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PROPOSAL FOR AN

Accelerator - based
NEUTRON GENERATOR
(ADDENDUM)

JANUARY 1976

MASTER

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Proposal For An

**Accelerator - based
NEUTRON GENERATOR
ADDENDUM TO BNL-20159**

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1. Introduction

This document is an addendum to the Brookhaven National Laboratory Proposal for an Accelerator-based Neutron Generator (BNL 20159), dated July 1975. It brings the proposal up to date and reports on the latest developments and work progress to January 1976.

The proposal by BNL to design, construct and operate a D-Li Intense Neutron source for CTR materials research and development has generated a lot of enthusiasm. The DCTR plan to schedule the funding of this project for FY 1978 leaves very little time to firm up the scope of the design and to establish sound cost estimates.

Since the release of our proposal in July 1975, we have therefore addressed ourselves principally to those areas of the proposal requiring technical solutions, to a better understanding of the radiation damage effects of the D-Li neutron spectrum, to a more comprehensive design of the experimental building, and to the improvement and updating of the construction schedule and cost estimates. In addition, in response to DCTR requests, we have carried out a preliminary study of the limitations of lithium targets and considered alternate target materials. Concurrently, we have also investigated the space charge limits of the proposed accelerator and established the design parameters and costs for a 200-mA facility.

The analysis carried out to date shows that both the accelerator and target can be expected to operate with deuteron beams of up to 200 mA and that the total neutron yield can be further increased by upping the deuteron energy to 35 MeV without detrimental effects on the "radiation damage effect match" of the higher average neutron energy. The resulting gain in experimental volume is shown in Fig. 1.1 where the volume for different deuteron currents is plotted

Fig. 1-1

vs. neutron fluxes for a 35 MeV facility. The fluxes shown are primary neutrons only.

We have, therefore, changed the cost estimates to reflect these changes and are providing two estimates as follows:

1. The cost estimate for the 100 mA facility includes the necessary plant investment to make it readily upgradable to 200 mA.

2. A second cost estimate has been developed for a 200 mA facility.

The total construction cost for a 100 mA facility is \$55,000,000 and that for a 200 mA facility is \$70,000,000. These costs are based on a four year construction period (FY 1978-FY 1981).

Both estimates are for a 35 MeV deuteron linac and contain the latest cost information available from potential vendors.

Apart from the desire to maximize the high flux volume of the neutron source, the 200 mA capability should be considered in view of the latest H^- ion source developments. The progress at BNL on H^- ion sources has been very rapid. In September 1975, a pulsed duoplasmatron ion source has produced > 50 mA of H^- ions⁽¹⁾. We believe that further development will show that D^- ion sources with 100 mA dc beams can be produced and will provide the potential to greatly increase the facility utilization at little additional cost.

As presented here, the 200 mA cost estimate can therefore accommodate a single 200 mA deuteron beam or two (D^+ and D^-) beams totaling 200 mA. To the first order, increased current costs can be extrapolated from the estimates shown in Section 7.

2. Radiation Damage Effectiveness

Yields

There is ample evidence from many independent experiments that, under deuteron bombardment, light-element targets, e.g., Li or Be, yield the highest neutron intensities⁽²⁾. The experimental results also indicate that the forward neutron yield increases as the deuteron energy is increased. Therefore, the selection of the deuteron energy upon which to base the LINAC design should be the maximum energy consistent with the desired neutron energy spectrum. Theoretical calculations indicate at this time that a 35 MeV energy is a good choice.

As to the choice of targets between Li and Be, thermomechanical properties aside, there seems to be little basis for a distinction. The forward neutron yields are similar. Some data indicate that Be has the higher yield, other that Li yields more neutrons. Part of the discrepancy can be attributed to uncertainties about the neutron yield below 3-4 MeV. Other differences must arise from the method of measurement e.g., foil dosimetry or time-of-flight and from calibration methods and detector efficiency corrections. Our neutron time-of-flight measurements at NRL⁽³⁾ were repeated using the same Li target, but a different Be target approximately eight months after the original measurements. The yield results for Li were identical to the first ones, but the Be yields were lower than before. Apparently differences from target to target can occur owing to thickness differences. Results of similar experiments performed at other laboratories indicate that the Be and Li yields are comparable and generally higher than those observed at NRL⁽⁴⁾. At this point it would be worthwhile to perform additional yield measurements at another laboratory under conditions acceptable to all those who have proposed to build a Li(d,n) source.

Spectra Including Reflected Neutrons

It has been stated repeatedly that the energetic neutrons in a fusion reactor spectrum create two problems in terms of the alteration of materials properties:

- a) cascades of atomic displacements, and
- b) transmutation products.

If the reaction cross sections are known, the rates of transmutation product production can be calculated accurately. In contrast, displacement cascades cannot be accurately characterized by calculations as to size and spatial distribution. Consequently, a quantity such as the damage energy cross section has been adopted by many as a good measure of relative damage effectiveness. We have pointed out that another fundamental quantity which controls subsequent displacement cascade damage is the primary recoil atom energy distribution, $P(T)$ ⁽⁵⁾. Comparison of this function for 14-MeV and $\text{Li}(d,n)$ spectra on the basis of recoil energy groups graphically illustrates the utility of the deuteron breakup source for simulation of displacement damage in a fusion reactor. Identical histograms would constitute perfect simulation. While this criterion is not completely met at deuteron energies of ~ 30 or 35 MeV, uncertainties in the calculations are sufficient to permit the conclusion that simulation is excellent. This conclusion is illustrated in Figs. 2.1 and 2.2 showing the histograms of $P(T)$ in Cr, Fe, Ni and Nb for neutron spectra produced by 29 and 34 MeV deuterons, and for a 14-MeV neutron spectrum. Neither the discussion we have presented previously nor that given elsewhere has treated seriously the potential for spectrum alteration offered by introducing reflecting materials into the irradiation cave. The importance of reflectors is most forcefully illustrated in the present context by noting the difference between the (D,T) neutron spectrum, and that anticipated at

Fig. 2-1

Fig. 2-2

the first wall (BENCHMARK, see ENL 20159). Two significant differences can be observed:

- a) The Benchmark spectrum is softer and broader than the (D,T) spectrum.
- b) Nearly eighty percent of the flux at the first wall is attributable to neutrons reflected by the blanket.

We can therefore conclude that:

- 1) A good measure of the quality of a simulation source is obtained by comparing the recoil spectrum it produces in a given material with the corresponding spectrum produced by the source being simulated.
- 2) 3-D neutronics calculations are necessary at once to determine appropriate configurations of reflectors for increasing fluxes and altering the $Li(d,n)$ spectra in the direction of better simulation. These calculations may affect the final choice of maximum LINAC energy.

Recoil Energy Models

Two distinct methods of damage analysis have been proceeding concurrently at different laboratories. One is based upon the solution of a set of integral equations relating a radiation-induced property change to a damage function⁽⁶⁾. The property change must be measured in a variety of neutron spectra in order that function can be accurately defined. Once this function has been determined it can be folded with a new spectrum to predict the magnitude of the property change which should be induced at the end of an irradiation to a prescribed fluence. This empirical approach does not make use of physical models relating property changes to radiation-induced defects. Therefore, a second method of damage analysis is developing slowly in which an attempt is made to construct damage functions on the basis of physical models⁽⁷⁾. For example, if the change in hardness of a solid depends upon the number or size of the defect cascades, then the damage function must relate the primary recoil energy to the number or

size of the cascades. This leads to the definition of a generalized damage function suitable for comparing the results of hardness experiments in different neutron sources, and for predicting the results which would be obtained in other sources. This second analysis technique is more difficult to apply because it requires some knowledge of the physical processes affecting a given material property. Conversely, it should ultimately be capable of providing insight into the atomic mechanisms by which properties are changed, and, therefore, of leading to methods of improving the radiation-resistance of structural materials.

Both of the methods outlined above have been applied to Li(d,n) spectra and compared with corresponding results for other neutron sources. Encouraging conclusions can be drawn in each instance. Inclusion of a Li(d,n) spectrum in the first method greatly reduces the uncertainty in the damage function deduced from the solution of the set of i integral equations corresponding to irradiations in i different neutron spectra⁽⁷⁾. Calculation of generalized damage functions for a Li(d,n) spectrum in the second case yields values comfortably close to those obtained for a 14-MeV or a Benchmark spectrum⁽⁸⁾. The distinction between a 30 and 35-MeV spectrum is not obvious when uncertainties in spectra and cross sections are taken into account.

These theoretical radiation damage models lead to the following conclusions:

- 1) Two current methods of damage analysis independently arrive at the conclusion that a Li(d,n) spectrum is an excellent choice for providing CTR type materials testing data.

- 2) Extension of damage analysis techniques is necessary and should be based upon better dosimetry results and cross section calculations/measurements.

⁴He Production vs. dpa

The ratio of ⁴He production to dpa is thought to be an important parameter in the radiation-damage process. Since dpa can be deduced from the damage energy

(i.g., the kinetic energy available to displace atoms), an equivalent ratio is often taken to be that of ^4He production to damage energy. A third equivalent ratio is that of the spectrum-averaged (n,α) cross section to the damage energy cross section. This ratio requires the fewest assumptions concerning the damage process, and is being used more frequently in comparisons of radiation damage produced by different neutron spectra.

Calculations of any of these ratios depend upon the assumptions made about the neutron cross sections at high energies. Data exist for very few elements. Therefore calculations of cross sections are necessary or extrapolations from lower energies must be made using nuclear systematics as a guideline. This state of affairs accounts for the apparently random disagreements found between quoted (n,α) cross sections or damage energy cross sections. Nevertheless, calculated ratios for $\text{Li}(d,n)$ spectra seldom differ by more than a factor of two, and generally are close to the values calculated for a 14-MeV spectrum.

3. Linac Design and Performance

The linac design has been reevaluated to allow the acceleration of higher beam currents (> 0.1 A). The calculations were made utilizing a linac structure similar to that described in Table IV-2 of BNL 20159.

The acceleration of larger beam currents requires stronger longitudinal and radial focusing forces to counteract the stronger space charge defocusing forces present. The linac design parameters were changed accordingly allowing for higher acceleration rates and stronger quadrupole magnets. The matched beam length and, average and peak radii were calculated for beam currents up to 0.5 A.

From this analysis we can draw the following general conclusions:

1. The maximum attainable accelerated beam current is limited by the maximum allowable electric field gradient in the linac. This gradient is determined by the onset of sparking in the gaps between drift tubes. At a frequency of 50 MHz and using Kilpatrick's sparking criterion⁽⁹⁾, this gives a maximum axial acceleration rate value of ~ 1 MeV/m for a stable phase angle of 35° and a gap to cell length ratio of ~ 0.2 .

2. Based on the above acceleration rate (~ 1 MeV/m) and an injection energy of 0.5 MeV, the maximum beam current is limited to about 300 mA for an ideal machine. The limit is ultimately determined by construction errors, e.g., misalignment, harmonic content and fringing fields of quadrupole magnets, etc... These effects will tend to lower the maximum current which can be accelerated to < 300 mA. In the above argument, the maximum current is defined as that current which can be accelerated without losses.

3. To accommodate a current of 200 A, the minimum aperture required in the first drift tube is ~ 4 cm. This aperture limits the operating system's radio-frequency to about 50 MHz to keep the acceleration efficiency reasonably high.

The drift tube aperture has to be quickly enlarged in subsequent drift tubes to minimize the possibilities of radial beam losses.

Table III-1 gives the parameters related to beam dynamics, including the above factors, used to establish the linac design parameters shown in Table III-2. This design is for a machine capable of accelerating 200 mA without beam losses.

Table III-1

Injection Energy	0.5 MeV
Injection $\beta = \frac{v}{c}$	0.023
Accelerated current (I)	0.2 A
Injected transverse emittance (ϵ)	$6\pi \times 10^{-4}$ m.rad
Radiofrequency (f)	50 MHz ($\lambda = \frac{c}{f} = 6\text{m}$)
Acceleration rate	1 MeV/m
Synchronous phase (tank #1)	35°
Synchronous phase (tanks 2-9)	30°
Initial drift tube bore diameter	4 cm
Initial quadrupole field gradient	2.4 kG/cm

TABLE III-2

Basic Linac Parameters

Cavity	1	2	3	4	5	6	7	8
Input Energy (MeV)	0.500	4.265	8.606	12.588	17.040	21.258	25.942	31.083
Input $\beta\gamma$	0.023	0.067	0.096	0.115	0.134	0.149	0.165	0.180
Output Energy (MeV)	4.265	8.606	12.588	17.040	21.258	25.942	31.083	35.522
Output $\beta\gamma$	0.067	0.096	0.115	0.134	0.149	0.165	0.180	0.192
Cavity Dia. (m)	3.78	3.78	3.78	3.78	3.78	3.78	3.78	3.78
Cavity Length (m)	3.729	4.381	3.787	4.480	4.243	4.703	5.161	4.456
Input Cell Length (m)	0.146	0.412	0.582	0.700	0.812	0.904	0.996	1.087
Output Cell Length (m)	0.392	0.562	0.681	0.793	0.885	0.977	1.069	1.141
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)	0.117	0.315	0.431	0.508	0.576	0.629	0.678	0.724
Output Drift Tube Length (m)	0.300	0.418	0.495	0.565	0.619	0.668	0.716	0.742
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	0.030	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)	1.6-1.2	0.6-0.5	0.50	0.25	0.23	0.23	0.23	0.23
Transit Time Factor	0.7-0.8	0.8-0.85	0.85	0.80	0.80	0.80	0.80	0.80
Stable Phase Angle	35°	30°	30°	30°	30°	30°	30°	30°
Cavity Excitation Power (kW)	402	306	276	318	300	345	372	322
Beam Power for 200 mA (kW)	753	868	796	890	844	937	1028	888
Average Shunt Impedance (M Ω /m)	32	36	36	37	37	37	37	37

4. Target Design and Performance

The choice of target materials for an intense neutron source utilizing the stripping reaction of energetic deuterons is limited to low Z materials because of their neutron production efficiency. The two best candidates are Be and Li. D_2O is also a good candidate because of its D_2 component.

Of these three materials, both Be and D_2O can be ruled out as targets for any power density much larger than a few kW/cm^3 . Although theoretically we can show that Be and D_2O can be utilized at higher power densities, practical engineering limits are quickly reached and possible designs will be unreliable at best. Be will fail because of its poor mechanical properties at high temperatures and D_2O is limited by its poor thermal properties in vacuum. A case might be made for a target consisting of a Li-cooled Be rotating wheel. However, this system adds nothing to a simple flowing liquid lithium target, except complexity and unreliability. These targets are discussed by Logan⁽¹⁰⁾ and Kukkonen⁽¹¹⁾.

The flowing liquid lithium jet (or sheet) is the only target which provides for efficient neutron production as well as efficient power removal. We have therefore concentrated our efforts on understanding the dynamics of this target and find no basis for concern, even for beam currents > 200 mA. The following discussion describes the parameters used for the analysis and presents the results of the numerical calculations.

Deuteron Beam Parameters

From the high energy end of the accelerator, the deuteron beam is guided to the target through a magnetic lens focusing system. The beam delivery to the target is independent of the conditions existing upstream, it is determined by the last few quadrupole lenses preceding the target and the beam space charge forces. Although, various schemes can be used to tailor the beam to either affect the neu-

tron equiflux geometry and/or to minimize the deuteron beam density distribution on the target, we assume here the most likely beam parameters which the target will experience:

- 1) Deuteron beam current, 200 mA
- 2) Energy, 35 MeV
- 3) Energy spread, ± 400 kV, gaussian, without debunching
- 4) Beam size, 10-cm width, (circular or elliptical)
- 5) Beam density distribution, gaussian

It is obvious that due to the spacial beam distribution described above, there will be one small section of the target which will experience a maximum power deposition. That section is a small element of lithium that traverses the deuteron beam at its median plane. This lithium element will accumulate the maximum integrated beam current seen during its transit time across the beam. That beam current density is 40 mA/cm for a 200 mA nominal beam current. The thermodynamic calculation is directed to that element of the target.

Energy Deposition Distribution in the Target

Whereas in BNL 20159 we had estimated analytically the deuteron beam energy deposition distribution in the target, we now have the capability to calculate this parameter numerically utilizing the UCRL computer code BRAGG. This computer program calculates the energy deposition distribution with respect to target depth and includes factors such as: straggling, energy spread, deuteron beam density distribution, energy spread distribution, angular distribution, etc.

Taking all known factors into account, we find that, utilizing the deuteron beam parameters given earlier, the peak energy deposition given in BNL 20159 was pessimistic, since it did not include energy spread. A more realistic estimate gives a ratio of 4 to 1 between the peak $\frac{dE}{dx}$ (at $x = 1.4$ cm) and the minimum at the target surface.

Figure 4.1 shows the energy deposition vs. target depth calculated for a 35 MeV deuteron beam impinging on a liquid lithium target.

Hydro and Thermodynamic Considerations

An ongoing study of the flowing liquid lithium target as proposed in BNL 20159 indicates the need for further analysis and experimental development. At this time, however, the following points can be made.

1. As proposed in BNL 20159: The target is likely to be stable hydrodynamically and the boundary layer at the back window will not materially affect the maximum temperature area of the sheet.
2. The free surface boundary layer is estimated to reach 1/2 of the nominal flow velocity at the beam interception point. This estimate is strongly influenced by the nozzle geometry and could become quite different depending on this geometry. This 1/2 of the nominal velocity will be used to calculate the surface Δt and corresponding evaporation rate.
3. The maximum temperature inside the target is much above the saturated temperature at $\sim 10^{-6}$ Torr. Under these conditions, and if we assume that impurities might exist to produce nucleation sites, boiling will take place. An estimate of the potential bubble growth rate during the fluid transit time across the target gives bubble diameters of > 0.1 cm/msec depending on the assumptions made. It is clear that this pessimistic bubble growth estimate is not acceptable and that this question has to be resolved before implementing such a target design.

In an effort to get around this potential boiling problem, and to create a comfortable safety margin, we are proposing to study a target geometry which will produce a pressure gradient across the target thickness. This target will consist of a curved surface ($R \sim 25$ cm) with the nozzle directed tangentially to that surface at 15° from the vertical axis (see Fig. 4-2). With $R = 25$ cm and the fluid

velocity, $v = 15$ m/s, the resulting centrifugal pressure at $r_{\text{max}} = 1.4$ cm is ~ 50 Torr and the corresponding saturated temperature is 1000°C which is above the hottest spot temperature produced by a 200 mA beam. This design is attractive as it eliminates any possibility of boiling. The target power dissipation limitation then becomes the result of surface evaporation. If the free surface velocity is 7.5 m/s, the peak evaporation rate to be expected from the 200 mA beam is about 5×10^{-5} g/cm²/s. When integrated over the whole beam surface area this becomes roughly 10^{-3} g/s. The lithium evaporated from the target is not considered a problem; as its sticking coefficient $= 1$, it will be collected on a condenser and returned to the sump.

This target design will be further analyzed and modeled to determine its stability and the possible formation of vortices.

RELATIVE ENERGY DEPOSITION $\Gamma(x) = \frac{dE}{d(\rho x)}(x) / \frac{dE}{d(\rho x)}(x=0)$

FOR VARIOUS D BEAM ENERGY SPREADS
vs PENETRATION DEPTH IN Li

FOR $\frac{dE}{d(\rho x)}$ AT SURFACE = 25.2 MeV/g/cm²

Fig. 4-1

Fig. 4-2

5. Experimental Area Design

The design of the experimental area as presented in BNL 20159 has been further developed to achieve the best compromise between the high radiation environment to be expected and maximum efficiency and flexibility in the operational utilization of the facility. The study has been carried out in enough detail with regard to the mode of operation and remote handling technology to give the potential user much freedom in the planning of experiments. This layout has also been used to arrive at a firm cost estimate.

In common with other laboratories, particularly the meson factories (e.g. LAMPF at LASL), the operations to be undertaken will involve both direct and remote interventions depending on radioactivity levels. When radioactivity is encountered, it will be hard gammas in high dose rates, but with little or no contamination. This contrasts very favorably with the problems associated with handling fissile materials.

The basic approach taken is that access to all radiation areas (including: beam switchyard, experimental caves, beam stop, hot cells and test bays,) will be from above, through plug holes in the staging area floor. This has the advantage of reducing the shielding problems to a minimum with the experimental-caves removable roofs the only concern with regard to biological shield. Access from above provides not only for overall simplicity and order but also ensures maximum utility of the best piece of remote handling hardware available, the overhead crane.

This design approach will also simplify the sealing of the target caves to allow the operation of the caves in a slightly positive pressure helium blanket.

Another feature will be the possibility of clearing all personnel from the staging area and continuing all manual operations remotely, using servo-manipulators, while radiation conditions exist. This is a necessary and efficient approach to moving radioactive rigs from the target caves to the hot cells or the hot storage areas. The same requirement also exists when the shielding of a target cave is re-

moved. However, the transfer of irradiated samples from an experimental set-up will be accomplished in-situ by direct transfer from a rabbit system to a transfer pig.

The ability to clear the staging area and remote operation is the simplest and most efficient solution to the problem. Following experience at CERN⁽¹²⁾, Los Alamos⁽¹³⁾, and FNAL⁽¹⁴⁾ this can be a straightforward and rapid procedure which is being used increasingly in accelerator laboratories and is envisaged for the planned fusion reactors.

Figure 5.1 shows an overall view of the experimental area. A 40 ton crane will have coverage of the entire area. It will have two control modes: normal pendant control and remote control from the remote operations control room. The crane will be designed for smooth and variable speed operation. The experimental staging area is shown with one target cave open and the remote servo-manipulator positioned to remove a target window. Hot cells, assembly area and the remote operation control room are located on the lower level at the end of the building.

The remote controlled servo-manipulator will be fundamental to the operation of the facility. As such, we plan the use of the most modern and versatile tool available, that being procured presently for the LAMPF experimental area at LASL.

Figure 5.2 shows a typical modular experimental assembly. The experiments will be contained in a support structure suspended from a standard shield plug. All necessary services for the experiments will be provided through pipes and feed-throughs in the shield plug as required. These assemblies can vary in design and operation in any way while retaining the standard external geometry of the plug and its relation to the target in the cave.

Holes matching the shield plug dimensions will be provided as required over the hot cells, assembly area and hot storage so that complete assemblies can be

moved to, and installed in, any of these places by remote means. Another access will be provided to the hot cells to allow shielded transport casks to be lowered in for loading.

Fig. 5-1

TYPICAL EXPERIMENTAL SET - UP

Fig. 5-2

6. Construction Schedule

The construction schedule for the facility, as given in BNL 20159 was based on the start of construction taking place at the beginning of FY 1977. In order to reflect the DCTR plans to schedule the funding of the D-Li neutron source at the beginning of FY 1978, we have revised the construction schedule accordingly as shown on Fig. 6.1.

Aside from a one year shift, the construction schedule is basically unchanged. Based on experience on similar projects we estimate the construction and commissioning period to last four years. This time estimate will be strongly influenced by the "prefunding" level of support for preliminary design and development. To meet this schedule, it is essential that this initial preliminary design and development effort be supported at the level shown in the financial appropriation plan shown in Table X-1. It is also imperative that an architect-engineering firm be chosen prior to the funding date.

Any changes in the initial scope of the facility will not materially affect the construction schedule.

FISCAL YEAR

Fig. 6-1

7. Construction Costs

On the basis of the change in schedule, we have reviewed and revised the facility construction costs upward to reflect escalation to mid 1976. The costs shown in Table VII-1 are therefore up-to-date costs. An escalation of 30% to mid-construction year has been calculated utilizing an 8% annual inflation rate based on the financial appropriation plan. This shows that the 30% total given here is reasonably accurate.

In addition, the new cost estimate includes the following changes and additions:

- 1) An increase in the deuteron beam final energy to 35 MeV. This increase in energy is accomplished within the same accelerator length but requires additional shielding and rf power.
- 2) The necessary fixed plant investment to make it possible to upgrade to 200 mA later on. These increases include items such as: larger capacity water cooling and lithium systems, larger electrical capacity, additional ports, inlets and connections as necessary for later additions, increased shielding, etc.
- 3) The cost estimate for a 200 mA facility as a possible change in scope for funding. These costs are shown in parentheses. The cost differences between the two estimates are shown in Table VII-2 giving the incremental costs for the additional 100 mA capability. This added capability can of course be deferred to later, in which case an added appropriate escalation factor has to be applied.
- 4) Better cost information for some components and systems resulting from more complete and detailed design and consultation with potential vendors. These improvements cover principally three areas:

a) A careful study has been made of rf systems in consultation with vendors resulting in rather firm cost information.

b) The design of the experimental area has been greatly improved with particular attention given to remote handling and efficient operation. This area was then cost estimated using the latest cost information available from the LAMPF procurement of remote handling systems.

c) The lithium loop design and costs have been carefully reviewed with the help of Atomics International and LMEC (Liquid Metal Engineering Center) to reflect the best cost information available.

Table VII-1
Cost Estimate Summary
(In Thousand Dollars)
(1976)

	<u>100mA Facility</u>	<u>(200mA Facility)</u>
<u>Schedule A: Buildings</u>	8070.....	(10590)
Improvement to land	110	(110)
Utilities	920	(1820)
Construction	5400	(6600)
Equipment	290	(290)
Contingency 20%	1350	(1770)
<u>Schedule B: E, D, I & A</u>		
20% of Schedule A.....	1610.....	(2110)
<u>Schedule C: Accelerator Systems</u>	24910.....	(31580)
Injectors	1600	(1760)
Matching Section	370	(370)
Accelerator	4540	(4540)
Rf System	5100	(9700)
Beam Transport	840	(840)
Cooling System	900	(1300)
Target System	1450	(1450)
Lithium System	4100	(4100)
Control System	1030	(1200)
Contingency 25%	4980	(6320)
<u>Schedule D: E, E, I & A</u>		
30% of Schedule C.....	7480.....	(9480)
<u>Schedule E: Escalation</u>		
30% of Schedule A, B, C & D.....	12620.....	(16130)
 Total	 54700	 (69900)

Table VII-2

Detailed Cost Estimate
(in Thousand Dollars)
(1976)

Schedule A: Buildings and Utilities.....8070 (2520)

1. <u>Improvement to land</u>	110	
Preparation, grading, seeding	20	
Paving, curbs	75	
Area lighting	15	
2. <u>Utilities</u>	920	(900)
Storm drainage	50	
Steam	320	
Water	30	
Sanitary Sewer	25	
Cooling Water (relocate)	25	
Electric Power	200	(300)
Electric Substation	270	(600)
3. <u>Construction</u>	5400	(1200)
General construction, foundation		
steel, shielding, walls, roofs	3700	(720)
HVAC	710	(200)
Plumbing and Sanitary	240	(100)
Sprinkler System	200	(50)
Bldg. Electrical Services	120	(100)
Experimental Area Power	240	
Lighting	140	(30)
Fire Alarm and Telephone	50	
4. <u>Equipment</u>	290	
Laboratory furniture	35	
Office furniture	20	
Machine tools	35	
Cranes	200	
5. <u>Contingency 20%</u>	1350	(420)

Schedule B: E, D, I & A

 20% of Schedule A.....1610 (500)

Schedule C: Accelerator.....24910 (6670)

1. Injectors (2).....1600 (160)

High Voltage Generators	600	
HV Platforms	65	
Faraday Cages	65	
Accel. Columns	330	
Column Supports	80	
Ion Sources + PS	80	(60)
High Vac. System	120	(60)
Low Vac. System	25	
Triplets	65	
Triplets Power Supplies	25	
Cooling System	25	(15)
Controls and Electr.	30	(15)
Installation	90	(10)

2. Matching Section.....370

Triplets Q	35	
Match. Magnet Q	20	
Q Power Supplies	30	
Bending Magnet	25	
Bending Magnet Power Supplies	10	
Bunchers	40	
Buncher Power Supply	30	
Viewing boxes & Scrapers	35	
Emission Devices	20	
Current Monitor	10	
High Vacuum System	15	
Low Vacuum System	10	
Vacuum Pipe & Hardware	30	
Installation	60	

3. Accelerator.....4540

Tanks & End Plates	2300	
Support System	50	
Drift Tubes	700	
Quad. Magnet	230	
Quad. Shuts	80	
Quad. Power Supplies	150	
High Vacuum System	350	
Low Vacuum System	120	
Cooling Hardware	30	
Cooling Controls	20	
Tuners	30	
Current Monitors	20	
Pick-up Loops	20	
Installation	440	

4. <u>RF System</u>	5100	(4600)
Low-Level System	250	(40)
PA tubes	280	(280)
PA sockets	1400	(1400)
Drivers System	560	(560)
Fil. Power Supplies	160	(160)
Plate Power Supplies	700	(700)
Crowbar System	160	(160)
3" Transmission Lines	80	(80)
14" Transmission Lines	160	(160)
14" Phase Shifters	160	(160)
Feed loops	280	(280)
Dummy Loads	70	
Controls	160	(120)
Installation	680	(500)
5. <u>Beam Transport</u>	840	
Quad. Magnet	230	
Quad. Power Supplies	130	
Bending Magnet	35	
Bending Magnet Power Supplies	20	
High Vacuum System	35	
Low Vacuum System	20	
Vacuum Pipe & Hardware	20	
Fast Valves	20	
Beam Dump	60	
Li. Collectors	40	
Debuncher	30	
Current Monitors	20	
Profile Monitors	50	
Installation	130	
6. <u>Cooling System</u>	900	(400)
Cooling Towers	120	(120)
CT pumps & Pipes	90	(90)
Rf Pumps	30	(30)
Rf Heat Exchanger	40	(40)
Demineralizer	30	(30)
Rf piping	100	(30)
Tank Pumps	30	
Tank Heat Exchanger	50	
Tank Piping	70	
Controls	200	(30)
Installation	120	(30)

7. <u>Remote Handling</u>	1450
Crane Controls	30
Servo Manipulator	250
Hot Cells	400
Transfer Pigs	150
Special Shielding & Reflector	250
Remote Operation Room	50
Special Tooling	30
Security & Monitors	40
Target Tooling	80
Transfer Track	20
Spare Manipulator	150

8. <u>Lithium Loop</u>	4100
Pumps	850
Drain Tanks	80
Heat Exchangers, Preheater	500
Vac. & Helium System	50
Piping & Valves	450
Remote Handling	200
Targets	200
Insulation	70
Tracer Heaters	180
Inst. & Controls	570
Purification System	280
Installation	570
Lithium	100

9. <u>Control System</u>	1030	(170)
Racks & Cables	100	(30)
Computers	130	
CAMAC System	160	(60)
Contro. Desk & Display	80	
Communication System	25	
Radiation Monit. System	45	
Local Controls	90	(30)
Beam Control System	70	
Installation	330	(50)

10. <u>Contingency 25%</u>	4980	(1340)
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Schedule D: E, D, I & A

30% of Schedule C.....7480 (2000)

Schedule E:

30% of Schedule A, B and D.....12620 (3510)

T O T A L.....54700 (15200)

8. Preliminary Design and Development Program

A preliminary design and R&D budget was included in the Schedule 44 submitted to ERDA in June 1975. It has been updated to include development of the lithium loop.

This program is outlined in Table VIII-1. The areas of required development are defined with corresponding estimated costs. These costs include the necessary contingencies associated with R&D activities.

To meet the proposed construction schedule, this development program has to be initiated as soon as possible and no later than Fall 1976. The financial appropriations plan proposes the start of preliminary design funding in FY 1977.

This proposed program will not be materially affected by the choice of beam current or energy parameters.

TABLE VIII-I

Preliminary Design, Research and Development Costs
(1976 costs in thousand dollars)

Preliminary Linac Design		400
Neutron Transport Design		
Cross sections and spectra meas.		300
Ion Source Development (D^+ & D^-)		900
50 kV test strand	250	
Magnets and power supplies	50	
Controls	50	
Measurement apparatus	120	
Sources and instrumentation	130	
Labor and MTSC	300	
RF System Development		900
Power supplies	100	
Tubes	30	
Cavities	200	
Load	50	
Transmission lines & hardware	40	
Controls and instrumentation	100	
Labor and MTSC	380	
Linac Development		450
Drift tubes and quadrupoles	110	
Beam monitors	80	
Buncher system	80	
Rf drive loop	60	
Labor and MTSC	120	
Lithium Loop Development		200
Film simulation	100	
Preliminary design	100	
Instr. & purification dev.	250	
Pump prototype	250	
Loop development	500	
		<u>4150</u>
Escalation 16.6%		<u>690</u>
Total		4840

9. Facility Operation and Operating Costs

Many years of experience with linacs (10 years with the BNL 50 MeV linac and 5 years with the new BNL 200 MeV linac), allow us to establish with confidence an operating schedule and expected reliability. Both of these machines have operated at an average of 92-95% of scheduled time and the average scheduled time over the years has been about 6000 hrs/year. The scheduled time quoted here is not dictated by the machine maintenance requirements but by experimental demands.

Based on the above experience we can plan on the following:

1) A long yearly shutdown of up to ~ 30 days for major maintenance, improvement or other changes. This long shutdown could be reduced to 15 days if only maintenance is involved.

2) A 24 hr. shutdown every two weeks for regular maintenance.

3) A minimum 90% reliability of the scheduled facility operating time.

This 90% reliability factor surmises that the three following steps in the design are taken:

a) The provision for two injection systems (one standby) at least until the ion source life and reliability have been established.

b) The conservative derating of all rf power amplifier tubes to guarantee their average lives to be $> 10,000$ hrs.

c) The proper design of the target window to avoid mechanical failure and the availability of other target caves in case of target failure.

The total plant efficiency factor to be expected is therefore 74% and the resulting operating time will be 6500 hrs/year.

The cost of operation is predicated upon 6500 hrs/year operating time and is unchanged from that given in BNL 20159. The operating costs for the 200 mA

facility are shown in brackets. All categories show an increase because of the higher utilization factor of the facility.

In addition to the operating cost of the facility, we have made an attempt at estimating the cost of an experimental program for the facility. This estimate is very tentative because it is difficult, if not impossible, to predict the experimenter's needs with any kind of accuracy. Again, the numbers in brackets are for the 200 mA facility. These are higher, assuming a higher utilization factor for the facility.

This budget is based on a comparison with existing national facilities of a similar nature. It covers the in-house expenditures to provide the user with the manpower and major capital equipment required by the users for a general experimental program. This budget does not provide for specific experiments, nor for post-irradiation analysis and measurement. It is expected here that any special equipment required for a specific experiment will be provided by the experimenter.

Both operating and experimental program costs are given in Table IX-1. These costs are shown in 1976 dollars, an appropriate escalation factor has to be added to project in the future.

TABLE IX-I

Facility Operation and Experimental Program Costs
(in thousand dollars)

<u>Facility Operation</u>	<u>100 mA</u>	<u>(200 mA)</u>
Energy	1,800	(3,400)
rf amplifier tubes	200	(400)
Maintenance and materials	600	(900)
Salaries	<u>900</u>	<u>(1,200)</u>
Total	3,500	(5,900)
 <u>Experimental Program</u>		
Capital equipment	600	(1,000)
Materials	300	(500)
Salaries	<u>400</u>	<u>(500)</u>
Total	1,300	(2,000)

10. Financial Appropriation Plan

The financial appropriation and commitment plan necessary to meet the proposed construction schedule is outlined in Table X-1 for a 100 mA and 200 mA facility respectively. This table updates the commitment schedule given in the Schedule 44 submitted to ERDA in June 1975 and includes all budget categories.

The basis for these commitment schedules include the following assumptions.

- 1) The preliminary design and development activities are allowed to proceed as soon as possible (v end CY-1976).
- 2) The project is authorized and funded in early FY 1978 including the necessary first year's appropriation.
- 3) The experimental program is allowed to start at reduced rate two years before operation. This early start is necessary to prepare for efficient and immediate use of the facility.
- 4) The costs escalation factor used is 8% per year, compounded annually.

Table X-1

Appropriation and Commitment Schedule
(In Thousand Dollars)

	<u>Fiscal Year</u>				
	<u>1977</u>	<u>1978</u>	<u>1979</u>	<u>1980</u>	<u>1981</u>
<u>100mA Facility</u>					
PD & D	1600	1600	600	350	
Construction		7500	17000	13000	4570
Exp. Program				500	800
Operation					
Subtotal	1600	9100	17600	13850	5370
Escalation 8%/year	(8%) 130	(17%) 1550	(26%) 4580	(36%) 4990	(45%) 2420
Total for 100 mA Facility	1730	10650	22180	18840	7790
<u>200mA Facility</u>					
PD & D	1600	1600	600	350	
Construction		10000	23000	15000	5760
Exp. Program				600	1000
Operation					
Subtotal	1600	11600	23600	15950	6760
Escalation 8%/year	(8%) 130	(17%) 1970	(26%) 6140	(36%) 5740	(45%) 3040
Total for 200 mA Facility	1730	13570	29740	21690	9800

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