A deuteron linear accelerator capable of accelerating continuous 100 mA beam currents to an energy of 30 MeV and producing high energy neutrons via deuteron breakup on a liquid lithium target will be described. The facility will contain two 500-kV injectors providing D^+ and D^- beams allowing the operation of two experimental targets simultaneously. The D^+D^- beams will originate from low-emittance duoplasmatron sources, be first accelerated in single or double-gap electrostatic 500-kV accelerators, then injected into the linear accelerator for acceleration to 30 MeV. The 30-MeV linac is a drift-tube structure operating at 50 MHz and divided into eight cavities which will give the possibility to vary the final deuteron energy between 10 and 30 MeV. The deuteron beams will be transported to the targets in a 60-meter long channel designed to control the beam delivery on the target as to time structure, spot size, etc. The beam will be stopped on a flowing liquid-lithium target capable of removing the 3 megawatts of beam power produced. The target-neutron source parameters are described in the complementary paper titled: "Production and Use of Li(d,n) Neutrons for Simulation of Radiation Effects in Fusion Reactors," by A. Goland, et al.

INTRODUCTION

An AIF (Atomic Industrial Forum) study titled "Report on Industrial Participation in the Fusion Power Program" [1] states that..."The most severe problem associated with fusion reactors is seen to be that of the effects on reactor materials of 14-MeV neutrons and other high-energy particles generated in a D-T reactor... Evaluation of materials to be used, in the so-called, first wall...is considered to be the pacing requirement in development of the planned Experimental Power Reactor."

*Work performed under the auspices of the U.S. Energy Research and Development Administration
Spurred by the promises of CTR, interest in 14-MeV neutron radiation effects has greatly increased in recent years. Responding to this interest, a number of 14 MeV neutron sources based on the D-T reaction have been proposed.

This paper describes an extremely versatile, intense neutron source based on the acceleration of a 100-mA deuteron beam to 30 MeV followed by stripping in a liquid-lithium target. The resulting neutron intensity, whose energy spectrum is centered at ~ 14 MeV, will be $> 2 \times 10^{16}$ neutrons sec$^{-1}$ produced in the forward direction with a 2$\pi$ sr distribution, highly peaked, however, on the deuteron beam axis. The production process enables us therefore, to obtain neutron fluxes $> 10^{15}$ neutron cm$^{-2}$ sec$^{-1}$ in a volume adequate for experiments. Figure 1, showing neutron fluxes vs. distance from the source, compares different Brookhaven Li(d,n) source configurations with D-T sources.

The following describes the accelerator and target facilities to produce and stop a 100-mA, 30-MeV deuteron beam. The neutron source parameters and capabilities are described separately in the companion paper entitled: "Production and Use of Li(d,n) Neutrons for Simulation of Radiation Effects in Fusion Reactors," by A. Goland, et al. [2]

DESIGN CHOICES

The fundamental choice of the combination of the 30-MeV deuteron accelerator and its associated liquid-lithium target to produce an intense neutron source was motivated by the desire to find the best compromise between many factors: such as, cost, technical feasibility, operational reliability, flexibility, and not least, the desire to give the user a viable experimental facility, one which tries to anticipate, as much as possible, the experimenters needs.

Among the many types of accelerators developed for nuclear physics and high energy physics, the linear accelerator, with a so-called drift-tube structure, is the best type potentially capable of delivering high-intensity, high-duty factor beams, hence its choice for this application. Additional considerations reinforcing this choice are the ease and good controllability of the beam injection and extraction from the machine, minimizing the radiation problems around the accelerator. The design strongly reflects the experience gained to date with proton linacs in general, and particularly the experience of the Brookhaven National Laboratory linac team.

Similarly, the choice of the target design, aside from the neutron production efficiency, is based on achieving the most reliable system possible to withstand the severe operating conditions imposed. The proposed target design parameters are conservative and the lithium loop design is the result of many years experience at Brookhaven in the handling of liquid metals.

The proposed design whose main characteristics are shown in Table I has not yet been optimized. It constitutes however, a conservative approach to a working design based on experience and scaling of existing operating facilities.
The proposed accelerator-target system will provide unique characteristics:

a) The neutron beam exiting the source will be highly directional (forward peaked), thus allowing the production of high fluxes in a relatively large volume usable for experiments.

b) The deuteron beam flexibility allows the tailoring of the flux and equiflux contours to meet the requirements of a given experiment. Thus, it is expected that fluxes > \(10^{15}\) n cm\(^{-2}\) sec\(^{-1}\) can be achieved for high fluence, accelerated tests.

c) This same beam flexibility allows the production of neutrons in the form of millisecond pulses as well as a dc beam. It is thus able to simulate proposed fusion reactors. (e.g. Theta-pinch type reactors, steady state Tokamak types, etc...).

d) The facility can be operated at different deuteron energies to produce variable neutron energies in discreet steps of \(~2\) MeV between 5 and 14 MeV.

e) The facility with its four target caves and two simultaneous and independent deuteron beams, will give the users the utmost operational flexibility in being able to set up experiments in a target cave while conducting irradiation in another, and to have complete freedom in the utilization of the whole experimental volume available under any desired conditions.

In addition, and also one of the most important aspects of this proposal is the choice of systems utilizing state-of-the-art, proven technology in the accelerator field and liquid-metal handling to achieve a viable and reliable neutron radiation test facility. It is to be emphasized here that we do not foresee any major obstacles in reaching the \(10^{15}\) neutrons cm\(^{-2}\) sec\(^{-1}\) proposed here and that this facility could be made operational as early as 1981.

**LINAC DESIGN PARAMETERS AND BEAM CHARACTERISTICS**

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 proton source in the Brookhaven 200 MeV linear accelerator injector for the AGS. This source has operated at currents up to 0.5A in a pulsed mode, changes in its design are being studied to permit dc operation. The injection system layout is shown in Fig. 2. The high voltage equipment will consist of a 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 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. \[3\] This device consists of two fundamental frequency bunchers separated by an analyzing
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. 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.

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 aperture. In turn, the choice of large aperture determines the transit time factor for a given frequency, hence the acceleration efficiency of the linac. For a large drift-tube aperture, it is therefore desirable to operate at low frequencies. At the same time, considerations of available rf power-amplifier systems for the large amount of power required, limits our choice of frequencies to the VHF region. With these considerations in mind, we have chosen a linac operating frequency of about 50 MHz resulting in the 3.8 m diameter linac cavity. Table II lists the major cavity parameters as extrapolated from the 200 MHz, 200 MeV proton linear accelerator at BNL. These parameters are far from being optimized, they will serve however to establish a design basis for the machine.

BEAM DYNAMICS

The major design parameters affecting 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 \( \epsilon \)**: \( 3 \pi \times 10^{-4} \) mrad
- **Radio frequency \( f \)**: 50 MHz \( (\lambda = \frac{c}{f} = 6 \) m)\)
- **Acceleration rate**: 0.75 MeV/m
- **Synchronous phase \( \phi_s \)**: -30°
- **Initial drift tube bore diameter**: 4 cm

Transverse Focusing

A + - + - quadrupole configuration with a phase advance per magnet period, \( \mu_{gp} \), of \( \pi/2 \) is 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 $\cos \mu_{SP} = \pm 1$.

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

**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. In a high current linac, repulsive space-charge forces become comparable to transverse quadrupole focusing forces, and longitudinal rf focusing 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):

$$
(k_B \lambda)^2 \bar{a} = \frac{(\beta \lambda e)^2}{\bar{a}^3} + \frac{45 \Omega \times e \lambda^3}{M_o \bar{c}^2} \left(1 - \frac{\bar{a}}{3 \bar{c}}\right)
$$

Here $k_B$ is the wave number of the transverse oscillation in the zero space-charge approximation, given by $\mu_{SP}/2B \lambda$ and $M_o$ 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 $\delta$, one finds $\bar{a} = 0.93 \text{ cm}$. The flutter factor, which is space-charge independent, takes the maximum transverse oscillation amplitude to about 1.4 cm.

One can now calculate the transverse and longitudinal space-charge parameters $\mu_{SP}^t$ and $\mu_{SP}^L$ equal to the ratios of the space-charge defocusing force to the external focusing force. They are given by:

$$
\mu_{SP}^t = \frac{45 \Omega \times e \lambda^3 \left(1 - \frac{\bar{a}}{3 \bar{c}}\right)}{(k_B \lambda)^2 M_o \bar{a}^2 \bar{c}^2}
$$

(2a)
\[ \mu^{sp}_{L} = \frac{30 \Omega \times e \lambda^{3}}{(k \beta \lambda)^{2} M_{0} \bar{a} c^{2}} \quad (2b) \]

where

\[ k_{L} = \frac{2 \pi e ET \sin |\phi|}{M_{0} \lambda \beta^{3}} \]

is the longitudinal wave number in the zero space-charge approximation. Equations 2a and 2b give \( \mu^{SP}_{L} = 0.60 \) and \( \mu^{SP}_{L} = 0.70 \) demonstrating the importance of space-charge forces in the proposed linac. Under these conditions, experience gained from operating machines [7] as well as from computer simulations [4,8] 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 most probably have to be enlarged continuously through tank 1 to allow for transverse beam growth. Because of the gradually increasing values of \( \beta \) 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 \( \mu^{SP}_{L} \) 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).

**Energy Spread**

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

\[ \Delta E = \pm M_{0} \beta^{2} c k_{L} (1 - \mu^{SP}_{L}) \]

which with the present design parameters yields \( \pm 27 \) 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 \( \pm 125 \) 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
\[ \Delta E = \pm M_0 \left[ \frac{2 \lambda^3 \varepsilon T (\phi \cos \phi - \sin \phi)}{\pi M_0} \right]^{1/2} \]

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

**HARDWARE DESIGN CONSIDERATIONS**

As stated, the accelerator will be a drift-tube structure of conventional, state-of-the-art design. It will be different, however, from existing modern proton linacs in that its duty factor will be 100%, hence particular attention will be paid to the thermal and radiation problems.

At 50 MHz and an acceleration rate of about 0.75 MeV/m, the total length of the machine will be about 40 meters, plus allowances for some drift lengths between cavities. These however will be kept short to avoid longitudinal debunching. In order then to limit the space between cavities, the eight cavities will be contained in a single vacuum tank. The tank will be constructed of copper clad steel containing both vacuum and rf power in an integral envelope, like all modern proton linacs. Water-cooled copper-boundary plates will be mounted inside to provide the separation between the 8 radio frequency resonators.

Figure 3 shows a typical linac cavity, with the drift-tubes aligned on its axis. The 66 copper drift-tubes mounted on the axis of the accelerator will each contain a dc, water-cooled, electromagnetic quadrupole. The drift-tubes and the tanks will demand an efficient water-cooling system to dissipate the \( \sim 1.2 \text{ MW} \) of excitation power and maintain a constant temperature. The accelerating cavities resonant frequencies will be maintained and adjusted by means of a servo system controlling the operating mean temperature. This scheme is being successfully used presently on the Brookhaven proton linac.

Radiation damage considerations dictate that the accelerator be built excluding all organic materials. Rubber hoses, vacuum viton seals, electrical organic insulation, etc., will all be replaced by radiation hardened materials. Although these are design constraints, today, radiation hardening is standard procedure in new accelerator designs and the technology is well developed.

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 \( \sim 10^{-7} \text{ Torr} \). 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 if it proves more economical. 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 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 tank's 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 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 100° 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 to the water will be about 3 megawatts.

**RADIOFREQUENCY AND CONTROL SYSTEM**

As given in Table II, on the basis of eight accelerator cavities, each rf system will be required to deliver about 600 kW. At this time we are planning, then, for eight independent rf drive chains fed from a master reference line and phase locked to it. Phase control will be affected in the low level stages of the drive system with comparison being made between accelerating cavity section and the reference line. The final amplifier will probably be drive modulated to allow for radiofrequency amplitude control. An S.C.R. controlled power supply at a voltage of ~ 20 kV and a current of 60 A will be required for the final amplifier. Possible tubes for the desired rf power level are the CFTH 518 and the EIMAC X 2159. Crowbar protection will be provided for the power supply or to turn off the rf if the beam is interrupted. The master reference line will be fed from a drive system utilizing a quartz crystal controlled oscillator at low frequency with varactor multipliers and suitable amplification. Power from the power amplifier will be fed into each cavity via 12" or 14" coaxial transmission lines and magnetic couplers. Figure 4 shows the block diagram.
of a typical rf system.

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.

All rf, and other machine operation, including beam control and radiation monitoring will be controlled by a common control system. This system will make use of local dedicated computers performing real time operations and receiving commands from and transmitting data to a larger central control computer which will carry out computations and interact with an operations console. CAMAC hardware will be used to interface with the local computers and to interact directly in a hard wired fashion with a malfunction and machine protection system for the linac.

Because of the huge potential for radiation, beam losses must be kept to a minimum and a radiation monitor system with various types of monitors including detectors in each drift tube of the high energy end will be an important diagnostic tool. Non-intercepting instrumentation will include dc beam-transformers, rf position and bunch length detectors and residual gas profile monitors. At the low energy end conventional emittance measuring units may be employed.

THE BEAM TRANSPORT AND TARGET SYSTEM

The lithium targets will be separated from the accelerator complex by a drift distance of 60 m. This distance is required to debunch the beam rf structure to achieve the desired dc beam at the target. It also has the advantage that the expected lithium vapor generated in the targets will not migrate all the way back to the accelerator, but will be trapped at predetermined places in the beam channel.

The beam will be transported with a conventional system of quadrupole lenses properly aligned on the axis. A bending magnet will then direct the beams to their appropriate experimental caves and additional quadrupoles following the bending magnet will control the beam spot size and geometry at
the target. The neutron flux distribution in the experimental volume is determined by the deuteron beam so that the controlled beam delivery on the target is a must. Different schemes are being studied to that effect utilizing the focusing properties of the system, the generation of hollow beams, scanning, etc... It is expected that users will have widely different requirements demanding different solutions and, we intend to be prepared to meet these demands.

The target itself is a thick film (1.5 cm thick) of flowing liquid-lithium with a 12 x 12 cm area. The film will flow across the beam vacuum pipe and be supported on the sides, and on the back by a vacuum window. Figure 5 shows the conceptual design of the target.

For a design power of 3 MW to be dissipated on the target we have tentatively selected a flow velocity of 10 m/sec (18 ft/sec). Tests and calculations carried out at Harry Diamond Laboratory show that at this velocity the film is stable and that this velocity can be increased if necessary. Utilizing the 10 m/sec mentioned, we see in Fig. 6 the temperature gradients to be expected in the film. The dashed lines gives the theoretical value based on range alone and the solid line gives the values which include straggling, as calculated from the Bragg curve. In addition, not shown here, is the added beneficial effect of the deuteron beam energy-spread which will tend to further suppress the maximum temperature point. The figure is based on an energy deposition, of 10 mA/cm horizontally. The additional factors such as energy spread, latent heat of vaporization of the lithium which is considerable (4600 cal/mole), the maximizing of the flow velocity, the internal pressure exerted by the beam in the target, indicate that the proposed design is very conservative and that we can hope to increase the power density deposition to yield neutron fluxes > 10^{15} n cm^{-2} sec^{-1}.

The lithium loop necessary to circulate the hot lithium will utilize standard liquid metal technology. The bulk temperature of the lithium being ~ 300° C provides for an essentially corrosion free system. The hot lithium will be pumped utilizing electromagnetic pumps and the cooling will be done through a lithium-air heat exchanger. The system will contain the necessary heating elements for start-up and all safeguards required in case of accidental spills.

FACILITIES

Figure 7 shows a plan view of the 30 MeV deuteron linac facility. It will be located at Brookhaven, adjacent to the existing 200 MeV proton linac, allowing for efficient use of operating and maintenance personnel as well as use of laboratory space.

The accelerator will be housed in a 20-ft wide shielded tunnel with the beam height 5 ft below ground level. Adjacent to the tunnel a light structure will house the rf systems and adjoining assembly area. The control room which is located at the high energy end of the machine will monitor the experimental areas as well. With the use of local computers and CAMAC controllers, we expect to greatly diminish the need for a large
number of cables.

Downstream from the accelerator the experimental building consists of a staging area with the necessary hot cells built on top of the target caves. The material samples to be irradiated will be transferred from the staging area to the targets through a duct system. The lithium target circulating and cooling system is housed adjacent to the experimental area. Figure 8 shows an architectural rendering of the facility, the accelerator complex is in the foreground.

CONCLUSION

This proposed facility is a practical and efficient way of producing the intense, high energy neutron beams needed for CTR material studies. The accelerator and liquid-metal technologies are well proven, state-of-the-art technologies. The fact that no new technology is required guarantees the possibility of meeting construction schedules, and more importantly, guarantees a high level of operational reliability.

If the CTR Division of ERDA looks kindly upon this proposal, it could be operational in 1981.

REFERENCES


2. A.N. GOLAND et al, "Production and Use of Li (d,n) Neutrons for Simulation of Radiation Effects in Fusion Reactors." This conference.


### TABLE I
PRINCIPAL CHARACTERISTICS OF THE ACCELERATOR-BASED NEUTRON GENERATOR

**Beam Characteristics**

1) **Maximum Energy** 30 MeV - Two simultaneous beams, D⁺ D⁻
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-ns pulses separated by 200 ns 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 x 10¹⁷ 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** ~ 4.5 Megawatts
4) **Strong Focusing Utilizing Electromagnetic Quadrupoles**

**Target Characteristics**

1) **Target Material**, 200°F flowing liquid lithium
2) **Target Size**, 12 x 12 cm x 1.5 cm thick
3) **Flow Rate**, 18 l/sec ≈ 10 m/sec
4) **Operating Bulk Temperature**, 200°F - 300°F
5) **Deuteron Beam Area on Target**, variable from 1 cm² to ~ 10 cm diameter
<table>
<thead>
<tr>
<th>CAVITY</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>INPUT ENERGY (MeV)</td>
<td>0.500</td>
<td>3.967</td>
<td>7.772</td>
<td>11.352</td>
<td>15.048</td>
<td>18.636</td>
<td>22.614</td>
<td>26.226</td>
</tr>
<tr>
<td>OUTPUT BY</td>
<td>0.063</td>
<td>0.089</td>
<td>0.108</td>
<td>0.125</td>
<td>0.139</td>
<td>0.153</td>
<td>0.165</td>
<td>0.177</td>
</tr>
<tr>
<td>CAVITY LENGTH (m)</td>
<td>4.662</td>
<td>5.075</td>
<td>4.773</td>
<td>4.928</td>
<td>4.784</td>
<td>5.303</td>
<td>4.816</td>
<td>5.178</td>
</tr>
<tr>
<td>INPUT CELL LENGTH (m)</td>
<td>0.139</td>
<td>0.390</td>
<td>0.547</td>
<td>0.661</td>
<td>0.761</td>
<td>0.848</td>
<td>0.934</td>
<td>1.007</td>
</tr>
<tr>
<td>INPUT GAP/LENGTH RATIO ( \frac{g}{L} )</td>
<td>0.200</td>
<td>0.236</td>
<td>0.259</td>
<td>0.275</td>
<td>0.290</td>
<td>0.304</td>
<td>0.319</td>
<td>0.334</td>
</tr>
<tr>
<td>INPUT DRIFT TUBE LENGTH (m)</td>
<td>0.111</td>
<td>0.296</td>
<td>0.405</td>
<td>0.479</td>
<td>0.540</td>
<td>0.590</td>
<td>0.636</td>
<td>0.671</td>
</tr>
<tr>
<td>DRIFT TUBE DIAMETER (m)</td>
<td>0.720</td>
<td>0.720</td>
<td>0.720</td>
<td>0.720</td>
<td>0.720</td>
<td>0.720</td>
<td>0.720</td>
<td>0.720</td>
</tr>
<tr>
<td>DRIFT TUBE APERTURE (m)</td>
<td>0.040</td>
<td>0.060</td>
<td>0.060</td>
<td>0.080</td>
<td>0.080</td>
<td>0.080</td>
<td>0.080</td>
<td>0.080</td>
</tr>
<tr>
<td>QUAD. APERTURE (m)</td>
<td>0.050</td>
<td>0.070</td>
<td>0.070</td>
<td>0.090</td>
<td>0.090</td>
<td>0.090</td>
<td>0.090</td>
<td>0.090</td>
</tr>
<tr>
<td>QUAD. LENGTH (m)</td>
<td>0.100</td>
<td>0.200</td>
<td>0.200</td>
<td>0.400</td>
<td>0.400</td>
<td>0.400</td>
<td>0.400</td>
<td>0.400</td>
</tr>
<tr>
<td>QUAD. FIELD STRENGTH (kG/cm)</td>
<td>( \approx 1.00 )</td>
<td>( \approx 0.50 )</td>
<td>( \approx 0.25 )</td>
<td>( \approx 0.25 )</td>
<td>( \approx 0.25 )</td>
<td>( \approx 0.25 )</td>
<td>( \approx 0.25 )</td>
<td>( \approx 0.25 )</td>
</tr>
<tr>
<td>STORED ENERGY (JOULES)</td>
<td>90</td>
<td>92</td>
<td>81</td>
<td>92</td>
<td>90</td>
<td>100</td>
<td>91</td>
<td>102</td>
</tr>
<tr>
<td>AVERAGE SHUNT IMPEDANCE (MO/m)</td>
<td>32</td>
<td>36</td>
<td>36</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
<td>37</td>
</tr>
<tr>
<td>TOTAL CAVITY PWR (kW)</td>
<td>207</td>
<td>182</td>
<td>158</td>
<td>169</td>
<td>161</td>
<td>178</td>
<td>162</td>
<td>177</td>
</tr>
<tr>
<td>TOTAL BEAM PWR. FOR 100mA (kW)</td>
<td>347</td>
<td>380</td>
<td>358</td>
<td>370</td>
<td>359</td>
<td>398</td>
<td>361</td>
<td>388</td>
</tr>
<tr>
<td>UNLOADED Q VALUE X 10(^{-3})</td>
<td>127</td>
<td>159</td>
<td>163</td>
<td>171</td>
<td>174</td>
<td>177</td>
<td>177</td>
<td>181</td>
</tr>
<tr>
<td>INPUT TRANSIT-TIME FACTOR</td>
<td>0.70</td>
<td>0.80</td>
<td>0.85</td>
<td>0.81</td>
<td>0.81</td>
<td>0.81</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>STABLE PHASE ANGLE</td>
<td>(-30^\circ)</td>
<td>(-30^\circ)</td>
<td>(-30^\circ)</td>
<td>(-30^\circ)</td>
<td>(-30^\circ)</td>
<td>(-30^\circ)</td>
<td>(-30^\circ)</td>
<td>(-30^\circ)</td>
</tr>
</tbody>
</table>
ONE ACCELERATOR CAVITY

CAVITY PHASE AND AMPLITUDE SIGNAL

PHASE SHIFTER

POWER AMPLIFIER

DRIVER AMPLIFIER

TO WATER TEMP CONTROL

LOW LEVEL CONTROL

R.F. AMPLITUDE AND FREQ. CONTROL

50 OHM REF. LINE

AMPLIFIER

TERMINATION

OSCILLATOR
DEUTERON BEAM

AUXILIARY CATCH BASIN WITH DRAIN

3" LITHIUM SUPPLY PIPE
18 l/sec FLOW
200°C

INLET NOZZLE

1.5 cm THICK LITHIUM FILM

VIRTUAL WINDOW

DEUTERON BEAM

VENTURI RECOVERY SECTION

LITHIUM RETURN
18 l/sec 4" PIPE
300°C max

TARGET ASSEMBLY

SECT. A-A
Accelerator-based
NEUTRON GENERATOR
FIGURE CAPTIONS

Figure 1 - Neutron Fluxes vs. Distance from Target for Different Neutron Sources
Figure 2 - Linac Injection System
Figure 3 - Linac Cavity with Drift-Tubes
Figure 4 - Block Diagram of a Typical rf Chain
Figure 5 - Conceptual Design of Liquid-Lithium Target
Figure 6 - Deuteron Range and Temperature Profile in Lithium Target
Figure 7 - Accelerator-based Neutron Generator Facility Floor Plan
Figure 8 - Architectural Rendering of Accelerator-based Neutron Generator Facility