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NIFTI And DISCOS:

New Concepts For A Compact Accelerator Neutron Source For Boron Neutron Capture Therapy Applications

by

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Abstract

Two new concepts, NIFTI and DISCOS, are described. These concepts enable the efficient production of epithermal neutrons for BNCT (Boron Neutron Capture Therapy) medical treatment, utilizing a low current, low energy proton beam impacting on a lithium target.

The NIFTI concept uses fluoride compounds, such as lead or beryllium fluoride, to efficiently degrade high energy neutrons from the lithium target to the lower energies required for BNCT. The fluoride compounds are in turn encased in an iron layer that strongly impedes the transmission of neutrons with energies above 24 KeV. Lower energy neutrons readily pass through this iron "filter", which has a deep "window" in its scattering cross section at 24 KeV.

The DISCOS concept uses a rapidly rotating, high g disc to create a series of thin (~ 1 micron thickness) liquid lithium targets in the form of continuous films or sheets of discrete droplets - through which the proton beam passes. The average energy lost by a proton as it passes through a single target is small, approximately 10 KeV. Between the targets, the proton beam is re-accelerated by an applied DC electric field. The DISCOS approach enables the accelerator - target facility to operate with a beam energy only slightly above the threshold value for neutron production - resulting in an output beam of low-energy epithermal neutrons - while achieving a high yield of neutrons per milliamp of proton beam current.

Parametric trade studies of the NIFTI and DISCOS concepts are described. These include analyses of a broad range of NIFTI designs using the Monte Carlo MCNP neutronics code, as well as mechanical and thermal-hydraulic analyses of various DISCOS designs.

Two illustrative point designs for NIFTI and DISCOS are described in detail. The first design is based on the NIFTI geometry with a fixed lithium target. The input proton beam energy (2.5 MeV) is well above the threshold value of 1.88 MeV; the output high energy neutron spectrum is degraded by fluorine and iron and hydrogen collisions down to the lower energies appropriate for BNCT treatment. The second design is based on a DISCOS target that operates with a proton beam energy (1.90 MeV) only slightly above threshold. A NIFTI iron/hydrogen "filter" then further degrades the relatively low energy output neutrons down to the final energy desired for BNCT treatment.

Both of the point designs result in a favorable output neutron energy spectrum for BNCT treatment, with advantage factors (depth of penetration and ratio of tumor/healthy tissue dose) that are comparable to those for current and proposed BNCT facilities. Both designs achieve output neutron fluxes that are useful for treatment, using low proton beam currents (~ 5 mA). The proton currents are a factor of 10 smaller than these previously proposed for accelerator based BNCT.

Executive Summary

Previous studies of accelerator/target systems designed to generate neutrons for BNCT (Boron Neutron Capture Therapy) medical treatment generally have required high proton beam currents, on the order of several tens of milliamps, with energies that are well above the threshold for neutron production. Accelerators for producing beam currents at this level are technically challenging, and costly as well. In addition, the target generated neutron energy spectrum typically has a substantial fast neutron component that would cause objectionable radiation dose in normal, non-cancerous tissue. The gamma dose to normal tissue is also significant. Finally, cooling of the accelerator targets at the required power levels is difficult.

In these previous designs, the high energy neutrons generated by the target/proton interactions are degraded to the treatment regime, i.e., on the order of 10 keV in energy, by scattering collisions with a suitable moderator (e.g., BeO, Al₂O₃, etc.) With such materials, to achieve the requisite energy degradation needed for a useful energy spectrum, the target must be located at some distance from the patient treatment zone. Consequently, for such systems the neutron utilization efficiency, that is, the ratio of the rate at which useful neutrons are introduced into the patient treatment zone to the rate at which neutrons are generated by proton/target interactions is typically in the range of 0.1 to 0.5 percent. That is, only 1/1000 th to 1/200 th of the neutrons in the target actually are available for use in the patient treatment zone. However, such efficiencies are still orders of magnitude greater than those achieved by medical reactor systems. Because of the inherently much greater distance between the neutron generating reactor core and the patient treatment zone - due to the inherent dimensional constraints imposed by criticality and the shielding requirements - the neutron utilization efficiency for medical reactors is on the order of 10⁻⁶. Thus for medical reactors, only about one millionth of the generated neutrons actually are available for use in the patient treatment zone.

Two new concepts are proposed that greatly increase the neutron effectiveness and utilization efficiency of accelerator-target sources for BNCT applications. The first concept, termed NIFTI (Neutron Intensification by Filtered Transmission through Iron), utilizes materials that tailor the neutron energy spectrum more effectively than conventional elastic scattering moderators. These materials enable the patient treatment zone to be located much closer to the target source, enabling a substantial increase in neutron utilization efficiency. Moreover, the energy distribution of the neutrons that reach the patient treatment region can be shaped and optimized for maximum effectiveness, typically with an average energy on the range of 10 to 30 keV, depending on design.

The second concept, DISCOS, employs a rapidly rotating disc to form a series of ultra thin targets (in the order of 1 micron in thickness) for the proton beam. The proton energy loss in traversing one target is small, on the order of 10 to 20 keV. The proton beam is successively re-accelerated between the series of thin targets, and operates just above the threshold value for neutron production. The average energy of the neutrons thus produced is then much less than those produced by a higher energy beam impacting a thick fixed target.

Two versions of the NIFTI Concept are described and analyzed. The first version, NIFTI-1 (Figure 1) has an iron filter between the treatment port and the neutron source. Iron has a deep window in its neutron scattering cross section at 24 keV. For neutron energies a few keV above this value, the scattering cross section is in the order of 100 barns, dropping to ~ 1 barn at the window.

As a result, the transmission of neutrons through the iron filter is strongly inhibited by scattering, until their energy drops below 24 keV. This results in a large peak in the energy of the transmitted neutrons at that energy (Figure 2).

To achieve practical beam currents, the NIFTI-1 system must operate with a DISCOS lithium target. By itself, the iron filter in NIFTI-1 cannot adequately condition the spectrum at the treatment port if the maximum neutron energy from the source is substantially greater than 60 to 70 keV.

To keep maximum neutron energy within this limit, the proton beam energy must not exceed a few keV above the (p, n) threshold. If just a single target is used, the neutron yield per proton is so low ($\ll 10^{-5}$ neutrons per proton) that the corresponding beam current would be impractically large, i.e., over a hundred milliamps. By periodically re-accelerating the beam between targets, and imparting an integrated energy of several hundred keV, the resulting total neutron yield per proton is in the order of 10^{-4} . This enables a much lower and more practical beam current of a few milliamps.

The second version, NIFTI-2, interposes a layer of fluoride compound between the neutron source and the outer iron filter. Fluorine is a strong inelastic scatterer [(σ_{in}) max ~ 3 barns] with a very low threshold energy [$E \sim 100$ keV]. High energy neutrons, i.e., above 100 keV, emanating from the neutron source are efficiently degraded in energy by inelastic collisions to energies well below 100 keV. They then are strongly inhibited by multiple scattering collisions with the outer iron filter until their energy drops below 24 keV, whereupon they pass through it. Figure 3 shows the flux and integral energy distribution for neutrons emanating from the treatment port of a NIFTI-2 design, based on a neutron source with a maximum energy of 350 keV.

NIFTI-2 can be used either with a thick fixed lithium target or with a DISCOS lithium target. In general, the overall neutron yield will be somewhat lower with the fixed target version, as compared to the DISCOS target version, resulting in a correspondingly higher beam current requirement for the fixed target.

NIFTI-1 and NIFTI-2 typically have neutron utilization efficiencies in the range of 5 to 10%. That is, of the total neutrons generated in the target, 5 to 10% are available for the treatment of patients. Based on a yield of 10^{-4} neutrons per proton, the corresponding proton currents required are in the range of 2 to 4 milliamps.

A wide range of NIFTI designs have been investigated. The studies, which are described in the report, include: examination of the effects of the maximum neutron energy from the source, the

nature of the neutron energy and angular distribution and the spatial orientation of the source, as well as the effects of varying the thickness of the iron filter, the thickness and composition of the fluoride inelastic scattering layer, the thickness and composition of the neutron reflector, the type of neutron transport geometry, and the thickness of any neutron "downshifter" used to tailor the final spectrum of output neutrons entering the patient treatment region.

Although further study is required to fully optimize the NIFTI concept, the results to date lead to the following conclusions:

1. The NIFTI concept enables accelerator/target devices used in BNCT applications to achieve neutron utilization efficiencies in the range of 5 to 10%, and beam currents of a few milliamps.
2. The spatial orientation of the NIFTI-1 neutron source has a noticeable effect on the neutron utilization efficiency and the output energy spectrum. The variation, however, is not a critical factor for design. Varying the orientation of the NIFTI-2 neutron source has only a small effect.
3. The NIFTI-2 system based on a thick fixed target is a practical and attractive option. However, the somewhat lower beam currents for NIFTI systems based on DISCOS targets may prove desirable.
4. The optimum thickness of the iron "filter" is in the range of 5 to 10 centimeters, for both NIFTI-1 and NIFTI-2.
5. Promising fluoride materials include lead fluoride (PbF_2) and beryllium fluoride (BeF_2), with an optimum thickness in the range of 5 to 10 centimeters.
6. Closed solid neutron transport geometries result in greater neutron utilization efficiencies than open cavity geometries.
7. Hydrogenous down-shifters significantly degrade neutron energy with an acceptable impact on utilization efficiency. The optimum thickness appears to be on the order of 1 to 2 centimeters (polyethylene equivalent).
8. The gamma photon flux that results from neutron capture and other processes is only about 1/100 of the neutron flux out of the treatment port.
9. The residual long-lived activation of a NIFTI assembly is very small. The only persistent isotope resulting from neutron activation that remains at 1 hour after shutdown is Fe^{59} (half life of 55 days), with a residual activity level in the assembly of well below 1 millicurie. There are several curies of ^7Be resulting from (p, n) reactions on ^7Li .

Two versions of the DISCOS target concept are described and analyzed. The first version, DISCOS-1, is based on the use of very thin metallic beryllium (Be) foils that are attached to the rim of a rapidly rotating segmented disc (Figure 4). Thin films of liquid lithium flow radially outwards on the disc, and onto the Be foils. The outwards centripetal acceleration on the liquid films is balanced by viscous drag forces. The thickness of the film is inversely proportional to the rotation rate, and can be as small as 1 micron.

Neutrons are generated by interaction of the proton beam with the liquid lithium films, and

to a lesser degree, by interactions with the Be foils. During their passage through a single Li/Be target, the protons lose on the average in the order of 10 keV in energy [the actual loss will depend on the thickness of the Li films and the Be foils].

The thermal energy generated in the target by the impacting proton beam is carried away by the outwardly moving lithium films. The films spin off at the outer edge of the Be foils, and are collected by an outer enclosing slot. The collected lithium is then cooled and recirculated to the hub of the rotating disc.

Using a multiple foil target with a DC electric field between the foils, the DISCOS-1 concept can re-accelerate the proton beam between the successive target foils (Figure 5). This arrangement enables DISCOS to operate with the proton beam just above threshold, with the output neutrons having only a few tens of keV energy, while at the same time achieving a reasonable value for the neutron yield per proton.

The second version, DISCOS-2, generates a thin sheet of small liquid lithium droplets (~ 1 micron diameter) at the periphery of a rapidly rotating disc (Figure 6). The droplets are spun out of the surface of the rotating disc, and travel outwards to a collecting slot similar to that in DISCOS-1. The proton beam impacts the droplet sheet, generating neutrons. Elimination of the supporting Be foils substantially increases the overall neutron-yield per proton, since the cross section for neutron production is considerably greater for lithium than for Be, while the proton energy loss per micron of thickness is considerably less.

Multiple droplet sheets can be also be used in the DISCOS-2 concept. Application of a DC electric field to the target region would then re-accelerate the proton beam between sheets.

A potential issue for the multiple foil or droplet sheet versions of DISCOS is the possibility of electrical breakdown, or parasitic electrical currents, that could be caused as a result of the applied DC field. The vapor pressure of lithium is very small ($< 10^{-6}$ mm Hg) at its maximum temperature of 100° C above the 179° C melting point. The corresponding mean free path for electron induced ionization of the neutron lithium vapor around the target is $\sim 10^8$ centimeters.

Such an exceedingly long mean free path makes it virtually impossible for electron induced ionization of lithium vapor to be a significant factor in electrical breakdown. However, secondary electrons produced by proton impact on the surface of multiple foil or droplet sheets could cause parasitic electrical currents between the foils and droplet sheets, and perhaps also cause avalanches leading to electrical breakdown. In this process, the initial proton induced secondary electrons would be accelerated by the electric field towards the adjacent foil or droplet sheet to hit it at relatively high energy. These electrons could eject tertiary ions, which would then travel in the opposite direction to produce still more electrons by surface impacts, with the eventual result being breakdown.

If parasitic currents or electrical breakdown caused by secondary electrons were to prove to be serious problems, it should be possible to overcome them by operating the multiple foil target in a magnetic field that is orthogonal to the electric field. Electrons ejected from the surfaces of foils

or droplet sheets would then gyrate in tight circles around the magnetic field lines, rather than being accelerated by the electric field to strike adjacent foils or droplet sheets. Instead, the electrons would helically spiral along the magnetic field lines, eventually reaching an external collector. The gyroradii of the electrons would be small; for example, the radius of gyration of a 100 eV electron is only 150 microns in a field of 2000 gauss.

Proposed proof of principle demonstration experiments for the DISCOS-1 concept are described. The first phase of experiments would be performed using a low vapor pressure inert liquid. Tests with a liquid metal such as NaK or lithium would be carried out in the second phase of experiments.

Preliminary designs have been carried out for the NIFTI-1 and NIFTI-2 concepts. Both design approaches appear viable. Figure 7 summarizes and compares the technical performance of the NIFTI-1 preliminary designs using the DISCOS target (Cases 1 and 2 in Figure 7) and the preliminary NIFTI-2 point design with a fixed lithium target (Cases 3 to 6). The letters "y" and "n" refer to whether or not a neutron "down-shifter" was employed in the design. In the cases where it was employed (letter "y"), the down-shifter was a one centimeter thick layer of water located immediately behind the iron filter - that is, between the iron layer and the neutron source.

In cases 1 and 2 average proton energy was 1.90 MeV. The protons experienced a 5 keV energy loss in traveling through the DISCOS target sheet. The proton beam current is unacceptably high (on the order of 200 mA), if the proton beam transits through only one sheet. To achieve an acceptably low current, the proton beam must either recirculate through an external accelerator, so that it can make multiple passes through the same sheet, or more likely, must travel through multiple thin targets in the DISCOS assembly, with periodic reacceleration between targets by an applied DC electric field. With an 80 sheet assembly, for example, the total energy loss for the proton beam would be 400 keV, and the required proton current would be only about 3 milliamps.

In the four NIFTI-2 cases, the proton beam current decreases by a factor of ~ 5 if the incident proton energy increases from 2.1 MeV to 2.5 MeV. This reflects the greater neutron yield at the higher proton energy. However, as proton energy increases the average energy of the output neutrons also increases.

Thus, lower currents in the NIFTI-2 approach have to be traded off against higher neutron energies. However, output neutron energies of ~ 30 keV appear acceptable, so that the required proton beam current for the NIFTI-2 approach can also be about 3 milliamps.

The neutron utilization efficiency for the NIFTI-1 and 2 concepts is very high, ranging from ~5 percent for NIFTI-2 to ~10% for NIFTI-1. That is, ~5 to 10% of the neutrons generated in the lithium target exit from the treatment port and are available for BNCT. These neutron efficiencies are more than tenfold greater than those achieved in previous accelerator - BNCT designs, and are the reason for the much smaller proton beam currents possible with NIFTI and DISCOS. The average energy of the output NIFTI neutrons ranges from a minimum of 12 keV to a maximum of 37 keV, depending on the particular case. The use of a neutron "downshifter" (in these designs, the

equivalent of 1 centimeter of H_2O), reduces the average energy of the neutrons by approximately 20 to 30%. For BNCT sources, the advantage depth is a measure of the penetration capability of the beam, while the advantage ratio is a measure of the tumor therapeutic dose to the background dose to healthy tissue integrated to the advantage depth. Figure 8 compares advantage depths and ratios for various types of neutron sources. The dots at the various indicated energies (i.e., 100 keV, 70 keV, 20 keV, etc.) refer to the advantage values for ideal monoenergetic neutron beams, (MIT calculations) while the triangles refer to the advantage values for the BMRR, assuming either a beam delimiter (Wheeler) and no delimiter (Fairchild). The goal is to maximize both the advantage depth and the advantage ratio - that is, to be in the upper right corner of the plot. The shaded region reflects the general type of performance characteristic of previous BNCT sources, either as proposed designs, or as constructed facilities.

After the NIFTI-1/DISCOS and NIFTI-2/fixed target preliminary designs were developed, they were examined in terms of their advantage factor performance - that is, what was the advantage depth and the advantage ratio. Based on this examination the designs were modified so as to maximize their advantage factor performance.

For the NIFTI-2/Fixed Target design, the modifications included:

1. Altering the fluoride layer composition from a mixture of BeF_2 and PbF_2 to BeF_2 only.
2. Incorporating the hydrogen used for neutron "downshifting" into the iron-titanium filter as a metal hydride ($FeTiH_x$).
3. Placing a thin (3 cm) lead shield between the treatment port and the patient.

These modifications significantly reduced the background gamma dose and softened the neutron spectrum, resulting in an improved advantage depth and ratio. For the NIFTI-1/DISCOS Target design, modifications #2 and #3 were incorporated (since a fluoride layer is not used in the NIFTI-1/DISCOS design, modification #1 did not apply).

Figure 9 gives the principal design and performance parameters for the resultant final point designs of NIFTI-2/Fixed Target and NIFTI-1/DISCOS. Figures 10 and 11 show the depth-dose distributions for the two designs, together with their corresponding advantage depths.

The advantage factor performance for the NIFTI-1/Fixed Target and NIFTI-1/DISCOS point designs appears competitive with other BNCT sources. Their performance should further significantly improve with continued optimization of the designs. The advantage factor performance of the ideal monoenergetic, non-directional neutron beams shown in Figure 8 represents an upper limit to accelerator based BNCT performance. Real systems will not achieve this ideal, but it appears possible to approach it relatively closely.

It is recommended that both the NIFTI and DISCOS concepts be developed further. At this point the NIFTI/fixed target approach appears to be favored, since the target technology is simpler. However, the DISCOS approach also should be carried forward, not only as a backup for BNCT use, but because of its potential for other uses. As an example, by operating just above threshold

DISCOS could efficiently generate specific excited nuclear states which would then produce monochromatic gammas. Such a DISCOS would be applicable to a wide range of elements and reactions.

The Monte Carlo neutronic analyses of the NIFTI designs are expected to yield accurate predictions of performance, provided that the nuclear data input is accurate. To verify the analyses, it is recommended that measurements of the neutron utilization efficiency and energy distribution for representative NIFTI assemblies be carried out using an available proton accelerator.

The verification of the expected NIFTI performance would validate the analytical methods and data used for the predictions, and provide the basis for proceeding with a prototype NIFTI assembly for BNCT applications.

Closed Solid Neutron Transport Geometries Used In 3D Neutron Analysis

NIFTI-1 Energy Regime

NIFTI-2 Energy Regime

Figure 1

**Output Neutron Energy Distribution From NIFTI-1 Target
Inside 7.5 cm Radius Iron Sphere Current vs Energy
(7.5 cm Radius Fe Sphere)**

Figure 2

**Figure 3 Output Neutron Energy Distribution From NIFTI-2 Assembly
with 2.1 MeV Proton Beam on Fixed Lithium Target**

—•— Flux * Fraction

Total Fraction Exiting "Treatment Port" = 0.0556

Liquid Film Cooling Of DISCOS-1 Target

Fig. 4

Re-Acceleration of Proton Beam By DC Field Between Multiple Sheets in DISCOS-1 Target

Fig. 5

Droplet Sheet In DISCOS-2 Target

Fig. 6

Figure 7

- Summary of NIFTI Preliminary Designs -

	1	2	3	4	5	6
Proton Energy (MeV)	1.9	1.9	2.1	2.1	2.5	2.5
"Down-Shifter"	n	y	n	y	n	y
Neutron Leakage (Port)	.1305	.0843	.0508	.0349	.0524	.0394
Neutron Leakage (Outlet)	.1894	.1208	.0684	.0462	.0760	.0560
Photon Leakage (Port)	.00234	.0134	.00122	.00474	.00106	.00406
Neutron Leakage (Except Outlet)	.08308	.0454	.0413	.0310	.0572	.0459
$\bar{E}$ (Neutron) [keV]	18.4	11.6	20.4	15.7	37.0	31.5
n/mA-s-cm ²	5.74 (6)	3.66 (6)	8.82 (7)	5.95 (7)	4.13 (8)	3.05 (8)
mA for 10 ⁹ n/cm ² -s	175*	273*	11.3	16.8	2.42	3.28
mA for 10 ⁹ n/cm ² -s	2.2**	3.4**	---	---	---	---

* 1 sheet DISCOS (5 keV energy loss)

** 80 sheets DISCOS (400 keV energy loss)

Figure 8 Advantage Factors for NIFTI-2 and NIFTI-1/DISCOS Point Designs

Figure 9**Principal Design and Performance Parameters
For NIFTI-2/Fixed Target and NIFTI-1/DISCOS Point Designs**

Design Parameter	NIFTI-2/Fixed Target Point Design	NIFTI-1/DISCOS Point Design
Proton Energy, MeV	2.5	1.904 to 1.889 (400 keV added by DC Field)
Proton Current, mA	5	5
Fluoride Layer	BeF ₂ , 10 cm Thick, 18 cm Diam.	None
Iron Filter	FeT ₁ H, 3 cm Thick, 18 cm Diam.	Fe/Mg, 5 cm Thick, 18 cm Diam.
Gamma Shield at Port Face	Pb, 3 cm Thick, 18 cm Diam.	Pb, 3 cm Thick, 18 cm Diam.
Performance Parameter		
Peak Total Dose Rate to Tumor,* RBE/min.	250	350
Peak Total Dose Rate to Healthy** Tissue, RBE/min.	90	110
Advantage Depth, cm	6.0	6.5
Advantage Ratio	3.7	4.75

* Includes α Particles (RBE Factor = 2.3); Neutrons (RBE Factor = 1.6); Gammas (RBE Factor = 1.0)

** Includes Neutrons and Gammas; Zero ¹⁰B Loading Assumed

Figure 10 **Dose-Depth Distribution for**
NIFTI-1/DISCOS Point Design

**Figure 11 Dose-Depth Distribution for
NIFTI-2 Fixed Target Point Design**

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1 Introduction and Background

Boron Neutron Capture Therapy (BNCT) is a promising approach for the treatment of inoperable brain tumors and other cancers ^(1, 2, 3). BNCT employs a boron containing compound that is preferentially taken up by cancer cells in the brain. When the ^{10}B in the compound absorbs a neutron, an energetic (MeV) alpha particle is released, killing the cell where the absorption takes place.

Energetic epithermal neutrons, as proposed by Fairchild ^(4, 5), enable penetration to the site of the tumor. Achieving a suitable neutron energy spectrum is very important for effective treatment. If the neutron energy spectrum is too low, their penetration depth into tissue is too small to reach the site of the tumor; if too energetic, the radiation dose to normal tissue is excessive.

BNCT treatment effectiveness is being experimentally investigated using nuclear reactors as the source of neutrons. In the U.S., several patients have been recently treated at Brookhaven Medical Research Reactor (BMRR), located at Brookhaven National Laboratory. Figure 1.1 shows the BMRR configuration ⁽⁶⁾. Leakage neutrons from the core are moderated and collimated to produce a suitable beam at the external treatment port.

Reactors have very low neutron utilization efficiencies. Typically, only about 10^{-6} of the neutrons that are released in the core are actually available at the treatment port. This is a result of the inherent dimensional constraints imposed by criticality, and the relatively long distances required to slow-down high energy neutrons using conventional moderator. Gamma shielding requirements are also a contributing factor. As a result, in the BMRR, for example, the treatment port is located at a distance of 177 centimeters from the center of the core. In the MURR (Missouri University Research Reactor) BNCT design, the treatment port is 310 centimeters from the center of the core.

As a result of this very low neutron utilization efficiency, a reactor based neutron source for BNCT requires high operating power, on the order of several megawatts, and is a large, very expensive, one of a kind facility with a limited capability to treat large numbers of patients.

In contrast, accelerator based neutron sources for BNCT appear to have very attractive features, as compared to reactor based neutron sources: much lower facility cost, greatly reduced residual radioactivity, much lower operating power, greatly reduced safety concerns, and a better neutron energy spectrum for treatment.

Compared to reactor based BNCT facilities, accelerator based facilities could be located at a much larger number of sites, enabling many more patients to be treated.

Various concepts for accelerator based BNCT systems have been proposed, in which a

particle beam interacts with a target to generate neutrons. Depending in the particular concept, the nuclear reaction involved can be a (p, n) reaction, a $H^3(d, n)He^4$ reaction, and so forth.

A particularly promising approach is the proton beam - lithium target concept, in which a low energy proton beam ($E \sim 2$ MeV) strikes a lithium target, generating neutrons by the (p, n) reaction. Its attractive features include:

- Relatively high neutron yield per proton ($\sim 10^4$)
- Low maximum energy of generated neutrons
- Simple, low energy proton accelerator
- Simple, readily cooled target
- Minimal shielding and residual radioactivity

A number of design studies of the proton beam - lithium target concept have been carried out. These previous studies, while they show that the concept is feasible, end up requiring the proton beam current to be in the range of 50-100 milliamps in order to achieve adequate neutron flux at the treatment port.

Wang, et al ⁽⁶⁾ have designed a proton beam - lithium target system using a BeO moderator. At a beam current of 50 milliamp, this design, shown in Figure 1.2, would achieve approximately $\frac{1}{2}$ of the BMRR neutron treatment flux, requiring that the patient exposure time be twice as long as that of the BMRR (Figure 1.3). The fast neutron dose and gamma ray dose per therapeutic epithermal neutron for the accelerator irradiation facilities are each approximately 30% greater than those for the BMRR.

Wu, et al ⁽⁷⁾ also have designed a proton beam - lithium target system using a BeO moderator. At a beam current of 20 milliamps, this design shown in Figure 1.4 would achieve approximately the same neutron treatment flux as the BMRR (Figure 1.5). The fast neutron dose per therapeutic epithermal neutron for the accelerator irradiation facility is approximately equal to that for the BMRR. The gamma dose per therapeutic epithermal neutron for the accelerator is approximately $2\frac{1}{2}$ times greater than that for the BMRR, however (Figure 1.5). The neutronic efficiency of the Wu design is approximately 5 times greater than that of the Wang design. That is, the beam current required is approximately 5 times smaller for the Wu design, when both are normalized to the same epithermal flux.

This greater efficiency for the Wu design primarily results using a thinner BeO moderator and locating the lithium target closer to the treatment port. However, as a result, the gamma dose per therapeutic neutron is increased.

In the remainder of this report, we examine new and more efficient approaches for degrading the energy and tailoring the spectral distribution of neutrons generated by a proton beam impacting a lithium target. These new approaches enable the design of accelerator based BNCT facilities that can deliver useful neutron irradiation fluxes with considerably smaller proton beam current requirements.

Configuration of BMRR (Brookhaven Medical Research Reactor)

1-3

Figure 1.1

Figure 1.3 Performance Parameters for Wang Design of Accelerator/BNCT Facility

PARAMETER	PROPOSED ACCELERATOR NEUTRON IRRADIATION FACILITY		BROOKHAVEN MEDICAL RESEARCH REACTOR
	10 mA beam	50 mA beam	
1. Epithermal-neutron fluence rate for energies of 1eV to 10keV ($\times 10^8$ neutrons/sq.cm.-sec.)	1.6	7.8	18.0
2. Absorbed dose rate from fast neutrons > 10 keV, free in air (cGy/min.)	0.96	4.8	5.3
3. Absorbed dose rate from gamma rays, free in air (cGy/min.)	0.22	1.10	1.20
4. Absorbed fast neutron dose per epithermal neutron fluence ($\times 10^{-11}$ cGy-sq.cm./neutron)	6.6	6.6	4.9
5. Absorbed gamma ray dose per epithermal neutron fluence ($\times 10^{-11}$ cGy-sq.cm./neutron)	1.4	1.4	1.1
6. Thermal neutron fluence rate at 2-cm depth in phantom ($\times 10^8$ neutrons/sq.cm.-sec.)	1.8	8.8	19.0
7. Whole body dose rate to patient (cGy/min.)	0.06	0.32	Data Not Available
8. RUFTED--Ratio of Useful Neutron Fluence To Entrance Dose equivalent	6.8	6.8	9.2
9. Neutron current/fluence at beam port surface	0.94	0.94	0.58
10. Treatment time based on therapeutic fluence of 1.0×10^{12} thermal neutrons/sq.cm. (minutes)	94	19	9
11. Treatment time based on therapeutic fluence of 5.0×10^{12} thermal neutrons/sq.cm. (minutes)	470	94	44

Figure 1.4 Accelerator Based Neutron Source for BNCT (Wu, et al.)

Figure 1.5

Performance Parameters for Design of Accelerator/BNCT Facility
(Wu, et al.)

	AT PATIENT IRRADIATION POSITION IN A	PROTON BEAM CURRENT		BMRR PARAMETERS (WANG, et al ⁽⁷⁾)
		1 in A	20 in A	
	Total Neutron Flux, n/cm ² sec	1.31 x 10 ⁸	2.62 x 10 ⁹	---
	Epithermal Neutron Flux (1 eV to 10 keV), n/cm ² sec	0.94 x 10 ⁸	1.88 x 10 ⁹	1.8 x 10 ⁹
	Neutron Dose per Epithermal Neutron, cGy/n/cm ²	4.3 x 10 ⁻¹¹	4.3 x 10 ⁻¹¹	4.9 x 10 ⁻¹
1-7	Gamma Dose per Epithermal Neutron, cGy/n/cm ²	2.7 x 10 ⁻¹¹	2.7 x 10 ⁻¹¹	1.1 x 10 ⁻¹¹
	Thermal Neutron Flux, n/cm ² sec	1.0 x 10 ⁸	2.0 x 10 ⁹	1.9 x 10 ⁹
	Total Dose to Tumor, cGy/min	1.78	35.6	---
At 6an Depth Tumor with 30 μg ¹⁰ B/g of Tissue				
	Fraction of Dose from ¹⁰ B (n, α)			67%
	Fraction of Dose from Fast Neutrons			5%
	Fraction of Dose from ¹⁴ N (n, p)			1%
	Fraction of Dose from Gammas			27%

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2.0 The NIFTI Concept

2.1 Neutronic Efficiency of BNCT Neutron Sources

Previous design studies of accelerator driven neutron sources for BNCT therapy have achieved only relatively low neutron utilization efficiencies. Here, neutron utilization efficiency is defined as

$$\eta_N = \frac{(J_n)_T A_T}{S_N} \quad (2.1.1)$$

where

A_T	=	area of treatment port, cm^2
$(J_n)_T$	=	neutron current at treatment port, $\text{n/cm}^2 \text{ sec.}$
S_N	=	neutron generation rate at accelerator target, neutrons/sec.

Typically, the neutron utilization efficiency for accelerator targets in these studies has been in the range of 1×10^{-3} to 5×10^{-3} , depending on design (Figure 2.1.1).

For a practical treatment facility, $(J_n)_T$ should be on the order of $10^9 \text{ n/cm}^2 \text{ sec.}$, and A_T on the order of 10^2 cm^2 . For a neutron utilization efficiency of $\sim 1 \times 10^{-3}$, this requires a proton beam current of ~ 100 milliamps, an impractically large value.

The neutron utilization efficiency for a reactor based neutron source is much smaller, on the order of 10^{-6} for the BMRR. This is a result of the necessarily much greater distance of the treatment port from the reactor core, as compared to an accelerator driven target.

2.2 Description of The NIFTI Concept

It is very desirable to develop neutron conditioning/transport designs that can achieve much greater neutron utilization efficiencies for BNCT therapy. With a neutron utilization efficiency of 10^{-1} , for example, the proton current for a useful accelerator - target source needs only be about 1 milliamp.

A new neutron conditioning/transport concept termed NIFTI (Neutron Intensification by Filtered Transmission through Iron) is proposed. NIFTI uses a thick iron containing "layer" to filter out unwanted high energy neutrons while letting neutrons of acceptable energy for treatment pass though almost unimpeded. Iron has a large "window" in its scattering cross section at 24 keV (Figure 2.2.1). The minimum scattering cross section is less than 1 barn; at a few keV above the "window", the cross section increases to ~ 100 barns ⁽¹⁾.

Figure 2.1.1

Comparison Between Li Target Designs

	Wang	Wu	NIFTI-2	NIFTI-2/DISCOS
Type of Target	Thick Li	Thick Li	Thick Li	Thin Li Film with Beam Reacceleration (10 Passes)
Initial Proton Energy, MeV	2.5	2.5	2.5	2.5
Energy Extracted Above Threshold, MeV	0.62	0.62	0.62	6.2
Neutron Yield/Proton J/ϕ [Current/Flux] Patient Dist From Source, cm	$\sim 1.5 \times 10^{-4}$ 0.94 60	$\sim 1.5 \times 10^{-4}$ 0.66 26	1.5×10^{-4} — 15	1.5×10^{-3} — 15
Neutron Utilization Efficiency (Fraction of Source Neutrons That Appear as epi-n Crossing 15x15 cm Plane) • MCNP Calculations • Geometric ($^{15}\text{Li}/4\pi R^2$)	1.71×10^{-3} 2.17×10^{-3}	6.25×10^{-3} 1.16×10^{-2}	$\sim 5 \times 10^{-2}$ 3.5×10^{-2}	$\sim 5 \times 10^{-2}$ 3.5×10^{-2}
Proton Current for Neutron Current of 10^9 n/cm ² sec at Patient, mA	59	16	2	0.2

Figure 2.2.1 Neutron Scattering Cross Section for Iron

Figure 2.2.2.2 Inelastic Neutron Scattering Cross Section for Fluorine

Neutrons with energies above ~ 25 keV are strongly impeded from transmission through a thick iron layer, but readily pass through once their energy drops below ~ 25 keV.

The second major feature of NIFTI is the use of a fluorine compound to inelastically degrade high energy neutrons. The inelastic cross section for fluorine has a threshold energy⁽¹⁾ slightly above 100keV, reaching a peak of 3 barns at ~ 300 kev (Figure 2.2.2). Fluorine appears to be unique among elements in its low threshold energy for inelastic scattering (most elements have threshold energies of at least 1 Mev), and its high value for the inelastic cross section.

Degradation of neutron energy by inelastic scattering is preferable to degradation by a moderator, because the neutrons, once degraded by inelastic collisions, stay relatively constant in energy, rather than continuing to lose energy to the point where they are no longer useful for BNCT therapy. It is important to note that the neutron energy after a typical inelastic scattering event in fluorine will be much lower than 100 kev.

2.3 NIFTI Energy Regimes

There are two energy regimes possible for NIFTI, i.e., NIFTI-1 and NIFTI-2. In the NIFTI-1 energy regime, the accelerator/target system operates with the proton beam energy slightly above the threshold for neutron production. The resultant neutron spectrum is relatively low in energy, with a maximum value of ~ 100 kev or less. The neutron angular distribution is strongly non-isotropic.

In the NIFTI-2 energy regime, the proton beam energy is well above threshold. Neutrons are generated over a wide spectrum of energies, with a maximum value of hundreds of kev and a more isotropic angular distribution.

Figure 2.3.1 illustrates the scattering/neutron filter arrangements used for the two energy regimes. 1-D spherical geometry is used in this illustration; more complex geometry designs for a treatment facility are described later.

For NIFTI-1 (Figure 2.3.1A) an iron filter (possibly with some added hydrogen and other scatterers) appears sufficient. The dependence of the spectral distribution of the filtered neutrons on the thickness of the iron layer and the energy spectrum of the neutron source is discussed later. For NIFTI-2 (Figure 2.3.1B) an inner layer of fluoride inelastic scatterer is used, with an outer iron filter. The dependence of the filtered neutrons on the source spectrum, thickness of fluoride inelastic scatterer, and thickness of iron layer is discussed later.

At this point, fluorine appears to be the best choice for the inelastic neutron scatterer, because it has

- Lowest threshold energy for inelastic scattering (~ 100 kev)
- High inelastic cross section (maximum of ~ 3 barns)
- Low absorption cross section
- Low energy degradation for elastic scattering ($\xi = 0.03$)
- High stability compounds with a wide variety of other elements

The mean distance a neutron travels before undergoing an inelastic scattering event in fluorine is given by

$$\lambda_{in} = \frac{1}{(\bar{\Sigma}_{in})_F} = \frac{1}{N_F (\bar{\sigma}_{in})_F} \quad (2.3.1)$$

where

$$\begin{aligned} N_F &= \text{atomic concentration of fluorine, cm}^{-3} \\ (\bar{\sigma}_{in})_F &= \text{average inelastic cross section over neutron energy spectrum, cm}^2 \end{aligned}$$

N_F ranges from ~ 4×10^{22} atoms/cm³ for high Z fluoride compounds such as PbF₂ to ~ 6×10^{22} atoms/cm³ for low Z compounds such as Teflon. A selection of fluoride compounds for possible use in NIFTI is given in Figure 2.3.2.

The mean removal length for inelastic scattering is given by

$$(L_R)^2 = -1 / \left[3 \bar{\Sigma}_S (\bar{\Sigma}_{in})_F \right] \quad (2.3.2)$$

where

$$\bar{\Sigma}_S = \text{average macroscopic total scattering cross section over neutron energy spectrum, cm}^{-1}$$

Taking $(\bar{\sigma}_{in})_F = 1.6 \times 10^{-24}$ cm² (1.6 barns), λ_{in} ranges between 10 centimeters for Teflon ($N_F \approx 6 \times 10^{22}$ atoms/cm³) and 15 centimeters for PbF₂ ($N_F \approx 4 \times 10^{22}$ atoms/cm³). The quantity, $(3 \bar{\Sigma}_S)^{-1}$, ranges from 0.74 to 0.72 centimeters. The removal length, L_R , is then in the range of 2.7 centimeters (Teflon) to 3.4 centimeters (PbF₂).

The quantity $(L_R)^2$ equals one-sixth of the mean square crow-flight distance that a neutron will travel from its point of origin until it is inelastically degraded in energy. The value of ~ 7 to 11 cm² for $(L_R)^2$ signifies that fluoride compounds are relatively good energy degraders, comparable in performance to the best conventional moderators, with the major advantage being that in fluorine, neutron energy degradation essentially ceases below 100 kev. In contrast, for conventional moderators, energy degradation continues all the way down to thermal energy.

By way of comparison, the corresponding age for water (H_2O) is 4.2 cm^2 , for beryllium (Be), 12 cm^2 ; and for heavy water (D_2O) 15 cm^2 . These ages correspond to an energy degradation of a factor of ~ 10 , i.e., from several hundred kev down to several tens of kev. The usual values for moderator age, i.e., $\tau = 33 \text{ cm}^2$ (H_2O), 90 cm^2 (Be), and 120 cm^2 (D_2O) correspond to an energy degradation of $\sim 10^8$ (2.2 Mev down to 0.025 ev).

2.4 Neutron Transport Geometries for NIFTI

Two neutron transport geometries are possible for NIFTI:

1. open cavity (OC) geometry
2. closed solid (CS) geometry.

The two geometries are shown in Figure 2.4.1. In the open cavity geometry (Figure 2.4.1A) the neutron source, plus its fluoride scatterer (if used) and iron filter, are located in an open cavity. Neutrons transmitted through the iron filter are scattered from the cavity walls. They finally either escape through the treatment port, are absorbed, or diffuse outwards through the cavity walls. The treatment port may be an open window, or it may incorporate a gamma shield (optional) to reduce unwanted radiation dose to patients.

In the closed solid geometry (Figure 2.4.1B) the neutron source, together with the fluoride inelastic scatterer (if used) and iron filter, are enclosed by a close fitting reflector. Neutrons transmitted through the iron filter at the treatment port directly interact with the patient, while a portion of the neutrons that interact with the surrounding reflector are scattered back into the treatment port.

The closed solid geometry permits the neutron source to be located at the minimum possible distance from the patient, which acts to increase neutron utilization efficiency. However, the neutrons leaving the source that do not travel in the direction of the treatment port tend to be lost by diffusion, though a portion is scattered back towards the port. The open cavity geometry collects and returns scattered neutrons back to the treatment port. This acts to increase neutron utilization efficiency. However, since the source is located further away from the patient than is the case for the closed solid geometry, the increased distance tends to decrease neutron utilization efficiency.

Scattering/Neutron Filter Arrangement

(4a) NIFTI-1 Energy Regime
[$E_{\text{max}} \sim 100 \text{ keV}$]

(4b) NIFTI-2 Energy Regime
[$E_{\text{max}} \sim 1 \text{ MeV}$]

Fig. 2.3.1

Figure 2.3.2

Potential Fluorine Compounds for NIETI-2

COMPOUND	DENSITY (g/cm ³)	FLUORINE ATOMIC DENSITY (atoms/cm ³)	MELTING POINT (° C)
PbF ₂	8.24	4.01 x 10 ²²	855
BeF ₂	1.99	5.09 x 10 ²²	800
VF ₄	2.98	5.64 x 10 ²²	325
TuF ₄	2.80	5.42 x 10 ²²	400
FeF ₂	4.09	5.25 x 10 ²²	1000
AlF ₃	2.88	6.01 x 10 ²²	1291
GaF ₃	4.47	6.37 x 10 ²²	800
Teflon	2.2	6 x 10 ²²	~ 100° C (max working)

Both types of neutron transport geometries require detailed MCNP neutronic analyses in order to obtain precise results. Results for closed solid geometries tend to be strongly affected by specific design parameters so that it is difficult to obtain good generalized rules. With open cavity geometries, some useful generalized results can be obtained that can help in the optimization process.

Consider the idealized open cavity geometry shown in Figure 2.4.2. It is assumed that the cavity is a "neutron hohlraum", with the neutron flux everywhere inside the cavity having the same value. This assumption is not strictly correct because of losses through the treatment port and the scattering effects due to the iron filter and fluoride layers that surround the neutron source, but it is reasonably accurate when the scattering from the cavity wall predominates - that is, when

$$\pi D_C L_C > D_T^2 \text{ and } \pi D_S^2 \quad (2.4.1)$$

It is also assumed that losses due to neutron absorption are small compared to losses due to diffusion through the cavity walls, and that the source neutrons are transported through the fluoride and iron filters with negligible absorption losses. Both of these assumptions are based on results of neutronic analyses.

The neutron leakage through the cavity wall can be approximated from diffusion theory, with

$$J_{CW} \equiv D_{CW} \nabla \phi_C = \frac{1}{3 (\bar{\Sigma}_S)_{CW}} \left(\frac{\phi_C}{\Delta X_{CW}} \right) \quad (2.4.2)$$

where

$$\begin{aligned} J_{CW} &= \text{neutron diffusion current through the cavity wall, n/cm}^2 \text{ sec} \\ \Delta X_{CW} &= \text{cavity wall thickness, cm} \\ \phi_C &= \text{neutron flux inside cavity, n/cm}^2 \text{ sec} \\ \bar{\Sigma}_S &= \text{macroscopic total cross section of cavity wall, cm}^{-1} [(\bar{\Sigma}_S)_{CW} = N_{CW} (\bar{\sigma}_S)_{CW}] \end{aligned}$$

For the BNCT application, it is desirable to have a relatively low rate of neutron energy degradation in the cavity wall. To accomplish this, the average energy decrement for an elastic scattering event should be as low as possible. The average logarithmic energy decrement per scattering event in the wall, ξ_{CW} , is given by

$$\xi_{CW} = \frac{2}{3 A_{CW}} \quad (2.4.3)$$

where

A_{CW} = atomic mass of the cavity wall material

The rate of energy degradation per cm^2 of cavity wall is approximated by

$$(L_R)_{CW} \cong \frac{\phi_C}{2} \Delta X_{CW} \xi_{CW} (\bar{\Sigma}_S)_{CW} \left(\frac{1}{\Delta U_{CW}} \right) \quad (2.4.4)$$

where

L_R = energy degradation rate, $\text{n/cm}^2 \text{ sec}$
 ξ_{CW} = average logarithmic energy decrement
 $(\Delta U)_{CW}$ = acceptable lethargy decrement for neutrons

Assuming that a factor of e ($= 2.72$) degradation in neutron energy is acceptable $[(\Delta U)_{CW} = 1]$, and that the energy degradation rate is the same order as the diffusion loss rate $[(L_R)_{CW} = J_{CW}]$, equations (2.4.2) and (2.4.4) can be combined

$$\frac{J_{CW}}{(L_R)_{CW}} = \frac{\phi_C}{(\Delta X)_{CW}} \left[\frac{1}{3 (\bar{\Sigma}_S)_{CW}} \right] \frac{2}{\phi_C \Delta X_{CW} \xi_{CW} (\bar{\Sigma}_S)_{CW}} = 1 \quad (2.4.5)$$

Rearranging,

$$(\Delta X_{CW}) = \left(\frac{2}{3 \xi_{CW}} \right)^{1/2} \frac{1}{(\bar{\Sigma}_S)_{CW}} = (A_{CW})^{1/2} \frac{1}{(\bar{\Sigma}_S)_{CW}} \quad (2.4.6)$$

where

A_{CW} = atomic mass of cavity wall material

Combining equations (2.4.2) and (2.4.6)

$$J_{CW} \cong \frac{\phi_C}{3} \frac{1}{(A_{CW})^{1/2}} \text{ n/cm}^2 \text{ sec} \quad (2.4.7)$$

For an open treatment port (no gamma shield) the neutron current through the port is given by

$$J_T \cong \frac{\phi_C}{4} n/cm^2 \text{ sec} \quad (2.4.8)$$

Combining equations (2.4.7) and (2.4.8)

$$\left(\frac{J_T}{J_{CW}} \right) \cong \frac{\phi_C}{4} \frac{3(A_{CW})^{1/2}}{\phi_C} \cong \frac{3}{4} (A_{CW})^{1/2} \quad (2.4.9)$$

For heavy scatterers, such as lead,

$$\left(\frac{J_T}{J_{CW}} \right)_{Pb} \cong \frac{3}{4} (207)^{1/2} \cong \frac{3}{4} (14.4) \cong 10.8$$

The neutron diffusion current through the cavity wall is thus approximately 10^{-1} of the current through the treatment port.

However, the corresponding value for $(\Delta X)_{CW}$ as given by equation (2.4.5) is approximately

$$\left[(\Delta X)_{CW} \right]_P \cong \frac{(A_{CW})_{Pb}^{1/2}}{\left[(\Sigma_S)_{CW} \right]_{Pb}} \cong \frac{(14.4)}{N_{Pb} (\sigma_S)_{Pb}} \cong \frac{14.4}{3 \times 10^{22} \times 11 \times 10^{-24}} \cong 43.6 \text{ cm}$$

This thickness appears too great to be practical, since the unfavorable geometry of such a thick wall would substantially increase neutron diffusion losses.

The large value of 44 cm for lead is a consequence of the low atomic concentration ($N_{Pb} \approx 3 \times 10^{22}$ atoms per cm^3) and modest scattering cross section ($\sigma_s \approx 11$ barns). Other materials are possible, with substantially higher cross sections and atomic cross sections ⁽¹⁾.

Candidate materials include vanadium (Figure 2.4.3), titanium (Figure 2.4.4) and nickel (Figure 2.4.5), either singly or in combination to eliminate "windows" in the scattering spectrum. Other materials that might be used in combination to eliminate windows include chromium (Figure 2.4.6) and manganese (Figure 2.4.7).

These materials are characterized by high atomic densities ($\sim 10^{23}$ atoms/cm³) and high average cross sections - on the order of tens of barns - in the multi kev energy range. Taking $N_{sw} \sim 10^{23}$ atoms/cm³ and $\bar{\sigma}_s \sim 30$ barns, the corresponding value of $(\Delta X)_{cw}$ becomes

$$(\Delta X)_{cw} = \frac{(A_{cw})^{1/2}}{10^{23} \times 30 \times 10^{-24}} = \frac{(50)^{1/2}}{3} = 2.4 \text{ cm}$$

While the above elements are excellent scatterers, with the consequent advantage that the cavity walls can be thin, they also have relatively low values of ξ (ξ for Ni, etc., is about $\frac{1}{4}$ that for lead), makes the ratio of

$$J_T/J_{cw} \sim 5 \text{ to } 6$$

as compared to ~ 11 for lead.

The situation can be improved somewhat by (singly or in combination)

- 1) operating with a higher value for $(\Delta U)_{cw}$, and/or
- 2) using a mixture of lead and some other scatterer (eg, Vanadium) for the cavity wall.

Since J_T/J_{cw} scales as $[(\Delta U)_{cs}]^{1/2}$, accepting a factor of e^2 in energy degradation (factor of 7.4) rather than 3 (factor of 2.72) increases J_T/J_{cw} by a factor of 1.4, so that J_T/J_{cw} for the vanadium, etc. type of cavity reflectors would then be in the range of 7 to 8.

Increasing the total macroscopic cross section for the cavity wall from the value of 0.33 cm⁻¹ for pure lead to the value of 0.66 cm for a mixture of Pb and vanadium type of scatterer would reduce ΔX_{cw} from 44 cm down to 22 cm. In addition, ξ_{cw} would be reduced by a factor of ~ 2 , as compared to a pure vanadium scatterer. These two effects would increase J_T/J_{cw} by a factor of 1.4.

It thus appears possible to tailor the composition of the cavity reflector and the amount of energy degradation so as to have an acceptable wall thickness on the order of ~ 20 cm with a value of J_T/J_{cw} of about 10.

Based on this value, the value of neutron utilization efficiency can be expressed for the idealized geometry shown in Figure 2.4.2 as

$$\eta_N = \frac{J_T \left(\frac{\pi D_T^2}{4} \right)}{J_{CW} \left[\pi D_{CW} L_{CW} + \frac{\pi}{2} D_{CW}^2 - \frac{\pi}{4} D_T^2 \right] + J_T \left(\frac{\pi D_T^2}{4} \right)} \quad (2.4.10)$$

Rearranging

$$\eta_N = \frac{J_T / J_{CW}}{\left[4 \frac{D_{CW} L_{CW}}{D_T^2} + 2 \frac{D_{CW}^2}{D_T^2} - 1 \right] + J_T / J_{CW}} \quad (2.4.11)$$

Figure 2.4.8 shows η_N as a function of D_{CW} , assuming that $D_T = 11$ cm ($A_T \sim 100$ cm²), the cavity length to diameter ratio equals 1 ($D_{CW} = L_{CW}$), and the relative leakage ratio, J_T/J_{CW} , = 10. The lower limit for D_{CW} depends on the energy regime considered. For NIFTI-1, the outer diameter, D_s , of the neutron source (i.e., the OD of the iron filter) is assumed to be 15 centimeters. For NIFTI-2, the D_s of the neutron source is taken to be 25 centimeters. [The extra interior volume holds the PbF_2 inelastic scatterer].

It is also assumed that the lower limits for D_{CW} in NIFTI-1 and NIFTI-2 are determined by the condition that

$$\left(D_{CW}^2 \right)_{Lower Limit} = 2 D_s^2 \quad (2.4.12)$$

This corresponds to having the minimum area of open cavity around the source neutron (at $\theta = 90^\circ$ in Figure 7) equal to the cross sectional area of the source.

As illustrated in Figure 2.4.9, on the basis of these idealized analyses the neutron utilization for the open cavity geometry are projected to be in the range of 20 to 30% for NIFTI-1, and in the range of 10 to 15% for NIFTI-2.

As noted earlier, neutron utilization efficiencies for closed solid NIFTI geometries are more difficult to estimate. In general terms, for closed solid geometries

$$\eta_N = K_{CS} \frac{A_T}{4 \pi \left(\frac{D_S}{2} \right)^2} = K_{CS} \frac{A_T}{\pi (D_S)^2} \quad (2.4.13)$$

The factor K_{CS} relates to how effectively the neutrons that originally travel outwards from the source in directions away from the treatment point are scattered back to the port. The value of $K_{CS} = 1$ corresponds to a pure geometric neutron utilization. That is, η_N is just the ratio of port area to the spherical surface area for the radius $D_S / 2$. For a treatment port area of 100 cm^2 , and $D_S = 15 \text{ cm}$, η_N for NIFTI-1 equals 14%. With a modest amount of scattering into the treatment port, i.e., $K_{CS} \approx 2$, the neutron utilization efficiency for the closed solid version of NIFTI-1 will be comparable to that for the open cavity version.

A similar situation holds for the closed solid version of NIFTI-2. For $K_{CS} = 1$ and $D_S = 25 \text{ cm}$, η_N equals 5%. With a modest amount of scattering into the treatment port, i.e., $K_{CS} \approx 2$, the value of η_N becomes comparable to that for the open cavity version.

Finally, it may be desirable to reduce the neutron energy to $\sim 25 \text{ keV}$ for optimum patient treatment. This would increase the degree of energy degradation in the cavity wall that was acceptable. This would result in an increased neutron utilization efficiency.

2.5 Optimization of NIFTI

Optimization of NIFTI will involve maximizing the neutron utilization efficiency, as discussed in the previous section. However, other factors are also involved, including:

- neutron generation efficiency
- target simplicity, reliability, and maintainability
- directionality and energy spectrum of neutrons leaving the treatment port
- gamma dose during treatment
- residual activation of the NIFTI assembly

The neutron generation efficiency is defined by

$$\eta_G = \# \text{ of neutrons generated per beam proton.}$$

η_G depends on the NIFTI energy regime and the target design. It generally will be in the range of $\sim 10^{-5}$ to 10^{-4} neutrons per proton, with the lower end of the range corresponding to the NIFTI-1 designs, and the upper end to the NIFTI-2 designs.

Neutron Transport Geometries For The NIFTI Concept

(a) Closed Solid Geometries

NIFTI-1 Energy Regime

NIFTI-2 Energy Regime

(b) Open Cavity Geometries

NIFTI-1 Energy Regime

NIFTI-2 Energy Regime

Fig. 2.4.1

Idealized Open Cavity Geometry

Fig. 2.4.2

Figure 2.4.4 Neutron Scattering Cross Section for Titanium

Figure 2.4.5 Neutron Scattering Cross Section for Nickel

Figure 2.4.6 Neutron Scattering Cross Section for Chromium

Figure 2.4.7 Neutron Scattering Cross Section for Manganese

Neutron Utilization Efficiency As A Function Of Cavity Diameter

Figure 2.4.8

The overall beam utilization efficiency is defined as

η_B = # of neutrons leaving the treatment port per beam proton.

In terms of the neutron utilization and generation efficiencies, η_B is given by

$$\eta_B = \eta_N \eta_G \quad (2.5.1)$$

η_B is thus a direct measure of the proton current required to produce the neutron current desired for treatment.

Figure 2.5.1 shows the proton beam current required, as a function of neutron generation and utilization efficiency, based on a treatment port area of 100 cm² and a neutron current of 10⁹ n/cm², seen at the port. This would enable treatment times on the order of a half hour.

Neutron utilization efficiency can be as low as 5% for the NIFTI-2 system, and still have the proton beam current below the goal of 3 milliamps. For the NIFTI-1 system, neutron utilization efficiency should be on the order of 10% to have a proton current of 3 milliamps.

At this point, 4 NIFTI design options appear possible, based on the various combinations of energy regime and neutron transport geometry. The 4 options are summarized in Figure 2.5.2. Detailed studies are needed to determine which of the 4 options offers the best performance, that is, has the greatest neutron current out of the treatment port for a given beam current.

However, the option with the lowest proton beam current may not necessarily be the optimum, particularly if all of the various options have low beam currents. Issues of target simplicity, reliability, maintainability, gamma dose, residual activation, etc., may outweigh differences in beam current performance.

Figure 2.5.1 Proton Beam Current Required As A Function of Neutron Generation Efficiency and Neutron Utilization Efficiency

Figure 2.5.2

Comparison of NIFTI Design Options

Energy Regime

TYPE OF GEOMETRY	NIFTI-1 [Max Neutron Energy to ~60 keV]	NIFTI-2 [Max Neutron Energy to ~ 1 MeV]
Open Cavity (OC)	<ul style="list-style-type: none"> • Maximum Neutron Utilization Efficiency of ~ 20% • Proton Beam Current in Order of ~ 3 mA • Complex Target • May Require Gamma Shield at Port 	<ul style="list-style-type: none"> • Maximum Neutron Utilization Efficiency of ~ 10% • Proton Beam Current in Order of ~ 3 mA • Simple Target • May Require Gamma Shield at Port
Closed Solid (CS)	<ul style="list-style-type: none"> • Neutron Utilization Efficiency & Beam Current Probably Less Than OC Designs • Complex Target • Gamma Shield Probably Not Necessary 	<ul style="list-style-type: none"> • Neutron Utilization Efficiency & Beam Current Probably Less Than OC Designs • Simple Target • Gamma Shield Probably Not Necessary

2.6 1-D Neutronic Analyses of NIFTI Sources

A set of 1-D, Monte Carlo (MCNP) neutronic analyses has been carried out for idealized NIFTI geometries to determine in how the thicknesses of iron filter and fluoride inelastic scatterer affect the neutron energy spectrum output. Two groups of analyses have been carried out:

- Group 1: NIFTI-1 energy regime; $E_{\max} \sim 100$ keV
- Group 2: NIFTI-2 energy regime; $E_{\max} \sim 1$ MeV

The Group-1 analyses use only a spherical iron (in some cases, hydrogen and other scattering material is included) layer around the neutron source. The Group-2 analyses use an inner layer of PbF_2 , with an outer layer of iron. For both groups, the inputs for the analyses are the thicknesses of the layers around the source, which are varied, together with the energy spectrum of the neutron source, which is also varied.

The outputs from the analyses are the resultant energy spectrum of the neutrons leaving the outer iron layer, together with the fraction of neutrons lost by absorption processes in the layers.

Figure 2.6.1 and 2.6.2 show initial calculations of the energy and angular yield of neutrons generated by proton impact on a thin lithium target, as developed by Thieberger⁽¹⁾. These calculations are based on the proton beam having an initial energy of 1.904 MeV, degrading to 1.889 MeV (a 5 keV decrease) on passage through the lithium target.

For the 1-D neutronic analyses, the angular distribution of the neutrons from the target was assumed to be isotropic, instead of forward peaked. This energy spectrum of the neutrons were assumed as shown in Figure 2.6.3. The first source has an essentially uniform distribution over the energy range 0 to 40 keV, and the second source, an essentially uniform distribution over the energy range 0 to 100 keV.

The Group - 1 analyses assumed that the point neutron source to be enclosed by a spherical iron shell, with variable radius. Figure 2.6.4 summarizes the results for the Group -1 analyses.

Figure 2.6.5 shows the resultant energy distribution of the neutrons leaving the surface of the 7.5 centimeter radius sphere for the 0 to 40 keV neutron source. (The surface current at a particular energy has been divided by its appropriate lethargy).

The large peak in surface current at 24 keV corresponds to the main "iron window" at 24 keV, where the scattering cross section drops from a peak of ~ 100 barns down to ~ 1 barn. Neutrons at energies above the "window" are inhibited by scattering collisions from diffusing out through the iron shell. Instead, they continue to scatter until they lose enough energy by elastic collisions that they can pass through the window.

The secondary peak at ~ 4 kev corresponds to a smaller "window" in iron (Figure 2.2.1) through which neutrons that are at energies substantially below 24 kev are readily transmitted.

Increasing the maximum neutron energy in the spectrum to 100 kev results in large peaks in the surface current at ~ 70 kev and ~ 80 kev, due to "windows" at these energies (Figure 2.6.6). As a result, iron by itself does not appear suitable for sources that have appreciable numbers of source neutrons at energies above ~ 60 kev.

However, there are ways to reduce output neutron intensity at high energy for sources with neutron energies above ~ 60 kev. One approach is to add scattering materials to the iron shell which have scattering peaks that overlap with the 70 and 80 kev windows in iron. For example, magnesium has a strong scattering peak at 80 kev. Adding magnesium to a mixture with iron greatly reduces the 80 kev peak in the surface current spectrum (Figure 2.6.7).

A second approach is to add a thin layer of moderator to "down-shift" the energy of the neutrons that leave the outer surface of the iron shell. A hydrogen containing material appears best for this purpose, since it will be much thinner than other moderators, and will enable a down-shift in energy by a factor of e with a single scattering collision.

The "down-shifter" layer can either be placed inside or outside the iron shell. Figure 2.6.8 shows the resultant spectrum of the neutrons leaving the iron surface when the "down-shifter" layer is outside the iron shell; Figure 2.6.9 shows the spectrum when the "down-shifter" is inside the shell. The effect of "down-shifter" thicknesses is also shown, for thicknesses of 0.1, 0.2, and 0.4 centimeters.

For neutron sources with maximum energies substantially above 100 kev, i.e., the NIFTI-2 energy regime, the best approach for reducing neutron energy to acceptable levels appears to have the neutrons inelastically collide with fluorine. This can be accomplished by placing a layer of fluoride compound between the neutron source and the outer iron shell, as shown in Figure 2.3.1B.

Figure 2.6.10 shows the energy spectrum of neutrons leaving the surface of the outer iron shell, for a neutron source that has a uniform energy distribution from 0 to 350 kev. Lead fluoride (PbF_2) is used as the inelastic scatterer with a radial thickness of 5, 7.5, or 10 centimeters, which is surrounded by a 5 or 7.5 centimeter layer of iron. Almost all of the high energy source neutrons are down-scattered to energies below 100 kev. Figure 2.6.11 shows additional results obtained for the NIFTI-2 energy regime.

As evident from Figure 2.6.10, these are still secondary peaks in the spectrum of the neutron current from the surface of the iron layer. The energy spectrum can be down-shifted using an outer layer of polyethylene. Figure 2.6.12 shows the resultant neutron spectrum for 4 thicknesses of polyethylene (0.1, 0.2, 0.4, and 0.5 cm) on the outside of the sphere, for the case where the PbF_2 layer has a thickness of 5 cm and the iron layer has a thickness of 5 cm.

Without the down-shifter, approximately 50% of the neutrons have energies below 75 keV, while with the 0.5 centimeter thick down-shifter, 61% have energies below 75 keV. Considering these neutrons with energies below 26 keV, without the down-shifter, 22% are in that category, while with the down-shifter, 38% are below 26 keV. Clearly, the down-shifter approach is effective in substantially decreasing the average energy of the output neutrons using only a very thin layer (0.5 cm) of polyethylene. An increased down-shifter thickness, e.g., 1.0 centimeters would have an even greater effect.

The effect of different fluoride compositions on the output neutron spectrum is shown in Figure 2.6.13. Beryllium fluoride results in a considerably softer output spectrum than lead fluoride, because of its higher atomic density of fluorine atoms. The fraction of output neutrons with energies above 75 keV is lower by a factor approximately 2 if BeF_2 is used, as compared to PbF_2 . This reduction factor is essentially constant over the energy range from 75 to 350 keV. With BeF_2 , only 19% of the neutrons have energies above 50 keV, as compared to 34% with PbF_2 .

It thus appears that BeF_2 is a strong candidate for the fluoride compound for a final NIFTI design, at least as part of the fluoride layer. In the preliminary design described in Section 4 of this report, a combination of BeF_2 and PbF_2 is used.

2.7 3-D MCNP Analyses of NIFTI Neutron Sources Using Closed Solid Transport Geometry

The closed solid neutron transport geometries used in the 3D MCNP analyses are shown in Figure 2.7.1. For the NIFTI-1 cases, the neutron source is placed immediately behind the iron "filter" that covers the treatment port at the front face of the assembly. A thick neutron reflector (e.g., Pb or Ti) is located behind the neutron source and around the iron "filter". This reflector redirects a significant fraction of the neutrons into the "filter" that would otherwise escape from the rear end of the outer cylindrical surface of the NIFTI-1 assembly.

For these analyses, the diameter of the treatment port is taken as 11 centimeters. It could be smaller or larger as desired; however, a value of 11 centimeters is reasonable for the initial analyses. The rest of the front face of the assembly is covered by a layer of LiH neutron absorber (and possibly also B_4C). This reduces the neutron current from the front face and results in a smaller-whole body radiation dose to the patient.

Results for four NIFTI-1 cases (200,000 neutron histories per case) are summarized in Figure 2.7.2, together with their design parameters. The neutron source was assumed to be isotropic in angle, and of uniform energy distribution over the range from 5 to 50 keV

Figure 2.6.1
Average neutron energy spectrum at angles between 40° and 50° from Li^7 (p,n)
for protons from 1.899 to 1.904 MeV [Thieberger ()]

Figure 2.6.2 Neutron Angular Yield From Li^7 (p, n)
Integrated From 1.899 to 1.904 MeV Proton Energies [Thieberger ()]

**Figure 2.6.3 Neutron Energy Spectrum Assumed
For 1-D Neutronic Analysis of NIFTI-1 and NIFTI-2**

Figure 2.6.4 Summary of NIFTI-1 Neutronic Analyses

(5 keV < E (source) < 40 keV)

Radius of Sphere (cm)	7.5	10.0	12.5
Fraction Escape	.982	.957	.914
Fraction Absorbed	.018	.043	.086
Escape (35 keV - 37 keV)	.004	.001	---
Escape (24 keV - 26 keV)	.197	.226	.240
Escape (3 keV - 5 keV)	.070	.050	.016

**Figure 2.6.5 Energy Distribution of Neutrons
From Surface of Iron Sphere (Radius = 7.5 cm)
Surrounding NIFTI-1 (0 to 40 keV) Neutron Source**

**Figure 2.6.6 Energy Distribution of Neutrons
From Surface of Iron Sphere (Radius - 7.5 cm)
Surrounding NIFTI-1 (0 to 100 keV) Neutron Source**

Figure 2.6.7 Effect of Addition of Magnesium to Iron Sphere in Reducing High Energy Peaks From NIFTI-1 Source (0 to 100 keV)

Figure 2.6.8

**Effect of Thin External Hydrogenous Moderator in
Down-shifting Neutron Energy from NIFTI-1 Source**

Polyethylene Thickness (cm)	.1	.2	.3
Total Escape	.985	.984	.983
Escape ($E < 26$ keV)	.517	.549	.578
Escape ($26 \text{ keV} < E < 50$ keV)	.147	.144	.139
Escape ($50 \text{ keV} < E < 75$ keV)	.220	.201	.184
Escape ($75 \text{ keV} < E < 100$ keV)	.115	.106	.098

Figure 2.6.9

**Effect of Thin External Hydrogenous Moderator in
Down-shifting Neutron Energy from NIFTI-1 Source**

Polyethylene Thickness (cm)	.1	.2	.3
Total Escape	.980	.972	.961
Escape ($E < 26$ keV)	.524	.556	.580
Escape ($26 \text{ keV} < E < 50$ keV)	.139	.130	.122
Escape ($50 \text{ keV} < E < 75$ keV)	.219	.201	.185
Escape ($75 \text{ keV} < E < 100$ keV)	.118	.113	.112

Figure 2.6.10

**Effect of Thickness of Iron and Lead Fluoride Shell
Around A NIFTI-2 Source on Neutron Energy**

Radius of PbF ₂ Sphere (cm)	5	7.5	10	7.5	10
Thickness of Fe Shell (cm)	5	5	5	7.5	7.5
0 - 26 keV	.2253	.3429	.4744	.3994	.5292
26 keV - 50 keV	.0828	.1018	.1054	.0901	.0886
50 keV - 75 keV	.1875	.1988	.1753	.1699	.1443
75 keV - 100 keV	.0726	.0563	.0408	.0506	.0359
100 keV - 200 keV	.2780	.2112	.1479	.2051	.1399
200 keV - 350 keV	.1435	.0749	.0373	.0626	.0303
Total Leak	.9897	.9859	.9811	.9777	.9682

Figure 2.6.11

Summary of NIFTI-2 Neutronic Analyses

5 keV < E (source) < 350 keV

5 cm Lead Fluoride Sphere Radius

Iron Layer Thickness (cm)	5.0	7.5
Fraction Escape	.974	.938
Fraction Absorbed	.026	.060
Escape (35 keV - 37 keV)	.014	.011
Escape (24 keV - 26 keV)	.115	.165
Escape (3 keV - 5 keV)	.127	.072

7.5 cm Lead Fluoride Sphere Radius

Iron Layer Thickness (cm)	5.0	7.5
Fraction Escape	.958	.912
Fraction Absorbed	.039	.085
Escape (35 keV - 37 keV)	.016	.011
Escape (24 keV - 26 keV)	.132	.174
Escape (3 keV - 5 keV)	.073	.038

Figure 2.6.12

**Effect of Thin External Hydrogenous Moderator in Down-Shifting
Neutron Energy From NIFTI-2 Source (Inside PbF₂/Iron Sphere)**

Thickness of Moderator (cm)	.1	.2	.3	.5
0 - 26 keV	.2572	.2898	.3217	.3815
26 keV - 50 keV	.0895	.0934	.0956	.0945
50 keV - 75 keV	.1754	.1643	.1541	.1351
75 keV - 100 keV	.0707	.0681	.0655	.0598
100 keV - 200 keV	.2622	.2475	.2331	.2069
200 keV - 350 keV	.1343	.1255	.1177	.1038

Figure 2.6.13

**Effect of Different Fluoride Compounds on
Neutron Energy Spectrum and Photon Production From NIFTI-2 Source**

($0 < E_s < 360$ keV)

(Source at Center of 10 cm OD Iron Sphere Surrounded by 10 of Fluoride Compound)

Leakage Neutron Energy Spectrum

Fluoride Compound	Lead	Iron	Vanadium	Beryllium
0 keV - 26 keV	.5291	.5695	.5734	.6683
26 keV - 50 keV	.0886	.0760	.0891	.0551
50 keV - 75 keV	.1443	.1344	.1156	.0801
75 keV - 100 keV	.0359	.0325	.0284	.0220
100 keV - 200 keV	.1398	.1203	.0984	.0783
200 keV - 350 keV	.0303	.0214	.0162	.0133
Total	.9682	.9541	.9212	.9172

Photon Production Mechanisms

Fluoride Compound	Lead	Iron	Vanadium	Beryllium
Neutron Capture	.5074	.5603	.6391	.5547
Bremsstrahlung	.1544	.1335	.2167	.2295
Proton Annihilation	.0271	.0314	.0532	.0574
1 st Fluorescence	.5155	.1754	.1762	.1496
2 nd Fluorescence	.1106	---	---	---
Total	1.3149	.9006	1.0823	.9913

The results indicate the following for NIFTI-1:

1. Neutron utilization efficiencies (fraction of neutrons passing through the treatment port) of ~10% are possible using iron filters ~10 centimeters in thickness.
2. Titanium is superior to lead as a neutron reflector for NIFTI-1. It increases the value of neutron utilization efficiency by ~50% as compared to lead.
3. The LiH absorber layer substantially reduces neutron leakage through the front face. However, to further reduce leakage to acceptable levels (i.e., a few percent of the neutrons passing through the treatment port) a more effective absorber layer is required. This could either be a higher cross section isotope (e.g., $^{10}\text{B}_4\text{C}$), enriched ^6LiH (natural lithium was used in the analysis), or a thicker layer of natural LiH.

Figure 2.7.3 shows the energy distribution of the neutron current out of the treatment port for Case #4. The iron "filter" is clearly very effective. Virtually all of the exiting neutrons are below 25 keV in energy, with the average being about 12 keV. With a thin external "downshifter" layer, e.g., of polyethylene, the average energy would be further reduced if desired. However, for most treatment cases, an average energy of ~12 keV appears very acceptable.

Figure 2.7.4 shows the effect of a thin external polyethylene layer on the energy distribution of neutrons from a NIFTI-1 source using a closed solid transport geometry.

Actual NIFTI-1 neutron sources will not be isotropic in angular distribution nor have a uniform energy distribution. Thieberger () has calculated the detailed energy and angular distributions of neutrons emitted from a lithium target subjected to a proton beam of initial energy 1.904 MeV, with an energy degradation of 5 keV, and a final energy of 1.889 MeV. Figure 2.7.5 lists the tabular values for the resultant angular and energy distributions of the neutron source. Figure 2.7.6 shows the corresponding graphical representation.

These clearly are two main groups of source neutrons - a low energy group with an average energy of ~25 keV and a high scattering angle of ~50 degrees, and a high energy forward scattered (average angle of ~20 degrees) group of ~80 keV average energy. There is a pronounced "valley" between the two groups.

The non-uniform angular/energy distribution behavior illustrated in Figures 2.7.5 and 2.7.6 affects the neutron utilization efficiency of the NIFTI assembly and the energy spectrum of the neutrons leaving the treatment port. Figure 2.7.7 compares the angular distribution of output neutron current from the source alone with the angular distribution of output neutron current that is produced when the source is inside a 20 centimeter diameter sphere.

Virtually all (98%) of the neutrons escape from the surface of the iron sphere. The angular distribution of the escaping neutrons is markedly altered from the original source distribution; however, with a much greater component at high angles (i.e., 60 to 120 degrees).

The neutron flux intensity values given in Figure 2.7.7 are integrated over the full energy spectrum.

The angular orientation of the neutron source in the NIFTI assembly affects both the neutron utilization efficiency and the spectral distribution of the neutrons exiting through the treatment port. Figure 2.7.9 gives the neutron utilization efficiency and integral spectral distribution for two NIFTI-1 and two NIFTI-2 cases:

NIFTI-1

Case 1: Neutron source with non-uniform energy and non-isotropic angular distribution (Figure 2.7.6 distribution), centered on, and immediately behind, the iron window. The 0 degree direction of the neutron source distribution is normal to and directed towards the iron window.

Case 2: Neutron source with non-uniform energy and non-isotropic angular distribution (Figure 2.7.6 distribution), centered on, and immediately behind, the iron window. The 0 degree direction of the neutron source distribution is parallel to the iron window.

NIFTI-2

Case 1: NIFTI-2 Neutron source, with non-uniform energy and non-isotropic angular distribution (Figure 2.7.8 distribution) centered on and immediately behind, the iron window. The 0 degree direction of the neutron source distribution is normal to and directed towards the iron window.

Case 2: Same as Case 1, except 0 degree direction is directed away from the iron window.

For all cases, the iron filter is 11 centimeters in diameter and 10 centimeters thick, reflector is titanium, and 20 centimeters in thickness.

For the NIFTI-1 design, depending on orientation of the neutron source, there is a substantial difference in the fraction of the source neutrons that exit through the patient treatment port. If the source is pointed towards the port, the neutron utilization efficiency is 10.7%; if pointed parallel to the port, the neutron utilization efficiency is reduced to 7.6%. This result appears logical, since the output neutrons are from a source close to threshold strongly forward peaked.

For the NIFTI-2 design, the effect of source orientation is less pronounced with the neutron utilization efficiency being 11.6% for a source oriented towards the treatment port, compared to a utilization efficiency of 9.4% for a source oriented away from the treatment port. The smaller effect is a result of the more uniform neutron angular distribution for the NIFTI-2 source.

In terms of mechanical design, the NIFTI-1 approach favors having the source parallel to the port, as described in Section 4 of this report, while the NIFTI-2 approach favors having the source oriented towards the port. As a result, the realities of orientation tend to favor NIFTI-2.

The NIFTI-2 geometry is similar to that for NIFTI-1, except that the neutron source is located inside the fluoride region that is positioned just behind the iron "filter" (Figure 2.7.1). Most of the high energy neutrons ($E > 100$ keV) generated by the impact of protons on the lithium target are inelastically scattered to much lower energies by the fluoride compound before being transmitted through the iron "filter".

Results for the four NIFTI-2 cases (200,000 histories per case) are summarized in Figure 2.7.10, together with their design parameters. For these analyses, the NIFTI-2 neutron source is assumed to be isotropic in angle, and of uniform energy distribution over the range from 5 to 350 keV.

Results indicate the following for NIFTI-2:

1. Neutron utilization efficiencies of ~10% can be achieved with PbF_2 inelastic scatterer and an iron "filter".
2. Titanium is not as effective a reflector material as lead for NIFTI-2. The use of Ti results in the neutron utilization efficiency being about 10% lower than that of lead.
3. Leakage through the front face around the treatment port significantly exceeds that from the treatment port itself, unless a layer of B_4C is used in addition to the LiH layer. This is a result of the greater neutron energy in NIFTI-2. Use of a higher cross section isotope or enrichment of the Li^6 isotopic content in the LiH layer appears desirable.

Figure 2.7.11 shows the neutron flux and energy distribution exiting the treatment port for Case 1. A substantial fraction (~50%) of the neutron current is at or above 26 keV. Figure 2.7.12 shows the effect of a thin polyethylene "down-shift" layer at the treatment port on the neutron energy distribution. With a layer of 0.6 centimeters) the neutron distribution can be down-shifted so that only 38% are above 26 keV.

Figure 2.7.13 shows the effect of increasing the diameter of the PbF_2 layer in back of the iron filter. Increasing the diameter of the lead fluoride layer is inevitably tied to increasing the treatment port diameter, since the neutrons transmitted through the PbF_2 and Fe layers are then available for patient treatment.

Based on the results shown in Figure 2.7.13, over the range of port diameters from 11 centimeters to 18 centimeters, there appears to be very little difference in neutron utilization efficiency. Thus, the diameter of the treatment port will not be a major factor in the optimization of the NIFTI-2 design - at least, in the diameter range from 11 to 18 centimeters.

Figure 2.7.1 Closed Solid Neutron Transport Geometries Used For 3D Neutronic Analyses

Figure 2.7.1

**Figure 2.7.2 Results of 3D MCNP Analyses For Closed Solid Geometries Using NIFTI-1 Source
[5 to 50 keV Energy (200,000 Histories)]**

Parameter/Result	Case #			
	1	2	3	4
Thickness of Iron Filter, Centimeter	7.5	10.0	10.0	10.0
Thickness of LiH Absorber, Centimeter (no B ₄ C)	5.0	5.0	5.0	5.0
Thickness of Reflector, Centimeter	30.0	30.0	20.0	20.0
Reflector Material	Pb	Pb	Pb	Ti
Fraction of Source Neutrons That Escape From NIFTI-1 Device	0.55658	0.58383	0.6959	0.60452
Fraction of Source Neutrons That Are Absorbed in NIFTI-1 Device	0.44336	0.41615	0.30402	0.39546
Fraction of Source Neutrons That Exit Through Patient Treatment Port	0.09658	0.07125	0.06943	0.09453
Fraction of Source Neutrons That Escape Through LiH Absorber on Front Face Around Treatment Port	0.09362	0.07954	0.06459	0.05260

Figure 2.7.3 Output Neutron Flux and Energy Distribution for NIFTI-1 Closed Solid Geometry
(Case 4)

—•— Flux * Fraction

Total Flux Exiting "Treatment Port" = 0.0945

Figure 2.7.4

**Effect of Hydrogenous Down-shifter on
NIFTI-1 Output Neutron Energy Spectrum (Case 4)**

Thickness of Downshifter	0.0	0.3	0.6
0 keV - 1 keV	.0106	.0143	.0179
1 keV - 10 keV	.0209	.0203	.0186
10 keV - 26 keV	.020	.0155	.0119
26 keV - 50 keV	.0047	.0038	.0032
50 keV - 75 keV	.0030	.0024	.0017
75 keV - 100 keV	.0006	.0004	.0003
Total	.0598	.0568	.0537

Figure 2.7.5

**Angular and Energy Distribution of Neutrons Produced
By Impact of Proton Beam on A Thin Lithium Target
(1.904 MeV to 1.899 MeV)**

Beam Energy Min., Max., step 1.899 1.904 .00001 MeV

Total Cross Section = 277 mb

Legendre ceff.: $b_1 = 0$ $b_2 = 0$

Neutron angle interval: from 0 to 10 degree

Solid angle for this interval = .0954554 Steradians

Energy Interval (KeV)			Neutrons/SR per proton	Neutrons per proton
0	to	5	3.72E-08	3.5E-09
5	to	10	1.91E-08	1.83E-09
10	to	15		
15	to	20		
20	to	25		
25	to	30		
30	to	35		
35	to	40		
40	to	45		
45	to	50		
50	to	55		
55	to	60		
60	to	65		
65	to	70		
70	to	75		
75	to	80		
80	to	85		
85	to	90	5.77E-07	5.50E-08
90	to	95	1.25E-06	1.19E-07
95	to	100	4.77E-07	4.55E-08

Figure 2.7.5 (continued)

**Angular and Energy Distribution of Neutrons Produced
By Impact of Proton Beam on A Thin Lithium Target
(1.904 MeV to 1.899 MeV)**

Neutron angle interval: from 10 to 20 degree				
Solid angle for this interval = .283466 Steradians				
Energy Interval (KeV)			Neutrons/SR per proton	Neutrons per proton
0	to	5	5.25E-08	1.49E-08
5	to	10	3.82E-08	1.08E-08
10	to	15		
15	to	20		
20	to	25		
25	to	30		
30	to	35		
35	to	40		
40	to	45		
45	to	50		
50	to	55		
55	to	60		
60	to	65		
65	to	70		
70	to	75		
75	to	80		
80	to	85	4.86E-07	1.38E-07
85	to	90	1.70E-06	4.81E-07
90	to	95	1.17E-06	3.31E-07
95	to	100	5.83E-08	1.65E-08

Figure 2.7.5 (continued)

**Angular and Energy Distribution of Neutrons Produced
By Impact of Proton Beam on A Thin Lithium Target
(1.904 MeV to 1.899 MeV)**

Neutron angle interval: from 20 to 30 degree
Solid angle for this interval = .4628637 Steradians

Energy Interval (KeV)			Neutrons/SR per proton	Neutrons per proton
0	to	5	4.95E-08	2.29E-08
5	to	10	9.15E-08	4.23E-08
10	to	15		
15	to	20		
20	to	25		
25	to	30		
30	to	35		
35	to	40		
40	to	45		
45	to	50		
50	to	55		
55	to	60		
60	to	65		
65	to	70	3.03E-07	1.40E-07
70	to	75	9.08E-07	4.20E-07
75	to	80	1.30E-06	6.03E-07
80	to	85	1.13E-06	5.22E-07
85	to	90	3.70E-07	1.71E-07
90	to	95		
95	to	100		

Figure 2.7.5 (continued)

**Angular and Energy Distribution of Neutrons Produced
By Impact of Proton Beam on A Thin Lithium Target
(1.904 MeV to 1.899 MeV)**

Neutron angle interval: from 30 to 40 degree
Solid angle for this interval = .6281976 Steradians

Energy Interval (KeV)			Neutrons/SR per proton	Neutrons per proton
0	to	5	1.42E-08	8.92E-09
5	to	10	1.69E-08	1.06E-07
10	to	15		
15	to	20		
20	to	25		
25	to	30		
30	to	35		
35	to	40		
40	to	45		
45	to	50	6.31E-08	3.97E-08
50	to	55	4.26E-07	2.67E-07
55	to	60	7.93E-07	4.98E-07
60	to	65	9.14E-07	5.76E-07
65	to	70	7.00E-07	4.40E-07
70	to	75	2.04E-07	1.28E-07
75	to	80		
80	to	85		
85	to	90		
90	to	95		
95	to	100		

Figure 2.7.5 (continued)

**Angular and Energy Distribution of Neutrons Produced
By Impact of Proton Beam on A Thin Lithium Target
(1.904 MeV to 1.899 MeV)**

Neutron angle interval: from 40 to 50 degree
Solid angle for this interval = .7744436 Steradians

Energy Interval (KeV)			Neutrons/SR per proton	Neutrons per proton
0	to	5	4.09E-07	3.17E-07
5	to	10	2.73E-07	2.11E-07
10	to	15	1.52E-07	1.17E-07
15	to	20	2.49E-07	1.93E-07
20	to	25	4.09E-07	3.17E-07
25	to	30	6.25E-07	4.84E-07
30	to	35	6.82E-07	5.28E-07
35	to	40	7.13E-07	5.52E-07
40	to	45	6.85E-07	5.31E-07
45	to	50	3.67E-07	2.85E-07
50	to	55	4.88E-08	3.78E-08
55	to	60		
60	to	65		
65	to	70		
70	to	75		
75	to	80		
80	to	85		
85	to	90		
90	to	95		
95	to	100		

Figure 2.7.5 (continued)

**Angular and Energy Distribution of Neutrons Produced
By Impact of Proton Beam on A Thin Lithium Target
(1.904 MeV to 1.899 MeV)**

Neutron angle interval: from 50 to 60 degree
Solid angle for this interval = .8971593 Steradians

Energy Interval (KeV)			Neutrons/SR per proton	Neutrons per proton
0	to	5	7.44E-08	6.68E-08
5	to	10	3.50E-07	3.14E-07
10	to	15	4.07E-07	3.66E-07
15	to	20	3.62E-07	3.25E-07
20	to	25	2.23E-07	2.00E-07
25	to	30	3.65E-08	3.28E-08
30	to	35		
35	to	40		
40	to	45		
45	to	50		
50	to	55		
55	to	60		
60	to	65		
65	to	70		
70	to	75		
75	to	80		
80	to	85		
85	to	90		
90	to	95		
95	to	100		

Figure 2.7.6 Graphical Representation of Energy and Angle of Neutrons Generated by 1.904 MeV Lithium Target
(1.904 MeV to 1.899 MeV) Impacting A Thin Lithium Target

**Figure 2.7.7 Angular Distribution of Output Neutrons From
Proton on Lithium Reaction (1.899 MeV to 1.904 MeV)
After Passing Through an Iron Shell**

Figure 2.7.8 Graphical Representation of Energy and Angle of Neutrons Generated By
2.1 MeV Proton Beam Impacting A Thick Lithium Target

Figure 2.7.9

**Effect of Source Orientation for
NIFTI-1 AND NIFTI-2 Designs**

NIFTI-1

Source Energy Range	0 keV < E < 100 keV	
Source Angular Range	0° < θ < 60°	
Source Orientation	Perpendicular to Window	Parallel to Window
Escape Fraction	.6026	.6303
Absorbed Fraction	.3974	.3697
Escape Fraction From Irradiation Port	.1069	.0755

NIFTI-2

Source Energy Range	0 keV < E < 360 keV	
Source Angular Range	0° < θ < 180°	
Source Orientation	Perpendicular, In Direction of Window	Perpendicular, Away From Window
Neutron Escape Fraction	.5943	.6145
Neutron Absorbed Fraction	.4056	.3864
Photon Escape Fraction	.00353	.00325
Photon Absorbed Fraction	.9965	.99678
Neutron Escape From Irradiation Port	.1164	.0936
Photon Escape From Irradiation Port	.00142	.00122

**Figure 2.7.10 Results of 3D MCNP Analysis For Closed Solid Geometries Using
NIFTI-2 Energy Source [5 to 350 keV Energy (200,000 Histories)]**

Parameter/Result	Case #			
	1	2	3	4
Thickness/Diameter of Iron Filter, cm	7.5/11	5.0/11	5.0/11	5.0/11
Thickness/diameter of PbF ₂ Layer, cm In Front of Neutron Source Behind Neutron Source	7.5/11 7.5/11	5.0/11 7.5/11	5.0/11 7.5/11	5.0/11 7.5/11
Thickness of LiH Absorber, cm	5.0	2.5	5.0	5.0
Thickness of B ₄ C Absorber, cm	—	2.5/1.0 (window)	--	--
Thickness of Reflector, cm	40	30	30	30
Reflector Material	Pb	Pb	Ti	Pb
Fraction of Source Neutrons That Escape From NIFTI-2 Device	0.58726	0.51096	0.57212	0.61454
Fraction of Source Neutrons That Are Absorbed in NIFTI-2 Device	0.41305	0.48925	0.42783	0.38547
Fraction of Source Neutrons that Escape Through Treatment Port	0.05564	0.05096	0.095647	0.103654
Fraction of Source Neutrons That Escape Through LiH and B ₄ C Absorber	0.09257	0.0341	0.08229	0.10926

Figure 2.7.11 Neutron Flux and Energy Distribution for
NIFTI-2 Closed Solid Transport Geometry (Case 1)

Figure 2.7.11

--- Flux * Fraction

Total Fraction Exiting "Treatment Port" = 0.0556

Figure 2.7.12

Effect of Hydrogenous Down-shifter on NIFTI -2
Neutron and Photon Leakage

Water Down-shifter Thickness (mm)	0.0	3.0	6.0
Neutron Escape Fraction	.5943	.5899	.5853
Neutron Absorbed Fraction	.4056	.4101	.4147
Photon Escape Fraction	.00353	.00372	.00415
Photon Absorbed Fraction	.9965	.9963	.9958
Neutron Fraction Escape From Irradiation Port	.0741	.0716	.0682
Fraction of Neutron < 29 keV Escaping From Irradiation Port	.4958	.5622	.6165
Photon Fraction Escape From Irradiation Port	.00071	.00071	.00087

Figure 2.7.13

Effect of Increased Diameter of PbF₂ Region on Neutron Flux and Energy Distribution for NIFTI-2 Closed Solid Transport Geometry (Case 1)

Diameter of PbF ₂ (cm)	11.0	18.0
Diameter of Fe (cm)	11.0	18.0
Length of PbF ₂ (cm)	12.5	18.0
Length of Fe (cm)	5.0	5.0
Position of Source (cm)	7.5	7.5
Distance of Source from Fe (cm)	5.0	5.0
Total Neutron Production	1.006	1.007
Total Photon Production	.798	.991
Total Neutron Leakage	.594	.549
Total Photon Leakage	.003	.006
Neutron Leakage Patient Port	.116	.116
Photon Leakage Patient Port	.002	.002
Neutron Leakage Patient Duct	.074	.074
Photon Leakage Patient Duct	.001	.001

2.8 3-D Analyses of NIFTI Neutron Sources Utilizing Open Cavity Transport Geometry

The open cavity geometries used in the 3-D transport analyses are shown in Figure 2.4.1. For the NIFTI-1 cases the source is placed in the center of the iron sphere located inside the cavity. The iron sphere acts as the "filter" for selecting the most desirable neutrons. A thick neutron reflector of either lead or titanium surrounds the cavity, and returns a fraction of the neutrons not moving in the direction of the irradiation port. The diameter of the irradiation port is 11 cm. in this design. However, an optimum size has not been determined. The diameter of the cavity is twice the diameter of the spherical source volume.

A system using this geometry, with a sphere 15 cm in diameter, and a lead reflector 15 cm thick, was considered. The results are shown on Figure 2.8.1. Approximately 3.2% of the neutrons leak out of the irradiation port.

Figure 2.8.1.

Results for a NIFTI-1 Source in An Open Cavity Geometry

Total Neutron Leakage	.9736
Leakage from Irradiation Port	.0321

Spectrum of Neutron Leaking From Port	
0 keV - 1 keV	.0002
1 keV - 10 keV	.0073
10 keV - 26 keV	.0212
26 keV - 50 keV	.0034

The NIFTI-2 geometry is similar to that of NIFTI-1, except that in this case the source is surrounded by a spherical volume of lead fluoride, which is located in a 5 thick shell of iron. The cavity volume must be appropriately adjusted to account for the increased source diameter.

In this case the lead fluoride inner sphere has diameter of 20 cm and the iron shell is 5 cm thick. The surrounding cavity is a cylinder with a 50 cm height and diameter. The lead reflecting walls of the cylinder are 15 cm thick. Results for this configuration are shown on Figure 2.8.2. Approximately 2% of the neutrons leak out of the irradiation port.

Figure 2.8.2

Results for a NIFTI-2 Source in An Open Cavity Geometry

Total Neutron Leakage	.9658
Leakage from Irradiation Port	.0216

Spectrum of Neutron Leaking From Port	
0 keV - 1 keV	
1 keV - 10 keV	.0007
10 keV - 26 keV	.0031
26 keV - 50 keV	.0083
50 keV - 100 keV	.0025
100 keV - 150 keV	.0040
150 keV - 200 keV	.0016
200 keV - 250 keV	.0009
250 keV - 300 keV	.0004
300 keV - 350 keV	~ 0.0

The above results indicate that for these geometric configurations the neutron flux at the irradiation port is approximately a third of the flux for the closed solid configuration described in section 2.7. Thus at this stage it will not be considered further. However, additional optimization studies may be carried out at a future time.

2.9 Gamma Dose Rates to Patient During NIFTI Operation

The neutrons emanating from the lithium based source interact with the surrounding material of the target/filter and in some cases the slowing down medium. During these interactions photons of various energies are generated by a variety of mechanisms. These photons proceed through the target assembly, and a fraction of them do eventually leak out of the patient treatment port, irradiating the patient with photons. This photon dose is generally not desired, since it merely increases the patient dose, without helping to destroy the tumor. The mechanisms for the creation of photons in these analyses include:

- 1) neutron capture (n, γ) reactions,
- 2) bremsstrahlung,
- 3) p-annihilation, and
- 4) fluorescence.

In the transport calculations that are carried out for the target assembly, the neutrons and the resulting photons are tracked simultaneously. This simultaneous calculation determine the relative neutron and photon leakage through the patient treatment port. It is expected that the number of photons leaking from the assembly will be small compared to the neutrons leaking from the assembly, since there is a large amount of self shielding in this target design. The photon self shielding results from the use of high "Z" materials of construction in the target (Pb, Fe).

Estimates of the fraction of neutrons and photons escaping from the patient treatment port were made for the NIFTI- (2/4) arrangement discussed above (Section 2.7). In this estimate a realistic neutron source resulting from protons with a maximum energy of 2.1 MeV impinging on the target was used. These neutrons have a maximum energy of 350 keV, and cover all angles, with a bias in the forward direction. The results of these analyses are summarized on Figure 2.9.1 for two source orientations. In the first case, the source is pointing in the direction of the patient treatment port, and in the second case, the source is pointing away from the port.

These results show a large reduction (lower by two orders of magnitude) in the photon leakage relative to the neutron leakage out of the patient treatment port. This result would indicate that the dose due to photon leakage will be acceptably low in a NIFTI based target design.

Furthermore, the leakage of both neutrons and photons is reduced approximately 18% by reversing the direction of the neutron source.

2.10 Residual Activation in NIFTI

Residual activation levels in NIFTI devices will be very low, because:

- Neutron source strengths are very low ($\sim 10^{12}$ n/sec)
- Fraction of neutron absorptions that lead to residual activation is very low.

Figure 2.10.1 shows the portions of the nuclide chart relevant to the principal material that would be used for NIFTI - iron, fluorine, lead - together with possible alternate reflector materials such as titanium and vanadium.

Most of the nuclear absorptions lead to stable isotopes or to radioisotopes that either quickly decay [e.g., $^{19}\text{F} \rightarrow ^{20}\text{F}$ (Half life of 11 sec)] or decay with out significant external radiation [e.g., $^{54}\text{Fe} \rightarrow ^{55}\text{Fe}$ (Half life of 2.73 years, but no gamma)]. Figure 2.10.2 summarizes those isotopes that could contribute to residual activation in NIFTI. Here, residual activation is defined as the activation remaining 1 hour after shutdown.

Figure 2.9.1

**Gamma Photons Generated and Escaping From the Irradiation Port
for Different Orientations Of NIFTI-2 Neutron Source**

Proton Energy 2.1 MeV
Neutron Source Energy Distribution $0 \text{ keV} < E_s < 350 \text{ keV}$
Neutron Source Angular Distribution $0^\circ < \theta_s < 180^\circ$

Source Orientation	In Direction of Port	Away From Port
(Photons Produced Per Neutron)		
Neutron Capture	.1998	.2095
Bremsstrahlung	.2323	.2462
Proton-annihilation	.0306	.0320
1 st Fluorescence	.2754	.2938
2 nd Fluorescence	.0598	.0625
Total Photon Source Per Source Neutron	.7979	.8440
Total Leakage	.0035	.0033
Total Capture	.7991	.8247
Pair Production	.0153	.0160
Photon Leakage Out of Irradiation Port Per Source Neutron	.0007	.0005

^{59}Fe is the only long-lived isotope produced by the various materials shown in Figure 2.10.1 with only about 10^{-3} of the neutron absorptions in iron leading to ^{59}Fe . Moreover, since only a small fraction of the total neutron absorptions in a NIFTI device will be absorbed in iron, and because the duty cycle for a NIFTI source - that is, the fraction of time it will actually be operating - will be low, the amount of residual activation will be negligible.

As an example, for the following conditions: the neutron source strength is 10^{12} n/sec, the duty cycle is 10% (i.e., NIFTI operates for $2\frac{1}{2}$ hours per day on the average), the fraction of NIFTI neutrons absorbed in iron is 1%, and the fraction of the iron absorptions resulting in ^{59}Fe is 10^{-3} , the total residual ^{59}Fe activity in NIFTI would only be about 20 micro-curies.

Figure 2.10.3 gives the total residual activation for the NIFTI-1 and NIFTI-2 designs analyzed in Figures 2.7.8 and 2.7.10. The versions of each design are shown. In the first version pure iron is used and in the second, a small amount (1 atomic %) of ^6Li is added to the iron, to preferentially capture the low-energy neutrons before they are absorbed by iron.

In addition to neutron activation, there will be residual activity due to ^7Be which has a half life of 53.3 days. The steady state activation inventory due to ^7Be will be directly proportional to the neutron generation rate and the daily cycle. For a neutron generation rate of 10^{12} n/sec, and a daily cycle of 10%, on the order of 3 curies of ^7Be will be present in the facility. With the fixed target option this will be located at the source position. With the DISCOS option, it will be located in the lithium circuit.

The gamma decay energy of ^7Be is 0.477 MeV. The gamma dose to the patient is negligible compared to that caused by other reactions during the treatment phase. The small ^7Be inventory appears to not pose any hazards or safety problems.

2.11 NIFTI Technical Issues

There do not appear to be any major technical issues for the NIFTI concept. Issues of heat removal and mechanical integrity for the DISCOS target for NIFTI-1 designs are discussed in Section 3 of this report. NIFTI-2 designs probably would use a fixed target approach in which a thin lithium film was deposited on an actively cooled substrate. The proton beam would impact on, and stop in, the lithium layer to generate the requisite neutrons. Because of the high neutron utilization efficiency of the NIFTI approach, the required beam current is only a few milliamps. The corresponding thermal load in a fixed NIFTI-2 target is then under ten kilowatts. This thermal load can be readily handled by a target of several square centimeters in area.

Properties of Isotopes Relevant to Residual Activation in NIFTI Designs

Fe55 ³⁺ 2.73 s ϵ no γ σ_a 17E1 E 231 	Fe56 91.72 σ_f 2.6, 1.4 E 231 	Fe57 ¹⁺ 2.1 σ_f 2.5, 1.6 E 231 	Fe58 0.26 σ_f 1.2, 1.5 E 231 	Fe59 ³⁺ 44.51 d β^- 468, 271, ... γ 1099.2, 1291.6, ... σ_a <10 E 1.565 	Fe60 ¹⁺ 1.5E6 a β^- 147 γ 58.6D, e- E 241 	Fe61 6.0 m β^- 2.8, 2.6, ... γ 1205.1, 1027.5, 297.9, ... E 3.98 	Fe62 68 s β^- 2.5? γ 506.1 E 2.53 	Fe63 ⁽⁵⁺⁾ 6 s β^- 994.8, 1427.2, ... E 6.6
Mn54 ³⁺ 312.2 d ϵ 834.8 σ_f <10 E 1.377 	Mn55 ⁵⁺ 100 σ_f 13.3, 14.0 E 4.938048 	Mn56 ³⁺ 2.578 h β^- 2.84, 1.04, ... γ 846.3, 1810.8, 2113.1, ... E 1.696 	Mn57 ⁵⁺ 1.45 m β^- 2.55, ... γ 122.1, 14.4, 692.0, ... E 2.692 	Mn58 ³⁺ 3.0 s → 65 s β^- 6.1, ... γ 1447- 2227 β^- 3.8, ... γ 810.8, 1323.1, 459.2, ... E 6.32 	Mn59 4.6 s β^- 4.4, 4.7, ... γ 726.1, 472.6, 570.5, ... E 5.18 	Mn60 ⁰⁺ 1.77 s 50 s β^- 5.7, ... γ 824, ... no γ IT 272 E 8.5 	Mn61 ⁽⁵⁺⁾ 0.71 s β^- 628.6, 206.8, ... 	Mn62 ³⁺ 0.9 s β^- 877.942, 1299, 1815, ...
Cr53 ³⁺ 9.50 σ_f 18.9 E 2.840462 	Cr54 2365 σ_f 36, 16 E 3.928894 	Cr55 ³⁺ 3.497 m β^- 2.49, ... γ 1528.1, ... E 2.603 	Cr56 5.9 m β^- 1.5 γ 83.9, 26.6, ... E 1.62 	Cr57 ⁽³⁺⁾ 21 s β^- 83.4, 850, 1752, 1535, ... E 4.5 	Cr58 7.0 s β^- 983, 126, ... E 3.8 	Cr59 1.0 s β^- 1239, ... 	Cr60 0.6 s β^- 	Cr61

V47 32.6 m	V48 15.98 d	V49 337 d	V50 0.250 1.4E17 s	V51 99.750	V52 3.76 m	V53 1.61 m	V54 49.8 s	V55 6.5 s
B ⁻ 1.89,... E γ 1794.0,...	B ⁻ .894,..., E γ 983.5, 1312.1,...	E noy	E _γ 7653.4 B ⁻ 7.7837 E _γ 461.681 E _γ 40.40 MeV E ⁺ 2.207	E _γ 4.5, 2.7	B ⁻ 2.47,... γ 1434.1,...	B ⁻ 2.5,... γ 1006.2,...	B ⁻ 3.0,... γ 834.8, 988.8, 2255.2,...	B ⁻ 5.4,... γ 517.7, 880.6,...
E 2.928	E 4.012	E 6.02	49.947182	80.543982	E 3.976	E 3.436	E 7.04	E 6.0
Ti46 8.0	Ti47 7.3	Ti48 73.8	Ti49 5.5	Ti50 5.4	Ti51 5.76 m	Ti52 1.7 m	Ti53 33 s	Ti54
B ⁻ 2.14,... γ 320.1,...	B ⁻ 1.8 γ 124.5, 17.0 e ⁻	B ⁻ 3.1,... γ 127.6, 228.4, 1675.6, 100.8,...						
E _γ 4.4 48.952830	E _γ 1.7, 1.6 48.961784	E _γ 7.8, 3.8 47.947947	E _γ 2.2, 1.2 48.947071	E _γ 1.77, .11 48.944732	E 2.472	E 1.97	E 5.0	E 4.4

F17 5/- 64.5 s B* 1.74 E 2.7609	F18 1+ 1.830 h B* 635 E 1.856	F19 4+ 100 B* 5.40... 1633.5... B* 2.8 mch, 21 mch 18.9964032	F20 2- 11.00 s B* 5.40... 1633.5...	F21 5/- 4.16 s B* 5.4... 350.7, 1395.1, ...	F22 4- 4.23 s B* 5.5... 1274.5, 2082.5, 2166.0, ...	F23 (5/-) 2.2 s B* 8.3... 1701.4, 2129, 1822.2, ...
E 2.7609	E 1.856	18.9964032	E 7.030	E 5.690	E 10.86	E 8.5

Bi206 ⁸⁺ 6.243 d ϵ 3.98 γ 803.7, 881.0, 516.2 E 3.76	Bi207 ^{9/-} 32.2 s ϵ 589.7, 1063.7D, 1770.2 E 2.397	Bi208 ⁽⁸⁺⁾ 3.88E5 s γ 2614.4 E 2.678	Bi209 ⁸⁻ 100 γ 1700.0, 1410.0, 678 ϵ 33.36 σ 0.05, 0.2 E 2.162	Bi210 ¹⁻ 3.06E6 s ϵ 5.01 d γ 1162 ϵ 4.848 γ 284.2, 305.2, 284 σ 0.05, 0.2 E 1.162	Bi211 ⁹⁻ AC C 2.14 m ϵ 6.623, 6.279 γ 350 E 210.98725	Bi212 ⁽¹⁵⁻⁾ 7 m ϵ 1.009 h γ 2251, 227.2, 440.4, 66.051, 39.8 ϵ 2.252 γ 211.991259 E 1.43	Bi213 ^{8+/-} 45.6 m ϵ 1.42, 1.02... γ 440.4, 5.87, 5.55 γ 323.8 E 1.43	Bi214 ⁽¹⁻⁾ RaC 19.9 m ϵ 3.27, 1.54, 1.51, 809.3, 1784.5, 1120.3, 650.0, 5.513, 63... γ 63... σ 0.05, 0.2 E 2.3	Bi215 7 m E 2.3
Pb205 ^{5/-} 1.5E7 s ϵ nov E 0.93	Pb206 24.1 γ 359, 14 σ 0.35, 0.2 E 206.974440	Pb207 ¹⁰⁻ 0.80 s γ 1063.1 γ 569.2 σ 0.76 γ 640.0, 2.0 σ 0.05, 0.2 E 206.974721	Pb208 ThD 82.4 γ 645 σ 0.45 E 208.980097	Pb209 ⁹⁻ 3.25 h ϵ 217.561 γ 48.5, 3.72 σ 0.5 E 208.980097	Pb210 RaD 22.3 s ϵ 317.561 γ 48.5, 3.72 σ 0.5 E 208.980097	Pb211 ⁽⁹⁻⁾ ACB 36.1 m ϵ 1.38... γ 404.8, 831.9, 427.0 E 1.3	Pb212 ThB 10.64 h ϵ 331.568... γ 238.6, 300.0... E 5.71	Pb213 10.2 m ϵ 331.568... γ 238.6, 300.0... E 5.71	Pb214 RaB 27 m ϵ 87.73... γ 351.8, 295.2, 242.0... E 5.03

Figure 2.10.2

Radioisotopes Contributing to Residual Activation of NIFTI Devices
Basis: 1 Hour After Shutdown

Principal Materials	Residual Radionuclides	Comments
Iron	^{54}Fe (Half Life of 44.5 days, 1.29 MeV Gamma)	Parent ^{58}Fe Has Only 0.28% Natural Abundance - ^{58}Fe Absorption Is Only $\sim 10^{-3}$ of Total Fe Absorption
Fluorine	None	11 Second ^{20}F Decays to Negligible Levels in 1 Hour
Lead	No γ Emitting Isotopes ^{205}Pb Is Electron Capture with 1.5×10^7 Year Half Life ^{209}Pb is β^- Emitter (no γ) with 3.25 Hour Half Life	0.8 Sec ^{207}Pb Decays to Negligible Levels in 1 Hour
Titanium	None	5.76 Minute ^{51}Ti Decays to Negligible Levels in 1 Hour
Vanadium	None	3.76 Minute ^{52}V Decays to Negligible Levels in 1 Hour
Lithium	^7Be (Half Life of 53.3 Days, 0.477 MeV Gamma)	Approximately, 3 curries of ^7Be will be present in a NIFTI facility at steady state.

Figure 2.10.3

Residual Activation in NIFTI Devices

Basis: NIFTI-1 and NIFTI-2 Designs Shown in Figures 2.7.8 and 2.7.10
 10^{12} n/sec Neutron Source Strength

	NIFTI-1 Design	NIFTI-2 Design
	Pure Iron	Pure Iron
Fraction of Neutrons Absorbed in Iron	0.0322	.0163
Fraction of Iron Absorptions Leading to ^{59}Fe (44.5 Days)	9.02 (-5)*	4.56(-5)*
Residual ^{59}Fe , millicuries	2.45	1.24
Fraction of Neutrons Absorbed That Result in short lived isotopes [^{20}F (11 sec) ^{207}Pb (0.8 sec) and ^{51}Ti (5.76 min)]	3.69 (-3)+	8.84(-3)+
Residual ^7Be Produced by (p, n) Reactions on ^7Li	~ 3 Curies	~ 3 Curies

- * Reduce total numbers of absorption by the parent isotopic abundance fraction, since the thermal absorption cross sections and resonance integrals for the different stable isotopes are essentially equal.
- + Includes all Pb components (Window and Structural).

The neutronics of the NIFTI design can be accurately modeled by 3D MCNP methods, using present nuclear data. It is not expected that there will be major differences between the analytic results and actual performance if the neutron source distribution is accurately characterized. However, before the construction of a prototype NIFTI device is undertaken, it would be desirable to experimentally validate the neutronics analyses, using a representative neutron source (of either the fixed or DISCOS type, depending on the final design approach) in combination with the proposed NIFTI assembly. The beam power level could be small compared to that for an actual NIFTI device.

Such a neutronics validation would enable final optimization of the prototype device and would provide verification of the output neutron energy and spatial distributions for patient treatment planning.

2.12 Assessment of NIFTI Options and Performance

Based on the initial studies described above, the following preliminary conclusions can be drawn:

1. The NIFTI concept enables neutron utilization efficiencies for practical BNCT accelerator based facilities to be in the range of 5 to 10%. That is, of the source neutrons generated in the lithium target, between 5 to 10% are available for patient treatment.
2. The proton beam currents corresponding to these neutron utilization efficiencies are on the order of a few milliamps, instead of the few ~~tens~~ of milliamps required in previous studies of accelerator based BNCT. This factor of 10 reduction in proton beam current results in facilities being able use existing commercial proton accelerator technology, rather than requiring R&D in advanced high current accelerators.
3. The NIFTI-2 concept with a thick fixed target is a practical option, with low beam current requirements, and acceptable output neutron energies. Depending on design, up to 66% of the output neutrons for patient treatment are below 26 keV in energy (based on a proton energy of 2.1 MeV). For the point design described in Section 4 of this report, which uses a higher proton energy (2.5 MeV), the coverage energy of the output neutrons is 37 keV. With optimization, this average energy could be further reduced, i.e., to well below 30 keV.
4. The NIFTI-1 concept results in a lower average neutron energy, and a smaller proton beam current requirement. However, the more complex DISCOS type target is needed, which will require R&D, as discussed in Section 3 of this report.
5. The spatial orientation of the target has a significant effect on the neutron utilization efficiency effect on the neutron utilization efficiency for NIFTI-1, with ~ 25% reduction when the source is oriented parallel to the treatment port, as compared to being oriented towards the

port. The reduction is smaller, ~ 15%, for NIFTI-2, when the source is oriented away from the port, as compared to being oriented towards the port. From the mechanical design point of view, for NIFTI-1 it is desirable to orient the source parallel to the port, while for NIFTI-2, it is desirable to orient it towards the port. This mechanical factor thus tends to favor the NIFTI-2 concept, as compared to NIFTI-1.

6. Closed solid neutron transport geometries are favored over open cavity transport geometries because of their higher neutron utilization efficiency.

7. The optimum thickness of the iron "filter" is in the range of 5 to 10 centimeters, for both NIFTI-1 and NIFTI-2.

8. The optimum fluoride materials include lead fluoride (PbF_2) and beryllium fluoride (BeF_2), with an optimum thickness in the range of 5 to 10 centimeters.

9. Titanium appears to be a better neutron reflector than lead for most NIFTI designs.

10. Polyethylene down-shifters significantly degrade average output neutron energy, with an acceptably small effect on neutron utilization efficiency.

11. The gamma photon flux out of the treatment port is very small compared to the epithermal neutron flux (~ 1 to 2%).

12. The residual neutron activation of the NIFTI assembly is very small; well below 1 millicurie, and consists primarily of ^{59}Fe (half life of 55 days). The residual activity of ^7Be , which results from (p, n) reactions on ^7Li is larger, but still is only a few curies.

References

1. Garber, D.I., and Kinsey, R.R., "Neutron Cross Sections, Vol. II, Curves," BNL 325, 3d ed (1976).

3.0 The DISCOS Concept

3.1 Description of the DISCOS Concept

A new concept is proposed for accelerator targets, termed DISCOS (Discs Incorporating Sector Configured Orbiting Sources). DISCOS appears very promising for generating neutrons for BNCT (Boron Neutron Capture Therapy) applications. DISCOS also appears promising for spallation target applications. Two versions of DISCOS are proposed. In this report, we examine the DISCOS concept as applied to the systems in which a proton beam impacts a lithium target to generate neutrons by the (p, n) reaction. However, the DISCOS concept could also be applied in other accelerator applications employing different particles and different targets.

The two versions employ different approaches to create one or more ultra thin (i.e., on the order of a few microns in thickness) lithium targets that would be impacted by the proton beam. The targets would be thin enough that the proton beam loses only a small portion of its energy - at most, a few tens of keV - in its passage through an individual lithium target.

After impacting a target, the protons in the beam would be re-accelerated to bring their energy back up to the initial value. This could be done by recirculating the beam and directing the beam back through a particle accelerator that would make up the energy lost in each repetitive pass through the lithium target. Alternatively, a multiple set of thin lithium targets can be used, within a DC electric field. The energy loss experienced by the protons in passing through a given target would then be compensated for by the energy gained in the DC field as the protons traveled to the next lithium target.

The DISCOS concept enables the efficient generation of low energy neutrons from lithium targets. The proton beam energy can be held just above the threshold value for neutron production, so that the output neutrons are born with low energies. If a single fixed target were used, however, the resultant neutron yield - i.e., neutrons generated per beam proton - would be very low, and the energy efficiency - neutrons per MeV of proton input energy - very small.

By re-accelerating the protons each time they pass through a thin lithium target, both the energy yield and energy efficiency can be increased by a large factor - on the order of 10 to 100 times, depending on design - while still maintaining the output of low energy neutrons. To achieve comparable neutron yields per proton and energy efficiency with a single fixed target, the initial energy of the proton beam would have to be far above the threshold value for neutron production, with the result that the output neutrons would have much greater average energy and a much higher maximum energy.

The two versions of DISCOS are termed DISCOS-1 and DISCOS-2. DISCOS-1, as described below, is based on a thin layer of liquid lithium that flows over an ultra-thin beryllium foil. DISCOS-2 is based on a sheet of discrete, ultra fine lithium droplets. In DISCOS-1 the proton beam impacts on the lithium film and Be foil combination, while in DISCOS-2, the beam only impacts the sheet of ultra fine droplets.

Figure 3.1.1 shows the basic DISCOS-1 target concept. The relatively thick support structure supports an ultra-thin (e.g., as thin as one micron, or even less) foil which intercepts the beam. The target disc is segmented into sectors so as to eliminate circumferential stresses. This enables much faster rotation, and more reliable, longer life operation. The same principle is used in the radial fiber super-fly-wheel that have been developed for energy storage applications.

The particle beam intercepts only the foil. The foil is cooled by radiation and conduction (dry option) or is directly covered by a thin liquid film that flows radially outwards on the foil (wet option). Figure 3.1.2 compares the two options. The wet option can utilize a liquid, e.g., lithium, that also serves as the target.

If a lithium target is used, the DISCOS-1 approach requires a backing foil to hold the lithium film. The foil produces parasitic losses of the proton beam, increasing the proton current needed to achieve the given neutron production rate.

The foil parasitic losses can be minimized by using a foil that is made of a low Z material, and having it as thin as possible. Beryllium foil appears to be the best choice, since it has low Z ($Z = 4$), appears fabricable as a thin metallic foil, and generates some neutrons when impacted by a proton beam (though not as much as a lithium film of equivalent stopping power). However, the presence of the Be foils still results in a lower neutron production rate as compared to having no foils at all.

The DISCOS-2 approach eliminates the Be foils that support the lithium target material. This results in a higher neutron production rate. In principle, thin lithium films could spin off the rim of the rotating disc and move radially outwards, where they then would be impacted by the proton beam. However, surface tension forces, and the differential rotation rates that would be associated with the changing radius, would result in a rapid breakup of the liquid film.

Instead of trying to produce a thin lithium film beyond the rim of the rotating disc, DISCOS-2 generates streams of small (micron diameter) lithium drops that move on controlled trajectories radially outwards from the rim of the disc.

Figure 3.1.3 shows a conceptual view of DISCOS-2. The lithium droplet streams leave the porous surface of the rotating disc and travel in a direction that is tangent to the point

where they are detached from the disc, with a velocity equal to the surface velocity of the disc. The multiple tangential trajectories of the ensemble of droplets leaving the disc results in a cloud of droplets that is azimuthally uniform around the disc, traveling outwards with the appropriate radial velocity.

3.2 DISCOS Heat Transfer Capabilities

In this section the heat transfer capabilities for the wet and dry versions of DISCOS-1 are compared. A 1 micron thick beryllium target foil and a 2 Mev proton beam are assumed. The power input to the Be foil is then

$$P_{Be} = I_B \Delta E_B \text{ watts} \quad (3.2.1)$$

where

$$\begin{aligned} I_B &= \text{Beam current, amps} \\ \Delta E_B &= \text{Proton energy loss after traversing the Be film, volts} \end{aligned}$$

Zucker () calculates ΔE_B as 26×10^3 volts for a 2 Mev proton incident on a 1 micron Be foil. (Figure 3.2.1). The power is then

$$P_{Be} = I_B (2.6 \times 10^4) \text{ watts} \quad (3.2.2)$$

For $I_B = 10^{-3}$ amp, $P_{Be} = 26$ watts

In DISCOS-1 this energy will be deposited around the full circumference of the rapidly rotating target, resulting in the local power density being relatively low.

$$\left(P_D \right)_{Be} \cong \frac{P_{Be} \Delta r_B}{2 \pi R_{Be}} \text{ watts/cm}^2 \quad (3.2.3)$$

where

$$\begin{aligned} \Delta r_B &= \text{radial width of beam, cm} \\ R_{Be} &= \text{radial distance from axis of rotation to center of beam spot, cm} \end{aligned}$$

Taking $\Delta r_B = 1$ cm and $R_{Be} = 10$ cm,

$$\left(P_D \right)_{Be} \cong \frac{2.6}{2 \pi} \cong 0.4 \text{ watts/cm}^2 \quad (3.2.4)$$

The DISCOS Target Concept

Fig. 3.1.1

Figure 3.1.2

Cooling of DISCOS-1 Target Foils/Films

- Dry foils (Be only) cooled by radiation or convection
 - Radiation favored for thin foils
 - Convection favored for thick foils
 - Proton currents up to ~10 mA are practical

- Lithium film/foils cooled by outwards movement of lithium film
 - Proton currents well above 10 mA are practical
 - Lithium film thicknesses as small as 1 micron are practical
 - Average film velocity scales as (thickness)²

Figure 3.1.3 The DISCOS-2 Target Concept

The temperature of the hottest spot on the circumferential film is given by the approximate expression (T_s = Temperature of the convection cooled support structure, e.g., 300 K),

$$(T_{\max})_c = T_s + \left(\frac{P_{Be}}{2\pi R_{Be}} \right) \frac{1}{k_{Be} \Delta Z_{Be}} \left[\Delta r_c + \frac{\Delta r_B}{2} \right] \quad (3.2.5)$$

where

- k_{Be} = thermal conductivity of Be, w/cm²°K
- ΔZ_{Be} = thickness of Be film (1×10^{-4} cm)
- Δr_c = distance of near edge of beam on film from the thick Be support structure, cm
- Δr_B = width of beam, cm

This expression assumes that the cylindrical foil can be approximated by 1-D heat transfer, and that the beam heating is uniform across its width Δr_B .

The thermal conductivity of Be at 800K average temperature is ~ 1.0 w/cm²°K [Handbook of Heat Transfer ()].

Figure 3.2.2 shows $(T_{\max})_c$ as a function of I_b for 2 cases: Case A (Δr_c and $\Delta r_B = 0.5$ cm) and Case B (Δr_c and $\Delta r_B = 0.2$ cm). Case A represents a relatively large beam with a large margin for position control, while case B represents a minimum size beam with accurate position control.

Even for case B, the maximum beam current that could be handled by DISCOS would be approximately 1 milliamp, assuming dry cooling without radiative heat transfer.

With radiative heat transfer, substantially higher beam powers could be handled. Curve C in Figure 3.2.2 shows the temperature, T_R , of the beryllium foil as a function of I_b , assuming an emissivity of 0.8 [surface is blackened], radiative heat transfer only (no conductive heat transfer), and $\Delta r_B = 1.0$ cm. The analysis also assumes that the radiative heat transfer is not blocked by adjacent surfaces.

With multiple sequential discs, radiation transport would be reduced because adjacent surfaces would radiate to each other. Curve D in Figure 3.2.2 illustrates the effect of this partial blockage, assuming that the effective emissivity would be reduced from 0.8 down to ~ 0.1 .

Clearly, radiation cooling of the Be foil(s) is much more effective than conductive cooling. For a maximum operating temperature of ~ 1000 K in a thin foil, one cannot go

above ~ 0.5 mA beam current based on conductive cooling only-even with favorable assumptions about beam spot size and the capability to control beam position. With radiation cooling, however, it is possible to operate with much higher beam currents, e.g., 3 mA, even if many multiple sequential foils are used.

This situation is reversed for a thick target, however. A 2 MeV proton will stop at a range of ~ 46 micron in beryllium foil. The temperature of the target foil, assuming only radiative cooling, is then given by

$$T_R = \left\{ \left(\frac{1}{2\epsilon_R\sigma_R} \right) \left(\frac{I_B (2 \times 10^6)}{2\pi R_B \Delta r_B} \right) \right\}^{1/4} \quad (3.2.6)$$

$$\sigma_R = 5.67 \times 10^{-12} \text{ watts/cm}^2$$

Curve C in Figure 3.2.3 shows the temperature of a thick Be foil ($\Delta Z_{Be} = 1000$ micron) as a function of I_B assuming that only radiative cooling is operating.

Conduction cooling is much more effective than radiative cooling if the surface of the thick foil is convectively cooled. The temperature of the front face of the beryllium is then

$$T_{cc} = 300 + \frac{I_B (2 \times 10^6)}{2\pi R_B \Delta r_B} \left[\frac{1}{h_c} + \frac{\Delta Z_{Be}}{k_{Be}} \right] \quad (3.2.7)$$

where

$$h_c = \text{coolant heat transfer coefficient, watts/cm}^2 \text{ } ^\circ\text{K}$$

Taking $R_B = 10$ cm, $\Delta r_B = 1$ cm, $k_{Be} = 1$ watt/cm $^\circ$ K and $\Delta Z_{Be} = 0.1$ cm (= 1000 microns),

$$T_{cc} = 300 + 31.8 I_B \left[\frac{1}{h_c} + 0.1 \right] \quad (3.2.8)$$

where I_B is expressed in milliamps.

Temperature values for the conduction/convection cooled DISCOS-1 target are shown as a function of I_B . Curve A is for $h_c = 10$ watts/cm 2 k (a high performance coolant circuit) and $h_c = 1$ watt/cm $^\circ$ K (a poor performance cooling circuit). There should be no problem in

cooling a thick Be target even for currents up to 10 mA milliamps, if active cooling is employed at the back of the thick target. Radiative cooling, on the other hand, is not effective.

Now consider the wet DISCOS-1 target option, as shown in Figure 3.2.4. A thin liquid film is formed on the Be foil target by flow from small exit holes in the thick support structure.

Centrifugal force transports the thin film radially outwards over the thin foil target, with the liquid eventually being spun-off from the outer edge of the foil target into a receiving slot located around the outside of the rotating disc (Figure 3.2.4).

An attractive coolant for DISCOS is liquid lithium, since it produces neutrons by (p, n) reactions. The thickness of the film is a function of the effective centrifugal g force; with

$$\tau_y = \mu \frac{d}{dy} (V_R)_y \quad (3.2.9)$$

where

$$\begin{aligned} \mu &= \text{viscosity of liquid, poise} \left(\frac{\text{dyne sec}}{\text{cm}^2} = \frac{\text{gm}}{\text{sec cm}} \right) \\ y &= \text{distance from surface of Be foil in direction normal to surface, cm} \\ (V_R)_y &= \text{liquid velocity in radial direction at position } y, \text{ cm/sec} \\ \tau_y &= \text{shear stress on liquid film, dynes/cm}^2 \end{aligned}$$

The shear stress relates to the g force on the liquid film by

$$\frac{d\tau_y}{dy} = -\rho g_R \quad (3.2.10)$$

where

$$\begin{aligned} \rho &= \text{density of fluid, g/cm}^3 \\ g_R &= \text{radial acceleration, cm}^2/\text{sec} \end{aligned}$$

combining (3.2.9) and (3.2.10)

$$\mu \frac{d^2 (V_R)_y}{dy^2} = -\rho g_R \quad (3.2.11)$$

Integrating ($y = 0$ @ surface of Be foil)

$$\frac{d(V_R)_y}{dy} = - \left(\frac{\rho g_R}{\mu} \right) y + C_1 \quad (3.2.12)$$

at the outer surface of the liquid film ($y = y^*$) the velocity gradient is

$$\frac{d(V_R)_y}{dy} = 0 \text{ for } y = y^* \quad (3.2.13)$$

so that

$$C_1 = + \left(\frac{\rho g_R}{\mu} \right) y^* \quad (3.2.14)$$

Integrating equation (3.2.12),

$$(V_R)_y = - \left(\frac{\rho g_R}{\mu} \right) \frac{y^2}{2} + \left(\frac{\rho g_R}{\mu} \right) y^* y + C_2 \quad (3.2.15)$$

The velocity $(V_R)_y = 0$ @ $y = 0$, so $C_2 = 0$, resulting in

$$(V_R)_y = \left(\frac{\rho g_R}{\mu} \right) \left[y^* y - \frac{y^2}{2} \right] \quad (3.2.16)$$

at $y = y^*$

$$(V_R)_y = \left(\frac{\rho g_R}{\mu} \right) [(y^*)^2 / 2] \quad (3.2.17)$$

with the average velocity of the film given by

$$\begin{aligned} \left(\overline{V_R} \right) &= \frac{\int_0^{y^*} \left(V_R \right)_y dy}{y^*} = \left(\frac{\rho g_R}{\mu} \right) \left(\frac{1}{y^*} \right) \left[\frac{(y^*)^3}{2} - \frac{(y^*)^3}{6} \right] \\ &= \left(\frac{\rho g_R}{\mu} \right) \frac{(y^*)^2}{3} \end{aligned} \quad (3.2.18)$$

The temperature use in the liquid lithium film is then

$$\Delta T_L = \frac{(P_{Be} + P_{LL})}{2\pi R_S \left(\overline{V_R} \right) y^* (C_P)_L} \quad (3.2.19)$$

where

$$\begin{aligned} P_{Be} &= I_B \Delta E_{Be} = I_B \times 2.6 \times 10^4 (\Delta y_{Be}) \\ P_{LL} &= I_B \Delta E_{LL} = I_B \times 8 \times 10^3 (y^{**}) \end{aligned} \quad (3.2.20)$$

with

$$\begin{aligned} I_B &= \text{proton current, amp} \\ \Delta Z_{BR} &= \text{thickness of Be foil in microns} \\ y^{**} &= \text{thickness of Lithium film in microns } (= 10^4 y^*) \end{aligned}$$

Figure 3.2.5 shows g_R as a function of I_B and y^{**} , for a fixed temperature rise of $\Delta T_L = 100K$ in the liquid film. Lithium parameters are: $\rho = 0.5 \text{ g/cm}^3$, $\mu = 6 \times 10^{-3} \text{ poise}$, $c_p = 2.1 \text{ J/cm}^3 \text{ } ^\circ K$. Beryllium foil thickness is: $\Delta y_{Be} = 1 \text{ micron}$, and $R_B = 10 \text{ cm}$.

Film thicknesses as low as 1 micron appear achievable at beam currents of 1 to 2 milliamps. If relatively high beam currents - i.e., on the order of 10 milliamps - are desired, film thicknesses of 2 to 3 microns are probably required.

The above analysis assumes that the flow of lithium over the Be foils is steady, i.e. constant with time. However, another option - that of non-constant flow - is possible. In this approach, the foil would be cooled with a relatively thick lithium film during the portion of its rotational period where it was not impacted by the proton beam. The liquid flow would then

be cutoff, and the film would thin out just prior to the time it was impacted by the proton beam. Figure 3.2.6 illustrates this pulsed cooling flow approach.

The temperature rise in the Be foil and its lithium film due to the impacting proton beam is given by

$$\Delta T_{TAR} = \frac{P_{Be} + P_{Li}}{\left(V_{\Theta} \right)_{TAR} \Delta r_B \left[\Delta y_{Be} C_{p_{Be}} + \Delta y^* C_{p_{Li}} \right]} \quad (3.2.21)$$

where

$$P_{Be} + P_{Li} = I_B \left[\Delta E_{Be} \Delta y_{Be} + \Delta E_{Li} \Delta y^* \right] \quad (3.2.22)$$

and

$$\left(V_{\Theta} \right)_{TAR} = \left(\frac{f_{TAR}}{60} \right) 2\pi R_B \quad cm/sec \quad (3.2.23)$$

where

f_{TAR} = target rotational frequency, rpm

Combining equations (3.2.21), (3.2.22) and (3.2.23) we have

$$\Delta T_{TAR} = I_B \frac{\left[\Delta E_{Be} \Delta y_{Be} + \Delta E_{Li} \Delta y^* \right]}{f_{TAR} R_B \Delta r_B \left[\Delta y_{Be} C_{p_{Be}} + \Delta y^* C_{p_{Li}} \right]} \left(\frac{60}{2\pi} \right) \quad (3.2.24)$$

Figure 3.2.7 shows ΔT_{TAR} as a function of f_{TAR} and I_B for the target parameters $R_B = 10$ cm, $\Delta r_B = 1$ cm, $\Delta y_{Be} = 1$ micron, and $\Delta y^* = 1$ micron. ΔT_{TAR} will decrease slightly as Δy^* increases, but the effect is small.

The temperature increase on the Be foil plus Li film is small for rotational frequencies of 10,000 RPM and greater, even with high beam currents (e.g., 10 milliamp).

The transit time on a liquid lithium film across the spot on the foil that has been impacted by the proton beam is given by

$$\Delta t_{TR} = \frac{\Delta r_B}{(\overline{V}_R)} = \frac{(\Delta r_B)(3)(\mu)}{(\rho g_R)(y^*)^2} \text{ sec} \quad (3.2.25)$$

The ratio of the distance traveled by the target rim during which a thick film thins down to a final thickness y^* , to the actual target circumference, can be approximated by

$$R_{CIRC} = \frac{\Delta t_{TR}}{\tau_{TAR}} = \Delta t_{TR} f_{TAR} \quad (3.2.26)$$

where

f_{TAR} = target rotational frequency, revolutions/sec

$\tau_{TAR} = \frac{1}{f_{TAR}} = \text{time to complete one revolution, sec}$

combining equations (3.2.25) and (3.2.26), we have

$$R_{CIRC} = \frac{\Delta r_B (3) (\mu)}{(\rho g_R)(y^*)^2} f_{TAR} \quad (3.2.27)$$

where

$$g_R = R_B \omega^2 = R_B (2\pi)^2 (f_{TAR})^2 \quad (3.2.28)$$

$$R_{CIRC} = \frac{\Delta r_B (3) (\mu)}{\rho R_B (2\pi)^2 (y^*)^2} f_{TAR} \quad (3.2.29)$$

Taking $\Delta r_B = 1 \text{ cm}$, $\mu = 6 \times 10^{-3} \text{ poise}$, $\rho = 0.5 \text{ g/cm}^3$, $R_B = 10 \text{ cm}$, we have

$$R_{CIRC} = \frac{9.1 \times 10^3}{f_{TAR} (y^*)^2} \quad (3.2.30)$$

Figure 3.2.8 shows R_{CIRC} as a function of rotation frequency and y^* (expressed here as film thickness in microns). The pulsed cooling approach requires the value R_{CIRC} to be well below one. This in turn requires y^* to be greater than 5 microns for practical rotational frequencies. As a result, the pulsed cooling approach probably offers no significant advantage over steady film cooling, as regards film thickness.

In summary, it appears practical to operate the DISCOS-1 target as thin with a lithium film as one micron, while staying well within the state of the art for rotating components. The temperature rise of the lithium film as it flows outwards on the thin Be foils will be modest, on the order of 100 K, at beam currents of a few milliamps. This level of beam current corresponds to the multi-foil version of DISCOS-1 that re-accelerates the proton beam in the DC field between foils, as described in the next section of this report.

However, the lithium temperature rise in the single foil version of DISCOS-1 that employs a recirculating beam would be unacceptably large at the nominal rotation rate - i.e., a rate that is on the order of 10,000 rpm. This results from the fact that the beam current is inherently much greater for the recirculating beam single foil target version than for the multi foil/single beam pass version that employs a DC field to re-accelerate the beam between the foils.

In the recirculating beam approach, the beam current would be tens to hundreds of milliamps, instead of the few milliamps required with the multi-foil DC field approach. As a result, the rates of heating would be 10 to 100 times larger than the rates considered in this section. Such high heating rates would either require an unacceptably large temperature rise for the liquid lithium layer, or would require an unacceptably thick lithium layer that would result in an excessively large proton energy loss.

Accordingly, the DISCOS-1 concept does not appear viable if a recirculating beam is used. It probably is viable with the DISCOS-2 concept, since the outwards velocity of the thin droplet sheet can be made much larger than that of the liquid film in DISCOS-1. As discussed in the following section, however, a recirculating beam may be unacceptably dispersed by repetitive passage through a single target. This would prevent the DISCOS-2 target from being feasible with a recirculating proton beam.

Figure 3.2.1

Proton Energy Loss in Beryllium Foils and Lithium Films
 Calculations for 2.0 MeV Proton [Zucker ()]

Li 0.531 g/cm ³	δx (μm)	Exit Energy (MeV)	Target Thickness (keV)	rms Energy Deviation (MeV)	rms Angle Spread (Rad.)
	1	1.992	8	1.90×10^{-3}	3.97×10^{-3}
	3	1.977	23	3.29×10^{-3}	6.92×10^{-3}
	10	1.921	79	6.00×10^{-3}	1.29×10^{-2}
	30	1.756	244	1.04×10^{-2}	2.38×10^{-2}
	100	1.052	948	1.90×10^{-2}	6.20×10^{-2}
Be 1.85 g/cm ³					
	1	1.974	26	3.59×10^{-3}	8.82×10^{-3}
	3	1.920	80	6.22×10^{-3}	1.56×10^{-2}
	10	1.724	276	1.14×10^{-2}	3.08×10^{-2}
	30	1.039	961	1.97×10^{-2}	7.55×10^{-2}
	100	*	--	--	--

* Proton stops @ 0.0046 cm = 46 μm .

Maximum Temperatures In Thin Beryllium Foils Impacted By Proton Beams

Fig. 3.2.2

Maximum Temperatures In Thick Beryllium Foils Impacted By Proton Beams

Figure 3.2.3

Liquid Film Cooling Of DISCOS-1 Target

Fig. 3.2.4

Acceleration On DISCOS-1 Liquid Film As A Function Of Proton Beam Current and Film Thickness

Fig. 3.2.5

Pulsed Flow Options For Liquid Film Feed To Rotating DISCOS-1 Target

Fig. 3.2.6

Temperature Increase In Target Foil As It Passes Through Proton Beam

Fig. 3.2.7

Ratio Of Target Rim Travel Distance To Target For Pulsed Liquid Film Cooling

Fig. 3.2.8

3.3 Reacceleration of The Proton Beam in DISCOS-1 and DISCOS-2

Following a suggestion by M. Goldhaber (), in the case of the DISCOS-1 target, it may be desirable to use a multiple foil target assembly with repetitive acceleration between foils. This differs from the recirculating beam approach, in that the energy additions are provided by DC fields in the gaps between the multiple target foils, rather than by a separate accelerator.

Figure 3.3.1 shows an illustrative arrangement of target foils for the re-acceleration version of DISCOS-1. The proton beam first impacts a target foil at ground potential producing neutrons and losing energy as it does. It then loses further energy due to the electric field between the ground foil and the first interior target foil, which is maintained at a positive potential (e.g., +200 kv) with respect to ground.

The proton beam then passes through the sequence of target foils, and is re-accelerated by the electric fields between the sequential series of foils. In the example shown, the average energy lost by the beam is 50 keV each time it passes through a foil. The foil may either be dry (i.e., Be), or wet (i.e., Be with a lithium film). This energy loss parameter can be adjusted over a wide range, depending on design considerations. On the one hand, a small energy loss in a foil would allow DISCOS to operate slightly above the neutron production threshold, generating a directed neutron beam in which the maximum energy of the neutrons was low. On the other hand, this would require a large number of foils, since the average energy loss per foil probably would have to be in the range of 5 to 10 keV. More detailed study is required to determine the optimum number of foils.

It is important to note that the energy lost by the proton beam as it penetrates the first ground foil and is decelerated by the first target foil, which is at +200 kv, is returned during the re-acceleration process, since the last target foil in the sequence is at -200 kv. In effect, the target arrangement enables the beam to operate at a quasi-constant energy (with an integrated total energy input of $2\Delta V_1$ (where ΔV_1 is the potential of the first target foil above ground)).

ΔV_1 will probably be in the range of 200 to 300 kv, so that the total energy used in the re-acceleration process will be 400 to 600 keV. [An additional energy input of ~500 keV could be imparted using a sufficiently thick first ground foil, if the higher energy neutron spectrum generated by this portion of the target is acceptable. This would increase the total energy loss per transit of the target to ~1000 keV.

Y.Y. Lee estimates that the proton beam cannot be collected and re-accelerated by an accelerator after passing through $800 \mu\text{g}/\text{cm}^2$ of lithium target. At 15 keV per $100 \mu\text{g}/\text{cm}^2$, this corresponds to a total energy loss of approximately 120 keV. It thus appears that an energy loss to 500 to 1000 keV for a single pass through the target assembly will cause sufficient dispersion of the beam that it cannot be re-accelerated.

This situation probably will hold for any multi-foil target assembly. Accordingly, multi-foil targets should be designed as once-through devices, with the maximum possible energy input during the single pass.

Re-acceleration of the proton beam by a DC field can also be applied to the DISCOS-2 concept, as illustrated in Figure 3.3.2. In contrast to the DISCOS-1 concept, however, an electric potential cannot be applied directly to the sheets of isolated, discrete droplets. Instead, the droplet sheets would be positioned in a DC field that was applied by external Be grid or ultra-thin foils maintained at high positive potential, and a final thick stopping target maintained at high negative potential.

In the example shown in Figure 3.3.2, the initial energy of the 2.2 MeV proton beam is reduced to 2.0 MeV by the first grid or foil, which is held at +200 keV relative to grid. The protons are then maintained by the DC electric field at a quasi-constant energy of approximately 2 MeV as they travel through the series of droplet sheets. A total of 400 keV is imparted to the protons during this process. After traversing the final droplet sheet the protons hit a thick stopping target that is maintained at -200 KV relative to ground. (In order to efficiently employ the energy imparted by the applied DC electric field, the first and last droplet sheets should be positioned relatively close to the positive grid/foil and the negative stopping target.)

The principle issue for the re-acceleration concept is the magnitude of the parasitic currents in the target assembly, and possibility of electrical breakdown between electrodes and/or foils. Protons striking a foil, grid, or droplet, will generate secondary electrons. These electrons will contribute to parasitic currents in the applied field, and can potentially lead to an avalanche type of electrical breakdown.

Positive ions that are on the order of a keV in energy typically generate about one secondary electron per impact on a solid or liquid surface (). The available data indicates that the yield of secondary electrons increases as the energy of the impacting ion increases, at least in the range of a few keV. It thus appears likely that ~2 MeV protons impacting a foil or droplet will generate multiple secondary electrons that are ejected from the surface.

These secondary electrons will then be accelerated by the applied electric field, traveling in an opposite direction to the ions (since the DC field direction is chosen to re-accelerate the ions in their direction of travel).

Depending on the yield of secondary electrons, the resultant parasitic electron current could be much larger than the proton beam current.

The accelerated secondary electrons potentially could cause electrical breakdown by two processes:

- collisions with, and ionization of, neutral background gas atoms
- generation of additional tertiary electrons and ions by impacts on surfaces.

The first process appears not to be of concern because of the extremely low vapor pressure of lithium at the target conditions. Figure 3.3.3 shows the vapor pressure of lithium as a function of temperature. At $T = 279^\circ \text{C}$ (100 K above the melting point), which is of the order expected for the maximum temperature in the lithium target, the vapor pressure is below 10^{-6} mmHg.

At this pressure the mean free path for ionization of a lithium atom by an electron is $\sim 10^8$ centimeters, based on an ionization cross section of $\sim 10^{-18} \text{ cm}^2$. Clearly with a target assembly dimensions of a few centimeters, breakdown caused by ionization of background lithium vapor will not be a problem.

Breakdown caused by secondary electrons generating tertiary electrons and ions could be a problem, however. Secondary electrons can gain on the order of 10 keV or more in the applied DC field before they strike the surface of an adjacent foil or a lithium droplet, generating new electrons and ions.

For DISCOS-1, the tertiary electrons generated by such impacts will not be a problem, since they will be immediately pulled back into the surface of the foil on which they are generated (due to the direction of the applied electric field). However, tertiary ions will travel away from the surface on which they are generated, picking up ~ 10 keV or more of energy before they collided with an adjacent foil to produce still more electrons and ions. Accordingly, there is a possibility that a cascading breakdown process could take place, in which each generation of ions and electrons produced even more ions and electrons.

In DISCOS-2, since the droplet sheets are not opaque, but allows passage of both ions and electrons, it becomes possible for the tertiary electrons and ions to both produce additional electrons and ions.

This potential for electrical breakdown, as well as the substantial parasitic currents that can be expected even if breakdown does not occur, appears to make it necessary to find a way to strongly inhibit the passage of secondary electrons in DISCOS target assemblies.

This appears possible using a magnetic field that is orthogonal to the direction of the applied electric field. By applying the magnetic field, the secondary electrons would gyrate in tight circles around magnetic field lines, and could not travel in the direction of the applied electric field. The radius of gyration (i.e., the Larmor radius) for electrons is given by

$$r_e = \frac{M_e (V_e)_{th}}{Be} \text{ meters} \quad (3.3.1)$$

where

- M_e = Mass of electron, kg
- B = Magnetic field strength, Tesla
- e = Charge of electron, coulombs
- $(V_e)_{th}$ = Thermal velocity of electron, m/sec

Using a magnetic field of modest strength (e.g., 0.2 Tesla, or 2000 Gauss), a 100 eV electron would have a Larmor radius of only 150 microns. Lower energy electrons would have even smaller Larmor radii. As a result, secondary electrons will be effectively trapped by the applied magnetic field, and unable to impact on adjacent target foils or droplets. This should completely eliminate secondary currents and the possibility of electrical breakdown. The trapped electrons will move in helical orbits, drifting along the magnetic field lines until they encounter the rotating disc or the surrounding enclosure.

The magnetic field would be generated either by conductor windings or by permanent magnets. If permanent magnets are used, the issue of the effect of radiation damage on magnet coercivity will have to be investigated.

These magnetic geometry options appear possible. In the first option, the magnetic field would be purely azimuthal, and generated by a coaxial current distribution (Figure 3.3.4 A). Current would flow through a conductor in the shaft of the rotating disc, and return through fixed conductors in the stationary enclosure outside of the disc. The resultant azimuthal magnetic field in the region of the beam would scale as $(R)^{-1}$, i.e.

$$B_\theta = K_\theta / R \quad (3.3.2)$$

In the second magnetic geometry option, the magnetic field would be radial. It could be generated by fixed conductor coils located in the outer stationary enclosure, in which current flowed azimuthally (Figure 3.3.4 B). Two circular coils would be used, with their currents oppositely directed. The resultant cusp field would be predominantly radial in the region of the target lithium films or droplet sheets. In this magnetic geometry option, the magnetic field in the target region would be relatively constant with R .

$$B_R \approx K_R \quad (3.3.3)$$

In these two magnetic geometry options, the magnetic field is azimuthally uniform with a constant magnitude at a given radius. In the third geometry option, the magnetic field direction is not constant and does vary with azimuthal angle. However, the magnitude of the field is constant with azimuth. Figure 3.3.4C shows an illustration of this geometry. Stationary conductor windings positioned around the disc generate a vertical magnetic field through which the disc rotates.

The three magnetic geometry options have different current requirements. Based on a lithium target radius of 10 centimeters and a magnetic field strength of 2000 gauss, the total current required for magnetic geometry option A is on the order of 100,000 amp turns. Using option B, the total current for 2000 gauss is reduced to approximately 25,000 amp turns, based on a 10 centimeter long target region. With option C, the total current required is on the order of 50,000 amp turns.

Option A appears to be less desirable than either option B and C, because of its greater current requirement, and the additional difficulty of transferring current to a set of moving windings in the rotating disc. The current measurements for options B and C appear reasonable. The power requirements would be relatively low, on the order of ten kilowatts.

The choice between option B and C will probably depend on which of the two inhibits electron mobility the best. More study, including experimentation, is needed to resolve this issue. In this connection, it should be noted that the magnetic field illustrated in Figure 3.3.4 C is oriented so that the field lines in the beam impact region intersect the rotating disc. The magnetic field can readily be oriented in a 90° direction so that the field lines in the impact region do not intersect the rotating disc, but instead lead away from it.

Figure 3.3.1 Re-Acceleration of Proton Beam By DC Fields Between Multiple Foils/Films DISCOS-1 Target

Re-Acceleration of Proton Beam By DC Field Applied To DISCOS-2 Target

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Be Grid or Foil at
Ground Potential ($V = 0$)

Be Grid or Foil at
 $V = +200$ kV

Thick Stopping Target at
 $V = -200$ kV

Target Enclosure at
Ground Potential ($V = 0$)

Figure 3.3.2

Vapor Pressure Of Lithium As A Function Of Temperature

Figure 3.3.3

Figure 3.3.4 Magnetic Geometries for Prevention of Electrical Breakdown in DISCOS Targets

(B) Radial (cusp) Magnetic Field

(C) Dipole Magnetic Field

3.4 Formation of Liquid Films in DISCOS-1

Figure 3.4.1 illustrates the steps involved in the foundation of a uniform liquid lithium film on a rotating disc. For a multi-disc target assembly with the discs at different potentials, it is necessary to have multiple feed lines. Each one must be separate from the others and at its appropriate electric potential, since lithium is a good electric conductor.

Figure 3.4.2 illustrates the critical steps (#4 and #5) in the process during which the individual streamlets emerge spread laterally and join to form a uniform and continuous film. Each streamlet is subject to the local centripetal acceleration, $a = rw^2$, and flows in response to it. There is a component of acceleration that acts parallel to the surface that makes the streamlet move radially outwards towards the rim of the disc, together with a component of acceleration that acts perpendicularly into the disc, making it spread laterally on the surface.

The ratio of lateral spreading velocity for the film to its radially outwards velocity is a function of the angle that the surface of the disc makes relative to the axis of rotation. At an angle of 45 degrees, for example, the lateral and outwards velocities are equal since the parallel and perpendicular components of the centripetal acceleration are the same.

For angles greater than 45 degrees ($\theta > 45$ degrees) the lateral spreading velocity is greater than the outwards velocity; for $0 < 45$ degrees, the radially outwards velocity is greater than the lateral velocity.

To first order, the lateral spreading velocity at any point R on the disc is given by

$$V_L \approx K \sin \theta_R \quad (3.4.1)$$

and the radial outwards velocity by

$$V_R \approx K \cos \theta_R \quad (3.4.2)$$

The relative lateral and radial displacements of the streamlet are then

$$\frac{\delta L}{\delta R} = \frac{\sin \theta_R}{\cos \theta_R} = \tan \theta_R \quad (3.4.3)$$

with

$$\Delta L = \int_{R_1}^{R_2} \tan \theta_R \delta R = \left(\tan \theta_R \right)_{AV} (R_2 - R_1) \quad (3.4.4)$$

The condition for merging of the streamlets is

$$\Delta L \approx \Delta X_{FH} \quad (3.4.5)$$

where

$$2\Delta X_{FH} = \text{Distance between streamlet feed holes}$$

Assuming that $\theta_R = 10$ degrees (a representative angle for the disc), that $2\Delta X_{FH} = 10^{-1}$ cm (a representative distance between streamlet feed holes), and that θ_R is constant over the radial distance $(R_2 - R_1)$, then the radial distance required for two streamlets to merge is given by

$$R_2 - R_1 = \frac{\Delta L}{\tan \theta_R} = \frac{0.1}{\tan (10^\circ)} = 0.57 \text{ cm} \quad (3.4.6)$$

In practice, a distance of ~ 2 to 3 times this value appears desirable, to allow the merging streamlets to form a smooth sheet of uniform thickness. However, the radial distance required is still small compared to the radius of the disc - that is ~ 1 to 1.5 cm compared to 10 cm.

The uniform lithium sheet would then flow radially outwards on the thin beryllium foils, to be impacted by the proton beam. It should be noted that the thickness of the lithium sheet will decrease with increasing radius both because of the increasing cross sectional area for flow, which scales directly as R , and the increasing g force, which also scales directly as R . When these effects are combined, the film thickness at a particular radius R will then scale as

$$(y^*)_R = (y^*)_{Ref} \frac{R}{R_{ref}} \quad (3.4.7)$$

where

$$\begin{aligned} (y^*)_R &= \text{Thickness at the radius } R \\ (y^*)_{Ref} &= \text{Thickness at the reference radius } R_{ref}. \end{aligned}$$

For a value of the nominal reference radius of $R_{ref} = 10$ cm, e.g., at beam center, and a 1 cm diameter proton beam, the lithium thickness would then change by $\pm 5\%$ over the diameter of the beam.

In the DISCOS-2 concept, the lithium droplets emerge from the pores in the surface of the rotating disc. At that point, they have a predominately azimuthal velocity

$$(V_{\theta})_{R_0} = R_0 \omega \quad (3.4.8)$$

where

R_0 = Outer radius of the disc, cm
 ω = angular velocity of the disc, radians/sec.

With the azimuthal velocity much greater than the radial velocity

$$(V_{\theta})_{R_0} \gg (V_R)_{R_0} \quad (3.4.9)$$

Typically, V_{θ} will be on the order of 10^3 cm/sec, compared to ~ 30 cm/sec for V_R .

Thus, at positions close to the surface of the disc the droplet trajectories will appear primarily azimuthal, with the apparent radial velocity relatively low. As the droplet continues to move outwards in radius on its straight line trajectories, however, the apparent radial velocity will increase with R according to

$$V_R = (V_{\theta})_{R_0} \sqrt{1 - \left(\frac{R_0}{R}\right)^2} \quad (3.4.10)$$

Figure 3.4.3 shows the outwards radial velocity of the droplets as a function of radius for different rotational rates, assuming that $R_0 = 10$ centimeters. Note that the droplet radial velocity becomes relatively constant after a distance of 2 to 3 centimeters beyond the rim of the disc.

The total equivalent thickness of the droplet sheet at radius R is given by

$$\Delta X = \frac{10^4 \dot{V}_{Li}}{2\pi R (V_R)} \text{ microns} \quad (3.4.11)$$

Where

$\dot{V}_{Li}$ = total volumetric flow rate of lithium from the rotating disc, cm³/sec.

As, $R \rightarrow R_0$, $V_R \rightarrow 0$, and the thickness of the droplet sheet becomes large. It is prevented from going to infinity, however, because V_R at the surface of the disc is not zero, but on the order of a few percent of $(V_0)_{R_0}$.

Figure 3.4.4 gives the total thickness of the lithium droplet sheet as a function of radius and disc rotation rate for a constant volumetric flow rate of 200 cm³/sec. It is important to note that this is the total equivalent thickness. In fact, the droplet sheet will probably be made up of multiple sheets, e.g., 100, with a separation distance between adjacent sheets on the order of one millimeter. A 2 MeV proton will have an energy loss of ~ 8 keV per micron of lithium thickness, so that a total equivalent thickness of 50 microns corresponds to a total energy loss of 400 KeV, a typical value for the NIFTI-1/DISCOS concept. This value of energy loss is achieved at a radius of 11.8 centimeters, for a rotational rate of 1000 rpm and a total volumetric flow rate of 200 cm³/sec.

The volumetric flow rate and rotational speed can be adjusted to give whatever total thickness is determined to be optimum.

Figure 3.4.5 shows the total lithium flow rate and the corresponding ΔT rise in the lithium stream (assuming a 5 mA total beam current and 400 KeV total energy loss in the lithium droplet sheet) as a function of rotational rate at a fixed radius of 12 centimeters (2 centimeters beyond the rim of the rotating disc) and a constant total sheet thickness of 50 microns.

The thermal power deposited in the lithium droplet sheets by the proton beam is

$$P_{LL} = I \Delta E_B = 5 \times 10^{-3} \times 4 \times 10^5 = 2000 \text{ watts} \quad (3.4.12)$$

with the corresponding temperature rise

$$\Delta T_{LL} = P_{LL} / (C_P)_{LL} \dot{V}_{Li} \quad (3.4.13)$$

For lithium $(C_P)_{Li} = 2.1 \text{ J/cm}^3 \text{ }^\circ\text{K}$.

As shown by Figure 3.4.5, the temperature rise in the lithium stream is negligible. The determining factor for liquid flow rate at any given rotational rate is the equivalent total thickness of the droplet sheet. Satisfying this requirement automatically results in a very low temperature increase in the lithium flow stream.

A nominal rotational rate of 1000 RPM appears satisfactory - the mechanical stress is very low in the disc, and the liquid flow rate very reasonable, i.e., $\sim 200 \text{ cm}^3/\text{sec}$.

At the equivalent sheet thickness of 50 microns with 1 micron diameter drops the average proton will hit ~ 100 drops in its path through the droplet sheets, with an average energy loss of $\sim 4 \text{ KeV}$ per collision (the proton does not usually travel through the full 1 micron diameter of the droplet). Between collisions, the protons will be re-accelerated by the DC electric field.

The generator for the droplet sheets would consist of ~ 100 stacked discs with each disc having many small discharge holes in their outer circumference; typically, the thickness of each disc would be on the order of 10^{-1} centimeters, with the discharge holes concentrated in a $\sim 10^{-2}$ centimeter thick region on the center plane. The full stack of 100 discs would then be ~ 10 centimeters thick. The thickness of each droplet sheet would then be approximately 10^{-2} centimeters, or about 4 mils, with $\sim 10^{-1}$ centimeters, or about 40 mils, between adjacent sheets.

Each sheet has sufficient 1 micron droplets to continuous liquid sheet of thickness 0.5 micron, with the droplets distributed throughout a zone 100 microns in thickness. Each 1 micron droplet will, on the average, then be approximately 20 microns distant from neighboring droplets.

Each of the ~ 100 separate liquid lithium supply ducts for the separate droplet sheets must not be electrically connected to the other ducts, in order that shorting of the applied DC electric field cannot occur with 100 sheets, the electric potential between adjacent sheets is only 4 KeV, with a gradient of 40 kV per centimeter.

Steps In The Evolution Of A Uniform Liquid Lithium Film On A Rotating Disc

3 - 37

Figure 3.4.1

Figure 3.4.2 Illustrative Design For Formation of A Uniform Liquid Lithium Film On A Rotating Disc

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Detail Of Streamlet Merging Region

Figure 3.4.3 Outward Radial Velocity In A Lithium Droplet Sheet As A Function of Radius
for Different Rotational Speeds

Figure 3.4.4 Integrated Equivalent Thickness of Lithium Droplet Sheets As A Function of Radius For Different Rotational Speeds

**Figure 3.4.5 Flow Rate and Temperature Rise As A Function of Rotational Rate
For Lithium Droplet Sheets**

3.5 DISCOS Technical Issues

The DISCOS-1 concept has 3 principal technical issues:

1. Uniformity of the liquid lithium film on the rotating Be foils.
2. Fabrication and attachment of ultra thin Be foils (≤ 1 micron).
3. Prevention of parasitic currents and electrical breakdown from the applied DC field.

The first issue appears not to be a problem. The high g force ($\sim 10,000$ g) caused by the rapid rotation should result in a very thin uniform film of lithium on the Be foils. However, this is a new idea, and should be experimentally validated. The next section of this report describes a proposed experiment for validation.

The second issue should be resolvable, but also will require experimentation. Ultra thin uranium-palladium foils, on the order of 1 micron thickness, were made in conjunction with the BNL chemonuclear program in the 1960's. They were uniform and exhibited good mechanical properties. These foils were fabricated by repeated rolling of metallic uranium-palladium in steel jackets. It should be possible to make thin metallic Be foils by this process, but some experimental fabrication work is needed to confirm this.

The attachment of thin metallic foils to a high speed rotating disc appears practical using some type of adhesive bonding technique. This would be investigated using thin Aluminum or gold foils in the proposed experiment described below.

The issue of electrical breakdown is probably the most important, and must be resolved by experiment. Initial experiments can be carried out on the rotating disc described in the following section, with electrons created by a pulsed laser or other auxiliary discharge; ultimately, however, a prototype DISCOS assembly would have to be tested using an impacting proton beam.

The DISCOS-2 concept also has 3 principal technical issues:

1. Formation of a sheet of ultra small (~ 1 micron) lithium droplets.
2. Possibility of, and effects resulting from, collisions between individual droplets in a droplet sheet.
3. Prevention of parasitic currents and electrical breakdown from the applied DC field.

The last issue is the same as that for DISCOS-1, and would be addressed using a similar approach.

Materials with very fine pores, i.e., on the order of 1 micron in diameter, are commercially available. These materials are typically used as filters, and are made of a wide variety of metallic (e.g., stainless steel) and non-metallic (e.g., Al_2O_3) substances. There appears to be no bar to using them to generate sheets of ultra fine droplets, using either stacked metallic porous discs that are separated by non-porous, non-metallic spacer discs, or porous non-metallic discs with suitable internal ducts. The experimental DISCOS assembly described in the next section of this report could be used for such experiments.

The issue of inter-droplet collisions must be experimentally investigated. Each droplet sheet has only a small volume fraction (typically about 0.5%) of droplets, which travel outwards in straight lines from their point of origin on the rotating disc. Collisions should be very rare. This conclusion can be experimentally validated using the proposed experimental assembly, also, the effect of collisions between droplets can be determined in the experiment.

3.6 Designs of a Proof of Concept Experiment for DISCOS

Figure 3.6.1 shows the disc assembly for a proof of concept experiment on DISCOS. Most of the equipment is presently available at BNL, except that the rotating disc and thin foils (for DISCOS-1) and porous droplet generator (for DISCOS-2) would have to be fabricated. The disc would have a diameter of 8½ inches and rotate at speeds up to 10,000 rpm, generating maximum rim accelerations of approximately 10,000 g.

Liquid collection slots would also be added to prevent splashing and bounce-back of the liquid droplets that leave the outer edges of the thin foils. The assembly would be oriented so as to prevent the collected liquid from dripping back onto the rotating disc.

Initial tests would be carried out using a low vapor pressure inert liquid to verify operability and performance. Subsequent tests would be carried out with a liquid metal, probably using room temperature NaK instead of hot lithium.

In the DISCOS-1 experiments, very thin metallic foils would be firmly bonded to the solid disc, and positioned so that they extended ~1 to 2 centimeters beyond the disc's rim. As a result of the high centripetal acceleration, the many liquid streamlets that issued from the central ring of feeder holes would move radially outwards on the surfaces of the bonded foils, spreading azimuthally with increasing radius, until they merged to form a thin continuous liquid film. This liquid layer would be uniform in thickness in the azimuthal direction, though it would thin out somewhat with increasing radius. As the liquid film flowed past the outer rim of the foils, it would breakup into a sheet of fine droplets, which would be collected at the periphery of the vacuum enclosure.

In the DISCOS-2 concept, the target for the proton beam is a sheet of ultra small lithium droplets (~1 micron diameter), and not liquid lithium films on ultra-thin beryllium foils as in the DISCOS-1 concept.

At this point, it is not clear whether the spin-off and breakup of a thin liquid layer from the surface of a rotating disc under high centripetal acceleration can produce a droplet sheet that is suitable for the DISCOS-2 concept. A portion of the experiments carried out on the DISCOS-1 type configuration will address this issue, to determine whether a suitable droplet sheet can be formed with this approach.

An alternate approach to forming DISCOS-2 type droplet sheets will also be tested. In this approach, a ring of porous matrix material will be attached to the rim of the rotating disc, and configured so that the outwards moving liquid must flow through and out of it. The diameter of the pores in the porous matrix will be very small - on the order of 1 to 2 microns - so that the droplets in the exiting sheet will be of the correct size.

Porous stainless steel frits with pore sizes of 1 to 2 microns are commercially available, and have been previously used in the BNL Particle Bed Reactor Nuclear Rocket Program.

The sight port in the enclosure will permit visual observation of the film and droplet behavior under high g rotational conditions. Strobe pictures and ultra fast movies can provide visual details on droplet size, liquid film uniformity and thickness, droplet trajectories and velocities, droplet sheet uniformity and concentration, etc.

In addition, the effects of pulsed heating caused by beam impact on the target can be modeled using laser heating. This can help determine local temperature distributions, the effects on film and droplet stability and integrity, and DISCOS's power handling capability.

In a second phase of the experiments, it appears possible to test the ability of DISCOS to operate with multiple foils or droplet sheets in a DC electric field. The disc could be axially segmented to produce 3 or so foil or droplet layers, which would then be immersed in a DC field.

These experiments will help to determine electric field capability, breakdown limits, parasitic current behavior, effect of surface finish, droplet size, etc.

A stress analysis of the rotating disc has been carried out using the ANSYS code, assuming aluminum as the disc material. Figure 3.6.2 shows the resultant stress distribution in the disc, for a rotational speed of 10,000 rpm. The maximum stress in the disc is modest, about 7000 psi.

3.7 Assessment of DISCOS Options and Performance

At this point, DISCOS-2 appears to offer better performance potential, since it does not have Be foils that parasitically degrade proton energy. As a result, the DISCOS-2 concept should have a substantially higher neutron yield (e.g., by roughly a factor of 2 to 3) per milliamp of proton current. On the other hand, DISCOS-1 could be technically simpler. At this point,

however, it is not possible to reach definitive conclusions about the relative technical difficulties of the two approaches. More experimental work is needed to resolve the technical issues, and in particular, to determine their capability to operate in applied DC electric fields. This issue is critical for DISCOS.

A second important issue is how thin can the Be foils be fabricated. If the maximum practical thickness of such foils must be substantially greater than 1 micron, then the DISCOS-1 concept can be ruled out. If films much thinner than 1 micron can be fabricated and used, then the DISCOS-1 approach probably could be favored.

Figure 3.6.1 Disc Assembly For DISCOS Proof of Concept Experiment

Axi-Symmetric Model

Von Mises Stress Plot

Angular Velocity:
10,000 rpm
about Y - axis

ANSYS 5.1 33
JUN 30 1995
10:35:08
PLOT NO. 1
.021125
1
1.5
2
2.5
3
3.5
4
4.5
5

Figure 3.6.2 Stress Distribution in Rotating Disc for DISCOS Proof of Concept Experiment

4.0 Preliminary Designs For NIFTI and DISCOS

4.1 NIFTI-2/Fixed Target Preliminary Design

Based on the parametric studies described in section 3 of this report, preliminary design for the NIFTI-2 concept have been defined and analyzed. Figure 4.1.1 shows the geometry for the NIFTI-2 preliminary designs. A thick fixed target is assumed, as shown in Figure 4.1.2. A two layer (beryllium fluoride-lead and fluoride) region is employed to inelastically degrade neutron energy. The outer iron filter impedes transmission of the neutrons till they drop below the 24 keV iron window.

The proton beam is assumed to enter the rear of the assembly and impact on the lithium layer located just behind the $\text{BeF}_2/\text{PbF}_2$ fluoride region. This arrangement minimizes neutron leakage. At the relatively high proton energies used with the NIFTI-2/fixed target approach, the angular spectrum of the generated neutrons is fairly uniform, so that target orientation does not have a significant effect.

The diameter of the treatment port has been increased to 15 centimeters from the 11 centimeter value used in section 3. The larger value is more in line with the treatment port diameters used in other studies.

Cooling of the fixed target (Figure 4.1.2) appears to be relatively simple. The total thermal power deposited by the proton beam is on the order of 10^4 watts, or approximately 0.5 KW/cm^2 of the target area. The corresponding temperature drop through the lithium film and copper support plate is modest, about 40° C . One millimeter diameter water coolant passages are provided 2.5 millimeters below the Li/Cu interface with a coolant flow rate of $100 \text{ cm}^3/\text{sec}$. The water temperature rise across the target will be on the order of 25° C . The film temperature drop in the water coolant is also modest, on the order of 20° C . Water velocity in the coolant passages is on the order of 4 meters per second, resulting in a pressure drop of approximately 10 psi.

The amount of water in the target region is equivalent to a disc 5 centimeters in diameter and 0.05 centimeters thick, for a total volume of approximately 1 cm^3 . This is far too small to have an appreciable effect on the output neutron energy spectrum.

The maximum temperature of the lithium layer will be on the order of 100° C , well below its melting point (179° C).

Figure 4.1.3 summarizes the input parameters for the NIFTI-2/fixed target preliminary designs, while Figure 4.1.4 summarizes the resultant output performance parameters. The effect of two proton beam energies - 2.1 and 2.5 MeV - is examined, together with the effect of a 1 cm thick water downshifter located between the iron and fluoride layers. This results in 4 cases.

The energy and angular distributions for the output neutrons from the fixed lithium target, together with the yield of neutrons per incident proton, were calculated by Thieberger (). These distributions were used as input for the MCNP analyses for the four NIFTI-2 designs.

Figures 4.1.5 and 4.1.6 give the energy spectra of the neutrons escaping through the treatment beam port for the 4 designs.

First consider the cases without a neutron down-shifter (letter "n"). Increasing the proton energy from 2.1 MeV to 2.5 MeV reduces the required beam current (based on an exit neutron current of 10^9 n/cm² sec) from 11.8 milliamps down to 2.42 milliamps, or almost a factor of 5. This results from the ~ 5 fold higher neutron yield achieved by the 2.5 MeV protons.

The average output neutron energy increases from 20.4 keV to 37.0 keV when the higher energy proton beam is used, however. A 37 keV neutron beam is probably still acceptable for treatment, as discussed in the next section of this report. However, if it proves desirable to have a somewhat lower average neutron energy, there are three options to accomplish this:

1. optimize the NIFTI-2 neutron conditioning zones,
2. use a neutron down-shifter,
3. operate at somewhat lower proton energy.

These options could be implemented separately or in combination. Option 1 would probably involve increasing the thicknesses of the fluoride and iron layers somewhat, so as to further soften the spectrum. Option 2, the use of a neutron down-shifter, appears to be very attractive. As shown in Figure 4.1.4, adding a downshifter for the 2.5 MeV beam case increases the beam current from 2.42 mA to 3.3 mA, and decreases the average neutron energy from 37 keV down to 31.5 keV.

A 3.3 mA beam is very acceptable from the accelerator and target point of view. Optimization of the fluoride and iron layers should bring the average output neutron energy to ~20 keV, with a proton current of only about 4 mA.

The fraction of the input source neutrons that exit through the beam port is in the range from ~5 to ~8%. This is a factor of 10 greater than the best previous design for an accelerator - lithium target BNCT facility. Note that the fraction of source neutrons that escape through the beam treatment port is substantially greater than the fraction that escape from the rest of the assembly. If desired the latter can be further reduced by using a thicker layer of neutron absorber.

Finally, the amount of gamma photons escaping through the treatment port is very small, on the order of 1 to 4 photons per 1000 source neutrons, depending on whether a down-shifter is used or not (Figure 4.1.4). Per 100 treatment neutrons, approximately 2 to 8 gamma photons escape.

The diagram illustrates a neutron beam line setup. A central vertical axis is labeled ζ . The beam line consists of several layers and components, labeled from top to bottom:

- Water Coolant Feed & Return Lines**: Indicated by arrows on the left side.
- Neutron Downshifter Layer Optional (Thickness = Z_4)**: A layer at the top of the beam line.
- Treatment Port (Diameter = $2 R_4$)**: A central opening in the beam line.
- Iron Filter Layer**: A layer below the treatment port.
- Lead Fluoride Layer**: A layer below the iron filter.
- Benlyllium Fluoride Layer**: A layer below the lead fluoride.
- Lithium Neutron Absorber**: A layer at the bottom of the beam line.
- Poly E/Boron Neutron Moderator/Absorber**: A layer below the lithium absorber.
- Fixed Lithium Target**: A target located to the right of the beam line.
- Beam Envelope**: A dashed line indicating the boundary of the beam.
- Beam Tube**: A tube through which the beam passes.
- Lead/Poly E/Boron Neutron Moderator/Absorber and Gamma Shield**: A shield at the bottom of the beam line.

Dimensions and radii are indicated by arrows and labels:

- $Z_1, Z_2, Z_3, Z_4, Z_5, Z_6$: Vertical distances between various layers.
- $R_1, R_2, R_3, R_4, R_5, R_6$: Radii of various components.
- D_B : Diameter of the beam tube.
- D_{GP} : Diameter of the treatment port.

4 - 3

NIFTI-2 Target Cooling Arrangement

Figure 4.1.2

Figure 4.1.3

Design Parameters for NIFTL-2/Fixed Target Preliminary Designs

Beam Diameter	=	3 centimeters
Beam Pipe Diameter	=	5 centimeters
Target Parameters	=	0.1 cm thick Li, 0.9 cm thick Al, 0.1 cm thick H ₂ O, 5 cm diameter
BeF ₂ Layer	=	5 cm thick, 15 cm diameter
PbF ₂ Layer	=	5 cm thick, 15 cm diameter
Iron Layer	=	5 cm thick, 15 cm diameter
Neutron Downshifter		
Lead Reflector	=	50 cm diameter, 25 cm thick behind target, 0.2% Boron
Outer Poly/Boron Absorber	=	10 cm thick, 5% Boron
Lithium Neutron Absorber on Front Face	=	2 cm thick Lithium Hydride
Proton Beam Energy	=	2.1 and 2.5 MeV (Parametric Study)

Figure 4.1.4

Performance Parameters for NIFTI-2**Fixed Target Preliminary Design**

1 cm "Downshifter" Included	n	y	n	y
Proton Energy (MeV)	2.1	2.1	2.5	2.5
Fraction of Generated Neutron That Exit Through Beam Port	.0684	.0462	.0760	.0560
Average Energy of Neutron That Exit Thru Beam Port (keV)	20.4	15.7	37.0	31.5
Flux of Exiting Neutron per mA of Beam Current ($\text{n/cm}^2 - \text{mA}$)	8.82 (7)	5.95 (7)	4.13 (8)	3.05 (8)
Fraction of Neutron That Escape Through the Front Face Other Than the Beam Port	.0413	.0310	.0572	.0459
Total Neutron Fraction Escaping	.1011	.0749	.1233	.0989
Photon Exiting Through Port per Neutron	.00122	.00474	.00106	.00406
Beam Current Required for $10^9 \text{ n/cm}^2 - \text{s}$ at Port	11.3	16.8	2.42	3.3

Figure 4.1.5

Energy Spectra for Neutrons Escaping
Through the Beam Port of NIFTI-2/Fixed Target Preliminary Designs

(Proton Energy 2.1 MeV)

1 cm "Downshifter" Included	No	Yes
0 keV - 1 keV	6.223 (-3)	1.214 (-2)
1 keV - 10 keV	1.107 (-2)	9.230 (-3)
10 keV - 26 keV	2.638 (-2)	1.274 (-2)
26 keV - 50 keV	6.718 (-3)	3.443 (-3)
50 keV - 75 keV	9.032 (-3)	3.965 (-3)
75 keV - 100 keV	2.040 (-3)	1.093 (-3)
100 keV - 150 keV	3.970 (-3)	2.088 (-3)
150 keV - 200 keV	2.215 (-3)	1.145 (-3)
200 keV - 360 keV	7.504 (-4)	3.362 (-4)
Total	6.840 (-2)	4.618 (-2)

Figure 4.1.6

**Energy Spectra for Neutron Escaping Through the Beam Port
of NIFTI-2/Fixed Target Preliminary Designs**

(Proton Energy 2.5 MeV)

1 cm "Downshifter" Included	No	Yes
0 keV - 1 keV	7.765 (-3)	1.230 (-2)
1 keV - 10 keV	8.034 (-3)	8.078 (-3)
10 keV - 26 keV	1.715 (-2)	1.032 (-2)
26 keV - 50 keV	5.467 (-3)	3.143 (-3)
50 keV - 75 keV	8.864 (-3)	4.295 (-3)
75 keV - 100 keV	2.887 (-3)	1.763 (-3)
100 keV - 150 keV	6.213 (-3)	3.736 (-3)
150 keV - 200 keV	4.729 (-3)	2.741 (-3)
200 keV - 300 keV	4.480 (-3)	3.055 (-3)
300 keV - 400 keV	3.204 (-3)	2.118 (-3)
400 keV - 500 keV	2.536 (-3)	1.593 (-3)
500 keV - 600 keV	2.466 (-3)	1.600 (-3)
600 keV - 700 keV	1.754 (-3)	1.062 (-3)
700 keV - 800 keV	4.333 (-4)	2.296 (-4)
Total	7.60 (-2)	5.604 (-2)

4.2 NIFTI-1/DISCOS Preliminary Design

Figure 4.2.1 shows the illustrative design for the NIFTI-1/DISCOS concept. In contrast to the NIFTI-2 designs, here the proton beam is assumed to come into the target region parallel to the treatment port, rather than normal to it. This is done to take advantage of the softer neutron spectrum at large angles relative to the direction of the proton beam.

Figure 4.2.2 summarizes the input design parameters for the NIFTI-1/DISCOS preliminary designs, while Figure 4.2.3 summarizes the output performance parameters. Figure 4.2.4 gives the neutron energy distribution.

Two cases are analyzed for NIFTI-1/DISCOS, the first with a neutron down-shifter (letter "y") and the second without a down-shifter (letter "n"). The down-shifter is a 1 centimeter thick layer of water just behind the iron filter (i.e., between the filter and the DISCOS target).

A proton beam energy of 1.889 to 1.904 MeV is assumed, with the beam losing 5 keV as it goes through 1 sheet of the DISCOS target. The resultant neutron source energy and angular distribution caused by the proton impacts on lithium are taken from calculations by Thieberger.

The neutron utilization efficiency for the NIFTI-1 designs is very high, in the range of 12% to 18%. That is, of the source neutrons generated in the target, 12 to 18% make their way to the treatment port and exit from it. Of the total number of neutrons that escape through the front face of NIFTI assembly, approximately 70 percent escape through the treatment beam port. This fraction could be substantially increased by using thicker neutron absorber on the portion of the front face surrounding the treatment port.

The average output neutron energy without a down-shifter is 18.4 keV, which appears acceptable. For treatment where less penetration is necessary, it may be desirable to use a down-shifter, which would reduce average neutron energy to 11.6 keV. This could be done simply by filling the 1 cm thick down-shifter cavity with water when desired. Thus, the design is very flexible and would have a readily adjustable capability to deliver a range of neutron energies.

Two values are shown for the proton beam current. The high value corresponds to using just one sheet on the DISCOS assembly; the low value corresponds to using 80 sheets, with 5 keV re-acceleration between sheets, resulting in a very low proton current requirement of ~ 2 to 3 milliamps. Determination of the optimum number of sheets will require more detailed study. Approximately 100 treatment neutrons exit from the beam port per exiting gamma photon.

Geometry For NIFTI-1/DISCOS Preliminary Designs

4 - 10

Figure 4.2.1

Figure 4.2.2

Design Parameters for NIFTI-1/DISCOS Preliminary Designs

Iron/Magnesium Filter Layer	=	7.5 cm thick, 15 cm diameter
DISCOS Target Region	=	5 cm diameter, 10 cm long
Neutron Generating Region	=	2 cm diameter, 10 cm long
Type of Target	=	DISCOS-2 (Lithium Droplet Sheet)
Proton Energy Range	=	1.904 to 1.889 MeV
Total Energy Added By DC Field	=	400 keV
Beam Tube Diameter	=	5 cm
Beam Diameter	=	2 cm
Reflector	=	Lead, 20 cm thick, 0.2% Boron
Outer Poly/Boron Absorber	=	10 cm thick, 5% Boron
Lithium Absorber on Front Face	=	2 cm thick Lithium Hydride

Figure 4.2.3

Performance Parameters for NIFTI-1/DISCOS Preliminary Design

Proton Energy	1.9	1.9
1 cm "Down-shifter" Included	n	y
Fraction of Generated Neutron That Exit Through Beam Port	0.1894	0.1208
Average Energy of Neutron That Exit Thru Beam Port (keV)	18.4	11.6
Flux of Exiting Neutron per mA of Beam Current (n/cm ² - mA)	5.74 (6)	3.66 (6)
Fraction of Neutron That Escape Through the Face Other Than the Beam Port	.0831	.0454
Total Neutron Fraction Escaping	.2140	.130
Photons Exiting Through Port per Neutron	.00234	.0134
Beam Current Required For 10 ⁹ n/cm ² - s at Port	175 ⁺ / 2.2 ⁺⁺	273 / 3.4

⁺ 1 sheet DISCOS (5 keV energy loss)

⁺⁺ 80 sheet DISCOS (400 keV energy loss)

Figure 4.2.4

**Energy Spectra for Neutrons Escaping Through
the Beam Port of NIFTI-1/DISCOS Preliminary Designs**

(Proton Energy 1.9 MeV)

1 cm "Downshifter" Included	No	Yes
0 keV - 1 keV	9.384 (-3)	3.478 (-2)
1 keV - 10 keV	1.856 (-2)	2.734 (-2)
10 keV - 26 keV	7.709 (-2)	3.674 (-2)
26 keV - 50 keV	3.932 (-2)	1.110 (-2)
50 keV - 75 keV	4.349 (-2)	1.036 (-2)
75 keV - 100 keV	1.564 (-3)	4.516 (-4)
Total	1.894 (-1)	1.208 (-1)

4.3 Comparison of Technical Performance Parameters for NIFTI-2/Fixed Target and NIFTI-1/DISCOS Preliminary Designs

Figure 4.3.1 summarizes the technical performance parameters for the NIFTI-2/Fixed Target and NIFTI-1/DISCOS preliminary designs. Both approaches achieve practical neutron currents out of the treatment port for a very low level of proton beam current, i.e., a few milliamps.

The NIFTI-1/DISCOS design clearly requires operation with multiple target sheets, to achieve these low proton beam currents. The neutron yield for a single sheet DISCOS is too low for a practical accelerator.

The NIFTI-2/Fixed Target design clearly favors operation at higher proton energy, i.e., 2.5 MeV, as compared to a lower proton energies. The increased neutron yield at 2.5 MeV reduces in proton beam current by a factor of 5.

The benefit of lower proton current is somewhat offset by a higher average energy for the output neutrons (37 keV without a neutron down-shifter, 31 keV with a down-shifter); however, optimization should significantly reduce the average neutron energy for 2.5 MeV proton beam neutron output energies on the order of 30 keV, however, still appear acceptable for treatment.

Generally, neutron utilization efficiencies (i.e., the number of neutrons leaking from the treatment port per source neutron) for the NIFTI-1 designs are substantially larger than for NIFTI-2 designs. This is expected, since the target is much closer to the treatment port for NIFTI-1 designs. However, even with NIFTI-2 designs, the neutron utilization efficiencies are 10 times greater than those of previous designs.

The number of gamma photons leaking from the treatment port per output epithermal neutron is very low, ranging from as little as ~ 0.02 (if a neutron downshifter is not used) up to ~ 0.1 if a down-shifter is used. This low gamma leakage helps to minimize background gamma dose to healthy tissue, an attractive feature.

Figure 4.3.1

**Comparison of Technical Performance Parameters for NIFTI-2/Fixed Target
and NIFTI-1/DISCOS Preliminary Designs**

	1	2	3	4	5	6
Proton Energy (MeV)	1.9	1.9	2.1	2.1	2.5	2.5
"Down-Shifter"	n	y	n	y	n	y
Neutron Leakage (Port)	.1305	.0843	.0508	.0349	.0524	.0394
Neutron Leakage (Outlet)	.1894	.1208	.0684	.0462	.0760	.0560
Photon Leakage (Port)	.00234	.0134	.00122	.00474	.00106	.00406
Neutron Leakage (Except Outlet)	.08308	.0454	.0413	.0310	.0572	.0459
$\bar{E}$ (Neutron) [keV]	18.4	11.6	20.4	15.7	37.0	31.5
n/mA-s-cm ²	5.74 (6)	3.66 (6)	8.82 (7)	5.95 (7)	4.13 (8)	3.05 (8)
mA for 10 ⁹ n/cm ² -s	175*	273*	11.3	16.8	2.42	3.28
mA for 10 ⁹ n/cm ² -s	2.2**	3.4**	---	---	---	---

* 1 sheet DISCOS (5 keV energy loss)

** 80 sheets DISCOS (400 keV energy loss)

5.0 Evaluation of NIFTI-2 and NIFTI/DISCOS for BNCT Treatment

5.1 BNCT Performance of Previous Neutron Sources

The effectiveness of neutron sources for BNCT treatment is evaluated in terms of three criteria:

1. Ability to penetrate tissue and deliver therapeutic doses at depth
2. Ability to maximize the desired radiation dose to tumors while minimizing background dose to healthy tissue
3. Ability to deliver the desired radiation dose in an acceptable treatment time.

The first criteria is assessed using the quantitative figure of merit termed "advantage depth" or "AD". As stated by Clement, et al ⁽¹⁾, the "advantage depth is defined as the depth in a given material at which the total therapeutic dose to the material is equal to the maximum total background depth to the material. The total therapeutic dose is the sum of the total background dose and the ^{10}B (n, α) ^7Li dose."

Figure 5.1.1, taken from Clement, illustrates this definition. At the depth termed $(\text{AD})_{\text{max}}$, the total therapeutic dose equals the background dose (dotted line) at the surface of the phantom, neglecting the contribution to the background dose from the ^{10}B reaction in normal healthy tissue. When the contribution from the ^{10}B reaction is included, the advantage depth decreases to the value $(\text{AD})_{\text{min}}$ (Figure 5.1.1).

The second criteria is assessed using the figure of merit termed the "Advantage Ratio" or "AR". As illustrated in Figure 5.1.1, the AR is the integral of the total therapeutic dose to the material (integrated from the surface to a given depth, eg, to the AD) divided by the integral of the total background dose to the same depth.

The AD is thus a measure of how deeply a given neutron beam can penetrate before it loses effectiveness, while the AR is a measure of the tumor dose relative to the integrated background dose to normal tissue.

The third criteria is evaluated by the figure of merit termed the "Advantage Depth Dose Rate", or "ADDR". This is a measure of the time required to deliver the therapeutic dose to a tumor at the AD (Figure 5.1.1). In general the value of dose rate is not as an important determinant of effectiveness as the AD and AR, provided that the irradiation time does not become excessively long, eg, much greater than one hour.

Figure 5.1.2 [taken from Clement], shows the dose-depth distribution for an ideal 2

keV monoenergetic, monodirectional neutron beam, based on an equivalent 10/1 ratio of ^{10}B loading (including geometric effects) in cancerous tissue to normal tissue ($30\ \mu\text{g/g}$ vs $3\ \mu\text{g/g}$).

As illustrated in Figure 5.1.3 [Clement, et al ⁽¹⁾] the ideal 2 keV beam comes close to achieving a maximum both for AD and AR over a wide range of neutron beam energies from 0.025 eV up to 1 MeV.

Clement plots the AD versus the AR for a range of ideal beam energies, as shown in Figure 5.1.4. Low neutron energies (eg., 0.025 eV) can have high advantage ratios, but limited ability to penetrate (i.e., low AD). High neutron energies (eg., 100 keV and above) have low AD's and low AR's, because the radiation dose from the fast neutrons starts to overwhelm the therapeutic dose from ^{10}B . The optimum neutron energies could thus appear to be in the range of $\sim 50\ \text{eV}$ to $\sim 50\ \text{keV}$.

A calculated dose-depth distribution for the BMRR is shown in Figure 5.1.5, as given by Wheeler, et al ⁽²⁾ at the 1989 International Workshop on Neutron Beam Design, Development and Performance for Neutron Capture Therapy. The results are obtained using DOT 4.3 to model the BMRR with the ENDFB-IV cross section library. The doses shown in Figure 5.1.5 are per MW of reactor power, and assume a 20 centimeter diameter beam delimiter made of lithium containing polyethylene.

Figure 5.1.6, also from Wheeler, shows the AD and AR as a function of beam diameter and ^{10}B loading in healthy tissue. Clearly, as in the context of Figure 5.1.4, the BMRR has somewhat lower AD and AR, as compared to the peak values of ~ 8 for AD and ~ 5 for AR for Figure 5.1.4. For example, for the BMRR the 20 cm diameter beam with $3\ \mu\text{g/g}$ ^{10}B has a AD of 7.5 and a AR of 3.6, as given by Wheeler.

The dose-depth distribution measured by Fairchild, et al ⁽³⁾, differ somewhat from the calculated distributions given by Wheeler. This appears primarily to be a result of not having the beam delimiter that was assumed by Wheeler, et al, for their calculations.

Figure 5.1.7 shows the dose-depth distribution given by Fairchild for the 25x25 centimeter BMRR beam based on a reactor power of 3 MW. [The 1.0 mm ^6Li added case is shown.] Compared to the dose-depth distribution in Figure 5.1.5, the advantage depth as given by Fairchild is slightly greater, 8.2 cm vs 7.5 cm, and the advantage ratio slightly less, 3.2 vs 3.6.

Figure 5.1.8 shows the two BMRR points for the AD vs AR plot of Figure 5.1.4 for both the Wheeler and Fairchild values. Note that the BMRR points achieve about the same advantage depth as the best ideal monoenergetic neutron beams, but significantly lower advantage ratios.

Figure 5.1.1
 Definition of Advantage Depths and Advantage Ratio
 After Clement

Figure 5.1.2

**Dose-Depth Distribution for Ideal 2 KeV Monoenergetic,
Monodirectional Neutron Beam
After Clement**

Calculated comprehensive depth-dose distribution of a 2-keV ideal beam (diameter = 17.8 cm) through a polyethylene head phantom. RBE dose rate calculated assuming an incident neutron current $J = 10^9 \text{ n/cm}^2\text{-s}$.

Figure 5.1.3 Advantage Depths and Advantage Ratios for Ideal Neutron Beams of Various Energies
[After Clement ()]

Energy	RBE AD (cm) Max/Min	AD (cm) Max/Min	RBE AR	RBE ADDR ^(a) (RBE-cGy/min)
0.025 eV	5.4/4.1	4.4/3.7	5.0	26
5 eV	7.4/6.4	6.3/5.7	5.0	38
35 eV	7.8/6.8	6.6/6.1	5.3	36
500 eV	8.2/7.2	7.0/6.5	5.2	31
2 keV	8.9/7.7	7.6/6.9	5.0	30
20 keV	8.3/7.9	7.5/7.3	4.5	30
70 keV	5.8/5.8	5.1/5.1	3.5	63
100 keV	5.1/5.1	3.9/3.9	3.0	80
1 MeV	1.6/1.6	1.3/1.3	1.2	300

(a) Data calculated assuming an incident neutron current $J = 10^9$ n/cm²-s.

Figure 5.1.4 Advantage Ratio Versus Advantage Depth for Ideal Neutron Beams of Various Energies
[After Clement ()]

Figure 5.1.5 Calculated Depth-Dose Distribution for BMRR Beam
[After Wheeler ()]

BMRR 20-cm Beam with 18x23 Phantom-
Axial Distribution.

Figure 5.1.6 Calculated Advantage Factors for BMRR Beam with Cylindrical Phantom
[After Wheeler ()]

Quantity	No ^{10}B in Healthy Tissue			$3\mu\text{g/g } ^{10}\text{B}$ in Healthy Tissue		
	$d^*=4.6$	$d=10$	$d=20$	$d=4.6$	$d=10$	$d=20$
<u>Advantage Depth:</u>						
No RBE (cm)	5.8	6.8	7.3	5.1	6.1	6.6
With RBE [†] (cm)	6.7	8.0	8.6	5.8	6.8	7.5
<u>Advantage Dose Rate:</u>						
No RBE (cGy/MW·min)	0.35	2.4	6.7	0.44	3.0	8.1
<u>Advantage Ratio:</u>						
No RBE	3.5	3.2	2.9	2.8	2.7	2.5
With RBE	5.9	5.5	5.0	4.0	3.8	3.6
% Low-LET Dose	18.2	22.7	26.7	17.7	22.3	26.2
% High-LET Dose	10.4	8.3	7.5	10.5	8.3	7.6
% ^{10}B Dose ($30\mu\text{g/g}$)	71.4	69.0	65.8	71.8	69.4	66.2

* d = diameter of beam delimiter (cm).

† RBE = 1.0 for all gamma rays, 1.6 for fast neutrons and $^{14}\text{N}(n,p)$ protons, and 2.3 for the $^{10}\text{B}(n,\alpha)$ reaction. (These values were set for this Workshop to provide consistency in intercomparisons.)

Figure 5.1.7

Measured Dose-Depth Distribution for BMRR

[After Fairchild ()]

DOSE DISTRIBUTIONS IN PHANTOM HEAD

Biologically-effective dose rate for the "current" epithermal-neutron beam configuration at the BMRR (power = 3 MW). The flux distribution obtained with a Cd filter 0.5-mm thick at the point of irradiation was used. Values for both RBE, and the ^{14}N and ^{10}B content were as prescribed for this Workshop.

Figure 5.1.8 BMRR Advantage Factors Compared to Advantage Factors For Ideal Monoenergetic Neutron Beams

5.2 BNCT Performance of NIFTI-2 Fixed Target and NIFTI-1/DISCOS Point Designs

The preliminary NIFTI designs described in Section 4 of this report did not incorporate analyses of BNCT performance. Following the completion of the preliminary designs, selected cases were analyzed to determine their BNCT performance. These analyses used a cylindrical polyethylene phantom as a stand-in for the patients head. The BNL phantom had the same dimensions and density as the phantom used for the MIT analyses.

Preparatory to the analyses of the BNCT performance of the NIFTI designs, analyses of the BNCT effectiveness of a 2 keV monoenergetic neutron beam were carried out, and compared to the results presented by MIT ⁽¹⁾. In general, there was reasonable agreement between the BNL and MIT calculations, though the degree of reflectivity of the neutron source played an important role.

Figure 5.2.1 compares the gamma photon dose rates as a function of depth for the BNL and MIT analyses. The BNL dose rate distribution agreed closely with the MIT values when a lead reflector (3 centimeter thickness) was placed behind the neutron source. This reflector acts to retain neutrons that are scattered back from the surface of the phantom that is next to the neutron beam. Without such a reflector, the BNL dose rate is a factor of ~2 smaller than the MIT dose rate.

Figure 5.2.2 compares the neutron dose rate - distributions for neutron heating. Here there is substantial disagreement between the MIT and BNL analyses, even with the presence of a neutron reflector. The dose rates agree relatively closely at small depths (e.g., ~1 cm), but diverge at greater depth. This discrepancy is difficult to understand, particularly since the BNL analyses are consistent on an energy basis. That is, the energy from neutron scattering events integrated throughout the phantom closely agree with the original energy carried by the neutrons present in the beam. The MIT analyses thus appear to overestimate neutron heating.

Figure 5.2.3 compares the dose rate distributions for alpha particle heating from ¹⁰B neutron absorptions. The agreement between the MIT and BNL analyses is good for the case where there is a lead reflector behind the neutron beam. Without the reflector, the alpha dose rate for the BNL analysis is approximately one-half of the MIT analysis. This reduction is comparable to that for the gamma photon dose.

The BNL analyses of the effectiveness of the 2 keV monoenergetic beam for BNCT were based on use of the MCNP code with ENDFB-VI cross sections. A total of 10 million neutron histories was used for each case. The heating rate in MeV/g sec. was calculated as a function of depth for the center portion ($D_0 = 6$ centimeter) of the 18 centimeter diameter cylindrical phantom, so as to correspond with the basis for the MIT analyses. Heating rates were calculated individually for gamma photons, neutrons, and alpha particles from neutron absorptions in ¹⁰B at a loading of 30 μ g/g of tissue. Relative biological effectiveness factors of 1.0 for photons, 1.6 for neutrons, and 2.3 for alpha particles were assumed in calculating the RBE dose rates, which are expressed in RBE/min. These effectiveness factors are the same as those assumed in the MIT

analyses.

The initial analysis of the NIFTI-2/Fixed Target and NIFTI-1/DISCOS preliminary designs described in Section 4 of the report indicated that although they exhibited excellent neutronic efficiencies and consequently required very low accelerator beam currents, their advantage factor performance, particularly the advantage depth, was not as good as desired. Neutron and gamma dose rates at the surface of the phantom were high, resulting in a relatively low advantage depth.

Accordingly, the designs were modified slightly to reduce neutron and gamma dose at the surface. This involved the following two modifications to the NIFTI-2/Fixed Target design:

1. Substitution of a pure BeF_2 inelastic neutron scattering layer for the mixed $\text{BeF}_2/\text{PbF}_2$ layer used in the preliminary designs.
2. Substitution of a FeTiH metal hydride layer for the non-magnesium layer used in the preliminary designs.

The above modifications soften the energy spectrum of the neutrons leaving the treatment port, reducing neutron dose rate in the phantom.

The third modification was to recess a thin, e.g., 3 centimeter thick, lead shield into the outer surface of the treatment port, so as to reduce the gamma dose rate in the phantom.

Figure 5.2.4 summarizes the principal design and performance parameters for the final NIFTI-2/Fixed Target Point Design; Figure 5.2.5 shows the resultant dose-depth distributions assuming a 18 centimeter diameter cylindrical phantom with a $30 \mu\text{g/g}$ loading of ^{10}B . The advantage depth of this NIFTI-2 point design is approximately 6 centimeters.

The NIFTI-1/DISCOS point design involves similar modifications to those for the NIFTI-2 point design, with the exception that the fluoride layer is not present. Design and performance parameter for the NIFTI-1/DISCOS point design are given in Figure 5.2.4. Figure 5.2.6 shows the dose-depth distribution for the NIFTI-1 design employing the same phantom as that used for the NIFTI-2 analysis.

The advantage depth for the NIFTI-1 design is slightly greater than that for the NIFTI-2 design. Figure 5.2.7 compares the advantage factors for the two designs to those given in previous studies.

These point designs show good BNCT performance. However, with further optimization of the assembly dimensions and the hydrogen content in the "downshifter", it should be possible to further improve the advantage factors for the two NIFTI designs, so as to achieve advantage depths in excess of 7 centimeters.

Figure 5.2.1 Comparison of Calculated Gamma Photon Dose-Depth Distributions for 2 keV Monoenergetic Neutron Beams

Figure 5.2.2 Comparison of Calculated Neutron Dose-Depth Distributions for 2 keV Monoenergetic Neutron Beam

Figure 5.2.3 Comparison of Calculated Alpha Particle Dose-Depth Distributions for 2 keV Monoenergetic Neutron Beam

Figure 5.2.4
Principal Design and Performance Parameters
For NIFTI-2/Fixed Target and NIFTI-1/DISCOS Point Designs

Design Parameter	NIFTI-2/Fixed Target Point Design	NIFTI-1/DISCOS Point Design
Proton Energy, MeV	2.5	1.904 to 1.889 (400 keV added by DC Field)
Proton Current, mA	5	5
Fluoride Layer	BeF ₂ , 10 cm Thick, 18 cm Diam.	None
Iron Filter	FeT ₁ H, 3 cm Thick, 18 cm Diam.	Fe/Mg, 5 cm Thick, 18 cm Diam.
Gamma Shield at Port Face	Pb, 3 cm Thick, 18 cm Diam.	Pb, 3 cm Thick, 18 cm Diam.
Performance Parameter		
Peak Total Dose Rate to Tumor,* RBE/min.	250	350
Peak Total Dose Rate to Healthy** Tissue, RBE/min.	90	110
Advantage Depth, cm	6.0	6.5
Advantage Ratio	3.7	4.75

* Includes α Particles (RBE Factor = 2.3); Neutrons (RBE Factor = 1.6); Gammas (RBE Factor = 1.0)

** Includes Neutrons and Gammas; Zero ¹⁰B Loading Assumed

**Figure 5.2.5 Dose-Depth Distribution for
NIFTI-2 Fixed Target Point Design**

**Figure 5.2.6 Dose-Depth Distribution for
NIFTI-1/DISCOS Point Design**

Figure 5.2.7 Advantage Factors for NIFTI-2 and NIFTI-1/DISCOS Point Designs

References

1. Clement, S.D., et al., "Monte Carlo Methods of Neutron Beam Design for Neutron Capture Therapy at the MIT Research Reactor (MITR-I), p. 51, in Neutron Beam Design, Development, and Performance for Neutron Capture Therapy, Harling, O., Bernard, J., and Zamenhof, R., ed, Plenum Press, New York (1989).
2. Wheeler, F.J., et al., "Physics Design for the Brookhaven Medical Research Reactor Epithermal Neutron Source," p. 83, *ibid* (1989).
3. Fairchild, R.G., et al., "Installation and Testing of An Optimized Epithermal Neutron Beam at the Brookhaven Medical Research Reactor (BMRR)," p. 185, *ibid* (1989).

6 Summary and Recommendations

The NIFTI and DISCOS concepts appear very promising for accelerator based BNCT. They enable large reductions, i.e., a factor of 10 or more, in the proton beam current required for patient treatment, while delivering an epithermal neutron beam that has an average energy on the order of 10 to 30 keV, depending on design.

With NIFTI, the proton accelerator requires only a few milliamps of current at ~ 2 MeV. These operational parameters are within commercial capability, so that R&D on new accelerators is not necessary.

The NIFTI-2 concept with a fixed lithium target is the simplest and easiest to develop. It has a somewhat higher average output neutron energy than NIFTI-1 with a DISCOS target. However, the output neutron energy for the NIFTI-2 concept appears acceptable for treatment.

The DISCOS target requires development of multiple thin film capability. It is more complex and has issues relating to high g operation, generation of and the potential for electrical breakdown. These issues do not appear to be "show-stoppers", but an experimental program is needed to validate the concept.

It is recommended that both the NIFTI-2 and NIFTI-1/DISCOS approach be vigorously pursued. Neutronic validation experiments on integral assemblies should be carried out to demonstrate that the analytic methods and nuclear data basis used for design are appropriate. Proof of principle demonstration experiments on DISCOS are also recommended.

With appropriate resources, these experiments could be carried out over a period of approximately 6 months. When completed, they will provide a firm foundation for proceeding with a prototype development program.