction.

Specific properties needed in a high-energy neutron source have been discussed at the recent Washington meeting on "Critical Questions in Fundamental Radiation Damage Research" and have been outlined by Persiani.¹ They can be summarized as follows:

1. P. J. Persiani, "Neutron Source Considerations for the CTR Materials Program," Argonne National Laboratory Report ANL/CTR-72-01.

FIG. I-1

SITE MAP

i) The facility should be instrumented for conducting in situ measurements of irradiated samples during and subsequent to irradiation.

ii) The source intensity should be high enough to provide a good simulation of the environment of a fusion reactor.

iii) Source parameters (intensity and neutron energy) should be flexible to accommodate a range of experimental needs.

iv) It should be possible to perform a number of experiments simultaneously.

Neutron sources in use at Livermore and proposed at Los Alamos are based on the D-T reaction. Both are essentially point sources with a spherically symmetric radiation pattern whose intensity decreases as $1/r^2$. At Los Alamos a total intensity of about 10^{15} neutrons per second is planned. The Livermore source will have an intensity lower by one or two orders of magnitude.

Deuteron breakup on a light-element target can be used to produce an intense neutron beam emitted primarily in the forward, or deuteron beam direction. The neutron energy spectrum will be peaked at an energy of about half the deuteron energy. At about 30-MeV deuteron energy, the neutron beam provides a good simulation of the neutrons at the first wall of a fusion reactor. Lowering the deuteron energy will result in neutron spectra peaked at lower energies which can be used to simulate the D-T neutron spectrum after it is degraded by passage through walls and blankets. Measurements of neutron spectra from deuteron breakup are presented in Section 3.2.

The Accelerator-based Neutron Generator will achieve an intensity of over 10^{16} neutrons per second, so that an intensity of 10^{14} neutrons per square centimeter per second can be made available over an area of 100 cm^2 .

With a deuteron beam of energy variable up to 30 MeV and of intensity variable up to 100 milliamperes incident on a target of a light metal, the resulting neutron source satisfies all of the requirements outlined above.

b) The Linear Accelerator

Deuterons can be accelerated to 30 MeV in a variety of accelerators including cyclotrons, synchrotrons and tandem Van de Graaff machines. All, however, are limited to rather low intensities; the linear accelerator is

the only machine that has the capability of accelerating a steady current of over 100 milliamperes. With linear accelerators, proton currents over 200 milliamperes have been accelerated, so the possibility is inherent of acceleration of higher currents if this is desired later.

Amongst the different types of available linear-accelerator designs, only one, namely the drift-tube linac is considered for this application. Drift-tube linacs are well developed and a number of them have been built in this country at: Brookhaven, Argonne, Fermilab, Berkeley and Los Alamos. These have shown satisfactory performance and have accumulated many years of operating experience.

Another type of linear accelerator, the helix linac, is potentially capable of the same performance. However, helix linacs have never passed the development stage and show no operating experience. In addition, the development done to date on both room temperature and superconducting helix linacs indicate that they have problems which would make them unreliable. These problems are connected with mechanical fragility, vibration and heat dissipation. Accordingly, helix linacs are not considered here.

c) The Lithium Target

Neutron beams of satisfactory intensity and energy spectrum can be derived from bombardment of beryllium or lithium targets. There is, however, the problem of dissipating the almost 3 megawatts of beam power (only about 25 kilowatts escapes in the form of neutron energy). This energy can be removed conveniently by making the target of flowing liquid metal. Lithium is admirably suited for this purpose. Its melting point is 180°C. It will enter the target region at a temperature of 200°C and will be heated by the beam to 280°C. At the higher temperature its vapor pressure still is quite low (10^{-6} Torr). The target will be a lithium jet 1.5-cm thick and 12-cm wide, to provide a target area of 10 x 10 sq.cm. The deuteron beam can be spread over this whole area or can be concentrated on a smaller area to give a higher intensity.

d) Positive and Negative Deuteron Beams

In Brookhaven's Accelerator Department there is a great deal of experience in the generation and acceleration of both positive and negative hydrogen ion beams. This experience can be helpful in the Brookhaven neutron generator where beams from two ion sources, one of positive ions and the other

of negative ions can be accelerated simultaneously in the linear accelerator. When these beams enter a deflecting magnet in the target area one will be deflected to the left, the other to the right, providing two simultaneous neutron beams to two experimental areas. Present planning is for a positive deuteron beam of about 100 milliamperes and a negative deuteron beam of about 10 milliamperes. Future addition of rf power amplifiers might make it possible to raise both beams to the 100-milliampere level.

e) Linear-Accelerator Parameters

The injectors for the linear accelerator will be 500-kV Cockcroft-Walton generators. The linear accelerator itself will consist of eight cavities with a total length of about 40 meters. The energy gain of 0.75 MeV/m is a conservative figure - the present 200-MeV proton linac operates with fields almost twice as high. But power required for tank excitation in a linac of given final energy is inversely proportional to tank length and hence directly proportional to rate of acceleration. The rate of acceleration has been chosen for the deuteron linac to make the power required for tank excitation (about 1.5 megawatt) reasonably small compared with the fixed power required for beam acceleration (3 megawatts).

The radiofrequency chosen for excitation of the linear-accelerator tanks is 50 MHz. On the 200-MeV proton linac the frequency is 200 MHz. For deuterons, however, the injection velocity is materially lower, and, for reasons connected with beam dynamics one is forced to the lower frequency. This results in a corresponding increase in tank diameter to about 3.8 meters.

The neutron-source characteristics, 30-MeV linac and target systems are described in more details in chapters III, IV and V.

1.3. Brookhaven Qualifications

Brookhaven includes a unique assembly of capabilities which make it eminently qualified to undertake construction and utilization of an intense neutron source based on a deuteron linear accelerator. Since its founding, nearly three decades ago, Brookhaven has been a major accelerator center. Twice it has constructed and operated accelerators with the world's highest energy. Alternating gradient ("strong") focusing was invented by a Brookhaven team which pointed out its revolutionary impact on the linear accelerator. Two major proton linear accelerators have been part of the accelerator pro-

gram, one for 50 MeV and the latest, now serving as injector for the 33-GeV Alternating Gradient Synchrotron, yields 200-MeV protons. The staff of Brookhaven's Accelerator Department includes many experts on linear accelerator design and operation. The deuteron linac involves no problems not already solved for proton linacs. It is planned, at present, to locate the deuteron linac adjacent to the operating 200-MeV proton linac. It is hoped that, to a considerable extent, the deuteron machine could be operated and serviced by the present 200-MeV operating crew. It is of interest to note the fact that the 200-MeV machine now performs satisfactorily during 90% of the time that it is required to be in operation. The peak current delivered by the 200-MeV linac in 200 microsecond pulses is 100 milliamperes.

It is, of course, intended that the deuteron linac neutron source be a national facility and that Brookhaven groups will use only a fraction of its time. There is much experience at Brookhaven in operation of this type since the AGS has an international group of users which carries out 70% of the experimental program.

A brief description of services supplied to users of the 33-GeV AGS will indicate Brookhaven's capabilities for coping with the needs of visiting experimenters. Each user group is given office space in adjacent buildings, an electronics trailer and an office trailer at the experiment, and a 10' x 20' building on a nearby parking area for storing inflammable materials. Apartments and dormitory rooms are supplied. Vending machines provide food and drink during late shifts. Standard high-energy electronic equipment is available from the "High Energy Equipment Pool". Also at the users' disposal are a well-stocked Research Library, a central computer department, machine shops, photography, health physics and instrumentation divisions, and all of the other normal facilities of a mature research center. During the summer a large number of academic and industrial visitors join in the research programs and enjoy the adjacent seaside summer resort facilities.

The AGS users are an international group, coming from all over the United States, Canada, Europe and elsewhere. They are organized in an active users organization known as the "High Energy Discussion Group" which meets every few months, discusses the ongoing program and makes recommendations to the Laboratory for future programs.

We would expect the new linac-neutron generator to become the same sort of facility as is the AGS. It will be thrown open without charge to all qualified users. Priorities will be established by a committee of users initially adopting the tested procedures that are used in ordering experiments on the AGS. It is planned that a group of probable users will be assembled immediately in order that their opinions about the experimental facilities can be expressed before construction begins. The new facility should be particularly useful to the Princeton CTR builders who will badly need materials-testing facilities for the components of the large Tokamaks under design and construction in the Plasma Physics Laboratory.

Another department in the Laboratory, the Department of Applied Science (DAS) has had the responsibility for the design and construction of other major facilities including the Brookhaven Graphite Research Reactor (BGRR) - (now shut down) and the High Flux Beam Reactor (HFBR), the first high-flux beam reactor dedicated to basic research. The Metallurgy Division of DAS has had extensive experience in liquid-metal technology dating back to 1960 having done development work on the uranium-bismuth liquid-metal reactor, high temperature corrosion work on materials for containing liquid cesium and sodium for space reactors and corrosion studies on stainless steels for the liquid metal fast-breeder reactor (LMFBR).

Although the Accelerator-based Neutron Generator will serve as a national facility for studying and testing materials for CTR's, several BNL divisions plan to use this facility. The Metallurgy Division of the DAS has been interested in the behavior of materials in radiation environments for the past 25 years -- work which includes radiation effects on graphite and on nickel-base alloys and steels. At the present time, it is conducting an important program on the effect of radiation (electrons, protons, neutrons) on superconductors. The conception of the Accelerator-based Neutron Generator is the outgrowth of work using the Brookhaven Linac Isotopes Producer (BLIP) for the production of high-energy neutrons by the reaction of protons on a beryllium target. When flux measurements of this CTR-division-funded work showed that the BLIP solid-Be-target system would not yield a high enough flux for CTR materials work, the Physics Department, the Accelerator Department and DAS working together developed the initial concept for the facility presented in this proposal.

The Solid State Division of the Physics Department has also been interested in the effect of radiation on materials since its inception. Brookhaven's Director has been a leader in the radiation-damage field for many years. Presently the Solid State Division is investigating the radiation effects produced in insulators, which are being considered for use in CTR devices, as well as the use of electrons, neutrons and gamma rays to produce defects in materials. Staff members in the Division use a variety of techniques, including positron annihilation, optical absorption, thermal luminescence, electrical resistivity and internal friction to study defects in metals and nonmetals.

A third but equally important group at BNL has proposed the use of solid "minimum-activity blankets" for breeding in CTR's. This concept is receiving serious consideration from CTR designers. This group would use the Accelerator-based Neutron Generator to study methods of recovery of tritium from materials of containment and the stability of minimum-activity blankets.

II. JUSTIFICATION OF NEED FOR THE PROJECT

2.1. Introduction

Congress' Office of Technology Assessment has just completed an analysis of the ERDA FY 1976 budget for the House Science and Technology Committee, and in the section on fusion power, reports on neutron sources for fusion plant materials testing as follows:

"The (fusion) technology program, almost everyone will now admit, was started somewhat late, and the difficulties to come were underestimated. In particular, new materials, to stand up under conditions to be expected in a fusion reactor, will take 10 years or more to develop, if the history of materials research is any guide at all. Only then, can one start to do real engineering and development on the next stages, knowing the materials limitations and possibilities. In particular, damage to materials by the high energy fusion neutrons will take years to determine, and experiments are hardly yet underway. Thus a strong request can be made for providing funds for intense neutron sources to be used in such experiments; none exist now, although it is known how to build them."

A great deal of research and development work is necessary to make a proper selection of materials which will withstand the radiation exposures expected in thermonuclear reactors. Since the neutron fluxes will be high in these devices, adequate simulation of service conditions for the materials of construction requires long-term high-flux exposures. The materials-testing programs must not delay the start-up times of prototype fusion reactors far into the future. This requires a CTR materials-testing source with the highest possible particle flux and a large volume of experimental space to accommodate the wide variety of research necessary.

Comparison with the breeder-reactor materials testing program is instructive. In spite of the widespread availability of fission reactors with fluxes of $10^{13} \text{ ncm}^{-2} \text{ sec}^{-1}$, materials testing did not begin in earnest until the construction of the EBR-II with fluxes two orders of magnitude higher. Similarly low-flux D-T sources will not suffice for CTR materials testing, so that it is necessary to construct a high-flux fast-neutron source. As there is at present no way of producing such a source by means of the D-T reaction, other methods are required. Recent considerations indicate that an accelerator-based source

concept is the most effective approach. Currently no such source exists. It is, therefore, imperative that the construction of the Brookhaven accelerator-based neutron generator be started at the earliest possible date.

2.2. Scientific Justification

14-MeV neutrons are necessary to simulate the neutron radiation environment expected in operating fusion reactors. The principal need for high-energy neutrons is based on the importance of nonelastic neutron scattering events including transmutations and nuclear reactions such as (n,α) , (n,p) and $(n,2n)$ in producing defects and impurities. Also, the importance of helium (He) production in determining the behavior of materials in a Liquid Metal Fast Breeder Reactor (LMFBR) has been demonstrated, and therefore there is reason to assume that the significantly higher production rates of He expected in fusion reactors will have a large effect on the behavior of CTR materials. Moreover, nuclear reactions such as the $(n,2n)$ reaction will produce significant amounts of transmutation products in the first wall of a fusion reactor over the lifetime of the reactor, and may cause marked changes in properties of the materials with which it is constructed.

High-energy neutrons are necessary for studying blanket designs. Neutronic calculations of tritium breeding for various blanket designs need to be tested, as well as the synergistic effects of liquid lithium and neutron radiation on corrosion problems. Another example of the need to study blanket concepts lies in the area of solid breeding and minimum activity designs. In some of these concepts, the tritium is bred in a solid material and recovered via diffusion. The effects of irradiation on the kinetics of tritium removal by diffusion will be an important parameter in establishing the viability of various reactor blanket designs.

It is possible to compile an extensive list of specific experimental programs which relate to the needs outlined in the above paragraphs. These include the effects of irradiation on the following: mechanical properties such as creep, fatigue and stress rupture, dimensional stability, surface properties, superconductivity, dielectric strength, etc. As indicated by the breadth of these needs, a neutron source should have the capability of simultaneously supporting a large number of diverse programs. The design we propose promises to accommodate this diversity of contemplated experiments.

One major advantage of the neutron flux produced by deuteron breakup arises from the nature of the breakup process. Since the neutron stripped from the energetic deuteron has a large momentum component in the forward or beam direction, the region of high neutron flux is concentrated in the vicinity of the slowly divergent forward beam. The initial cross section of the neutron beam is that of the incident deuteron beam. The neutron beam diverges much more slowly than it would from an isotropic neutron source of equivalent strength. Essentially all the neutrons are emitted over the forward 2π steradians, so that the flux is highest precisely in the region where experiments can be placed. Fig. II-1 shows the available neutron flux with respect to z , (distance from the target). The four $\text{Li}(d,n)$ curves given are for four different deuteron beam configurations. For comparison, two 1-cm^{-3} D-T sources of different source strengths are given.

The beam-target geometry is quite flexible and can be tailored with a large degree of latitude to produce the flux distribution desired by the experimenter. However, since there will be many experimenters with, presumably, differing ideal desired distributions, a compromise must be found. One configuration envisioned is a deuteron beam 1 cm in diameter swept 10 cm horizontally across the lithium target to produce an essentially 1×10 cm source area of nearly uniform current density.

This broad region of uniform flux would be desirable for comparative studies since several samples could be stacked side by side across the flux contour. This "line source" would produce the highest flux levels. However, the contours of constant flux in the vertical direction would not be uniform but fairly strongly peaked (see Section 3.3).

Expanding the beam vertically to 3-cm height would produce a uniform flux profile vertically over approximately a centimeter, and would lower the peak flux levels by a factor of three. These variations of profile would take place over a volume up to about 30 cm out from the face of the target window, but beyond this distance, changes in the beam configuration make little difference in the flux distribution. These tailoring options are meant only for the very-high-flux experiments.

Neutron sources should be compared on the basis of several radiation-damage parameters such as the (n,α) cross section, the damage energy cross sec-

FIG. II-1

tion, E_D (a measure of defect production efficiency), the damage energy and ratios of these quantities. For a given neutron spectrum a suitable comparison can be made by calculating spectral averages of these parameters.

Table II-1 gives such a comparison for Nb of the effectiveness of various neutron sources. The entry labeled BENCH represents the first-wall neutron spectrum in a fusion reactor calculated on the basis of a standard blanket design. If the BENCH spectrum is adopted as reference, then the following conclusions concerning (d,n) neutrons for the deuteron energy range under consideration can be drawn:

a) The value of $\langle \sigma_{n,\alpha} \rangle$ (2nd column) exceeds the BENCH value by about a factor of 3 when Nb is exposed to (d,n) neutrons. Other sources fail to produce an equivalent amount of helium by at least an order of magnitude, except in the case of a 14-MeV source, for which $\langle \sigma_{n,\alpha} \rangle$ is larger by a factor of 4.5, and thus is slightly less representative of the BENCH reference conditions than the Li(d,n) source.

b) The Li(d,n) source leads to a damage-energy cross section (4th column) that is very similar to that from 14-MeV neutrons. Both sources exceed the BENCH value by about a factor of three, with the 14-MeV value differing slightly more from the reference than the (d,n) values.

c) The ratio of damage-energy cross section to (n, α) cross section (5th column) can be regarded as a measure of the ability of a source to simulate the simultaneous generation of defects and helium. For the Li(d,n) source, this ratio differs by less than a factor of two from the BENCH value. For the appropriate deuteron energy, ~ 23 MeV, the ratio can be made to agree almost exactly with the BENCH value.

d) The total damage energy per primary recoil (6th column) is about 5 times larger than that for BENCH. The 14-MeV-source value is about four times larger than the BENCH value, while values for other sources are lower by factors of two or more.

e) By varying the energy of the incident deuterons, the values of relevant damage parameters can be varied according to the required simulation demands.

Table II-1

Radiation-Damage Parameters Calculated for Neutrons
from Various Sources Incident on Nb

	$(\sigma_{n,\alpha})$ barn	(σ_{Total}) barn	(E_D) barn-eV	$(E_D)/(\sigma_{n,\alpha})$ (eV)	$(E_D)/\sigma_{Total})$ (eV)
<u>Neutron Source</u>					
HFIR	1×10^{-5}	6.00	2.2×10^4	2.2×10^9	3.7×10^3
EBR-II-7	6×10^{-6}	6.35	2.8×10^4	4.6×10^9	4.4×10^3
LAMPF	4×10^{-4}	6.61	5.6×10^4	1.4×10^8	8.4×10^3
BENCH	2×10^{-3}	5.72	9.5×10^4	4.7×10^7	1.6×10^4
"14 MeV"	9×10^{-3}	3.96	2.7×10^5	3.0×10^7	6.9×10^4
Li(d,n)(30 MeV)	7×10^{-3}	3.22	2.5×10^5	3.6×10^7	7.8×10^4

Table II-2 illustrates in an absolute sense the value of a Li(d,n) source on the basis of displacement and gas production rates in Nb. There are some special cases such as Ni, for which the High Flux Isotope Reactor (HFIR) is an excellent source because the helium production rate is very high. Generally, however, the Li(d,n) source comes closest to reproducing the simultaneous displacement rates and gas production rates expected in the first wall of a fusion reactor.

Table II-2

Defect Production Rates in Nb at Various Nuclear Facilities

Facility	Flux $\text{ncm}^{-2}\text{sec}^{-1}$	Displacement rate dpa/sec	He ppm/sec	dpa/He
HFIR	6×10^{14}	1.49×10^{-7}	0.06×10^{-7}	24.8
EBR-II-7	4×10^{14}	1.24	0.02	51.7
LAMPF	2×10^{13}	0.12	0.08	15
BENCH	2×10^{14}	2.11	4.00	0.5
"14 MeV" (RTNS)	2×10^{12}	0.06	0.20	0.3
Li(d,n)(30 MeV)	1×10^{14}	2.70	6.50	0.4

Another instructive way to compare a simulation source with a 14-MeV source is to calculate the fraction of recoil atoms it produces which fall within prescribed recoil energy groups. Table II-3 makes such a comparison for three metals which are widely separated across the periodic table: Al, Nb and Au. The table reveals quite clearly that there is good correspondence between the recoil groups produced by 14-MeV neutrons and by Li(d,n) neutrons using 30-MeV deuterons incident on a lithium target. This kind of comparison is even more revealing than the spectral averages given in Tables II-1 and II-2. Details of the displacement cascade processes depend upon the distribution of recoil energies, and the correspondences shown in Table II-3 mean that Li(d,n) neutrons can simulate the effects of 14-MeV neutrons rather well in this respect. Thus the data in Table II-3 provide added justification for the construction of the proposed neutron source.

Table II-3

Percentage of Recoil Atoms Produced in Each Energy Group
During Exposure to Neutrons from a Li(d,n) Source
or a 14-MeV Source

Energy Group keV	<u>Al</u>		<u>Nb</u>		<u>Au</u>	
	30-MeV d on Li	14 MeV	30-MeV d on Li	14 MeV	30-MeV d on Li	14 MeV
0 - 0.1	0.1	0.0	0.3	0.3	0.0	0.0
0.1 - 1.0	0.5	0.0	2.8	2.9	9.6	9.3
1 - 5	2.0	1.6	10.4	11.0	22.0	22.0
5 - 10	2.4	1.8	9.0	10.1	8.7	8.7
10 - 50	15.1	11.1	20.1	21.4	24.8	14.4
50 - 100	11.0	7.9	14.1	6.2	24.4	28.0
100 - T _{max}	68.9	77.3	43.3	48.1	10.5	17.6

The construction of a high-current 30-MeV deuteron linac will provide a unique facility producing high fluxes of fast neutrons needed for CTR-related radiation-damage and blanket studies. The outstanding characteristics of this intense neutron source are:

a) Total source strength $\sim 2 \times 10^{16}$ neutron sec^{-1} , 10 to 20 times higher than any existing or proposed neutron 14-MeV source facility.

b) This total source strength is highly directional (forward peaked) and can be available on an area up to 100 cm^2 , or can be concentrated to produce peak fluxes of more than 10^{15} neutron- cm^{-2} - sec^{-1} .

c) The flux can be varied to suit a given experiment. The maximum flux is limited by the target heat-dissipation ability. It is expected that experience will show that the target design is very conservative and that fluxes can therefore be increased.

d) Although the maximum deuteron energy will be 30 MeV, it can be reduced stepwise to a minimum of ~ 10 MeV. This has the effect of varying the mean neutron energy from 14 MeV to about 6 MeV in steps of ~ 2.5 MeV.

e) The neutron flux can be produced in a pulsed, modulated or essentially continuous mode, giving complete flexibility in simulating different fusion-reactor modes from dc Tokamak to pulsed pinch-type machines.

f) The proposed target design gives complete flexibility for the setting up of experiments to utilize the total neutron flux available.

g) Two additional target caves permit the setting up of experiments while the machine is in operation.

h) The possibility to upgrade the facility to higher neutron intensities, if necessary at a later date, is built into the initial design.

It is proposed that both D^- and D^+ beams be accelerated simultaneously. The maximum current of the D^+ component will be 100 mA and that of the D^- one about 10 mA. The availability of two beams and their use to provide neutrons for a wide range of experimental programs significantly increases the flexibility of this source concept. The high-current D^+ beam can be directed to more than one target area. Because the experimental programs to be conducted at the high-flux, high-fluence targets range from bulk materials irradiations and in situ measurements of mechanical properties such as creep, to blanket studies and shield designs, the possibility of more than one target operation is a great advantage. While post-irradiation measurements are being made on experiments set up in one target area, irradiations will be conducted in another target area.

Many of the experimental programs will be conducted at the high-flux, high-fluence targets. The principal aim of these programs is to study the response of materials to neutron fluences $\geq 10^{21}$ neutrons cm^{-2} . To achieve fluences in this range requires exposures of the order of a year. This long exposure time limits the number of experiments that can be accommodated at the high-flux, high-fluence targets. However, there are a large number of programs that do not necessarily require high fluences. To increase the utilization of this facility it is also desirable to provide access to other users without affecting the high-fluence usage of the source. To meet this broad range of needs, the second beam, which is independent of the primary beam, has been included. This beam is considered to be a very flexible one whose operating parameters would be dictated by the individual user. The current would be variable from zero to 10 mA and it could be operated continuously or in a pulsed mode. A list of experimental programs that could be supported by this beam is given to illustrate its effectiveness. This list is representative of programs and is not necessarily complete or comprehensive.

a) Test of high-fluence experiments:

An experiment to be conducted at one of the high-flux, high-fluence targets requires a major commitment of beam time, so that the effectiveness of such experiments should be maximized. The D^- beam could be used to test the design and operation of high-fluence experiments.

b) Transient effects in materials:

The D^- beam can be operated in a pulsed mode to study the transient response of insulators to short intense neutron bursts. A clear application of this mode of operation is to the insulator problem associated with the Los Alamos Scientific Laboratory (LASL) theta-pinch design. The plasma burn time and repetition rate of the LASL Reference Theta Pinch Reactor could be easily simulated. It would also be possible to study the more general problem of cyclic neutron bursts as they affect materials not only in pulsed plasma reactors but also in laser-driven reactors.

c) Low-temperature irradiations:

One area important to CTR is radiation effects in superconductors. A liquid-helium-temperature irradiation facility with capacity sufficient for the irradiation of small superconducting magnets could be included at one

target. Because superconducting magnets are important components of several reactor concepts, understanding of the effects of neutron irradiation on the behavior of superconducting magnets is of great importance.

A fundamental understanding of the effects of fusion reactor neutrons on superconducting materials is also necessary. Liquid-helium-temperature irradiations are important elements of existing experimental techniques in studying fundamental effects of radiation.

d) Neutron flux-dependence studies:

A number of irradiation effects which will occur in a CTR may be sensitive to the magnitude of the neutron flux. Determination of this sensitivity is quite important in establishing permissible wall loadings. As an example of this type of study, one could determine the neutron sputtering yield as a function of neutron flux.

e) Neutron dosimetry development:

Development of dosimetry techniques is required to meet CTR needs. Dosimetry will also be necessary to support the experimental programs at the neutron source.

f) Neutron cross sections:

With the exception of a small interval of about 1 MeV around a neutron energy of 14 MeV, there is a scarcity of cross-section data in the medium neutron energy range of 1 - 25 MeV. Neutrons produced by the D^- beam will be ideally suited for cross-section measurements owing to the high fluxes available and the capability of operating the beam in a pulsed mode suitable for time-of-flight measurements.

The foregoing discussion demonstrates the need for an intense neutron source of broad utility. The source described here is capable of supporting a broad and diverse range of experimental programs while at the same time having the characteristics of a dedicated neutron source for high-fluence irradiations of materials for the CTR program. It should also be emphasized that any experiment carried out with the D^- beam can also be done with the D^+ beam if high-fluence exposures are required. Moreover, the D^- beam can be reduced in dimension also, so that the current density is comparable to that of the D^+ beam. This implies that the D^- beam will also be useful for high-flux experiments if this becomes desirable. The proposed neutron source, because it is a

versatile facility and is capable of supporting a broad spectrum of experiments, will be built and operated as a national facility. Scientists from all of the national laboratories, universities, and other organizations involved in CTR materials work would have experimental space and facilities made available to them on a priority basis designated by a CTR materials research User's Committee and the CTR Division staff.

The "materials community" recognizes the need for a facility comparable to that which is available to power reactor materials research scientists and designers. The proposed BNL accelerator-based neutron generator is the only device proposed to date, short of an operating fusion reactor, that can provide reasonable experimental volumes and neutron fluxes comparable to an operating fusion reactor within the time frame necessary to meet the demands of the CTR program.

III. SOURCE CHARACTERISTICS

3.1. High-energy-neutron production by deuterons.

There are many processes which lead to the production of energetic neutrons when a target is bombarded with high-energy deuterons. A simple way to think about these processes is to relate them to the distance at which the deuteron passes a target nucleus. If this distance is several times the radius of the nucleus, the deuteron can dissociate in the Coulomb field of the nucleus. Electrodissociation of the deuteron by the Coulomb interaction between the proton and the charge of the target nucleus has a cross section which is proportional to Z^2 . It is small compared to other cross sections except in targets of heavy nuclei and at very high deuteron energies. At grazing incidence the proton or the neutron can be "stripped" off leaving the other particle to proceed in the forward direction with the velocity of the incident deuteron. Finally, a direct collision can occur between one of the two constituent particles of the deuteron and a nucleus. If that particle is the proton, the neutron can proceed independently. In addition to these processes, deuteron capture can take place leading to the formation of an intermediate compound nucleus and subsequent production of decay products. The reactions ${}^7\text{Li}(d,n){}^8\text{Be}$ or ${}^6\text{Li}(d,n){}^7\text{Be}$ are typical examples.

The stripping reaction is the most interesting process for the purpose of the present discussion because it gives rise to a narrow forward cone of energetic neutrons whose most probable energy is approximately equal to one half the incident deuteron energy. The protons resulting from the reaction are stopped in the target. The kinetic energy of the deuteron is reduced by the height of the Coulomb barrier when it reaches the nucleus and also is reduced by the deuteron binding energy. Thus, the maximum of the neutron energy distribution will be displaced toward lower energy. On the other hand the peak in the proton energy distribution will shift slightly higher because, unlike the neutron, it regains the barrier energy in escaping the nucleus.

Serber¹ extended the idea of stripping in 1947 to explain the characteristically well-collimated beam of neutrons observed experimentally in deuteron bombardment experiments. The deuteron is the best candidate for stripping because the neutron and proton are weakly bound and described by a

diffusely broad wave function. Using a simple model equivalent to an impulse approximation Serber showed that the criterion for stripping could be roughly given as

$$E_d > 2(R/d)E_0 \quad , \quad (1)$$

where E_d is the deuteron kinetic energy, R the nuclear radius, d the mean separation of the neutron and proton in the deuteron, and E_0 the binding energy of the deuteron (2.23 MeV). Numerically, this reduces to the condition

$$E_d > 3.07A^{1/3} \quad , \quad (2)$$

where A is the atomic mass number of the target nucleus. Thus, the limiting deuteron energy in Serber's theory is about 6 MeV for Li. In fact, experimental evidence indicates that stripping reactions extend to lower energies as well. The theory can be used to show that the total cross section for stripping is given by

$$\sigma = \frac{1}{2} \pi R d \quad , \quad (3)$$

and thus is energy independent. Taking $d = 2.18 \times 10^{-13}$ cm, and $R = 1.5A^{1/3} \times 10^{-13}$ cm gives $\sigma = 3.1A^{1/3} \times 10^{-26}$ cm², and leads to stripping cross sections ranging from 0.1 b for Li to 0.3 b for U. The $A^{1/3}$ dependence of σ suggests that the neutron yield is highest in targets of high atomic mass. Experiments indicate the contrary. In fact, Schweimer² has shown that for 50-MeV deuterons the neutron yield decreases by a factor of 10 when the atomic number of the target material increases from 4 to 79. This is attributed to the fact that the number of atoms within the range of the deuteron decreases by a factor of 11 from Be to Au. An effect of this magnitude overshadows the slight increase in cross section with mass number, and mandates the use of a low- A target for maximum neutron yield.

The angular and energy distributions of neutrons from stripping (or breakup as it is often designated) can be calculated for a thin target on the

basis of Serber's model. The results are

$$P(\theta)d\Omega = (1/2\pi)[\theta_o/(\theta_o^2 + \theta^2)^{3/2}]d\Omega, \quad \theta_o = \left(\frac{E_o}{E_d}\right)^{1/2}, \quad (4)$$

and for an opaque nucleus,

$$P(E)dE = \frac{1}{4} \pi R d \frac{E_o E_d}{[(E - \frac{1}{2} E_d)^2 + E_o E_d]^{3/2}} dE, \quad \theta=0 \quad (5)$$

The full width at half maximum (FWHM) of the angular distribution for an opaque nucleus is $1.6 (E_o/E_d)^{1/2}$. The FWHM of the energy distribution is $1.533(E_o E_d)^{1/2}$. It can be readily determined from the expression for the energy distribution that the energy spectrum has its maximum at $\frac{1}{2} E_d$. However, as mentioned earlier, because the deuteron loses energy in surmounting the Coulomb barrier E_B , the center of the neutron energy distribution will be shifted to lower energy by an additional amount $\frac{1}{2}(E_B + E_o)$. Moreover, the use of a thick target will further reduce the mean energy. Serber has also considered the effects of deflection of the deuteron in the Coulomb field of the target nucleus as well as multiple-scattering. Both effects tend to broaden the beam with increasing atomic number.

In competition with the stripping reactions are compound-nucleus processes of comparable total cross section. Most of the latter will give rise to the (d,n) reaction, and will produce a nearly isotropic neutron distribution which can be described as an evaporation spectrum, i.e., $\sigma(e) \propto E e^{-E/\tau}$, where τ is an appropriate nuclear temperature. Additional secondary neutrons will be emitted as the excited residual nucleus decays to its ground state.

The foregoing considerations demonstrate why a thick Li target is the natural choice as an intense source of energetic neutrons from (d,n) reactions. Deuteron breakup will be the predominant reaction in the target. For 30-MeV deuterons the angular distribution will have an approximate FWHM,

$$\Delta\theta = 1.6(E_o/E_d)^{1/2} = 1.6(2.23/30)^{1/2} = 0.436 \sim 25^\circ,$$

and the energy distribution will have its maximum near 14 MeV with an approximate FWHM,

$$\Delta E = 1.533 [E_0(E_d - E_B - E_0)]^{1/2} = 1.533(2.23 \times 26.4)^{1/2} = 11.8 \text{ MeV.} \quad (7)$$

These breakup neutrons will be superimposed upon an isotropic distribution of neutrons arising from compound-nucleus formation. Depending upon the Q of each reaction which occurs between the deuteron and the target nuclei, the neutron energy spectrum and angular distribution will vary among targets of different materials. For this reason it is necessary to measure yields and angular distributions for each target and deuteron-energy combination of interest.

3.2. Li(d,n) Spectra.

Using the neutron time-of-flight spectrometer at the U.S. Naval Research Laboratory Cyclotron Facility³ we have determined neutron spectra from the (d,n) reactions in a thick lithium target. The target was a cylinder 2 cm long and 2 cm in diameter consisting of natural lithium. Data were obtained for five deuteron energies which were nominally 14.5, 20, 25, 30 and 35 MeV. The energy of the deuterons incident on the Li target was approximately 1-1.5 MeV lower in each case because the beam was required to traverse 25 μ m of Al, 7.5 cm of air and 25 μ m of Havar alloy before entering the target. Figure 111-1 illustrates the experimental arrangement schematically.

A 5-cm diameter NE-213 liquid scintillator coupled to a photomultiplier tube was used to detect the neutrons at the end of the 3-m flight path. The fast timing signal from the photomultiplier assembly determined the arrival time of the neutrons. These neutron-flight, start and stop signals, provided the input timing signals for a time-to-amplitude converter (TAC). The output of the TAC was routed into an analogue-to-digital converter (ADC) interfaced to an EMR-6050 computer. The scintillation amplitude or linear signal from the PM tube base entered a secondary ADC, and neutron-gamma pulse shape discrimination signals were routed to a third ADC. The flight time and pulse-height signals from the first two ADC's were recorded in a two-parameter mode subject to a software gate on the output of the third ADC. This neutron gate assured that only those scintillation events associated with neutrons were processed by the computer.

SCHEMATIC ARRANGEMENT FOR NEUTRON TIME-OF-FLIGHT SPECTRAL MEASUREMENTS

FIG. III-1

The two-parameter accumulation of data records the number of events, $N(E_{ni}, E_{pj})$, in the i th j th bin. This bin has neutron energy width ΔE_{ni} and pulse-height width ΔE_p . The x axis is in equal increments of time but not energy, hence, the bin-width dependency on the channel index " i ." The neutron energy spectrum $f(E_n)$ for a specific number of incident deuterons is defined such that $f(E_n)\delta E_n$ is the number of neutrons per Coulomb-steradian having energy in the increment between E_n and $E_n + \delta E_n$. This spectral distribution is then related to the accumulated data by the expression:

$$f(E_n) = \frac{1}{Q\Omega\epsilon_{ni}\Delta E_{ni}} \sum_j N(E_{ni}, E_{pj}) \quad , \quad (8)$$

in which Q is the integrated target current in Coulombs, Ω is the detector solid angle, and ϵ_{ni} is the detector efficiency which is calculated by use of the Kurz⁴ code. This spectral expression is evaluated in the computer and is presented on a line printer, together with the average neutron energy given by:

$$\bar{E} = \frac{\int_0^{E_n^{\max}} E_n f(E_n) dE_n}{\int_0^{E_n^{\max}} f(E_n) dE_n} \quad . \quad (9)$$

In evaluating this average energy the neutron spectral amplitude is extrapolated to zero for vanishing neutron energy.

At 12.8 MeV and 33.8 MeV, angular distribution data were taken for angles of $0^\circ - 20^\circ$ in 5° intervals. In addition, the $\text{Be}(d,n)$ energy spectrum was measured in the forward direction at 33.8 MeV for comparison with earlier NRL results taken when the target was inside the cyclotron vacuum chamber.

Analysis of the $\text{Be}(d,n)$ data produced a value for the yield in the forward direction which is in good agreement with the previous NRL result, and with other published $\text{Be}(d,n)$ yields. Figure III-2 shows the $\text{Li}(d,n)$ neutron spectra for the five deuteron energies mentioned previously. As predicted by theory the mean energy of the neutrons increases with increasing deuteron energy and is approximately $0.4E_d$. The yield also increases with increasing

FIG. III-2

energy as reported by others. The FWHM of each distribution is in reasonably good agreement with that predicted by Serber's stripping theory, taking into account that a thick target was used. The agreement improves as E_d increases because the stripping theory itself improves as E_d increases and because other effects such as deflection of the deuterons by the Coulomb interaction with the nucleus decrease with increasing energy.

Figure III-3 exhibits graphically the dependence of the mean neutron energy at 0° , $\langle E_n(0^\circ) \rangle$, upon the incident deuteron energy. The figure shows that $\langle E_n \rangle$ lies between 0.4 and 0.55 times E_d , approaching the lower value as the deuteron energy increases. For a given energy $\langle E_n \rangle$ varies only slightly as the scattering angle is increased, whereas the yield decreases. These results confirm the prediction that the forward direction is strongly favored in the (d,n) stripping reaction.

Table III-1 contains values of the measured yields in neutrons/sr C for all measurements performed. Extrapolation to zero neutron energy would increase the yields by about 5 percent. Yields at other angles for the lowest and highest deuteron energies are also shown. The FWHM estimated from these results are once again in good agreement with the predictions of stripping theory, the agreement as expected being better for the higher-energy deuterons.

Table III-1

Neutron Yields From Li(d,n) Reaction in Neutrons/sr-C

$E(\text{deut})$ (MeV)	$\langle E_n(0^\circ) \rangle$ (MeV)	$Y(0^\circ)$	$Y(5^\circ)$	$Y(10^\circ)$	$Y(15^\circ)$	$Y(20^\circ)$
13.42	7.63	9.685×10^{15}	9.419×10^{15}	7.810×10^{15}	6.338×10^{15}	4.992×10^{15}
18.95	8.46	3.247×10^{16}	-	-	-	-
24.84	10.32	7.129×10^{16}	-	-	-	-
28.94	12.21	1.057×10^{17}	-	-	-	-
34.06	14.46	1.469×10^{17}	1.313×10^{17}	0.8687×10^{17}	0.5904×10^{17}	0.4160×10^{17}

FIG. III-3

The absolute yields, however, appear to be lower than those derived from interpolations of data published by others. Until this discrepancy is clarified, the results quoted here for neutron fluxes should be regarded as conservative. Further experiments are in progress.

3.3. Flux distributions and contours

The neutron flux produced by a 100-mA, 30-MeV deuteron beam on a lithium target, aside from the target characteristics, is entirely dependent upon the deuteron beam geometry and density distribution. A computer program has been developed to calculate the neutron fluxes from the proposed target allowing for changes in the deuteron beam parameters. The calculation methods and parameters used for the program are described in Appendix A.

For the purpose of this proposal this section describes the neutron flux distributions and contours for one deuteron beam geometry only, impinging on the 1.5-cm-thick flowing lithium target. This geometry was chosen as one possible operating mode which would satisfy the desires of experimenters in stacking a number of samples in a row exposed in a very-high-flux region. Other modes of operation and/or deuteron beam geometries are possible (see Section 3.4).

In the calculations given in Appendix A, the deuteron beam from the linac travels in the z direction (horizontal) and impinges normally on the front surface of the liquid lithium film at the $z=-R_d$ plane. Lithium is flowing in the y direction (downwards). The source volume is a rectangular prism. The dimension in the x direction (horizontal) is the width B and in the y direction the height A . The thickness of the source (in the z direction) is the mean range R_d of deuterons. Thus deuterons are stopped at the $z=0$ plane. The origin of the Cartesian x, y, z coordinates is the midpoint of this exit surface. The flux values were computed for an observation point grid $P(\vec{r})=P(x, y, z)$ with positive values of x, y and z . Because the flux distribution is symmetric with respect to the z axis, this gives a complete description for the half space $z \geq 0$. For an arbitrary source point we use a symbol $Q(\vec{r}_1)$ or $x=x_1, y=y_1$ and $z=z_1$. The value of z_1 is always ≤ 0 . The computer code includes the effect of the finite area and thickness of the source, the variation of the neutron yield from a thin layer Δz_1 as a function of the penetration depth of the deuterons ($R_d - |z_1|$), the angle θ , and the coordinate y_1 . The dependence upon y_1 takes into account

the vertical intensity profile of the deuteron beam (see Fig. A-3). The calculations are based on the measured values of the forward yield $Y(0^\circ)$ (Fig. A-4) and the angular intensity distribution $F(\theta)$ (Fig. A-5) for $\text{Li}(d,n)$ reactions. The angular-distribution values are in good agreement with the data of other measurements. However, additional information is needed especially for angles $\theta > 30^\circ$. The measured forward yield $Y(0^\circ)$ values are, in contrast, lower than the published data⁽⁵⁾ for $E_d=5-19$ MeV and for $E_d=40$ MeV.⁽⁶⁾ The difference is very close to a factor of 2. The same trend can be found by comparing with the additional published data.⁽⁷⁻¹⁰⁾ Should the yield values we use here turn out to be too low, the computed flux values may be multiplied by the corresponding scale factor.

The neutron energy spectra measured for thick targets are, strictly speaking, valid only for large distances $z \gg B/2$. For smaller z values the energy spectra shift to lower energies because the effective angle θ is increasing and the effective deuteron energy is decreased. Because of the lack of measured energy spectra as a function of E_d , for angles larger than 20° , this complex effect was not included in the computer code.

The calculated neutron flux contours given in this section pertain only to the specific source parameters mentioned earlier: a 100-mA, 30-MeV deuteron beam, 10 cm wide, 1 cm high, impinging on a 1.5-cm-thick lithium target. The vertical beam intensity profile is approximately Gaussian and uniform horizontally. This $\text{Li}(d,n)$ source is referred to in the figures as source "H".

Figure III-4 shows the neutron flux ϕ for various source geometries as a function of the distance z from the source exit surface. The first curve is for a point source. It gives the theoretical upper limit for the neutron flux from a $\text{Li}(d,n)$ source with a 100-mA, 30-MeV beam. The next curve for a square source 1 cm^2 approximates a focused $\sim 1\text{-cm-diam.}$ deuteron beam. This beam power density could be approached if the velocity of the lithium flow were to increase to 20-50 m/sec and/or the high latent heat of vaporization (App. B) were used for heat dissipation.

For the "H" source the calculated flux values are about $2.3 \times 10^{15} \text{ n cm}^{-2} \text{ sec}^{-1}$ for $z=0$, 1.6×10^{15} at $z=0.1 \text{ cm}$ and 5.8×10^{14} at $z=1 \text{ cm}$ ($x=y=0$). For the square $1 \times 1 \text{ cm}$ source the corresponding values are 1.9×10^{16} , 1.3×10^{16} and $3.2 \times 10^{15} \text{ n cm}^{-2} \text{ sec}^{-1}$.

FIG. III-4

The next curve is for a square source 10 x 10 cm with a constant intensity profile ($I \neq I(y)$). This source geometry gives flatter flux contours especially in the vertical plane, but the flux values are much lower than for the "H" source.

Figure III-5a shows some equiflux contours in the $y=0$ plane for the "H" source. The broad, relatively flat contours for the 6×10^{14} and the 2×10^{14} $\text{n/cm}^2 \text{ sec}$ curves are of special interest and are discussed in Section 3.4 where multiple samples needing identical fluxes are treated. Even at a flux level of 5×10^{13} $\text{n/cm}^2 \text{ sec}$ the contour near the axis is still flat enough to provide equal flux for two or three adjacent samples.

Figure III-5b shows the y - z plane counterpart ($x=0$) of Fig. III-5a. The rapid falloff in the high-flux region reflects the particular deuteron beam geometry chosen for the calculation. At 20 cm the contour (2×10^{13} $\text{n/cm}^2 \text{ sec}$) is approaching in shape its counterpart in the $y=0$ plot.

The calculated available volume within the 1×10^{14} $\text{n cm}^{-2} \text{ sec}^{-1}$ boundary is about 100 cm^3 .

Figure III-6 shows the relative flux values with respect to z if the B dimension of source "H" were to be reduced; all other parameters remaining constant. On the z axis the dependence on B is strong for $z < 1 \text{ cm}$ and decreases rapidly as z increases.

It is to be noted from the figures in this section that substantially higher fluxes can be achieved by reducing the source area and conducting the experiments close to the target exit surface.

3.4. Flexibility

The flux contours, shown in Figs. III-5a and b, result from a deuteron beam of 100 mA at 30 MeV having a height of 1 cm and a width of 10 cm. This particular beam shape was selected for the following reasons: (a) the highest-intensity values close to the target are obtained using a horizontal linear current density of 10 mA/cm, and (b) the flux contours are relatively broad and slowly varying in the horizontal (x) dimension near the source. The price paid for a small (1 cm) vertical beam size is the sharp-peaked flux contour in the vertical direction in the high flux region. An experiment utilizing such a contour could consist of several samples (say 5-10) stacked side by side along the horizontal contour line. Their midpoint gauge lengths would be

FIG. III-5a

FIG. III-5b

FIG. III-6

located at the highest flux point, the gauge length being short enough to avoid the strong flux gradients in the vertical direction. Should this vertical gradient in the flux be deemed too severe, the vertical dimension of the deuteron beam can be increased to the point where the gradient in the flux would be acceptable.

The optimum size of the vertical dimension of the deuteron beam will be determined after meetings and discussion with the prospective users of the facility. What is to be remembered here is that the flux-contour tailoring will affect significantly only the highest-flux region. Figs. III-4 and III-6 show that after reaching a distance of ~ 20 cm from the source, altering the dimensions of the beam has very little effect on the contours. The source can be approximated by a point source beyond this distance, with only the total deuteron beam current and energy determining the flux.

The maximum energy of the incident deuterons is fixed at 30 MeV. However, as discussed in chapter II, the energy may be reduced to a value for which the neutron flux spectrum gives a better simulation of a desired parameter, say $\sigma_{n,\alpha}$. However matching one parameter might mean a poorer simulation of some other related parameter such as dpa. By studying Table II-1 a feeling can be obtained for such tradeoffs.

The design current for the D^+ deuteron beam is 100 mA producing a 10-mA/cm linear density across the 10-cm-wide target. The implications of higher beam current densities are treated in Section V and related Appendices. There are two ways of increasing the current density. The first is to raise the total deuteron current. Inherent in the design of the linac system is the capability of increasing the beam current to 200 mA. Implementation of this option will depend upon the experience gained in operating the target at linear current densities higher than 10 mA/cm. This experimentation on the target is easily accomplished by the second means of increasing the current density; namely, by decreasing the horizontal dimension to 5 cm. Fewer samples could be arranged side by side along the equiflux contour produced by this geometry. The advantage would be a larger volume of flux $>10^{15}$ n cm⁻² sec⁻¹. Operational experience and consultation with users will guide the decision to implement these possibilities of increasing flux levels and/or yields.

The primary beam on target will be circular, ~ 1 cm in diameter, and roughly Gaussian in beam density profile. There are two ways of producing the desired 1×10 cm source area on the lithium target: the beam can be defocused in the horizontal dimension, or it can be swept electrostatically over the horizontal dimension. If the beam is swept through 10 cm at megahertz frequencies, there will be a time structure on the highest-flux regions. The flux will oscillate with tenths of microseconds periods. At distances > 20 cm, the flux will be essentially time independent. Whether or not this time fluctuation in the highest-flux regions causes effects not realized for a pure dc source is being seriously investigated. If the time dependence is to be important for a given measurement, then the defect(s) contributing to the parameter changes must have effective lifetimes which are long compared with the period of the sweep. If this criterion is not satisfied by the defects, then the implementation of the defocusing scheme to produce a dc deuteron beam at the lithium target would be indicated. In this case, the beam, through the last bending magnet, would be the same as for the ac-scanned case, but instead of being scanned horizontally across the lithium target, the beam would be defocussed horizontally to a width of 10 cm. The beam would now be dc on the target giving a dc neutron flux. In that case the neutron flux contour will be different from that of Figs. III-5a and b since the horizontal deuteron profile is no longer uniform, but rather a broad, flat-topped Gaussian. This produces somewhat higher flux values on the axis and makes the horizontal equiflux contours narrower. It also changes the target heat-deposition profile. The horizontal deuteron beam profile can be made uniform if desired by using non-linear elements in the multipole system that provides the horizontal defocusing.

For those fusion reactor designs where the burn is repetitive, a pulsed neutron beam of the same period and time duration as the reactor would better simulate the radiation environment. Studies involving transient effects would then be possible. With the accelerator-based neutron generator, this pulsing mode can be achieved in two ways. The first is to pulse the ion source of deuterons and the second is through the pulsing either of the linac itself, or possibly through the deactivation of one of the bending magnets. Although it is possible to pulse the high-current D^+ beam, that beam would seem best

left alone for high-fluence testing, and the pulsed-mode operation be relegated to the lower-yield D^- beam. By varying the D^- source, the desired pulse length and repetition rate would be supplied to the D^- target without disturbing the operation of the D^+ beam.

The uses of this D^- beam are numerous, over and above its possible pulsed-mode applicability (see chapter II). Although designed for 10 mA, one tenth that of the D^+ beam, if the D^- beam were focussed on a 1 cm^2 area, the near-target neutron flux would be nearly that from the D^+ target. Test runs with samples scheduled for the D^+ beam could be carried out using this D^- source. In particular, short-term, high-flux exposures for such specialized uses as electron microscopy, low-temperature irradiation of superconductors, first-wall studies, etc. could be carried out. The availability of this second beam, over which the experimenter has control of the time structure (swept or continuous dc), and the availability of the pulsing mode, all make the D^- beam a useful adjunct to the primary D^+ beam.

3.5. High-Energy Beam-Transport System

The high-energy beam-transport system is being considered here because it is the system whose mode of operation is used to affect the neutron source characteristics. It has several functions:

- a) It directs the particles to the individual target station.
- b) It is used to control the location of the beam spot on the target, possibly as a function of time.
- c) It is used to control the beam spot size on the target.
- d) It provides the drift length necessary to control the time structure of the beam current on the target.
- e) It prevents lithium vapor, evaporated from the target, from reaching the linac.

Inside the linac the beam consists of a train of bunches of charged particles. At its exit each bunch is about 2 cm long, has an average diameter of about 2.8 cm and travels along the system axis with a velocity of 53×10^6 m/sec (at 30 MeV). The distance between consecutive bunch centers of equal polarity is 1.0 m. The beam current at the linac exit is deeply modulated at the linac's radio frequency and its harmonics, forming pulses 4 nsec wide, 200 nsec apart. The spread in particle velocities that is associated with the

deviations of their energies from the mean causes the bunches to elongate while they travel towards the target area. By increasing the energy spread and/or the drift distance one may increase the bunch length relative to the fixed distance between bunch centers and reduce the modulation of the beam intensity as perceived by the target to close to zero, leaving a practically constant intensity. The maximum energy spread possible is limited by the linac; therefore achievement of a dc beam requires a certain drift distance between linac and target. The proposed system requires an easily achievable energy spread of 1 MeV (full width-half maximum) if a dc beam is to be produced on targets 60m downstream of the linac. The energy spread is desirable in itself because it also spreads the energy deposition range in the target.

A bending magnet is used to separate the beam's positively and negatively charged components and to direct each towards a target station. This makes it necessary to dispose the targets symmetrically with respect to the system axis. This arrangement prevents target vapor from reaching the sensitive structures in the linac. Atoms or ions of target material cannot follow the bend imposed on the trajectories of the accelerated ions. Instead they will hit the vacuum chamber wall before or in the vicinity of the bending magnet and condense there to a fluid or a solid depending on the local temperature of the wall.

The bending magnet introduces an angular dispersion, proportional to the tangent of the nominal bending angle and to the momentum error. Since energy spread is unavoidable and even desirable, this dispersion must be accepted. A sequence of six quadrupoles between the bending magnet and each target station is used to cancel the increase in cross sectional widths of the beam that might result from the dispersion.

Fig. III-7 shows the beam "switchyard" and its magnets. The four stations are arranged in two pairs, symmetric with respect to the system's (linac) axis, the pairs are separated by a 2m-wide tunnel leading to a beam dump. The beam reaches this dump if the bending magnet is left unexcited. This mode may be used when the linac is operated for diagnosis and adjustment. It also allows for future expansion without interference with the existing target area.

FIG. III-7

In order to have independent control of the beam spot location on each target small steering devices, acting horizontally and vertically, are provided in the vicinity of the centers of the quadrupole systems. Since the angles of bending required for moving the spot inside a $10 \times 10 \text{ cm}^2$ square are quite small, the increase in spot size due to the associated dispersion is negligible. The rate with which the spots may be moved is limited by the steering devices installed. They may consist of a combination of magnets, deflecting plates and travelling wave structures depending on requirements.

The instantaneous dimensions of the beam spot on a target are controlled by means of the six quadrupoles between it and the bending magnet. By properly correlating the quadrupole excitations among each other, any combination of spot width and height may be obtained, regardless of the dispersion introduced by the bending magnet and only limited by the available aperture. In this manner the spot characteristics can be controlled independently for the positive and for the negative beams.

The detailed instantaneous distribution inside the spot and the directly correlated flux density distribution in the neutron beam cannot be controlled in this way. It is expected to be bell-shaped. The time-average distribution can be shaped arbitrarily by "painting" the target with a beam spot of small size. For example, if the spot is swept across at constant speed, the time average distribution becomes rectangular with rounded edges. This approach introduces a time dependence in the neutron flux pattern that may be objectionable for some experiments. It should be unimportant if the basic period is short compared with the relaxation times occurring in the experiment being performed. Thus, the shortest relaxation time likely to be encountered sets the maximum sweep period and the minimum band width for the beam steering equipment.

Upstream of the bending magnet the beam is contained transversely by a quadrupole sequence that may be regarded as a continuation of the transverse focussing system of the linac. The sequence is extended beyond the bending magnet towards the beam dump. It is adjusted once to produce a beam of standardized characteristics at the input to the bending magnet.

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IV. THE 30-MEV LINAC

4.1. Introduction

This section of the proposal deals in detail with the design of the accelerator itself and its associated equipment.

Amongst the many types of accelerators developed for nuclear physics and high-energy physics, the linear accelerator, with a so-called drift-tube accelerating structure, is the best type potentially capable of delivering high intensity, high-duty-factor beams, hence its choice for this application (see Section 1.2).

Additional considerations reinforcing this choice for this application are the ease and good controllability of the beam injection and extraction from the machine, minimizing the radiation problems around the accelerator.

The theory of linear accelerators is well understood.^(1,2,3) A number of linacs for protons and heavy ions are operating successfully with peak currents >100 mA and duty cycles of up to 30%. A 3-MeV research proton linac has been built at Chalk River (Canada) combining a 100-mA beam current and cw (100% duty factor) operation. Although no deuteron linacs are presently in operation, the technology of proton linacs is directly applicable to the acceleration of deuterons. Therefore the design described in the following pages strongly reflects the experience gained to date with proton linacs in general, and particularly the experience of the Brookhaven National Laboratory linac team, which, with its long history in machine building, has accumulated more than 200 man-years of linac experience.

The proposed design whose main characteristics are shown in Table IV-1 has not yet been optimized. It constitutes, however, a conservative approach to a working design based on experience, extrapolation and scaling of existing operating facilities.

The immediate design goal for this accelerator is an average beam current of 100 mA. However, the design calculations are based on a 200 mA beam which will allow the upgrading of the beam current at a future date.

4.2. Linac Design Parameters

The injection system will consist of two 500-kV, 0.5-A, direct current generators to permit simultaneous acceleration of D^+ and D^- ions. The positive ion source will be of the duoplasmatron type presently used as a

TABLE IV-1
Principal Characteristics of the Deuteron Linac

Beam Characteristics

- 1) Maximum energy 30 MeV
- 2) Average acceleration rate 0.75 MeV/m
- 3) Energy variable above 10 MeV in steps of about 5 MeV (10, 15, 20, 25, 30 MeV)
- 4) Beam microstructure, 4-nsec pulses separated by 200 nsec at 50 MHz.
- 5) Time structure at the target, beam debunched at target essentially dc with maximum 5%, 50-MHz flux modulation
- 6) Average current 100 mA (6.2×10^{17} deuterons/sec) (D^+ beam)
- 7) Beam duty cycle 100% (cw operation)
- 8) Average beam power 3 megawatts (D^+ beam)
- 9) Beam pulsing possible

Accelerator Physical Characteristics

- 1) Total length of accelerator 40 m made up of 8 cavities, each about-5 m long and 3.8 m diameter
 - 2) Injectors 2 x 500-kV, 0.5A power supplies
 - 3) Total rf power $\sim$ 4.5 megawatts for 100 mA
 - 4) Strong focusing utilizing electromagnetic quadrupoles
-

proton ion source in the Brookhaven 200-MeV linear accelerator injector for the AGS. This source has operated at proton currents up to 0.5 A at a duty factor of 0.5%, but has not been tested in a continuous mode of operation. The injection system layout is shown in Fig. IV-1. The-high voltage equipment will consist of a high voltage transformer-rectifier system for each injector and a single-gap accelerating column with titanium electrodes to minimize microdischarges. Each accelerating column will have a re-entrant section housing a quadrupole triplet followed by beam diagnostic equipment to measure the beam quantity and quality. Also at this location, a dc chopper will deflect the

PREINJECTOR AND
LOW ENERGY BEAM TRANSPORT

FIG. IV-1

beam away from the accelerator in the event of a malfunction and will divert the beam during the switching time of a high-energy chopper used for pulsed beam operation. This will be followed by a second quadrupole triplet to focus the beam at the entrance to the electromagnetic buncher.⁽⁴⁾ This device utilizes a double-gap coaxial transmission line resonator operating at 50 MHz through which the beam passes twice, once as it enters a 270° bending magnet and once as it exits from the magnet. Slits placed at the maximum dispersion point within the magnet will intercept those particles which are outside the linac energy-acceptance region and would not be accelerated to the final energy. If not intercepted in this low-energy area, these particles would gain some energy in a nonsynchronous manner and eventually strike the walls of the drift tubes giving rise to unwanted gamma and neutron radiation. If necessary a second energy-modulating cavity⁽⁵⁾ can be added to facilitate longitudinal matching of the beam to the linac acceptance. Four to six separately-energized quadrupole magnets will be used to match the injected beam to the radial acceptance of the linac and a viewing box immediately upstream of the first accelerating cavity will house emittance and beam current measuring equipment.

In a drift-tube accelerator the optimal design of the machine in terms of power economy and initial capital cost depends upon the following physical requirements:

- 1) The drift-tube aperture must be large enough to allow lossless beam transmission but small enough in relation to the drift-tube gap to avoid serious fringing field effects. These give rise to a poor transit time factor and hence would require more radio-frequency power for acceleration. A very large aperture would also increase the cost of the focusing quadrupoles housed inside the drift-tubes.

- 2) The gap size must be large enough to allow spark-free operation at the chosen acceleration rate.

- 3) The choice of larger dimensions for the accelerating structure increases the cost of the structure itself and of the vacuum pumping system but minimizes the power density on the copper walls and eases the cooling system requirements.

The choice of 50 MHz as an operating frequency takes account of these factors and also of available radiofrequency power sources. More detailed cost optimizations may cause a small change in design frequency. Table IV-2 summarizes the chosen design parameters.

TABLE IV-2

Basic Linac Parameters

Cavity	1	2	3	4	5	6	7	8
Input Energy (MeV)	0.500	3.967	7.772	11.352	15.048	18.636	22.614	26.226
Input $\beta\gamma$	0.023	0.063	0.089	0.108	0.125	0.139	0.153	0.165
Output Energy (MeV)	3.967	7.772	11.352	15.048	18.636	22.614	26.226	30.109
Output $\beta\gamma$	0.063	0.089	0.108	0.125	0.139	0.153	0.165	0.177
Cavity Dia. (m)	3.78	3.78	3.78	3.78	3.78	3.78	3.78	3.78
Cavity Length (m)	4.662	5.075	4.773	4.928	4.784	5.303	4.816	5.178
Input Cell Length (m)	0.139	0.390	0.547	0.661	0.761	0.848	0.934	1.007
Output Cell Length (m)	0.376	0.532	0.647	0.747	0.833	0.920	0.992	1.067
Input Gap/Length Ratio ($\frac{g}{L}$)	0.200	0.236	0.259	0.275	0.290	0.304	0.319	0.334
Output Gap/Length Ratio ($\frac{g}{L}$)	0.234	0.257	0.273	0.288	0.301	0.316	0.330	0.350
Input Drift Tube Length (m)	0.111	0.298	0.405	0.479	0.540	0.590	0.636	0.671
Output Drift Tube Length (m)	0.288	0.395	0.470	0.532	0.582	0.629	0.665	0.694
Drift Tube Diameter (m)	0.720	0.720	0.720	0.720	0.720	0.720	0.720	0.720
Drift Tube Aperture (m)	0.040	0.060	0.060	0.080	0.080	0.080	0.080	0.080
Drift Tube Inner Corner Radius (m)	0.040	0.040	0.040	0.040	0.040	0.040	0.040	0.040
Drift Tube Outer Corner Radius (m)	0.080	0.080	0.080	0.080	0.080	0.080	0.080	0.080
Drift Tube Stem Dia. (m)	0.050	0.080	0.080	0.080	0.080	0.080	0.080	0.080
Quad. Aperture (m)	0.050	0.070	0.070	0.090	0.090	0.090	0.090	0.090
Quad. Length (m)	0.100	0.200	0.200	0.400	0.400	0.400	0.400	0.400
Quad. Field Strength (kG/cm)	~ 1.00	~ 0.50	~ 0.25	~ 0.25	~ 0.25	~ 0.25	~ 0.25	~ 0.25

The design considerations for acceleration of a 100 mA deuteron beam in a cw configuration require a conservative choice of parameters, since the beam will be largely space-charge limited, and any significant beam loss along the accelerator will cause difficult activation problems. Specifically, this means strong transverse focusing (reasonably high quadrupole strength in a + - + - configuration), strong longitudinal focusing (reasonably high accelerating gradient), and a conservatively large drift-tube bore.

The design parameters related to the beam dynamics are as follows:

Injection energy	0.5 MeV
Injection $\beta = v/c$	0.023
Accelerated current (I)	0.1 A
Injected transverse emittance (ϵ)	$3\pi \times 10^{-4}$ mrad
Radio frequency (f)	50 MHz ($\lambda = \frac{c}{P} = 6$ m)
Acceleration rate	0.75 MeV/m
Synchronous phase (ϕ_s)	-30°
Initial drift-tube bore diameter	4 cm

a) Transverse Focusing

A + - + - quadrupole configuration with a phase advance per magnet period, μ_{SF} , of $\pi/2$ was chosen in order to operate in the center of the widest possible stability diagram. If the quadrupole magnets in the beginning of tank 1 occupy about 2/3 of the cell length, one finds that magnetic gradients must be approximately 1.2 kG/cm, leading to a pole tip field of as low as 2.4 kG. It can easily be shown that under these conditions, taking into account the rf transverse defocusing and the longitudinal phase excursions, the operating region stays well within the transverse stability limits given by $\cos \mu_{SF} = \pm 1$.

For a constant phase advance per magnet period, the quadrupole gradient will vary as β^{-1} down the machine assuming a fixed ratio of magnet to cell length.

b) Matched beam sizes and space-charge parameters

It is important to match the beam transversely as well as longitudinally to ensure minimum beam loss and transverse emittance growth.^(6,7) In a high-current linac repulsive space-charge forces become comparable to transverse quadrupole focusing forces, and longitudinal rf defocusing forces

and space-charge effects have to be included in the calculation of matched beam sizes. Assuming that the beam bunch is a uniformly charged ellipsoid, space-charge forces are linear and can easily be incorporated in the beam envelope equations from which the matched beam sizes are derived.

With $\bar{a}$ being the average beam radius ($\bar{a} = \sqrt{a_x a_y}$, and a_x and a_y are the half-widths of the beam in the x and y directions) and $\bar{c}$ the half length of the bunch, one can calculate $\bar{a}$ from the equation (nonrelativistic approximation):

$$(k_t \beta \lambda)^2 \bar{a} = \frac{(\beta \lambda \epsilon)^2}{\bar{a}^3} + \frac{45 \Omega g I \lambda^3 \left(1 - \frac{\bar{a}}{3\bar{c}}\right)}{M_0 \bar{a} \bar{c}} \quad (1)$$

Here k_t is the wave number of the transverse oscillation in the zero space charge approximation, given by $\mu_{SF}/2\beta\lambda$ and M_0 is the deuteron rest mass in energy units. All other symbols were defined in the beginning of this section. Assuming that the half length of the beam bunch, $\bar{c}$, corresponds in phase spread to ϕ_s one finds $\bar{a} = 0.93$ cm. The flutter factor, which is space-charge independent, ⁽⁸⁾ takes the maximum transverse oscillation amplitude to about 1.4 cm.

One can now calculate the transverse and longitudinal space-charge parameters μ_t^{sp} and μ_l^{sp} equal to the ratios of the space-charge defocusing force to the external focusing force. They are given by:

$$\mu_t^{sp} = \frac{45 \Omega e I \lambda^3 \left(1 - \frac{\bar{a}}{3\bar{c}}\right)}{2 \frac{2}{(k_t \beta \lambda) M_0 \bar{a} \bar{c}}} \quad (2a)$$

$$\mu_l^{sp} = \frac{30 \Omega e I \lambda^3}{2 \frac{2}{(k_l \beta \lambda) M_0 \bar{a} \bar{c}}} \quad (2b)$$

where

$$k_l = \frac{2\pi e E T \sin |\phi_s|}{M_0 \lambda \beta^3} \quad (3)$$

is the longitudinal wave number in the zero-space-charge approximation. Equations 2a and 2b give $\mu_t^{sp} = 0.60$ and $\mu_l^{sp} = 0.70$ demonstrating the importance of space-charge forces in the proposed linac. Under these conditions experience gained from operating machines⁽⁹⁾ as well as from computer simulations^(6,10) indicates that some transverse emittance growth is to be expected in the low-energy part of the linac. The drift-tube bore having a 4 cm aperture at injection will probably have to be enlarged continuously through tank 1 to allow for transverse beam growth. Because of the gradually increasing values of β this can be done without appreciably lowering the transit time factor T which is proportional to $[I_0(2\pi R/\beta\lambda)]^{-1}$. Further computer studies are required to determine the necessity for such a design feature.

As can be seen from Eqs. 2a and 2b, a constant value of μ_{SF} down the machine is ideally consistent with a constant transverse beam size except for a weak energy dependence of $\bar{c}$ (the half length of the beam bunch).

c) Energy Spread

To match the beam longitudinally it is required that the deuteron beam enters the linac with an energy spread given by

$$\Delta E = \pm M_0 \beta^2 c k_l \left(1 - \mu_l^{sp} \right) \quad (4)$$

which with the present design parameters yields ± 27 keV. This can be achieved with the bunching scheme described earlier. With the adiabatic $\beta^{3/4}$ growth in energy spread found to hold under space-charge conditions,⁽⁶⁾ a perfectly matched beam would have an energy spread of ± 125 keV at 30 MeV.

A more pessimistic estimate for the output energy spread can be obtained if one assumes that an imperfectly matched beam will fill the bucket area that is calculated without space charge at injection. The energy spread of this bucket is

$$\Delta E = \pm M_0 \left[\frac{2\lambda\beta^3 eET(\phi_s \cos \phi_s - \sin \phi_s)}{\pi M_0} \right]^{1/2} \quad (5)$$

and is ± 60 keV in this case. Again, assuming a $\beta^{3/4}$ -type growth one finds $\Delta E = \pm 275$ keV at 30 MeV.

4.3. The rf System

Based on the linac parameters given in Section 4.2, the requirements are for a radio frequency system which will produce 4.5 megawatts cw at about 50 MHz. Table IV-3 lists the radio frequency parameters as calculated from the linac design parameters. The important considerations in the design of such a system are: a) minimum operating costs, b) minimum construction cost, and c) high reliability.

To minimize the operating cost, it is necessary to obtain the maximum anode efficiency of the power amplifier stages which are by far the most critical items in this respect, and the most costly as well. In general, high power vacuum tubes for cw duty, class C operation, will have an expected lifetime of 10,000 hrs, although this figure can be changed significantly by the operating conditions. To minimize the downtime due to failures, it is desirable to minimize the number of high power tubes in the system, which also, reduces the amount of auxiliary equipment. Conversely, somewhat greater reliability can be achieved by having a great number of parallel stages, thus having the capability of reduced power operation in the case of a tube failure.

High power vacuum tubes are available for service up to 2 MW cw at frequencies up to 30 MHz. Some of these tubes and their variations run at reduced power levels at frequencies of 50-110 MHz, typically 600 kW cw and 1.5 MW for long pulse operation. It is proposed that, as far as possible, these types of tubes and associated circuitry be used.

An important consideration in the application of rf systems for accelerators, is the type of matching condition seen by the power-amplifier tube when the accelerator tank is no longer loaded with the beam. The low-level control system will sense the change and will reduce the rf drive power to the power amplifier, but even so a spike of high reverse power will travel back to the tube and cause a high dissipation condition in the anode circuit. Both the transmission lines and associated tube components have to be able to withstand these conditions as part of the normal service.

Experience has shown that, with high-power amplifiers, it is desirable to operate at less than rated power; thus, a tube with 800 kW power output rating will operate reliably at 600 kW.

TABLE IV-3

Radio Frequency Parameters

Cavity #	1	2	3	4	5	6	7	8
Stored Energy (Joules)	90	92	81	92	90	100	91	102
Average Shunt Impedance ($M\Omega/m$)	32	36	36	36	37	37	37	37
Total Cavity Pwr (kW)	207	182	158	169	161	178	162	177
Total Beam Pwr for 100 mA (kW)	347	380	358	370	359	398	361	388
Unloaded Q Value	137,280	158,900	162,650	171,270	174,400	176,900	176,910	181,060
Input Transit-Time Factor	0.70	0.80	0.85	0.81	0.81	0.81	0.80	0.80
Output Transit- Time Factor	0.83	0.84	0.86	0.81	0.81	0.81	0.80	0.79
Stable Phase Angle	-30°	-30°	-30°	-30°	-30°	-30°	-30°	-30°

Fig. IV-2 shows the basic block diagram of a typical rf system. Eight such systems, delivering about 600 kW each, will power the eight linac cavities via coaxial transmission lines and magnetic loop couplers.

The mechanical construction of the major rf system components will include quick disconnect features and lifting devices at well-defined interfaces for easy removal and replacement of modules. High-voltage circuitry will be physically separated from low-voltage wiring and components for reasons of safety; proper interlocks and high-voltage grounding systems will be provided. The large oil-filled power supplies will be installed outdoors in standard subyard enclosures to NEMA standards with approved switchgear and line surge protection.

"Turn on" and "run up" sequences will be preprogrammed locally using solid-state logic components in rf-tight enclosures with interfacing to the control system computer. The radiofrequency source will be a crystal-controlled oscillator. A tuned amplifier will distribute the rf signal at a power level of 1 kW via a properly terminated 50-ohm rigid coaxial line. The phase stability of the distribution system is important as it is used as a reference for setting the linac cavities' phases.

Directional couplers will supply the rf power at a few watts to the low level rf control system in each module, where varactor diodes and pin diodes will be used for rf amplitude and phase control. Signals for use in the tank temperature control system will originate from that same point.

From this point on, the accelerator cavities and the rf systems are combined into three closed control loops. Externally applied reference voltages provide set points for cavity rf amplitude (gradient), cavity phase and frequency. Signals from the cavities and rf systems will be available for computer monitoring and control purposes.

A buffer amplifier will provide an rf input at a nominal 1 kW level to the driver power amplifier consisting of two stages of amplification. This unit will be similar to commercially available TV transmitters, and will contain power supplies with control and protective circuitry. The driver amplifier will provide the 20-40 kW of required drive power to the final power amplifier stage.

FIG. IV-2

The plate power supplies will consist of conventional 3-phase transformer-rectifiers with filter networks. They will be oil insulated with S.C.R. controls in the primary circuit, allowing rapid shut down in case fault conditions arise in the system. Depending upon stored-energy considerations and the tube manufacturers' recommendation, it may be necessary to incorporate a crowbar energy-diverting system or systems. The power-amplifier outputs will be conveyed to the accelerator tank via 12" diameter 50-ohm coaxial transmission lines. Adjustable phase shifters will be required to optimize the type of mismatch that is presented to the amplifier output under transient beam loading conditions. The coupling into the accelerating cavities will be adjustable by varying the penetration of the coupling loops. Directional couplers will provide signals to the control circuitry for detecting changes of line conditions.

Signals proportional to the cavity gradients derived from pick-up probes in the cavities will be compared with reference voltages from the control system. The difference signals will be amplified and used to control the input level of the rf power into each module. Similarly phase detectors will sense the cavity phases with respect to the reference transmission line and will supply a correction signal to a varactor diode which will maintain the phases at set values.

Signals from the feed loop directional couplers will sense the reactive nature of the accelerator cavities when a departure from resonance occurs, this will act on the water temperature control systems to maintain the cavities' resonant frequency at a set value.

4.4. Mechanical Design and Services

A number of linear accelerators have been built in recent years introducing the latest concepts in advanced mechanical technology such as electron-beam welding, ceramic electrical insulation, metallic vacuum seals, etc. Although these machines are different from the one proposed here, their design concepts are directly applicable.

The major difference in parameters for this new linac, besides its physical size (operating frequency) is its 100% duty factor. This mode of operation puts severe constraints on beam losses which would result in radiation damage of machine components. In addition, heat dissipation and temperature control become of major concern in the design. High-duty-factor linacs

have been built (e.g. LAMPF at LASL, 12% duty factor, and the rebuilt Hilac at LBL, 30% duty factor). These two facilities provide a good basis for the solution to these problems. The mechanical design of the accelerating structure will therefore utilize well developed and well proven technologies.

The rf resonant cavities and vacuum envelope will be combined to form a single tank fabricated with copperclad steel sheets rolled and welded to the proper dimensions. The separation between rf cavities will be accomplished with copper bulkheads mounted inside the tank at the appropriate intervals. These bulkheads will be water cooled and support all intercavity instrumentation. Access ports will be provided in each cavity for rf power, vacuum, drift tubes, etc. and also to provide personnel access into each cavity.

The overall tank design will include the necessary stiffening structure to support the external atmospheric pressure and limit any deflection to acceptable levels. The entire structure will rest on four adjustable pads to provide the necessary flexibility required for aligning the system.

The heat dissipated in the tank walls will be carried away by the water cooling system. A water jacket designed to maximize the surface area in contact with the fluid will be welded to the tanks external surface. The cavities' resonant frequency is directly related to the dimensional stability of the system and it is therefore mandatory that the thermal stability be maintained to within a fraction of one degree. This is accomplished by the careful design of the water circuits to avoid large temperature gradients and by the proper choice of a control servo-system to maintain the temperature constant during operation.

The 8 combined rf cavities will contain a total of 66 copper drift-tubes. Each drift-tube, itself containing a quadrupole electromagnet, will be supported from the top of the tank by a support stem carrying the dc power and cooling water for the drift tube shell and quadrupole magnet. In a departure from existing linac designs, it is planned to eliminate the drift-tube bore-tube and to transfer the vacuum seal to the support stem. It is also planned to encapsulate the magnet windings in ceramic in order to achieve a radiation-

proof system which should prove almost 100% reliable. This design approach is mandated by the high current cw operation of the linac where an accidental beam-spill on bore-tubes would almost surely mean the loss of vacuum and severe damage to the magnet's electrical insulation. Fig. IV-3 shows a typical proton linac cavity with assembled drift tubes indicative of the proposed design.

The dc quadrupole magnets will utilize hollow conductors for direct cooling and shunts will be used to achieve the required current distribution allowing the utilization of economically large and well-regulated power supplies.

The accelerator is expected to operate at a pressure of $\sim 10^{-7}$ Torr. This low pressure parameter is common practice in all operating linacs and can be met with state-of-the-art commercially available equipment. The preliminary design is predicated upon the use of ion pumps. However, cryogenic pumping will be considered for economy reasons. The need to protect against radiation damage dictates that all vacuum seals be inorganic which inherently helps in producing a "clean" vacuum system and in minimizing the capital cost of the pumping system.

The rf excitation power dissipated in the tank walls and drift tubes will be ~ 1.2 megawatts. This power loss is high, it is a direct result of the 100% duty factor. To operate the cooling system efficiently it is planned to maintain the linac operating mean temperature between 110° and 120° F. The cooling system will consist of two closed loop circuits providing separate cooling for the rf cavities on the one hand and the drift tubes and quadrupole magnets on the other hand. The two circuits are the result of different requirements of flow, velocity and pressure drop in the two systems.

The rf system will be cooled by a separate loop circulating about 2000 GPM of low conductivity water. The rf system's losses will be about 3 megawatts.

The cooling system's hardware, consisting of pumps, heat exchangers, and water treatment equipment, will be located in the Mechanical Services Area to be maintained and operated by the central water group of the Laboratory.

4.5. The Control and Monitoring System

A coordinated data control system will allow control of the entire facility from a central operations control room. The various functions covered by the system will include: a) all accelerator equipment processes, surveil-

FIG. IV-3

lance and fault isolation, b) beam behavior monitoring, beam diagnostics, radiation loss monitors, c) monitoring all machine services (e.g., vacuum, cooling systems, power, etc.), d) surveillance and protection of the lithium loop system, and e) targets and experimental caves monitoring.

The control system will be based upon the use of a central computer. However, because of real-time requirements of certain control functions and to make most efficient use of the central computer, the system will have three different control levels.

1) A hardwired system will cover all basic security interlocks and fast beam interrupts. This system will include all functions demanding 100% reliability. The status of the system will be monitored by the central computer at all times. The system will operate directly on the protective devices.

2) A local processor system will control all machine functions which can be preprogrammed (e.g., turn-on processes, fixed-point monitoring, etc.). The local systems will interface with the central control room so that the status of all machine functions will be available for display by the central computer.

3) A main-frame computer with the necessary peripheral equipment located in the central control room will perform all the coordinated control, programmable functions and machine and beam status monitoring for the entire facility.

The proposed implementation of the control system is shown in Fig. IV-4. The central computer, including a large disc type memory, will provide the required display capability and service the operator consoles. At the second level, smaller processors will pass on commands and reference values from the operators while gathering data on a cyclic basis from the controlled elements within their domains. Thus, monitored up-to-date machine status implementation will always be available to the operator. In addition, these computers will provide the logic needed to turn on rf equipment and other power supplies during startup or after a beam-inhibiting malfunction.

The interface between computers and equipment will utilize the CAMAC system. CAMAC crates containing the command and data acquisition modules will be located near the equipment to be controlled. These will provide dc references

CONTROL SYSTEM BLOCK DIAGRAM

FIG. IV-4

to the controlled local feed-back loops of the elements via DAC's, and read-back sampled monitor signals of all parameters of interest. Communications between all computer and accelerator systems will be digitized with the exception of some analog signals which will be transmitted through a multiplexed video system.

The ability to make accurate and repetitive measurements of the beam characteristics is of major importance to the successful operation of the accelerator. Techniques have been developed to measure beam emittances, positions, currents, longitudinal and transverse profiles. These techniques fall into two broad categories of instruments, destructive and nondestructive. In most cases the instrumentation developed intercepts all or part of the beam and the measurements are made practical because of the low average beam power of the accelerators.

In the case of this linac with its 100% duty factor, the measurement techniques are more difficult because of the high average beam power. This beam power produces severe thermal problems on the transducers as well as radiation damage at the higher energies. These problems are particular to emittance and profile devices. However, nondestructive measurement methods exist permitting beam diagnostics without beam interceptions, utilizing residual-gas ionization profile monitor. Beam position and current measurement devices will be designed using the conventional technology of sensitive rf pickups. The 50 MHz fundamental frequency of the acceleration make the instrumentation looking at beam bunches more practical than it is for higher frequency accelerators.

Ionizing radiation monitors will be installed in the drift-tubes in all but the first cavity of the accelerators. These will give the most sensitive measure of beam interception and will be used for both monitoring and fast beam interruption. Similar monitors will be used in the High Energy Beam Transport and Experimental Areas. This system will be monitored and set to prevent undue radioactivity buildup in any area of the facility due to equipment malfunction or operator error.

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V. THE TARGET SYSTEM

5.1. The Flowing Thick Film of Liquid Lithium

The target for the deuteron beam will be a thick film of flowing liquid lithium. A liquid target is necessary because of the 3-MW power dissipation in the target. The deposition of the energy in the target by the beam and the removal of the heat from the lithium are treated in Appendices B, C and D. The film will be 12 cm wide and 1.5 cm thick. The target parameters are listed in Table V-1.

For a power dissipation of 3 MW and a flow rate of 18 l/sec the temperature of the lithium in the catch basin will rise to $\sim 280^{\circ}\text{C}$ for liquid entering the target area at $\sim 200^{\circ}\text{C}$. This flow rate has been selected to avoid temperatures in the lithium which may give rise to corrosion problems in the stainless-steel process equipment. At operating temperatures up to 400°C , stainless steel can be used for piping, valves, pumps, etc. in the loop with very little corrosion. Further, this flow rate also ensures that the maximum temperature at the hottest point in the film, near the end of the range of the 30-MeV deuterons at ~ 1.1 cm, does not exceed the boiling point of the lithium at that point in the film.

The vertical flowing thick film will be confined on three sides, between two vertical side plates and the vacuum window which separates the machine vacuum space from the sample area. Figure V-1 shows the target assembly which will act as a beam stop and heat sink. Samples closest to this window will, of course, receive the highest fluxes. The window will probably be made of stainless steel, but could also be made of some CTR "first-wall candidate material" if such material could meet the corrosion and pressure requirements of the window.

At present it is proposed that the minimum vertical dimension of the deuteron beam be 1 cm. If greater uniformity of the flux density over the highest flux region in the target area is desired, the possibility of increasing the beam vertical dimension to any value up to 10 cm is built into the machine capability. This allows the high-neutron-flux region to be tailored in flux profile to fit the given sample test requirements. These options are treated in Section 3.4.

FIG. V-1

Table V-1

Target Parameters

Beam power	3 MW
Beam width	10 cm
Max. beam area	100 cm ²
Deuteron range	1.12 cm
Film size	1.5 cm x 12 cm
Film flow rate	~ 10 m/sec
Melting point of lithium	180.6°C
Lithium entrance temperature	~ 200°C
Lithium exit temperature (bulk)	~ 280°C
Lithium vapor pressure (200°C)	3x10 ⁻⁹ torr
Lithium vapor pressure (320°C)	2.2x10 ⁻⁶ torr
Lithium flow rate	18 liters/sec
Evaporation rate (T=179°C)	6x10 ⁻¹⁵ g/cm ² sec
Evaporation rate (T=325°C)	6.3x10 ⁻¹¹ g/cm ² sec

If one wishes to use the beam configuration employing the greater vertical dimensions, the dimensional stability of the flowing thick film becomes a consideration. In Appendix D, the hydrodynamical equations of flow are solved and the question of stability of the film treated. For the Reynolds number specified by the design parameters (1.6×10^4) the film is stable. Simulation of the lithium film using water or water-plus-additive and matching the Weber number and/or the Reynolds numbers have been carried out at both BNL and HDL (Harry Diamond Laboratories). Figure 9 of Appendix D demonstrates the stability of a water film with the Weber number of the water flow matched to that of lithium. The conclusion is that the design parameters are easily met and that higher flow rates can be sustained if required.

It should be pointed out that although a 10x1-cm raster is proposed for the deuteron profile in the film, the final configuration will not be established until the flux-profile needs of the users are established. The calculations show that all of the options are feasible including the possibility

of increasing the deuteron beam current to raise the neutron yield. The design parameters as proposed are conservative and it is expected that the actual operation of the target will show that the power density can be increased.

5.2. The Lithium Loop

The targets for the production of high-energy neutrons will be thick films of lithium flowing downward, while being bombarded by high-energy deuterons. Both positive and negative deuterons will be simultaneously accelerated, thus leading to the possibility of operating two targets concurrently. Two additional target areas are provided to allow for the setup of new experiments while the other two targets are in operation.

Figure V-2 shows the schematic flow diagram of the lithium loop which will supply lithium to the targets. The following is a general description of the normal operation of the loop. However, by way of introduction, these points should be made:

a) The lithium loop as a whole is of conventional design, requires no unusual materials or construction methods, and viewed in the perspective of the extensive experience which BNL has had in construction and operation of liquid-metal loops (uranium-bismuth, NaK, sodium and mercury), should be reliable and easy to operate.

b) The loop will be capable of supplying lithium to two targets at a time. The maximum heat release at a D^+ target is 3 megawatts; at a D^- target 0.3 megawatts. To this, one must add parasitic heat inputs from heating the pipelines and vessels, and the power input from the pumps, giving a total necessary heat dissipation capacity of about 3.8 megawatts (or about 13×10^6 Btu/hr).

Referring now to the flow diagram, and starting with the targets, there is a separate 4" gravity drain line from each target to the dump tank. (All lines to targets are separate and independent, to permit blocking off one or more targets for repair, installation of experiments, etc., while other targets are running).

The pressure at the open stream of lithium in the targets and in the dump tank (or pumping drum) is about 10^{-5} Torr.

Lithium flowing at a rate of 18 l/sec (285 GPM) through a 3-megawatt D^+ target will be heated $\sim 80^\circ\text{C}$ (144°F); through a 0.3-megawatt D^- target the heating will be only $\sim 8^\circ\text{C}$. At present, it is expected that the same flow

FIG. V-2. LITHIUM LOOP FLOW DIAGRAM

rate of 285 GPM will be sent through each of the two targets in use. Since the lithium supply temperature to the targets is 400°F, generally then, with two targets operating the average temperature in the dump tank will reach only about 480°F, but if only the D^+ target is operated, the dump-tank temperature will reach 550°F.

Any pumping loop handling a liquid metal with a melting point above ambient temperatures requires certain auxiliaries peculiar to the problems of freezing of the liquid metal. Since lithium melts at 354°F, all lines, valves, vessels, targets, etc. which may contain lithium or be exposed to lithium vapor must be heated to a temperature well above 354°F to about 400°F, before the liquid metal may be introduced in the system. This is accomplished by wrapping the pipe, valve, vessel or other parts with resistance heating wire or strip heaters. The heating circuits are well sectionalized and usually manually controlled. Insulation is then applied over the heating elements. A large number of temperature-monitoring thermocouples are applied to all parts at frequent intervals, and connected to a readout instrument which will recognize temperatures above or below appropriate limits, or failed thermocouples, and sound an alarm.

An exception to the above application of heaters is the finned lithium cooler. It is not practical to apply heaters and insulation here and at the same time expect the device to act as a cooler when heat is to be dissipated. In order to heat the lithium cooler, an auxiliary electrical heater is provided to heat a stream of air from an auxiliary fan, which will be blown through the coil to bring its temperature up to 400°F.

From the pump suction leg on the dump tank, the lithium is pumped to the cooler, which is a bank of externally finned tubing. In the cooler, with the targets operating, the liquid is cooled to 400°F by ambient air flowing over the outside of the fins. The air flow is modulated to provide a constant outlet temperature from the cooler.

The cooled lithium is delivered by way of independent branch lines to whichever one or two of the four targets are in use. A vacuum equalizer line runs from each target to the dump tank.

The flow diagram indicates three 285 GPM linear-induction electromagnetic liquid-metal pumps, developing about 200 ft of lithium (about 43 PSIA)

total dynamic head. Two pumps at 285 GPM each would result in normal flow to two targets; the third pump is a spare.

As an alternate to the electromagnetic pumps, mechanical centrifugal pumps might be employed. In this case, such pumps would very likely have the impellers submerged in the dump tank under several feet of liquid lithium to provide the necessary Net Positive Suction Head (NPSH), to prevent cavitation in the entrance to the pump.

Other auxiliaries needed are a lithium cleanup system (presumably a conventional cold-trapping or hot-trapping unit) to remove lithium-deuteride and lithium-tritide which will be formed; a vacuum system for the dump tank, a small drain tank for draining pumps, and some pump piping, (which are below the lowest part of the loop) and a fill and discard system.

The piping system shown on the flow diagram is based on the assumption that all parts of the loop are self-draining back to the dump tank, except as previously noted, the pumps and certain closely associated piping. If the possible engineering layout of the loop is such as to preclude complete self-draining, certain auxiliary drain lines of small size may be required.

The flow sheet does not undertake to show power supplies and instruments. Obviously power will be required for pumps, fan motors, heaters and other miscellaneous devices. An instrument and control system will be required for normal and abnormal conditions. Under normal conditions, the principal variables which must be controlled and held at steady values are the lithium flow rate (285 GPM or 570 GPM), the lithium outlet temperature from the cooler, 400°F, and the vacuum in the targets and dump tank. The air flow to the cooler must be varied to accomplish temperature control of the lithium. Control will be achieved by means of throttling air dampers, cooler bypass, or a variable-speed fan drive.

Whenever conditions become abnormal in the loop and cannot be corrected by the normal instrumentation, emergency instruments will shut down the pumps and cooling fan and initiate gravity drainage of all parts back to the dump tank, turn on the air heater, and shut down the linac or divert the beam to the special beam dump target.

5.3. Safety Considerations

The loop operates under very mild conditions, the piping is relatively small and can be designed for good flexibility leading to reasonable

stresses. Therefore a catastrophic failure causing a large leak of lithium seems very unlikely; however, small leaks cannot be ruled out. The piping will be traced with liquid metal leak detector wires, which will warn of small leaks and show the approximate location thereof. Unfortunately, it is not possible to operate the entire lithium system with pressures above atmospheric, therefore small leaks in some areas may leak air inward, leading to production of lithium oxide in small quantities inside the piping. This would cause the loss of vacuum and lead to shutdown and drainage. It may be necessary to blanket such subatmospheric areas with argon, which will cause no oxidation, but will, likewise, lead to loss of vacuum.

The hot air leaving the lithium cooler, as well as air purged from the experimental cells, will pass through a water scrubber. The water need not be circulated continuously; circulation will be initiated by alarms from smoke-detector cells located at strategic points throughout the loop complex.

When construction of all parts of the loop is complete and the complex is vacuum tight, heatup of all parts may be started and all parts brought to 400°F. The EM pump cells may be heated by turning on pump power at a low level, and the cooler heated with the auxiliary heater. A recheck of vacuum integrity must then be made and any leaks discovered under temperature and stress investigated and repaired. The system may then be filled with helium at atmospheric pressure.

By means of temporary arrangements, the lithium is melted in the shipping drums, and delivered with temporary piping to the dump tank until the required inventory of about 120 cu ft (1700 kilograms) (about 15 50-gallon drums) is accumulated. The temporary piping is removed and the tank and loop pumped down to a high vacuum.

One pump is lined up to pump through the cooler, the lithium clean-up system, and the startup bypass back to the tank, and circulation is started. When instruments and controls have established a steady lithium flow, another pump may be started to insure that parallel operation is smooth. The auxiliary heater should be fired at maximum capacity in order to cause the main cooling fan to go on at a low rate.

Lithium will then be delivered to one target at a time as the startup bypass is closed off to explore the operation and changes in pressures

that take place as more piping is placed in the circuit. Level in the pumping tank will be monitored carefully to be sure the gravity returns are working properly.

To insure the integrity and the reliability of the system, all materials, fabrication and installation procedures will conform to the provisions of Section III of the ASME code.

VI. EXPERIMENTAL AREA

6.1. General Description

This chapter describes the experimental area facility. The neutron source and target characteristics are discussed in Sections III and V respectively.

The design and physical layout of the experimental area is crucial in providing the experimenter the most flexibility in a very severely constraining radiation environment. The layout constraints are also very dependent on the beam optics required to achieve the desired real space beam distribution on the targets. Figure VII-2 shows a plan view and cross sections of the buildings, including the experimental area with the fan shape geometry of the target caves dictated by the beam optics and the shielding requirements.

From the high energy end of the accelerator a 60 meter long, beam transport system separates the target areas from the rest of the facility. This distance is necessary in debunching the beam to obtain a dc beam on the target. In addition this distance makes it possible to locally contain the high radiation environment and minimizes the potential lithium contamination of the accelerator itself.

The beam transport system ends at the beam switchyard where a bending magnet will direct the beams to their appropriate targets. The D^+D^- beams will allow the simultaneous use of two targets, hence it is anticipated that two experimental caves will be in operation at all times. The provision in the design for four target caves is based upon the desire to give the user the utmost flexibility in his ability to run experiments while at the same time preparing and setting up new experiments. It is also anticipated that a target cave may be rigged for high temperature experiments ($500^\circ - 1000^\circ\text{C}$) while another cave may provide a cryogenic environment for the irradiation of superconducting materials. These different experimental environments seem to reinforce the need for a multiple-target system.

The accelerator is designed so that the D^+D^- beams can be utilized singly and independently, or simultaneously. However, one has to note the fact that for simultaneous operation, the beam switchyard bending magnet will bend the beams by the same angle but in opposite directions, thus limiting the choice of which two targets can be used at any one moment. Also, arbitrarily

setting the polarity of the bending magnet assigns the D^+ beam (high intensity) to the two targets on the left hand and the D^- beam (low intensity) to the other two on the right. With the addition of a few magnets, the operation of the targets can be made truly independent of each other. A scheme will be studied to this effect.

The disposition of the caves with respect to the experimental staging area has been chosen to provide access to the targets from above. This choice is based upon BLIP⁽¹⁾ (Brookhaven Linac Isotope Producer) experience. BLIP, as its name implies, is an irradiation facility utilizing the AGS-linac 200-MeV proton beam. It has been operated successfully for about 3 years. It is designed around the use of a water-tank into which the targets (experiments) are lowered in position through a channel system. This approach has given entire satisfaction and it is intended to extend this proven design for this application. Above each target the 8 ft thick shielding will feature a removable plug which will contain all necessary feed and transport systems for experimental samples. In addition, each cave will have an 8 x 8 ft access plug (removable shielding) so that bulky equipment can be lowered into the caves if necessary. This shielding plug will also be the only means of access for personnel in the rare instances when personnel might have to intervene in the target area.

It is expected that the residual radiation levels in the target caves after long irradiation exposures will forbid human intervention in the caves. Remote handling will be used and the targets and surrounding experimental equipment will be designed accordingly.

The preliminary design provides for 12 x 16 x 8 ft high target caves. The targets will be located near the upstream wall, 4 ft off the floor. The experimental space available is thus very generous. From the target face, 2π steradians is available extending 4 ft vertically, 6 ft horizontally and 12-14 ft in the forward direction. At this preliminary stage, the caves are lined with concrete. It is, however, desirable that a study be made of possible absorbers and moderators to control the backstream neutron flux and the residual

(1) F. L. Horn "Remote Targetting System for Accelerator Production of Isotopes", Proc. Conf. Remote Systems Technology, 1972.

radiation problem. The possibility of utilizing a carbon or water shield will be studied. The design shows three identical target caves with the fourth one being different in that it is larger and has personnel access. It is intended to utilize this target cave for low intensity work (e.g., instrument calibration, neutron cross section measurements, etc.).

In line with the beam transport, a small heavily shielded tunnel extension will contain a beam dump to receive the full beam power for a few milliseconds in cases of target or magnet malfunction. It is complementary to the fast beam-interrupt system. The beam dump is also required as a beam stop to be used during the tune-up and commissioning of the accelerator.

The experimental staging area covering the target caves provides the space necessary for hot cells, experimental support equipment, etc. The building has a surface area of about 5600 ft² and is serviced by a 20 ton crane. The crane capacity is required for the removal of the target cave shielding.

Sufficient capacity in electrical power, water and other services will be provided to satisfy any foreseeable experiment requirements.

6.2. Shielding

The shielding requirements for the accelerator, beam transport tunnel and target caves have been calculated. Appendix E gives the basis for the estimate.

The accelerator tunnel shielding has been calculated on the basis of a continuous 0.1% beam loss distributed linearly along the accelerator length and the accidental loss of the total beam for 2 msec with the same distribution. The shielding thickness varies from 2 ft of concrete at the low energy end of the machine to 4 ft thick concrete at the high energy end. Based on the experience gained with proton linacs, the loss parameters used for the calculation are extremely conservative and it is expected that the beam losses will be much smaller than the 0.1% used here.

The accelerator tunnel will be separated from the beam transport tunnel by a 5 ft thick concrete shield, even though the beam transport system loss rate is not expected to be worse than the accelerator's. This separation shield is to insure against any catastrophic failure in the beam switchyard area which might affect the accelerator itself.

The beam transport tunnel shielding will consist of 2 ft of concrete covered by 8 ft of sand. The shielding was estimated on the bases of 0.1% continuous beam loss and more importantly, the catastrophic possibility of a beam spill in the switchyard area.

The target caves will be completely buried with the exception of the 8 ft thick roof shielding and the 6 ft thick back wall. These thicknesses were determined using as parameters the neutron spectra previously given (see Chapter III) at full source intensity (2×10^{16} nsec⁻¹). Although calculations show that the target cave shielding is adequate for these conditions, it is intended to upgrade the shielding design to minimize the background and residual radiation. As indicated earlier, the possibility of additional graphite or water shields will be studied.

6.3. Health Physics and Hot Labs

Brookhaven National Laboratory has a long history and experience in the handling of radioactive materials and safety aspects of radiation facilities. These Laboratory services will be extended to cover the needs of the accelerator-based neutron generator. The Health Physics and Safety division will provide the necessary manpower to monitor all aspects of radiation related safety including radioactive materials handling and personnel monitoring.

The Laboratory hot storage area will be made available for the cooling-off period and disposition of radioactive components and materials. By the same token, the existing hot labs (shops) will be available to do repair and maintenance on contaminated hardware.

VII. BUILDINGS AND UTILITIES

7.1. Location and Site Work

The facility will be located in a wooded area adjacent to and south of the existing linac injector for the Alternating Gradient Synchrotron. The area will be cleared and graded to produce the minimum ecological disturbance. Figure VII-1 shows the overall project layout including its location with respect to the AGS linac injector.

The site work includes the construction of access roads to the accelerator buildings and to the experimental staging area. A parking area for approximately 30 cars will be provided near the laboratory and office building. Utility trenches required for power and water will follow new and existing roadways, thus avoiding any unnecessary clearing of trees.

Storm sewers will be installed to direct the site water run off into an existing storm drainage system.

7.2. Buildings

The facility will contain 50,000 sq.ft (gross area) of building space consisting of five major elements: 1) an accelerator tunnel and underground target rooms with a connecting beam-transport tunnel; 2) an rf equipment and adjacent assembly area; 3) an experimental staging area; 4) a lithium-loop building, and 5) a two-story laboratory and office building. The ratio of net-to-gross floor area will be approximately 85 percent. Figures VII-2 and VII-3 show floor plans and cross sections of the buildings.

The accelerator tunnel (20 ft wide by 26 ft high) will house the 12 ft diameter accelerator and its two injectors. It will be serviced by a 10-ton crane required for the erection and maintenance of the machine. The tunnel will be separated from the adjacent areas by concrete shielding to protect personnel and equipment in the case of accidental beam spills. This shielding will vary in thickness from 2 ft at the low energy end of the accelerator to 4 ft at the high-energy end (see Section VI). The low-energy end of the tunnel will contain two Faraday cages (500 sq.ft each) which surround the two 500-kV dc injectors. A steel grating platform will be erected around the injectors and the accelerator for personnel access to the equipment.

The beam-transfer tunnel, separated from the accelerator tunnel by 5 ft of concrete, will be 50 meters long. The tunnel cross section of 7 x 7 ft

WEST FIFTH AVENUE

EXISTING
WOODS

EXISTING WOODS

NEW
COOLING
TOWER

NEW PAVED ROAD

EXISTING
WOODS

NEW PAVED ROAD

POWER
SUB-STATION

PARKING

RETAINING
WALL

EXISTING WOODS

RETAINING
WALL

70

80

90

80

80

FIG. VII-1

PLOT PLAN

SECTION A-A

SECTION A-A

2

FIG. VII-2

LOWER LEVEL FLOOR PLAN

SECTION C-C

2

FIG. VII-3

UPPER LEVEL FLOOR PLAN

will provide enough space for the necessary equipment with the beam axis being one foot off center to create a narrow service passage. The tunnel will be buried under approximately 8 ft of earth to protect against accidental beam loss and backstreaming radiation.

The rf equipment, magnet power supplies and the control electronics, will be housed in the rf equipment area located adjacent to the accelerator tunnel. An assembly area with a light-duty 2-ton crane is contiguous to the rf equipment area. The combined areas cover approximately 14,200 sq.ft. An additional area of about 2,600 sq.ft will house the cooling systems and other mechanical services for the facility. This entire structure will be on a single floor, 16 ft clear height. It will be a light structure, steel framed with metal roof decks, insulated built-up roofing, metal sandwich wall panels and concrete floors. Hangers will be provided from the roof structure to support all the cable trays and cooling pipes.

The experimental staging area (approximately 5,600 sq.ft) will be similar in construction to the rf equipment area. However, it will be reinforced to support the 20-ton crane required to remove the target cave access plugs. The experimental staging area is built on top of the target caves with an 8 ft concrete shield separation in between. The concrete shield above the targets will contain all the access ports for the remote handling of experiments.

The Lithium Loop Building will be primarily a below-grade concrete structure with a steel joist and metal deck roof. This facility will be connected to a pump room below the beam switchyard by an underground access/service passage as indicated on Figure VII-2. A monorail will be provided to raise and lower equipment to the underground passage level. A stack will be erected to exhaust filtered air from the Lithium Facility and disperse it to the atmosphere.

The laboratory and office building (approximately 10,000 sq.ft) will be located between the accelerator building and the experimental staging area building giving direct access to both areas, and will be planned for an occupancy of about 30 persons. It will contain, in addition to the laboratories and offices, a control room strategically located at the junction of the accelerator, rf equipment and beam transport tunnel. This building will be a

two story, steel framed structure with a metal roof deck, masonry exterior and interior walls, suspended acoustical ceilings and resilient flooring on concrete floor slabs.

The entire facility will be thermally insulated and will be air conditioned to remove the heat produced by the accelerator electronic equipment, and to keep the temperature and humidity within recommended equipment tolerances. An automatic sprinkler system and a smoke- and fire-detection system will be installed in all buildings and will be connected to the Brookhaven National Laboratory Fire Department alarm system.

A more detailed breakdown of the building's volume and areas is given in Table VII-1.

Table VII-1

Areas and Volumes

	<u>Sq. Ft.</u>	<u>Cu. Ft.</u>
Accelerator Tunnel & Injector Rooms	7,000	203,000
Beam Transport Tunnel	2,500	27,000
Target Rooms	2,500	50,000
Control Room	1,100	13,000
Experimental Staging Area	5,600	123,000
Lithium-Loop Building	2,300	36,000
Rf Equipment Area	8,000	144,000
Assembly Area	6,200	112,000
Laboratories and Offices	<u>7,200</u>	86,000
Total Net:	42,400	
Corridors, Vestibules, Elevator, Stairs	2,900	35,000
Toilets, Janitors Closets, Etc.	600	7,000
Mechanical Services	2,600	47,000
Exterior Walls	<u>1,500</u>	<u>-----</u>
Total Gross:	50,000	883,000

LEGEND

- EXISTING UTILITIES
- W — DOMESTIC WATER
- RW — RELOCATED COOLING WATER
- ST — STORM DRAINAGE
- SA — SANITARY DRAINAGE
- SC — STEAM & CONDENSATE
- E — ELECTRIC, FIRE ALARM & TELEPHONE

FIG. VII-4

UTILITY PLAN

7.3. Utilities

The utilities necessary to serve the facility are shown on Figure VII-4. These consist of the following:

- a) Electric: A 10 MVA, 13.8-kV extension will be installed from the existing 200-MeV linac. The lines can be pulled from the main Fifth Avenue substation through an existing duct bank. The 10 MVA lines will be brought to the new linac substation which is contiguous to the assembly area as shown in Figure VII-2.
- b) Domestic Water: The water treatment plant for the laboratory is located nearby. An 8-inch main will be run from the major water main on Upton Road, and will provide the make-up for the cooling tower and closed loops.
- c) Cooling Water: All cooling will be accomplished through a forced-draft cooling tower. Secondary circuits covering air conditioning, rf cooling, accelerator cooling, will all be closed loops and will reject their heat through heat exchangers to the primary loop.
- d) Telephone and Fire Alarm: These will connect to an existing duct bank serving the existing 200-MeV linac which has sufficient spare capacity for the new facility.
- e) Steam: An 8-inch underground steam main will be run from the end of the existing system on Cornell Avenue to a steam reduction station in the Equipment area.
- f) Sanitary Sewer: Sewage will be collected from the new buildings by gravity, then will be pumped through a 6-inch pressure main to a connection with the existing Laboratory sanitary-sewer system.
- g) Existing Well Water: An existing cooling-water main passes through the project site. A portion of this main will be relocated to clear the construction area.

VIII. CONSTRUCTION SCHEDULES, COSTS AND MANPOWER

8.1. Construction Schedule

The schedule for the construction of the Accelerator-based Neutron Generator is shown in Figure VIII-1. As is indicated in the schedule, it is assumed that preliminary design and development efforts now in progress will continue in anticipation of the expected approval of the project. The combined preliminary design and development is necessary to meet the proposed commissioning date for the facility and is contingent upon the continued support of the development program.

Completion of the facility and first operation are expected four years after the date of approval. It should be noted that this four year construction period cannot be materially changed. It is defined by the critical path going through AE Title I Design, AE Title II Design, building construction, machine installation and tests. The construction period could be shortened by about 6 months if the funds were made available for Title I building and machine designs, 6 months before formal approval.

During the Title I design phase a comprehensive PERT scheduling program will be instituted to define the real critical path and to control the construction progress. Although PERT is expected to refine the schedule, it is not likely to change the time required for construction as these estimates are based on solid experience with similar projects.

8.2. Manpower

The manpower required for the design and construction of the 30-MeV accelerator and its associated equipment is shown in Table VIII-2. It does not cover the work done by the AE and it is based on utilizing commercially designed equipment wherever possible.

The estimate is given by year and is broken down into two broad categories, professionals (engineers and scientists) and nonprofessionals (technicians, clerical and others). The totals estimated are: 100 man years for professional and 170 man years for nonprofessional personnel. This estimate does not cover the research and development activities which will phase out during the construction program.

F I S C A L Y E A R

FIG. VIII-1

Table VIII-1

Personnel Estimate

(Man Years)

	<u>Fiscal Year</u>							
	1977		1978		1979		1980	
	P	NP	P	NP	P	NP	P	NP
Administration	2	3	2	4	2	4	2	4
AE liaison	1	1	1	1	1	1	1	1
Injectors	1	1	1	2	1	2	1	1
Accelerator	3	2	3	4	3	6	3	5
Radio frequency	2	2	2	4	2	6	2	6
Beam Transport	1	-	1	1	1	2	1	4
Vacuum	1	1	1	2	1	3	1	3
Targets	1	1	1	1	1	2	1	4
Water	1	-	1	-	1	1	1	1
Power	1	-	1	-	1	1	1	1
Controls	1	1	2	4	2	6	2	6
Mech. Eng. General	1	-	3	3	3	3	3	3
Drafting	4	4	4	4	4	4	2	2
Electrical Eng. General	3	4	3	4	3	6	3	6
*Lab. Services	-	2	-	4	-	4	-	4
<u>T O T A L</u>	23	22	26	38	26	51	24	50

*Lab Services include purchasing, receiving, warehousing, riggers, and other specialized functions as required.

8.3. Cost Estimate

The details of the estimated costs are presented in the following sections: Tables VIII-2 gives a summary of the cost estimate, Table VIII-3 lists the detailed cost of all systems as estimated in May 1975.

Site, Buildings and Utilities

The estimates are based on considerable previous construction experience at Brookhaven. All excavation, domestic water, heating, air condi-

tioning and cranes are included in this schedule. Appropriate amounts are also included to extend all necessary utilities to the desired building location.

Accelerator and Target System

This section covers the cost of all accelerator components, associated equipment, beam-transport and target systems. The costs were estimated on the basis of actual costs of the 200-MeV Brookhaven linac injector indexed from 1968 to 1975 by an appropriate amount to allow for the intervening inflation increments. Wherever possible, estimates from vendors have been used. The cost estimate also includes the spares deemed necessary for reliable operation of the facility.

Engineering, Design, Inspection and Administration

The "in-house salaries" estimate is derived both by the preceding man-power schedule estimate and by published data relating EDI&A as a percentage of project cost for similar projects. This percentage is given as about 20% of the cost of buildings and utilities, and 25% of the cost of the accelerator system.

These costs do not include the manpower devoted to research and development, nor the manpower which will be required at the end of the project to initiate the start of operation and experimental equipment design and construction.

Contingencies

Based on experience at the laboratory and comparisons with other construction projects, the contingency is figured on 20% of Schedule A and 25% of Schedules B and C.

Escalation

The cost estimate that follows is based on current costs. In order to project these numbers to reflect the actual costs at the anticipated time of construction, an escalation estimate is included in Schedule D. This estimate, based on guidelines released by ERDA, has been computed as follows:

7%	remainder of 1975
10%	1976
7%	1977
7%	1978
<u>35% compounded rate to mid-construction year.</u>	

8.4. Facility Operation

As a national laboratory and anticipating a high demand level for experimental time, it is anticipated that the facility will operate on a continuous 24-hour/day schedule. Based on this assumption, it will require a staff of about 30 engineers and technicians, including 10 machine operators. A summary of the estimated annual operating cost is given below. This cost is based on 1975 dollars as it is impossible at this time to predict the escalation required for power costs.

Energy 60,000 MW hrs. @ 30\$/MW hr	\$1,800,000
Amplifier tubes (9)	200,000
Maintenance (including hardware and trades)	600,000
Salaries (professional, scientific & support)	<u>900,000</u>
TOTAL/Year	\$3,500,000

Table VIII-2

Cost Estimate Summary
(In Thousand Dollars)

<u>Schedule A: Buildings</u>		6,300
Improvement to land	100	
Utilities	700	
Construction	4300	
Equipment	150	
Contingency 20%	1000	
 <u>Schedule B: E, D, I & A</u>		
20% of Schedule A		1,300
 <u>Schedule C: Accelerator System</u>		19,500
Injectors	1400	
Matching Section	300	
Accelerator	3950	
Rf System	4300	
Beam Transport	750	
Cooling System	750	
Target System	3200	
Control System	950	
Contingency 25%	3900	
 <u>Schedule D: E, D, I & A</u>		
25% of Schedule C		4,900
 <u>Schedule E: Escalation</u>		
35% of Schedule A, B, C & D		<u>11,000</u>
	T O T A L	<u>43,000</u>

Table VIII-3

Detailed Cost Estimate

(In Thousand Dollars)

Schedule A: Buildings and Utilities 6,300

1. Improvement to land 100
 - Preparation, grading, seeding 20
 - Paving, curbs 70
 - Area lighting 10
2. Utilities 700
 - Storm drainage 45
 - Steam 300
 - Water 25
 - Sanitary Sewer 25
 - Cooling Water (relocate) 20
 - Electric Power 130
 - Electric Substation 155
3. Construction 4300
 - General construction, foundation
 - steel, shielding, walls, roofs 2750
 - HVAC 560
 - Plumbing and Sanitary 220
 - Sprinkler System 180
 - Bldg. Electrical Services 110
 - Experimental Area Power 220
 - Lighting 220
 - Fire Alarm and Telephone 40
4. Equipment 150
 - Laboratory furniture 30
 - Office furniture 15
 - Machine tools 30
 - Cranes 100
5. Contingency 20% 1050

Schedule B: E, D, I & A

20% of Schedule A 1,300

Schedule C: Accelerator 19,500

1. <u>Injectors (2)</u>	1400
High Voltage Generators	500
HV Platforms	60
Faraday Cages	60
Accel. Columns	300
Column Supports	75
Ion Sources + PS	75
High Vac. System	100
Low Vac. System	20
Triplets	60
Triplets Power Supplies	20
Cooling System	15
Controls and Electr.	30
Installation	80
2. <u>Matching Section</u>	300
Triplets Q	30
Match. Magnet Q	15
Q Power Supplies	26
Bending Magnet	20
Bending Magnet Power Supplies	8
Bunchers	35
Buncher Power Supply	30
Viewing boxes & Scrapers	15
Emittance Devices	15
Current Monitor	6
High Vacuum System	15
Low Vacuum System	7
Vacuum Pipe & Hardware	20
Installation	60
3. <u>Accelerator</u>	3950
Tanks & End Plates	2000
Support System	40
Drift Tubes	580
Quad. Magnet	210
Quad. Shunts	70
Quad. Power Supplies	130
High-Vacuum System	320
Low-Vacuum System	100
Cooling Hardware	20
Cooling Controls	20
Tuners	30
Current monitors	15
Pick-up loops	15
Installation	400

4.	<u>RF System</u>	4300
	Low-Level System	250
	PA tubes	220
	PA sockets	1200
	Drivers System	560
	Fl. Power Supplies	120
	Plate Power Supplies	400
	Crowbar System	160
	3" Transmission Lines	80
	14" Transmission Lines	160
	14" Phase Shifters	160
	Feed loops	160
	Dummy Loads	70
	Controls	160
	Installation	600
5.	<u>Beam Transport</u>	750
	Quad. Magnet	210
	Quad. Power Supplies	120
	Bending Magnet	30
	Bending-Magnet Power Supplies	20
	High-Vacuum System	30
	Low-Vacuum System	20
	Vacuum Pipe & Hardware	10
	Fast Valves	20
	Beam Dump	50
	Li. Collectors	40
	Debuncher	30
	Current Monitors	10
	Profile Monitors	40
	Installation	120
6.	<u>Cooling System</u>	750
	Cooling Towers	110
	CT pumps & Pipes	80
	Rf Pumps	20
	Rf Heat Exchanger	30
	Demineralizer	20
	Rf piping	70
	Tank pumps	20
	Tank heat exchanger	40
	Tank piping	60
	Controls	200
	Installation	100

7.	<u>Target System</u>	3200
	Expt. Hot Cells System	1800
	Li Pumps	300
	Piping & Valves	150
	Heat Exchanger	130
	Tritium Separator	270
	Controls	150
	Installation	400
8.	<u>Control System</u>	950
	Racks & Cables	50
	Computers	120
	CAMAC System	160
	Contr. Desk & Display	80
	Communication System	20
	Radiation Monit. System	40
	Local Controls	80
	Beam Control System	60
	Installation	300
9.	<u>Contingency 25%</u>	3900

Schedule D: E, D, I & A

25% of Schedule C 4,900

Schedule E: Escalation

35% of Schedule A, B and D 11,000

T O T A L 43,000

APPENDIX A

Neutron Flux Calculations for a Three-Dimensional Source

The primary neutron flux values close to a finite-size source are difficult to estimate with any kind of accuracy. The differential yield $dY(\theta, E)$ from a thin layer of a thick target is a function of both the penetration depth of the bombarding particles and the neutron emission angle.

For a point source in vacuum we can calculate the flux values $n \text{ cm}^{-2} \text{ sec}^{-1}$ using the following simple equation

$$\phi(\vec{r}) = \frac{Y(\theta, E_d)}{r^2} = \frac{Y(0^\circ, E_d)F(\theta, E_d)}{r^2} \quad (1)$$

where $\vec{r}$ is the vector to the observation point P, θ the angle between $\vec{r}$ and the positive z axis or the incident direction of the bombarding beam (Fig. A-1) and $Y(\theta, E_d)$ the yield at angle θ per unit solid angle.

Fig. A-1. A Li(d,n) Point-Source Geometry

$Y(\theta)$ and also the relative angular intensity $F(\theta) = Y(\theta)/Y(0^\circ)$ are functions of the bombarding energy E_d . The relations between the total yield

$Y(4\pi)$ (n/sec), the total forward yield $Y(2\pi)$ (n/sec) and $Y(0^\circ)$ (n/sec sr) are the following:

$$Y(2\pi) = 2\pi Y(0^\circ) \int_0^{\pi/2} F(\theta) \sin \theta d\theta$$

$$Y(4\pi) = 2\pi Y(0^\circ) \int_0^\pi F(\theta) \sin \theta d\theta \quad (2)$$

Fig. A-2 shows the geometry for a finite-size source. The dimensions of the rectangular prism in the x, y and z directions are B, A and R_d respectively. In the liquid-lithium target the range R_d of the 30-MeV deuterons is 1.12 cm, B=10 cm and A=1 cm. Lithium is flowing in the y direction. The intensity I of the deuteron beam is assumed to be constant in the x direction and approximates a Gaussian distribution in the y direction (see Fig. A-3).

If we take an infinitesimal source volume $dx_1 \cdot dy_1 \cdot dz_1$ around a point $Q(\underline{r}_1) = Q(x_1, y_1, z_1)$, we get an expression for the differential flux of the primary neutrons at $P(\underline{r})$

$$d\phi(\underline{r}) = \frac{dY(\theta, \underline{r}_1) dV}{|\underline{r} - \underline{r}_1|^2} \quad (3)$$

For $dY(\theta, \underline{r}_1)$ we can write

$$dY(\theta, \underline{r}_1) = \frac{dY(\theta, z_1)}{dz} \frac{I(\underline{r}_1)}{\int_S I dS} \quad (4)$$

Intensity $I(\underline{r}_1)$ is simply $I(y_1)$ and it is symmetric ($I(-y_1) = I(y_1)$) and S is the area of the source (AB).

From the measurements described in Section III-2 we get the forward yield $Y(0^\circ)$ for a thick natural-lithium target as a function of the deuteron energy. The yield curve is presented in Fig. A-4. The agreement between the

A THREE-DIMENSIONAL - SOURCE GEOMETRY

FIG. A-2

FIG. A-3

FIG. A-4

data used here and data published in the literature is discussed in Section III-3.

When we know the $Y(0^\circ, E)$ curve, we can use the tabulations for protons⁽¹⁾ to get the forward yield as a function of deuteron range R_d or as a function of z_1 . The range for deuterons has been calculated from the proton range R_p values by using Eq. 5

$$R(E) = 1.999 R_p \left(\frac{E}{1.999} \right) . \quad (5)$$

The range values can be fitted by using Eq. 6 with a good accuracy (typically better than 0.5%)

$$\frac{R(\text{cm})}{\rho (\text{g/cm}^3)} = R\left(\frac{\text{g}}{\text{cm}^2}\right) = a_0 + a_1 E + a_2 E^2 . \quad (6)$$

Table A-1

(MeV)	a_0	a_1	a_2
4-14	-2.43×10^{-3}	2.325×10^{-3}	5.914×10^{-4}
14-40	-0.02259	5.033×10^{-3}	4.9936×10^{-4}
40-100	-0.1814	0.012256	4.1517×10^{-4}

The coefficients for R in g/cm^2 are given in Table A-1 together with the corresponding energy intervals.

To get the range $R(\text{cm})$ we simply divide $R(\text{g/cm}^2)$ by the density of liquid lithium. For these calculations a value 0.515 g/cm^3 has been used. From Eq. 6 we get also the energy E as a function of $R(\text{g/cm}^2)$ by using the values of Table A-1

$$E(\text{MeV}) = \frac{-a_1 + \sqrt{a_1^2 - 4a_2[a_0 - R(\text{g/cm}^2)]}}{2a_2} . \quad (7)$$

The energy E given as a function of $R(\text{cm})$ or $z_1(\text{cm})$ in Fig. C-1 (App. C) is for $\rho=0.515 \text{ g/cm}^3$ (liquid). From Eqs. 6 and 7 we can get the relationship between E and z for all values needed or $0 \leq E \leq E_d$ and $-R \leq z \leq 0$.

The angular distribution for the $\text{Li}(d,n)$ reaction has been measured only for thick targets and some values of E_d (2-7). Fig. A-5 shows the relative intensity $F(\theta)$ as a function of angle θ for some deuteron energies. The extrapolation of $F(\theta)$ to 90° is based on the data of Daruga⁽²⁾.

For the flux calculations we converted these $F(\theta, E_d)$ curves to $F(\theta, z_1)$ values and used in addition an assumption $F(\theta, 0)=1$. This means that we supposed an isotropic angular distribution for $E_d \rightarrow 0$, which should be reasonable. A linear interpolation (and extrapolation) of $F(\theta)$ values as a function of z_1 was used to cover the whole range of interest $-R \leq z_1 \leq 0$ and $0 \leq \theta \leq 90^\circ$. By combining the Eqs. 3 and 4 and by integrating over the source volume we get the final expression for the flux at $P(\vec{r})$

$$\phi(\vec{r}) = \frac{1}{A \cdot B} \int_0^{-R_d} \int_{-B/2}^{B/2} \int_{-A/2}^{A/2} \frac{I(y_1)}{(\vec{r} - \vec{r}_1)^2} \cdot \frac{dY(\theta, z_1)}{dz_1} dx_1 dy_1 dz_1 \quad (8)$$

where $I(y_1)$ is normalized to give

$$\int_{-B/2}^{B/2} \int_{-A/2}^{A/2} I(y_1) dy_1 dx_1 = AB \quad (9)$$

and the derivative of the yield can be calculated from

$$Y(\theta, z_1) = Y(0^\circ, z_1) \cdot F\left(\arccos \frac{z - z_1}{|\vec{r} - \vec{r}_1|}\right) \quad (10)$$

A straightforward Fortran-code "FLUX" was written for CDC 7600 computer to perform the three-dimensional integration over the source volume. The flux

FIG. A-5

values were computed for a grid of discrete observation points (x, y, z) . Because of the symmetry, only positive values of x , y and z are needed to describe the system completely. The computed flux values and contours for the $Li(d, n)$ source are presented in Figs. III-4 to III-6 as a function of various parameters. Integrating over the x_1 dimension beginning from $x_1=0$ the code gives intermediate results. Thus we get flux values as a function of the source width B . Fig. III-6 shows some representative curves.

The same procedure can be applied also for integration over the y_1 coordinate. However, it is only meaningful for a source of constant $I(y_1)$. Likewise integrating over the thickness of the source from $z_1=0$ to $z_1=-R_d$ we get the flux as a function of R_d or bombarding energy E_d . At large distance $z \gg B$ the flux values can also be calculated from Eq. 1.

For further discussion of the results, see Section 3.3.

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APPENDIX B

Pertinent Properties of Liquid Lithium

This is a brief summary of the pertinent physical properties of liquid lithium related to its use as a target liquid. For more detailed information see the review articles^(1,2,3), and other references.

The atomic mass A_r of natural lithium is 6.941 based on fraction $f = 7.42\%$ of ${}^6\text{Li}$ ($A_r = 6.01512$) and $f = 92.58\%$ of ${}^7\text{Li}$ ($A_r = 7.01600$). The density of liquid lithium $\rho = 515 \text{ kg/m}^3$ at 200°C decreases linearly to 374 kg/m^3 at 1600°C . It can be expressed in equation form as

$$\rho \text{ (kg/m}^3\text{)} = 535.2 - 0.101 t(^{\circ}\text{C}) \quad . \quad (1)$$

The volume increases 1.5% by melting. The melting point of lithium is 180.6°C and boiling point 1343°C . The vapor pressure of lithium can be presented between the melting and boiling points by the equation

$$P(\text{torr}) = 10^{10.2788 - 8283.1/T(^{\circ}\text{K}) - 0.7081 \log_{10} T(^{\circ}\text{K})} \quad . \quad (2)$$

This equation is a good fit for the experimental measurements of the vapor pressure between 460°C and 1400°C . Between the melting point and 700°C we can use a simpler equation (the difference between this and Eq. (2) is $\sim 2\%$)

$$P(\text{torr}) = 10^{8-8100/T(^{\circ}\text{K})}, \quad 1 \text{ torr} = 133.32 \text{ N/m}^2. \quad (3)$$

From this equation we get also a convenient formula for the boiling temperature as a function of pressure

$$t(^{\circ}\text{C}) = \frac{8100}{8 - \log_{10} P(\text{torr})} - 273.15 \quad . \quad (4)$$

The values of saturated vapor pressure presented in Table C-1 in Appendix C are calculated by using Eq. (2). The heat of fusion is about 0.43 MJ/kg and the heat of vaporization L as a function of temperature is given by

$$L(\text{MJ/kg}) \simeq 22.61 - \frac{t(^{\circ}\text{C})}{1180}, \quad (5)$$

which gives $L(750^{\circ}\text{C}) = 22 \text{ MJ/kg}$, $L(1000^{\circ}\text{C}) = 21.8 \text{ MJ/kg}$ and $L(1343^{\circ}\text{C}) = 21.5 \text{ MJ/kg}$. For comparison the heat of vaporization for water is 2.26 MJ/kg at 100°C . The average specific heat C_{av} between 200°C and $200^{\circ}\text{C} + \Delta t$ is given by

$$H(200^{\circ}\text{C} + \Delta t) - H(200^{\circ}\text{C}) = C_{av} \Delta t = \int_{200^{\circ}\text{C}}^{200^{\circ}\text{C} + \Delta t} C_p dt, \quad (6)$$

where H is the enthalpy (or heat content) of Li . By using the values H from ref. (6) we get

$$C_{av} (\text{KJ/kg}) = 4.25f. \quad (7)$$

The correction coefficient f is a monotonic function of Δt in the range given in Table B-1. For the thermal conductivity λ between 200°C and about 1100°C we can write

$$\lambda \left(\frac{\text{W}}{\text{m}^{\circ}\text{C}} \right) = 40.12 + 19.04 \times 10^{-3} T(^{\circ}\text{C}).$$

TABLE B-1

$\Delta T (^{\circ}\text{C})$	50	60	70	80	90
f	1.082	1.07	1.058	1.047	1.038
$\Delta T (^{\circ}\text{C})$	100	125	150	200	800
f	1.031	1.021	1.014	1.006	.998

The viscosity η of lithium can be represented between the melting point and 1500°C by Eq. (9)

$$\eta(\text{cP}) = \frac{273.5 \pm 1.6}{T(^{\circ}\text{K})} \quad (\text{cP} = 10^{-3} \frac{\text{Nsec}}{\text{m}^2}) \quad , \quad (9)$$

which is a good fit to the experimental data. The viscosity of ^6Li is 42% lower than its value for ^7Li at 188°C and 33% at 266°C. (2,4) The surface tension of liquid lithium from the melting point up to at least 1300°C can be represented by a simple expression

$$\sigma \left(\frac{\text{dyn}}{\text{cm}} \right) = 429.3 - 0.16 T(^{\circ}\text{C}) \quad \left(\frac{\text{dyn}}{\text{cm}} = 10^{-3} \frac{\text{N}}{\text{m}} \right) \quad . \quad (10)$$

The speed of sound has been measured from the melting point to 800°C. The results can be fitted with an equation

$$c \text{ (m/sec)} = 4623 - 0.591 T(^{\circ}\text{C}) \quad . \quad (11)$$

The isothermal compressibility β can be calculated from Eq. (12) by using Eqs. (1) and (11) for ρ and c respectively

$$\beta \left(\frac{\text{m}^2}{\text{N}} \right) = \frac{1}{\rho c^2} = \frac{1}{[535.2 - 0.101 T(^{\circ}\text{C})] [4623 - 0.591 T(^{\circ}\text{C})]^2} \quad (12)$$

The experimental values of the electrical resistivity can be described by

$$\rho \text{ (n}\Omega\text{m)} = 215.5 + 0.262 T(^{\circ}\text{C}) \quad (13)$$

between the melting point and at least 1400°C. Values of the self-diffusion coefficient of lithium can be calculated from the following equation between 195°C and 450°C

$$D \left(\frac{\text{cm}^2}{\text{s}} \right) = (1.41 \pm 0.12) \times 10^{-3} \exp - \frac{1422 \pm 45}{T(^{\circ}\text{K})} \quad . \quad (14)$$

Purified lithium does not wet stainless steel at 316°C, but does at 399°C.⁽²⁾ Above 600°C lithium can be expected to wet virtually all metallic materials.⁽¹⁾

Metals like Mo, Nb or Nb-1Zr, Re, Ta, V, W, Zr and some alloys of them can be used up to 800-1000°C with a negligible attack at least for a period of some months.^(1,2) Austenitic and ferritic stainless steels and pure iron are good for use up to 600-700°C. Beryllium is good up to 600°C.⁽⁶⁾ One of the most promising ceramics for resistance to lithium at 375°C is hot-pressed and high-purity BeO.⁽¹⁾

The erosion resistance of several materials to 1093°C lithium impinging at velocities from 33 m/sec to 45 m/sec has been measured in 100-h test.⁽⁵⁾ An Nb-1Zr specimen was nearly unaffected, but W-2ThO₂, TaC, TiC and ZrC were badly eroded. The flow nozzles used were also Nb-1Zr. The velocity of the 1083°C lithium was between 55 and 82 m/sec in the nozzle during the 100-h tests. No clear defects in the nozzle were detected. In other tests of 1083°C lithium flowing through Nb-1Zr pipes for 10,000 h, no corrosion, was found for velocities of 6-12 m/sec.⁽⁵⁾ Nb-1Zr can be used between 760 and 1300°C for lithium flow of 45 m/sec at least for 20,000 h (or 2-3 years).⁽⁷⁾ The temperature difference between lithium and the wall was 110-540°C. The resistance of various materials to wear in lithium from 316°C to 538°C has been measured by rubbing rotating discs against curved and flat shoes in lithium. Molybdenum-cemented TiC, NbC and WC and carbide coated Nb-1Zr had excellent characteristics at 538°C, but untreated Nb-1Zr and T-111 were very poor.

The lithium cavitation tests at 260°C and 816°C for 10 h showed a more severe damage rate at the lower temperature. Mean depth of penetration was 3.8 μm in Nb-1Zr and 25 μm in annealed Nb-1Zr. The lowest depth was 0.77 μm for T-111. At 816°C the values were one order of magnitude smaller. At 260°C the cavitation rate in lithium is greater than in water, but less than in other liquid metals.⁽⁶⁾

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APPENDIX C

Deuteron-Target Considerations

In order to achieve a forward neutron yield of $> 1 \times 10^{16}$ neutrons sec^{-1} using a 100 mA beam of 30-MeV deuterons, a low-Z material such as lithium or beryllium is best, because the (d,n) yield is highest for low-Z materials and decreases with increasing Z. The measurements described in Chapter III, indicate that the values for the forward yields on lithium and beryllium are not very different. The next question to be answered is how to cool the target receiving the power input of $P = (30 \text{ MeV})(100 \text{ mA}) = 3$ megawatts.

Extensive study indicates that a flowing-liquid-lithium film target with an air-cooled heat exchanger in the loop is the most viable system. A rotating beryllium target cooled with liquid lithium or D_2O is another possibility but it would introduce another degree of complexity. The dimensions of the flowing-liquid-lithium target depend upon the following considerations.

To achieve the highest fluxes from the yield produced, the area of the target intercepted by the deuteron beam should be as small as possible. This means that the power or heat dissipation density in the target should be maximized. Downward vertical flow is envisioned for the liquid film. In order to minimize corrosion and lithium-vapor backstreaming to the vacuum system, an operating temperature range from 200 to 300°C was chosen. To limit the bulk temperature rise with the 3 MW input, to under 100°C, requires a flow rate of 18 l/sec of lithium. If a 12-cm width and a 1.5-cm thickness are selected (range of 30-MeV deuterons is 1.12 cm), the velocity of the fluid at the target interface will be ~ 10 m/sec. An analysis of the flow and temperature gradients in the lithium sheet is given in Appendix D. In the short time (~ 1 msec) a lithium element is flowing across the source height, neither heat conduction nor turbulent convection affect the temperature distribution produced in the film by the deuteron beam. The current density is thus limited by the maximum temperature allowable at the hottest position in the film; this temperature is coupled to the flow rate of the film.

Since heat conduction and convection play no role in heat dispersal, the vertical current profile is irrelevant and for the sake of temperature considerations we can consider the deuteron beam simply as a uniform line (hori-

zontal) source. For a current of 100 mA and a 10 cm wide beam, one has a linear current density of 10 mA/cm, or a power input of 0.3 MW/cm.

Figure C-1 shows the range and energy loss curves for deuterons on lithium. The dashed curve is the simple dE/dx vs x plot with the classical range R_0 situated at 11.2 mm from the entrance surface. For liquid lithium, $\rho=0.515$ g/cm³, $R_0(30 \text{ MeV})=11.2$ mm. Using the flow-rate and power input parameters above, one calculates that the temperature rise of the lithium at the end point R_0 would be 1780°C as the film exits the beam. Fortunately, the classical dE/dx expression is not the correct one to use for the distribution of stopped charged particles in matter. One must take straggling of the particles into account to achieve the proper distribution. The curve of $dE(x)/dx$ for no straggling reflects the distribution of particles if there were no direction-changing collisions along the pathlength. However, the multiple scattering of the deuterons along the path causes multiple changes in direction of the particles causing the depth of penetration into the stopping material to be somewhat different than the pathlength. As particles are scattered through different angles, a distribution of deviations from a penetration of R_0 into the material is established. The $dE(x)/dx$ curve with straggling effects included is shown by the solid curve in Fig. C-1. Note the broadening of the distribution of end points of the particles at R_0 . The peak of the straggling distribution is about 0.2 mm from the end point R_0 , giving a ratio of deviation to total range of $0.2/11.2=0.018$. A parameter more significant to the spreading out of the end-point energy deposition throughout the film is the half width of the end-point distribution peak which is ~ 1 mm. The effectiveness of straggling as a means of distributing the end-point energy over a half width of 1 mm is obvious when compared to the half-height value of <0.05 mm at 20 MeV/mm for the case of no straggling.

A calculation of the maximum temperature rise in the film gives a value of 550°C at a point ~ 1.1 cm (peak of the straggled distribution) from the entrance surface. The temperature on the surface of the film is 260°C, a rise of only 60°C. The vapor pressure of lithium at 260°C (see Table C-1) is $<10^{-6}$, so that back streaming of lithium vapor from the film would appear to be no problem. Still, cold trapping will be done. The only consideration is the effect of the 750°C temperature along a plane in the film.

FIG. C-1

Since this highest-temperature lithium is confined inside the film, there is no problem unless the lithium there vaporizes (boils). Problems would arise then if the boiling were violent enough to affect the dimensional stability of the film to the point where not enough lithium were between the incoming deuteron beam and the exit vacuum window behind the film. Should the beam reach this window, the window would quickly burn out, thereby disrupting the vacuum integrity. This boiling would then have to take place during the transit of the film through the beam to be of consequence, since, if it takes place after exiting the beam, it is simply a matter of designing the catch basin to circumvent backstreaming.

Table C-1 shows the vapor pressure of lithium as a function of temperature. For a temperature of 750°C, boiling will begin at a pressure of ~ 1 torr. Since the accelerator vacuum will be about 10^{-6} torr, boiling of the lithium would seem very probable. The internal pressure of the film in the beam area is, however, higher than the ambient pressure because of the radia-

Table C-1

Vapor Pressure of Liquid Lithium vs Temperature

<u>Vapor Pressure (Torr)</u>	<u>Temperature (°C)</u>
10^{-6}	305
10^{-5}	350
10^{-4}	402
10^{-3}	463
10^{-2}	537
10^{-1}	630
1	743
10	890
100	1094
760	1343

tion pressure of the deuteron beam. A nonrelativistic calculation of the momentum transfer of the stopped deuteron beam to the lithium film over an area of $1 \text{ cm} \times 10 \text{ cm} = 10 \text{ cm}^2$ gives a value for the pressure at the end of range of 0.83 torr. Based on these assumptions, the hottest point of the film will be below the equilibrium boiling point as it exits the deuteron beam.

There are three considerations that mitigate the possibility of vapor formation in the film. The first, mentioned above, is that the highest temperature is only realized at the bottom of the deuteron sweep where the lithium is exiting the beam. Instabilities setting in there will only show up out of the beam line and in the catch basin, and are thus of no real concern. Second and most important is the fact that the above estimates are based on the deuteron beam being monoenergetic. Any spread in the energy of the incoming deuterons further enhances the effect of straggling to produce a broader end-point distribution, thus distributing the heat deposition over a broader range. Since the temperature 750°C that corresponds to the boiling point at the operating pressure of ~ 1 torr at $x = \sim 11.2 \text{ mm}$ into the lithium is achieved assuming no energy spread of the deuteron beam, any energy spread, whether natural to the cw beam or intentionally imposed on the beam, will further decrease the maximum temperature below this value.

The third mitigating effect on vapor formation is harder to evaluate in a dynamic system such as the flowing thick film. In equilibrium, when the boiling point of a liquid is reached, the substance cannot be made to "boil" until additional heat equal to the latent heat of vaporization is added to the liquid. With the enormous latent heat of liquid lithium, $22 \times 10^3 \text{ J/g}$ at 750°C , there is a large safety factor built in which allows a much higher "effective" temperature rise than 750°C . The solution to the hydrodynamical equations of flow for the film assuming heat input for a monoenergetic beam with straggling, and including the effect of the latent heat indicates that the velocity of the film could be lowered from 10 m/sec to 1 m/sec with no problem if one was willing to accept some vaporization (see Appendix D). This would not be practical, since the temperature of the lithium coming from the catch basin to the heat exchangers would then be 750°C . The highest desirable temperature in the loop is 300°C to 400°C to keep corrosion to a minimum, corrosion being more severe

at high temperatures. No advantage, then, will be made of the high latent heat of lithium in the target design except as a safety factor.

A P P E N D I X D

FLOW AND SIMULATION OF A LIQUID LITHIUM
SHEET UNDER INTENSE DEUTERON
BOMBARDMENT

by

TADEUSZ M. DRZEWIECKI
HARRY DIAMOND LABORATORIES
FLUIDIC SYSTEMS RESEARCH BRANCH
ADELPHI, MARYLAND 20783
APRIL 1975

ABSTRACT

This paper is a final report on Brookhaven National Laboratory Contract no. 352035S regarding the flow properties and simulation of a liquid lithium sheet bombarded by 30 MeV Deuterons. This information is to be used in the design of an intense neutron emission test facility for the determination of mechanical properties of materials under 14 MeV neutron bombardment typical of Controlled Thermonuclear Reactors (CTR). The problem has been formulated in terms of a sheet of incompressible fluid with a uniform velocity distribution with energy deposition in the depth dimension over a specified area. The governing equation for the temperature distribution is a non-homogeneous second order partial differential equation in two dimensions (the depth and streamwise directions). Using a modified separation of variables technique, an infinite series, eigen-value solution is found. The huge amount of energy deposition however causes some computational difficulties, and for that reason a simple one-dimensional approximation is justified since the full solution indicates that the only significant temperature gradients are in the streamwise dimension in the region of energy deposition. If 3 megawatts are deposited uniformly in the fluid it is found that the maximum temperature rise can be kept to 300°C if the mean flow velocity is 2.4 m/s. When realistic energy deposition function is included it is found that the stream velocity must be about 10 m/s to keep the temperature below the boiling point for the given internal pressure. However, if the incident energy is allowed to be absorbed by the enormous latent heat of vaporization of lithium the velocity may be reduced to 1 m/s keeping a large part of the flow at the vaporization temperature. The resultant Weber

number for the free surface flow is 23, and the associated nozzle-width Reynolds number is 1.6×10^4 . Using these two similarity parameters alone it is not possible to simulate the lithium flow, however introducing the modified Reynolds number permits ready similitude by noting that the additional variable of nozzle length permits the formation of two flows both with identical nozzle exit velocity profiles and identical free surface properties. A short nozzle for water simulation will provide information for the longer nozzle lithium flow. Suggested nozzle plan-views are presented. A simple stability analysis indicates that under the conditions stated the flow should be laminar and photographic evidence seems to verify the laminarity of the flow.

NOMENCLATURE

A	- constant of integration
A_i	- beam incident area, m^2
A_c	- flow cross-sectional area, m^2
b	- sheet thickness, nozzle width, m
B	- constant of integration
c	- specific heat capacity, $m^2/s^2/^\circ C$
c_d	- nozzle discharge coefficient, -
$C_{1,2}$	- constants of integration
D_n	- constant of integration
D	- nozzle constant, -
e	- energy, J
E_n	- constant of integration
F	- force, N
F_n	- constant of integration
G_n	- constant
h	- convective heat transfer coefficient, $kg/s^3/^\circ C$
I	- current, amperes
k	- thermal conductivity, $kg \cdot m/s^3/^\circ C$
L	- length, m
L_v	- latent heat of vaporization, J/kg
m	- mass, kg
m_a	- mass per particle, kg/part
$\dot{m}$	- mass flow rate, kg/s
N_B	- Biot Modulus, hb/k , -
N_p	- Peclet Number, $bU\rho c/k$, -
N_R	- Reynolds number, $\rho Ub/\mu$, -
N_R'	- modified Reynolds Number, $N_R/((L_N/b)(1 + 1/\sigma)^2)$, -
p	- pressure, N/m^2
q	- power, watts

- q''' - power per unit volume, watt/m³
- $r_{1,2}$ - roots of differential equation 7
- t - time, s
- T - temperature, °C
- u - velocity component in x-direction, m/s
- U - free stream velocity in x-direction, m/s
- v - velocity component in y-direction, m/s
- V - velocity, m/s
- w - velocity component in z-direction, m/s
- x - coordinate dimension, m
- X - separation variable for independent variable x
- y - coordinate dimension, m
- Y - separation variable for independent variable y
- z - coordinate dimension, m

Greek Symbols

- δ - boundary layer thickness, m
- δ^* - displacement thickness, m
- θ - dimensionless temperature variable, $(T - T_\infty)/(T_0 - T_\infty)$
- λ_n - eigen value, -
- μ - absolute viscosity, N · s/m²
- ν - kinematic viscosity, m²/s
- ρ - density, kg/m³
- σ - aspect ratio, L_z/b , -
- τ - surface tension, N/m
- ϕ - variable for removal of non-homogeneity from eq. 3

Subscripts

H_2O	-	water
i	-	incident
Li	-	lithium
n	-	integer
N	-	nozzle
o	-	$x = 0$ condition
v	-	vaporization temperature condition
x	-	x -direction
y	-	y -direction
z	-	z -direction
∞	-	ambient condition

1. INTRODUCTION

With the advent of Controlled Thermonuclear Reaction, a design technology for the CTR components will be required. The environment of a controlled thermonuclear reaction is one of intense neutron emission. Containers will have to be designed to hold the reaction and subsequent by-products, however the mechanical properties of materials are unknown when subjected to the expected 14 MeV neutrons. To determine these mechanical properties a test facility has been proposed by the Brookhaven National Laboratory¹ which utilizes the emission properties of Lithium when bombarded by high energy deuterons. The deuterons would be accelerated in a linear accelerator (LINAC) to 30 MeV and impinged on a target area of lithium. The resultant reaction will produce an emission of 14 MeV neutrons in a plane field from the bombarded area, as opposed to a point source where the strength decays as the square of the distance from the source. The intense energy deposition within the lithium may, however, raise the temperature above the melting and even the boiling point. Thus the removal of heat is of paramount importance. In light of this heat removal problem Brookhaven¹ has suggested that the system be operated with a liquid lithium sheet, and that with an appropriate mass-flow-rate the total incident (approximately 3 Megawatts) energy can be convected away as heat, maintaining a desired lithium temperature. Experimental design of such a system, however, is hampered by the difficulty of working with liquid lithium, but if the flow can be simulated in a room-

¹BNL Memorandum from A. Romano et. al. to J. Hendrie, dated 11/13/74 and revised 1/21/75.

temperature liquid, such as water, then visual examination of the surface conditions and sheet continuity can be made quite readily.

The determination of a modified Reynolds number by Drzewiecki², that relates the discharge coefficient of any given planar nozzle to any other nozzle, allows one to have different nozzles with essentially identical exit velocity profiles. This Reynolds number includes the nozzle length in addition to its width and height (e.g. as in wetted perimeter). This added parameter, nozzle length, will allow the matching of the viscous/stability effects, through modified Reynolds number in addition to the free surface, surface-tension effects through the Weber number, in any simulation of the lithium flow.

It is then the purpose of this paper to: present an analysis of the flow and temperature field of the liquid lithium sheet; determine the appropriate flow rate for the adequate convection of the heat deposited; and present nozzle designs for both the actual lithium target and the simulation fluid. In addition a simple stability analysis will be presented to determine the nature of the flow (laminar or turbulent) and photographic evidence of a water sheet will be shown to support the analysis and to demonstrate the optical clarity of the flow.

2. ANALYSIS

2.1 Statement of the Problem

Consider a jet of fluid issuing from a nozzle into essentially a vacuum or at worst a low-pressure and density gas, with a free surface

²Drzewiecki, T. M., "Fluerics 37: A General Planar Nozzle Discharge Coefficient Representation," Harry Diamond Labs Technical Memorandum HDL-TM-74-5, August 1974.

on one side and bounded on the three other sides by essentially rigid, non melting, high thermal conductivity metal plates. The jet is formed in a smooth nozzle and the flow field is depicted in figure 1.

Figure 1. Conceptual view of liquid lithium target

Consider, further, that the liquid sheet is being bombarded by deuterons so that energy is being deposited in the fluid as a function of the depth dimension, and that it can be considered as internal energy

generation within the fluid. If it is assumed that edge effects are negligible then a temperature distribution will be expected in the streamwise or x-direction and in the depth dimension y. Furthermore if the Reynolds number of the nozzle flow is sufficiently high (> 10000) then the exit velocity is essentially uniform and there are no appreciable boundary layers.

2.2 General Solution

The energy equation for an incompressible, constant conductivity moving fluid with internal energy generation is given as equation 1.

$$\rho c \left[\frac{\partial T}{\partial t} + u \frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} + w \frac{\partial T}{\partial z} \right] = k \left[\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right] + q'''(y) \dots \quad (1)$$

where

- ρ = fluid density
- c = fluid specific heat
- k = fluid thermal conductivity
- $q'''(y)$ = rate of internal energy generation per unit volume
- T = fluid temperature
- x, y, z, t = independent variables
- u, v, w = velocity components x, y, and z-direction

The following assumptions simplify eq. 1:

1. Steady state - $\partial/\partial t = 0$.
2. Uniform velocity - $u = U, v = w = 0$.
3. No edge effects - two dimensionality - $\partial/\partial z = 0$

The application of the above assumptions leads to eq. 2.

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} - \frac{U \rho c}{k} \frac{\partial T}{\partial x} + \frac{q'''(y)}{k} = 0 \quad (2)$$

The boundary conditions for this equation are:

1. Negligible heat transfer through the free surface to the vacuum - $\left. \frac{\partial T}{\partial y} \right|_{y=0} = 0$. (For a surface temperature of 500°C the radiation heat transfer is about 130 watts compared to the 3×10^6 watts converted by the flow.)
2. Heat transfer through the back plate is essentially the same as convective heat transfer to the back surroundings if plate material thermal resistance is low comparable to convective resistance of the air.

$$k \left. \frac{\partial T}{\partial y} \right|_{y=b} = -h (T(x, b) - T_{\infty}).$$

where h is the film coefficient.

3. The flow leaves the nozzle at a constant uniform temperature - $T(0, y) = T_0$.
4. As the flow passes the deuterium bombardment region the temperature becomes constant in the streamwise direction - $\frac{\partial T}{\partial x}(L, y) = 0$.

The governing equation (eq. 2) is a linear, dimensional non-homogeneous partial differential equation, with two homogeneous and two non-homogeneous boundary conditions. By an appropriate non-dimensionalization the second boundary condition can be made homogeneous.

Let

$$x' = x/b \text{ and } y' = y/b$$

and

$$\theta(x', y') = \frac{T(x', y') - T_{\infty}}{T_0 - T_{\infty}}$$

The normalized governing PDE becomes eq. 3. (Note that the ' has been dropped for simplicity).

$$\frac{\partial^2 \theta}{\partial x^2} - N_p \frac{\partial \theta}{\partial x} + \frac{\partial^2 \theta}{\partial y^2} + \frac{q'''(y)b^2}{k\Delta T} = 0 \quad (3)$$

where

$$N_p = \text{Peclet number} = \frac{bU\rho c}{k}$$

b = sheet thickness

$$\Delta T = T_0 - T_\infty$$

The boundary conditions become:

1. $\frac{\partial \theta}{\partial y}(x, 0) = 0$
2. $\frac{\partial \theta}{\partial y}(x, 1) = -\frac{hb}{k} \theta(x, 1)$
3. $\theta(0, y) = 1$
4. $\frac{\partial \theta}{\partial x}(L, y) = 0$

Conditions 1, 2 and 4 are homogeneous.

Equation 3 can be readily solved by separation of variables if the non-homogeneity due to the energy deposition is removed. This can be done by assuming a solution in the form

$$\theta(x, y) = X(x)Y(y) + \phi(y)$$

Equation 3 then becomes

$$Y(y) \frac{d^2 X}{dx^2} - N_p Y(y) \frac{dX}{dx} + X(x) \frac{d^2 Y}{dy^2} + \frac{d^2 \phi}{dy^2} + \frac{q'''(y)b^2}{k \Delta T} = 0$$

Letting

$$\frac{d^2 \phi}{dy^2} + \frac{q'''(y)b^2}{k \Delta T} = 0 \quad \dots(4)$$

then the separated equations become

$$\frac{1}{X(x)} \frac{d^2 X}{dx^2} - \frac{N_p}{X(x)} \frac{dX}{dx} = -\frac{1}{Y(y)} \frac{d^2 Y}{dy^2} = \lambda_n^2 \text{ (constant)} \quad \dots(5)$$

with the boundary conditions:

$$1. \quad \frac{\partial \theta}{\partial y}(x, 0) = 0 \quad X(x) \frac{dY}{dy} + \frac{d\phi}{dy} = 0$$

$$\frac{dY(0)}{dy} = \frac{d\phi(0)}{dy} = 0$$

$$2. \quad \frac{\partial \theta}{\partial y}(x, 1) = -\frac{bh}{k} \theta(x, 1) \rightarrow X(x) \frac{dY}{dy} + \frac{d\phi}{dy} = - (X(x)Y(1) + \phi(1)) \frac{hb}{k}$$

$$\frac{dY(1)}{dy} = -\frac{hb}{k} Y(1) ; \quad \frac{d\phi}{dy} = -\frac{hb}{k} \phi(1)$$

$$3. \quad \theta(0, y) = 1 \quad X(0)Y(y) + \phi(y) = 1$$

$$X(0) = \frac{1 - \phi(y)}{Y(y)}$$

$$4. \quad \frac{\partial \theta}{\partial x}(L, y) = 0 \quad \frac{dX(L)}{dx} = 0$$

Note that boundary condition 3 now is a matching condition between the two solution sets.

The governing equations 4 and 5 now will yield to analysis noting that equations 5 are both homogeneous and the Y equation has two homogeneous boundary conditions and is in the Sturm-Liouville form.

The solution to equation 4 is simply

$$\phi(y) = -\frac{b^2}{k\Delta T} \int [sq'''] dy + C_1 y + C_2 \quad \dots(6)$$

Boundary condition 1 demands that $C_1 = 0$. Boundary condition 2 demands that

$$C_2 = \frac{b}{\Delta T} \left[\frac{1}{h} \int q'''(y) dy + \frac{b}{k} \iint q'''(y) dy dy \right]_{y=1} \quad \dots(6a)$$

where $q'''(y)$ is a known function of the depth y. Therefore eq. 6 becomes

$$\phi(y) = -\frac{b^2}{k\Delta T} \iint q'''(y) dy dy + C_2 \quad \dots\dots\dots (6b)$$

Equation 5 for X and Y may now be solved. The X equation is

$$\frac{d^2 X}{dx^2} - N_p \frac{dX}{dx} - \lambda_n^2 X(x) = 0 \quad \dots\dots\dots (7)$$

and the Y equation

$$\frac{d^2 Y}{dy^2} + \lambda_n^2 Y(y) = 0 \quad \dots\dots\dots (8)$$

The solution of the Y equation, eq. 8, is

$$Y(y) = A \cos \lambda_n y + B \sin \lambda_n y \quad \dots\dots\dots (9)$$

The boundary condition 1 stipulates that $\frac{dY(0)}{dy} = 0$, which yields that

$B = 0$. Boundary condition 1 at the convective side yields the eigen value λ_n where,

$$\lambda_n \tan \lambda_n = \frac{hb}{k} \equiv N_B \quad \dots\dots\dots (10)$$

where $\frac{hb}{k}$ is defined as the Biot Number or Modulus, N_B . Equation 10

is a transcendental equation whose value for λ_n approaches $(n - 1) \pi/2$ for

$N_B \gg 1$ for $n = 1, 2, 3, \dots$. The Y solution is thus

$$Y(y) = \sum_{n=1}^{\infty} A_n \cos \lambda_n y \quad \dots\dots\dots (11)$$

The solution of the X equation, eq. 7, is

$$X(x) = D_e e^{r_1 x} + E_e e^{r_2 x} \quad \dots\dots\dots (12)$$

where

$$r_{1,2} = \frac{N_p}{2} \pm \sqrt{\left(\frac{N_p}{2}\right)^2 + \lambda_n^2} \quad \dots\dots\dots (13)$$

Application of boundary condition 4, where $\frac{dX(L)}{dx} = 0$, results in,

$$D_n = \frac{E_n}{2\lambda_n^2} \left\{ e^{-2L \sqrt{\frac{N_p^2}{4} + \lambda_n^2}} \left[N_p^2 - 2N_p \sqrt{\frac{N_p^2}{4} + \lambda_n^2} + 2\lambda_n^2 \right] \right\} \quad (14)$$

The X solution is therefore,

$$X(x) = E_n \frac{r_1^2}{2\lambda_n^2} e^{-2L\sqrt{\frac{N_p^2}{4} + \lambda_n^2}} e^{r_1 x} + e^{r_2 x} \dots (15)$$

where E_n is an as yet undefined constant and $r_{1,2}$ are given by eq. 13.

The solutions for X and Y are now multiplied together and it is noted that the multiplication of the two constants A_n and E_n results in a new constant F_n .

$$X(x)Y(y) = \sum_{n=1}^{\infty} F_n \left\{ \frac{r_1^2}{2\lambda_n^2} e^{-2L\sqrt{\frac{N_p^2}{4} + \lambda_n^2}} e^{r_1 x} + e^{r_2 x} \right\} \cos \lambda_n y \quad (16)$$

Boundary condition 3 can now be used to solve for the constant F_n where $X(0)Y(y) = 1 - \phi(y)$, with

the orthogonality criteria of the Sturm-Liouville solutions,

When $x = 0$ equation 16 reduces to a function of y only with a new constant equal to G_n where

$$G_n = F_n \left\{ \frac{r_1^2}{2\lambda_n^2} e^{-2L\sqrt{\frac{N_p^2}{4} + \lambda_n^2}} + 1 \right\} \dots (17)$$

which results in an equation

$$1 - \phi(y) = \sum_{n=1}^{\infty} G_n \cos \lambda_n y \dots (18)$$

By orthogonality, and noting that, from the Sturm-Liouville equation,

eq. 8, the weighting function is identically equal to 1, then over the interval $y = 0$ to $y = 1$,

$$G_n = \frac{\int_0^1 (1 - \phi(y)) \cos \lambda_n y \, dy}{\int_0^1 \cos^2 \lambda_n y \, dy} \quad \dots\dots\dots (19)$$

or

$$G_n = \frac{\sin \lambda_n - \lambda_n \int_0^1 \phi(y) \cos \lambda_n y \, dy}{\frac{\lambda_n}{2} + \frac{\sin 2 \lambda_n}{4}} \quad \dots\dots\dots (20)$$

where $\phi(y)$ is given in equation 6b. The solution to the entire non-homogeneous governing partial differential equation is then,

$$\theta(x, y) = \left\{ \sum_{n=1}^{\infty} F_n \left[\frac{r_1^2}{2\lambda_n^2} e^{-2L\sqrt{\frac{Np^2}{4} + \lambda_n^2}} e^{r_1 x} + e^{r_2 x} \right] \cos \lambda_n y \right\} - \frac{b^2}{k\Delta T} \iint q'''(y) \, dy \, dy + C_2 \quad \dots\dots\dots (21)$$

where F_n is obtained from eqs 17 and 20, C_2 from eq 6a, and $r_{1,2}$ from eq 13.

Equation 21 is unwieldy and difficult to set up numerically due to the large values involved in the exponents when typical values for this problem are substituted. It is however an exact solution.

2.3 Approximate Solution

Intuitively one would not expect much thermal redistribution of the deposited energy due to conduction if the flow rate is sufficiently high. If one makes an order of magnitude analysis of the governing PDE, eq 3, then it is apparent that only the convective term and the internal energy terms are important. This is shown in equation 22.

$$\underbrace{\frac{\partial^2 \theta}{\partial x^2}}_1 - N_p \underbrace{\frac{\partial \theta}{\partial x}}_2 + \underbrace{\frac{\partial^2 \theta}{\partial y^2}}_3 + \underbrace{\frac{q'''(y)b^2}{k\Delta T}}_4 = 0 \quad \text{..... (22)}$$

The temperature variable θ may vary from 1 at $x = 0$ to a value $(T_v - T_\infty)/(T_0 - T_\infty)$ where T_v is the vaporization temperature of lithium. Typical values would be about 3 to 4, thus the temperature differential is low and of the order of (1). The x-dimension is between 1 and 5 and the y-dimension is 1, both then which are of order 1. For typically expected flow velocities of 1 - 10 m/s, N_p may take on values between 10^3 and 10^4 . The values of the energy deposition term are likewise high. This then results in the conduction terms in both x and y directions (1 and 2) being negligible. The simplified governing equation is then,

$$N_p \frac{\partial \theta}{\partial x} = \frac{q'''(y)b^2}{k\Delta T}$$

or rewriting in dimensional form

$$\frac{\partial T}{\partial x} = \frac{q'''(y)}{\rho c U} \quad \text{..... (23)}$$

with the boundary condition that $T(x=0) = T_0$ results in the solution,

$$T(x) = \frac{q'''(y)}{\rho c U} x + T_0 \quad \text{..... (24)}$$

The temperature rises linearly in the streamwise direction.

If one assumes that the energy is deposited uniformly in the fluid then $q'''(y) = \text{constant}$. In the case at hand a 100 mA flow of 30 MeV deuterons impinging on the lithium deposit 3 megawatts or $q''' = 3 \times 10^6 \text{ kg m}^2/\text{s}^3$. Table I lists the values of the important physical and thermodynamic properties of liquid Lithium.

Table I Physical and Thermodynamic Properties
of Liquid Lithium³

Mass density	-	530 kg/m ³	-8
Specific heat capacity	-	4186.8 m ² /s ² /°C	- c
Thermal conductivity	-	46.8 kg m/s ³ /°C	- k
Latent heat of vaporization	-	22.777 x 10 ⁶ J/kg	- L
Absolute viscosity	-	0.5 x 10 ⁻³ N s/m (T = 200°C)	- μ
Surface tension	-	350 x 10 ⁻³ N/m	- τ

If the temperature is not to exceed 500°C or when $T_0 = 200^\circ\text{C}$ a temperature rise not to exceed 300°C then the velocity of the fluid required for a cross sectional area A of .02 m² is:

$$U = q''' L_x / \rho c \Delta T = q / \rho c A \Delta T = 2.25 \quad \text{..... (23)}$$

where q is total power deposited, and for a temperature rise of 600°C:

$$U = 1.125 \text{ m/s}$$

Unfortunately uniform energy deposition does not occur in this problem. The energy of a deuteron decays in a medium of liquid lithium as shown in Figure 2.⁴ From this figure it is apparent that a 30 MeV deuteron has a range of 11.22 mm in the liquid lithium, in other words it will be stopped in that distance. The peak change in energy per unit depth, assuming straggling⁴ (energy dispersion), occurs at about 0.17 mm from the range and is 12.5 MeV/mm. The energy deposited per unit time per unit volume, q''' , is obtained from the deuteron current, the cross-sectional area and the change in particle energy per unit depth as:

$$q''' = \frac{I}{A_i} \frac{de}{dy} \quad \text{..... (24)}$$

³Cairns, E. J., Cafasso, F. A., and Maroni, V. A., "Lithium in Fusion Reactors: A Review", August 1972.

⁴Personal Communication with C. L. Snead of Brookhaven, 21 March 1975 (Deuteron Energy and Energy Deposition as a function of distance)

FIGURE 2. DEUTERON ENERGY AND ENERGY DEPOSITION VS. PENETRATION DEPTH

where

I - current $\equiv$ no. particles/sec

A_i - incident area - $m^2 = L_z \cdot L_x$

de - change of energy per particle - J

dy - change of length

$L_{x, z}$ - are streamwise length and lateral width of sheet

Therefore as can be seen eq. 24 yields an answer whose dimensions are in power (rate of energy with time) per unit volume. Substituting eq 24 into equation 23 we get

$$U = \frac{\frac{I}{A_i} \frac{de}{dy} L_x}{\rho c \Delta T} = \frac{I \frac{de}{dy}}{\rho c L_z \Delta T} \quad \dots (25)$$

where it should be noted that the stream velocity is independent of the streamwise length over which the deuteron beam acts.

The allowable temperature rise depends on the vaporization temperature which in turn is dependent on the absolute pressure of the flow. Using a simple momentum transfer approach⁴ the incident pressure can be determined, in a non-relativistic calculation. For an energy per particle of 30 MeV and a total energy deposited per second of 3×10^6 J/s, and noting that $\Delta e = 1/2 m \Delta V^2$ or $1/2 \frac{(\Delta m V)^2}{m}$, then the particle change in momentum per unit time $\frac{\Delta m V}{\Delta t}$ is $(2 \frac{\dot{m} \Delta e}{\Delta t})^{1/2}$. The mass per second is

$$\dot{m} = m_a I$$

where m_a is mass per particle, I number of particles per second. The mass is the atomic mass multiplied by the atomic mass unit. Therefore for 100 mA of current and atomic mass of 2.01, the force exerted on the surface is:

$$\frac{\Delta(mv)}{\Delta t} = (2 \times 2.01 \times 1.667 \times 10^{-27} \times 6 \times 10^{17} \times 3 \times 10^6)^{1/2}$$

atomic
kg/
part/s
J/s
mass/part
atomic
mass

$$F = 0.11 \text{ N}$$

The pressure exerted is the force per unit incident area or F/A_i . For an area $10 \text{ cm} \times 1 \text{ cm}$ the pressure is 110 N/m^2 (0.83 torr) and for $10 \text{ cm} \times 3 \text{ cm}$ the pressure is 37 N/m^2 (0.28 torr). The vaporization temperature of liquid lithium is obtained from the equation for vapor pressure versus temperature as given in reference 3.

$$T_v(^{\circ}\text{C}) = 8100/(8 - \log_{10} P_v) - 273 \quad \text{..... (26)}$$

The melting temperature is relatively constant at about 180.6°C thus for this problem to provide a margin of error the initial temperature of the lithium can be assumed as 200°C . Substituting this information and an expression for the pressure, $p = .11/A_i$ into eq. 26 results in an expression for allowable temperature rise as a function of incident area or:

$$\Delta T = 8100/(11.1 + \log_{10} A_i) - 473 \quad \text{..... (27)}$$

Substituting this equation into eq 25 yields an equation for minimum velocity required to maintain a temperature rise less than the vaporization temperature.

$$U = I \frac{de}{dy} / [\rho c L_z (8100/(11.1 + \log_{10} A_i) - 473)] \quad \text{..... (28)}$$

For $(de/dy)_{\text{max}} = 12.5 \text{ MeV/mm}$ (from figure 2) and for

$$A_i = 10 \text{ cm} \times 10 \text{ cm} ; U = 13.5 \text{ m/s}$$

$$A_i = 10 \text{ cm} \times 3 \text{ cm} ; U = 11.95 \text{ m/s}$$

and

$$A_i = 10 \text{ cm} \times 1 \text{ cm}; U = 10.69 \text{ m/s}$$

The above calculated velocities correspond to no absorption of heat by the latent heat of vaporization, which is quite considerable. Allowing the total heat buildup to include the latent heat may considerably reduce the velocity required.

If an energy balance is made assuming now that the temperature of the fluid is at the vaporization temperature the result is an equation similar to eq. 23 where

$$U = q''' L_x / \rho L \quad \text{..... (29)}$$

where

L - latent heat of vaporization

Writing eq 29 in terms of the current and energy deposition yields

$$U = \frac{I}{\rho L L_z} \frac{de}{dy} \quad \text{..... (30)}$$

which is independent of streamwise length and which for the present problem yields $U = 1.0 \text{ m/s}$, for the maximum energy deposition of 12.5 MeV/mm , using the values of table I and $L_z = 10 \text{ cm}$. This is an order of magnitude lower than if no heat absorption were allowed and is clearly the most advantageous mode of operation. By substituting into equation 25, $U = 1 \text{ m/s}$ and solving for the distance L_x at which the maximum temperature rise occurs for the different values of energy deposition with depth results in the fact that the streamwise location of the vaporization temperature, T_v , varies. For the value of de/dy given in figure 2, and a stream velocity of 1.0 m/s the temperature distributions

are shown in figures 3, 4 and 5. Figure 3 shows the linear temperature rise to T_v and then constant with streamwise distance. Figure 4 shows the depth wise temperature profiles and Figure 5 shows the isotherms at the vaporization temperature and the temperature for half of the temperature rise.

For the depth dimension past the point of maximum deposition the temperature drops to the initial temperature since even without energy deposition the convective term in eq 22 is still dominant, and the conduction terms are negligible. The graphs in figures 3, 4, and 5 have assumed a depth of fluid at 2 cm, but it is clear that one could reduce this considerably to as low as 1.2 cm. The only question would arise is that of boundary layer growth that would affect the streamwise velocity. For this reason the boundary layer thickness at the nozzle exit should be determined, noting that if flow is in the direction of gravity a favorable pressure gradient exists and thus the boundary layer thickness at the nozzle is a conservative value.

For a stream velocity of 1 m/s the nozzle exit Reynolds number is

$$N_R = \frac{\rho U b}{\mu} = \frac{530 \times 1 \times 0.02}{.5 \times 10^{-3}} = 2.12 \times 10^4$$

The modified Reynolds number $N_R' = N_R / [L_n / b (1 + 1/\sigma)^2]$ where L_n is the nozzle length and σ the nozzle aspect ratio.² For even a very long nozzle $L_n \sim 10 b$ $N_R' > 2000$ and the discharge coefficient c_d is about 0.9 (see ref 2). For large aspect ratio the discharge coefficient may be approximated by the function²:

$$c_d = (1 - 2 \frac{\delta^*}{b}) \quad \dots (31)$$

FIGURE 3. STREAMWISE TEMPERATURE DISTRIBUTION - $B = 2\text{CM}$

FIGURE 4. DEPTH TEMPERATURE DISTRIBUTION - $L=10\text{CM}$

FIGURE 5. ISOTHERMS - $B = 2\text{CM}$

where δ^* is the nozzle exit displacement thickness. Now noting that the boundary layer thickness, δ , is about 3.3 δ^* the expression for δ is then

$$\frac{\delta}{b} = (1 - c_d)/0.6 \approx .17$$

In other words the boundary layer thickness is 17% of the width. Reducing the width to 1.5 cm does not appreciably change the percentage, thus 12.45 mm of the 15 mm depth is at the stream velocity. The Reynolds number is then reduced to 1.6×10^4 . A simple flow stability analysis conducted in reference 5 indicates that the flow in a nozzle will stay stable (laminar) up to Reynolds numbers $N_R = 1.764 \times 10^5/D^2$ where:

$$D = 1.75 \sqrt{L_N} \quad (\text{see ref 2 and 5})$$

One can then solve for the required length of nozzle by equating the critical Reynolds number to the required flow Reynolds number, yielding $L_n = 3.6$. This is then equivalent to a nozzle with a moderate contraction and a straight section of 2.6 b. Such a nozzle is shown in figure 6.

2.4 Flow Simulation

In order to visually observe the flow without having to resort to the difficulties of liquid Lithium the flow can be simulated using another fluid such as water. The two flow parameters that are important are the Reynolds number which relates the inertial to the viscous forces and the Weber number which relates the viscous forces to the surface

⁵Drzewiecki, T. M., "Fluerics 34: Planar Nozzle Discharge Coefficients," Harry Diamond Labs Technical Memorandum, HDL-TM-72-33, September 1973.

tension forces on the free surface of the sheet. The Weber number is defined as

$$N_w = \frac{\rho b U^2}{\tau} \quad \dots (32)$$

and is evaluated as $N_w = 22.7$ for $U = 1.0$ m/s and $b = 1.5$ cm, using values for ρ and τ from table I. For water to have the same Weber number requires that

$$(b U^2)_{H_2O} = N_{w,Li} \frac{\tau_{H_2O}}{\rho_{H_2O}} \quad \dots (33)$$

For water $\rho = 10^3$ kg/m³ and $\tau = 76.2 \times 10^{-3}$ N/m thus

$$(b U^2)_{H_2O} = \frac{22.7 \times 76.2 \times 10^{-3} \text{ N/m}}{10^3 \text{ kg/m}^3} = 1.73 \times 10^{-3} \frac{\text{m}^3}{\text{s}^2}$$

Substituting this value into the Reynolds number where $N_R = \frac{\rho U b}{\mu} = \rho U^2 b / \mu U = 1.6 \times 10^4$ and solving would require $U_{H_2O} = 0.108$ m/s, and $b \approx 15$ cm which would be quite cumbersome. It is important that the Reynolds number give a measure of the velocity distribution in the flow. When the modified Reynolds numbers of two nozzle flows are equal the discharge coefficients are equal and so, therefore, are the velocity distributions. The lithium modified Reynolds number is $N_R' = N_R / (L_N / b (1 + 1/\sigma)^2) = 3.36 \times 10^3$ for $\sigma = 10/1.5$. Holding the same aspect ratio between the two flows results in

$$U_{H_2O} = 0.1153 \frac{(L_N/b)_{Li}}{(L_N/b)_{H_2O}} \quad (34)$$

Since the shortest length nozzle allowed is $1.0 b$ and the Lithium nozzle is $3.6 b$ then the maximum water velocity possible is

$$U_{H_2O}|_{\max} = 0.1153 (3.6) = 0.415 \text{ m/s}$$

Figure 6. Schematic of Lithium prototype nozzle

Figure 7. Schematic of water simulation nozzle

whence

$$b_{\max, H_2O} = .01 \text{ m} = 1.0 \text{ cm} \quad \text{since } bU^2 = 0.00173.$$

The nozzle width will be two-thirds that of the actual Lithium prototype, as shown in figure 7.

The resultant flow is stable by the criterion of the previous section.

Figure 8 shows the water simulation model made of plexiglas.

Figure 9 shows the clarity of the flow under operating conditions. Note the smooth free surface. By not allowing the flow to take any sharp turns the velocity distribution at the exit is virtually straight with no cross-currents to make the surface wavy.

3. SUMMARY AND CONCLUSIONS

This report has presented a solution, in general and approximate form, of the flow of a liquid Lithium sheet bombarded by an intense beam of 30 MeV deuterons at 100 mA. By using the latent heat of vaporization it is possible to have the total incident energy convected away using a stream velocity of about 1 m/s. There is no appreciable heat conduction in any direction in the bombarded field. Even if the flow were turbulent it is not felt that there would be sufficient effective thermal conduction. A simulation model is proposed using water to simulate the Lithium flow. The temperature field is not simulated -- only the flow characteristics. A nozzle 3.6 times shorter than the prototype is proposed with a 1 cm x 6.7 cm exit. The actual Lithium nozzle will be 1.5 cm x 10 cm with an effective length of 5.4 cm made up of a 3.9 cm straight section and a moderate contraction ratio of 7 to

Figure 8. Photograph of plexiglas water-simulation model

Figure 9. Photograph of simulated liquid target (water)

1 and a contraction length of 5 to 1. The temperature in the prototype will reach the vaporization temperature but should not vaporize. Expansion effects are expected to be countered by the acceleration of the flow in a downward direction.

The conclusion that can be made based on the analysis presented herein is that a 14 MeV neutron emission test facility is feasible using a liquid Lithium target. Further *in situ* tests and actual verification seems to be warranted.

APPENDIX E

SHIELDING CALCULATIONS FOR AN ACCELERATOR-BASED NEUTRON GENERATOR

Introduction

Two situations require biological shielding from neutrons released by nuclear interactions when deuterons stop in various materials.

a) Linac neutrons whose average energy increases at approximately a uniform rate as a consequence of spillage described in the text.

b) Experimental Cave neutrons of constant average energy from 0.1A, 30 MeV deuterons stopping in a thick, light metal, target under steady state conditions.

Calculations have been made to determine the thicknesses of ordinary construction concrete to reduce the neutron intensity rate to 1.11×10^4 neutrons $\text{ft}^{-2} \text{sec}^{-1}$ ($2.5 \text{ m rem hr}^{-1}$) (1).

Neutron sources

To simplify the calculations, the deuteron loss was assumed to occur at a sequence of points (4.75 ft apart) differing in energy by one MeV. Numerically this amounts to 2.115×10^{13} deuterons $\text{MeV}^{-1} \text{sec}^{-1}$.

The neutrons impinging upon the inner shield surface were summed vectorially for the incident neutron intensity rate. The summing was limited, for the case of the linac, only to those sources whose energy was above the Coulomb barrier estimated at about 8.5 MeV for the drift-tube bore materials, (Cu and Fe).

Neutron yield rate

The energy of the spilled deuterons $E_d \leq 30 \text{ MeV}$ will be degraded by the bore materials until they are no longer viable for neutron production (i.e. below 8.5 MeV when their residual range⁽²⁾ is 0.1 g cm^{-2}). If $R(E_d)$ is the entire range, then for a distance, $\Delta \rho_e = R(E_d) - 0.1 \text{ g cm}^{-2}$, the deuteron will have neutron production potential.

At each point, along $\Delta \rho_e$, there is an associated interaction cross section which appears as the solid curve on Fig. E-1 taken from ref. 3 for the $\text{Fe}^{56} (d, 2n) \text{Co}^{56}$ reaction. For a given incident deuteron energy, the average cross section $\sigma(E_d)$ was determined, and plotted on the dashed curve of Fig. E-1.

The neutron yield rate $\dot{Y}(E_d)$ for a source of energy E_d is:

$$\dot{Y}(E_d) = 2 \dot{S} \frac{N}{A} \sigma(E_d) \Delta \rho_e(E_d) \quad (1)$$

neutrons $\text{MeV}^{-1} \text{ sec}^{-1}$ where,

$2\dot{S} = 2 \times 2.115 \times 10^{13} \text{ deut MeV}^{-1}$. The 2 comes from the $(d, 2n)$ reaction

$N/A = \text{nuclei density, } \frac{(\text{Avogadro's no.})}{(\text{At. weight})}$

An average $\bar{A} = 60 \text{ g/mole}$ was used for the drift-tube bore materials.

Neutron angular distribution

The relative angular distribution $A(\theta)$ for 15 MeV deuterons on a thick Cu target has been published⁽⁴⁾.

Let $\dot{Y}(\theta, E_d)$ be the yield rate for neutrons sr^{-1} at θ from a source of energy E_d . Combining $\dot{Y}(E_d)$, the total yield, (eq. 1) with $A(\theta)$ gives

$$\dot{Y}_i(\theta, E_d) = \frac{\dot{Y}(E_d) A(\theta_i)}{\sum_i A(\theta_i) \Delta\omega(\theta_i)} \quad (2)$$

neutrons $\text{sr}^{-1} \text{ MeV}^{-1} \text{ sec}^{-1}$. The Σ is the normalizing factor needed because $A(\theta_i)$ is relative and was found numerically by dividing $A(\theta)$ into 18 equal subintervals of 5° each. $\Delta\omega(\theta_i)$ is a small solid angle containing θ

$$\Delta\omega(\theta_i) = 4\pi \sin \Delta\theta_o \sin \theta_i \text{ sr.} \quad (3)$$

where $\Delta\theta_o = 2.5^\circ$.

FIG. E-1

Beam stop and side shields

With reference to parts a) and b) discussed in the introduction, part a) pertains to a long narrow box formed by the concrete enclosure around the linac and part b) is concerned with a similar structure somewhat cubical in proportions. In both cases the end walls perpendicular to the deuteron beam direction act as beamstops and those parallel to the beam serve as sideshields.

The neutrons from a source travel a distance R ft, in air before striking an inner surface of the building wall and in so doing, their intensities are reduced from that given in (eq. 2) by a factor of $R^{-2} \text{ ft}^{-2}$. Let W ft be the perpendicular distance from the beam to a side wall, then

$$\frac{1}{R^2} = \frac{\sin^2 \theta}{(k W)^2} \quad (4)$$

where k is the fractional distance from the beam to the wall.

For a beam-stop $0 < k < 1$

For a side-shield $k = 1$

If $\dot{\phi}(E_d)$ is the neutron intensity $\text{ft}^{-2} \text{ MeV}^{-1} \text{ sec}^{-1}$, then from (2) and (4)

$$\dot{\phi}_j(\theta_j, E_d) = \frac{\dot{Y}(\theta_i, E_d)}{(k W)^2} \sin^2 \theta_i \quad (5)$$

where j identifies the source. The total neutron intensity $\text{ft}^{-2} \text{ sec}^{-1}$ is $\dot{\phi}$, the vector sum of (5) over the viable sources.

$$\dot{\phi}_{\text{in}} = \sum_j^{\rightarrow} \dot{\phi}_j \text{ neutrons } \text{ft}^{-2} \text{ sec}^{-1} \quad (6)$$

The sum was done graphically to find $\dot{\phi}$ at various intervals z down the linac for which there is a vector resultant taken as the scalar sum of (eq. 6) and an angle α which is the angle the resultant makes with beam direction.

Average neutron energy

Before the concrete thicknesses can be calculated, an interaction length for neutrons in the material must be known and this is dependent upon the average neutron energy $\bar{E}_n$.

The neutron intensity $I_n(E_n)$ per MeV has been reported for 15 MeV deuterons on a thick Cu target⁽⁵⁾ and the results take the form

$$I_n(E_n) \sim E_n e^{-E_n/\epsilon} \text{ neutrons MeV}^{-1} \quad (7)$$

where ϵ is about 2 MeV. One recognizes equation (7) as a Maxwellian distribution with the most probable value at its peak amounting to $\bar{E}_n = 4$ MeV, or nearly one-fourth the incident deuteron energy.

According to eq 6, the e^{-1} value for the interaction length in concrete can be expressed as

$$\lambda(\bar{E}_n) = 2.41 \bar{E}_n^{0.28} \text{ inches} \quad (8)$$

Concrete thicknesses

The incident neutron intensity rate given by eq (6), the interaction length $\lambda(\bar{E}_n)$ from eq. (8) and the critical flux rate for neutron $\phi_c = 1.11 \times 10^4$ neutrons $\text{ft}^{-2} \text{ sec}^{-1}$ ($2.5 \text{ m rem hr}^{-1}$), combine into the equation

$$\phi_{in} \exp \left(- \frac{D_c}{\lambda(\bar{E}_n)} \right) = \phi_c \text{ neutrons ft}^{-2} \text{ sec}^{-1} \quad (9)$$

where D_c is the distance in concrete (not thickness) required to satisfy eq (9). The direction α of the resultant flux intensity rate yields the thicknesses of the concrete, T_c ft. For beamstops

$$T_c = D_c \cos \alpha \text{ ft.} \quad (10a)$$

and for sideshields

$$T_c = D_c \sin \alpha \text{ ft.} \quad (10b)$$

If shielding materials other than concrete are considered, $\lambda_c (\bar{E}_n)$ for concrete can be scaled by density. For example

$$\text{Water: } \lambda_w = 2.4 \lambda_c$$

$$\text{Sand: } \lambda_s = 1.5 \lambda_c$$

The calculated thicknesses, T_c , are given in the following tables:

Linac

a) Beam stop

From equation (5), $W = 10'$. Beam-stop thicknesses have been calculated for $k = 0.2, 0.5, 0.8$ assuming 0.1% of a 0.1 amp deuteron beam is spilled uniformly along the linac axis.

TABLE E-1

End wall thicknesses, T_c in feet parallel to deuteron beam

k	0.2	0.5	0.8 - 8'
T_c	4.75	4.35	4.16

(k W) or 10 k is the perpendicular distance from the deuteron beam.

b) Sideshield

Z is the distance in feet from the entrance to the linac and $W = 10$ ft. Same conditions for the beam spill as a).

TABLE E-2

Sidewall thicknesses, T_c in feet perpendicular to deuteron beam

Z	134.	123.2	115.7	104.0	93.5
T_c	3.05	2.80	2.65	2.45	2.20
Z	85.2	75.3	64.9	52.2	<40'
T_c	2.05	1.90	1.70	1.43	None

Experimental caves

An experimental cave is assumed to be 12 feet long (target to backwall). A 0.1 amp deuteron beam of 30 MeV is stopped in a thick lithium target. The angle θ is the polar angle from the direction of the deuteron beam. For $\theta < 20^\circ$ the neutron beam strikes the backwall and for $\theta > 20^\circ$ it strikes a sidewall which is assumed to be 5 feet from and parallel to $\theta = 0^\circ$.

The angular distributions⁽⁷⁾ were interpolated for 30 MeV and extrapolated to 35° .

a) Back wall

TABLE E-3

Backwall thicknesses, T_c in feet in the direction from $\theta = 0$					
θ	0°	5°	10°	15°	20°
T_c	9.7	9.5	9.3	8.8	8.5

TABLE E-4

Sidewall thicknesses, T_c in feet in the direction from $\theta = 0$				
θ	20°	25°	30°	35°
T_c	3.1	3.6	4.2	4.1

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K. Batchelor	A. Goland	R. Lankshear
J.P. Blewett	P. Grand	W. Moore
J. Claus	D. Gurinsky	J. Sheehan
T.M. Drzewiecki (1)	J. Hendrie	T. Sheehan
R. Chasman	J. Kukkonen	L. Snead
R. Gluckstern (2)		R. Witkover

-
- (1) Harry Diamond Laboratories, Adelphi, Md. 20783
 - (2) U. of Maryland, College Park, Md. 20742