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High Neutronic Efficiency, Low Current Targets for Accelerator-Based BNCT Applications

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Abstract

The neutronic efficiency of target/filters for accelerator-based BNCT applications is measured by the proton current required to achieve a desirable neutron current at the treatment port (10^9 n/cm^2-s). In this paper we will describe two possible target/filter concepts which minimize the required current. Both concepts are based on the Li-7 (p,n)Be-7 reaction.

Targets that operate near the threshold energy generate neutrons that are close to the desired energy for BNCT treatment. Thus, the filter can be extremely thin (~5cm iron). However, this approach has an extremely low neutron yield (n/p ~1.0(-6)), thus requiring a high proton current. The proposed solution is to design a target consisting of multiple extremely thin targets (proton energy loss per target ~10 keV), and re-accelerate the protons between each target. The protons can then be maintained at close to the threshold energy as they traverse the targets, and at the same time achieving a much higher neutron yield due to the re-acceleration and multiple target interactions. Thus, a target with a reasonable number (~20-30) sequential targets would result in high energy neutronic efficiencies.

Targets operating at higher proton energies (~2.5 MeV) have a much higher yield (n/p ~1.0(-4)). However, at these energies the maximum neutron energy is approximately 800 keV, and thus a neutron filter is required to degrade the average neutron energy to the range of interest for BNCT (10-20 keV). A neutron filter consisting of fluorine compounds and iron has been investigated for this case. Typically a proton current of approximately 5 mA is required to generate the desired neutron current at the treatment port. The efficiency of these filter designs can be further increased by incorporating neutron reflectors that are co-axial with the neutron source. These reflectors are made of materials which have high scattering cross sections in the range 0.1 - 1.0 MeV.

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. An energetic alpha particle is released when a neutron is absorbed by the ^{10}B, which kills the cell where the absorption takes place. The use of energetic epithermal neutrons (~10 keV), as first proposed by Fairchild [4,5], enables penetration to tumor sites deep inside the body. Achieving a suitable neutron energy spectrum is very important for effective treatment. If the energy is too low, the neutron intensity at the tumor site is too low to be effective; if the energy is too high, the radiation dose to normal tissue is excessive.

BNCT treatment effectiveness is being investigated experimentally using nuclear reactors as neutron sources. In the US, several patients have recently been treated at the Brookhaven Medical Research Reactor (BMRR) at Brookhaven National Laboratory. Leakage neutrons are collimated to produce a suitable beam at the external treatment port. Reactors have a very low neutron utilization efficiency. Typically only about 10^{-6} of the neutrons that are released from the core are actually available at the treatment port. This results from the inherent dimensional constraints imposed by criticality, and the relatively long distance required to slow the high energy neutrons down. Gamma shielding requirements are also a contributing factor. As a result, in the BMRR, the treatment port is located at a distance of 177 cm from the center of the core. In the MURR (Missouri University Research Reactor) BNCT design, the treatment port is 310 cm from the center of the core. As a result of this low

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neutron utilization efficiency, reactor based neutron sources for BNCT require high operating power, on the order of several megawatts. Such a reactor is generally very expensive, a one of a kind facility, and with a limited capability to treat large numbers of patients.

In contrast, accelerator based neutron sources for BNCT appear to have attractive features as compared to reactor based neutron sources: lower facility cost, reduced residual radioactivity, lower operating power, reduced safety concerns, and potentially an improved neutron energy spectrum for treatment of tumors. In addition, 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 on the particular concept, the nuclear reaction involved can be a X(p,n)Y reaction, a ^{3}He(d,n)^{4}He reaction, etc. A particularly promising approach is the ^{7}Li(p,n)^{7}Be based concept. In this case a low energy proton beam (~2 MeV) strikes a lithium target, generating neutrons. The attractive features include:

- Relatively high neutron yield per proton ($\sim 10^{-4}$)
- Low maximum energy of the neutrons (keV range),
- Simple, low energy accelerator,
- Simple target design, and
- Minimal shielding for residual radioactivity.

A number of design studies based on the ^{7}Li(p,n)^{7}Be reaction have been carried out. These studies, while they show that a feasible concept can be designed, require a proton beam current in the range of 20-50 mA, in order to achieve an adequate neutron flux at the treatment port. Wang, et al[6] have designed a system based on the proton-lithium reaction using a beryllium oxide moderator. At a beam current of 50 mA, this design would achieve approximately half the BMRR neutron treatment flux. This would require that the patient would be exposed for twice as long as at the BMRR. The fast neutron dose and gamma ray dose per therapeutic epithermal neutron for this accelerator based facility are both approximately 30% greater than those for the BMRR. Wu, et al.,[7] also have designed a system using the proton-lithium reaction and beryllium oxide as a moderator. At a beam current of 20 mA this source would achieve approximately the same neutron treatment flux as the BMRR. The fast neutron dose per therapeutic epithermal neutron for this accelerator design is approximately equal to that of the BMRR. However, the gamma ray dose for this facility is approximately two and a half times as great as that of the BMRR.

The neutronic efficiency of the Wu design is approximately five times greater than that of the Wang design. That is the beam current required is approximately five times smaller for the Wu design than for the Wang design for the same epithermal flux. This increase in efficiency is attributable to the thinner beryllium oxide moderator used in the Wu design, thus locating the treatment port closer to the lithium target. However, this results in an increase in the gamma dose at the treatment port.

In the remainder of this paper we will examine new and more efficient approaches to degrading the neutron energy and tailoring the spectral distribution of neutrons generated by a proton beam interacting with a lithium target. The object of these new approaches is to deliver useful neutron irradiation fluxes with considerably smaller proton beam currents. For a practical treatment facility the neutron current at the treatment port should be approximately 10^{9} n/cm^{2}-s, and most treatment ports have an area of about 100 cm^{2}.

2. DESCRIPTION OF TARGET/FILTER 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 0.1, for example, the proton current for a useful accelerator-target source needs only be on the order of 1 mA.

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 through almost unimpeded. Iron

has a "window" in its scattering cross section at 24 keV, as illustrated in Figure 1.[8] The minimum scattering cross section is less than 1 b; while at a few keV above the "window," the cross section increases to ~ 100 b. Neutrons with energies above ~ 25 keV are strongly impeded from transmission through the 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 scattering cross section for fluorine has a threshold energy slightly above 100 keV, reaching a peak of 3 b at ~ 300 keV, as illustrated in Figure 2. Fluorine appears to be unique among elements in having a low threshold energy, combined with a high value for inelastic scattering cross section. Most other elements have thresholds of approximately 1 MeV, and have lower cross sections. 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 with fluorine will be much lower than 100 keV. In summary, fluorine has the following desirable properties as a neutron energy degrader:

Low threshold energy for inelastic scattering (~100 keV).
High inelastic cross section (peak 3 b).
Low absorption cross section.
Low neutron energy degradation due to elastic scattering.
Forms stable compounds with a wide variety of other elements.

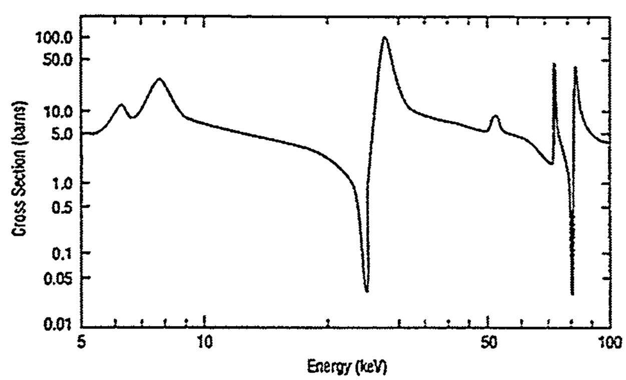

Figure 1. Neutron Scattering Cross Section for Iron.

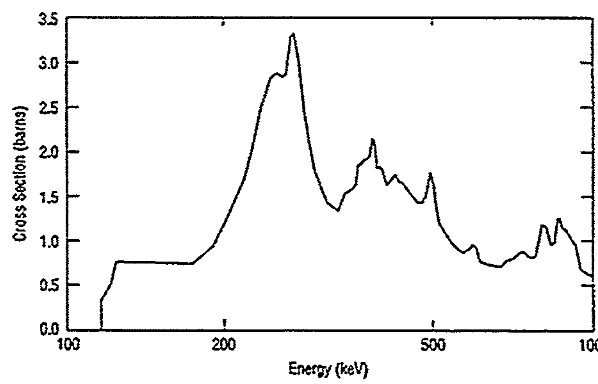

Figure 2. Inelastic Neutron Scattering Cross Section for Fluorine.

Both lead and beryllium fluorides satisfy the above conditions. Many other fluoride compounds would have significant parasitic neutron absorption and the possibility of being gamma-ray emitters. Teflon would degrade in a radiation field.

There are two energy regimes possible for the NIFTI concept, depending on the energy of the proton beam energy and the resulting neutron energy distribution, i.e. NIFTI-1 and NIFTI-2. In the NIFTI-1 energy regime, the accelerator/target system operates with a proton beam energy slightly above threshold for neutron production (~ 1.9 MeV). The resultant neutron spectrum is relatively low in energy, with a maximum value of ~ 100 keV. The angular distribution of the neutrons is strongly peaked forward in this case. In the NIFTI-2 energy regime, the proton beam energy is well above the threshold (2.2 MeV - 2.5 MeV). Neutrons are generated over a wider energy range (up to 800 keV), and have a more isotropic angular distribution.

The geometric configuration to be used for the NIFTI target/filter arrangements are shown in Figure 3. 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.

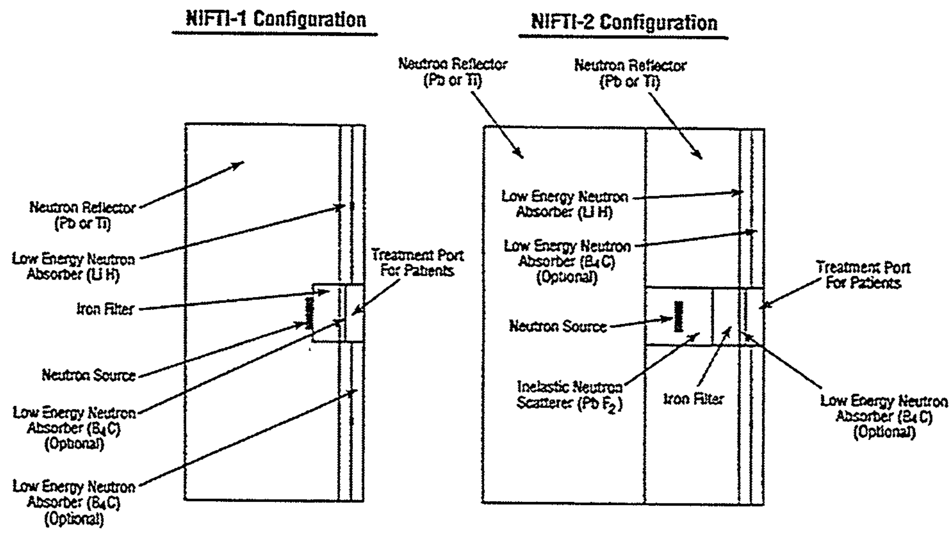

Figure 3. NIFTI Target/Filter Arrangements.

This 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.

Optimizing the geometric arrangement will involve the following factors:

1. Neutron utilization efficiency (number of useful neutrons).
2. Neutron generation efficiency.
3. Target simplicity, reliability, and maintainability.
4. Directionality and energy spectrum of neutrons leaving the treatment port.
5. Gamma dose during treatment, and
6. Residual activity of the target assembly.

The number of neutrons leaving the treatment port per proton is given by the product of the number of neutrons generated per proton (neutron generation efficiency) and the number of neutrons leaving the port per neutron generated in the target (neutron utilization efficiency). It is thus seen that the number of neutrons leaving the port per proton is directly proportional to the proton current required to produce the desired neutron current at the treatment port. It can be shown that for the NIFTI-1 system the neutron utilization efficiency needs to be approximately 10% to ensure a proton current of a few mA's. In the case of the NIFTI-2 system a value of 5% is sufficient to ensure an acceptably low proton current.

At this stage two NIFTI designs appear possible based on the various combinations of energy regime and geometry. Detailed studies are needed to determine which of the options offer the best performance. In this case performance is defined by the highest neutron current at the treatment port for a given proton current. However, the option with the lowest proton current may not be the optimum, particularly if all the options have low currents. Issues such as target simplicity, reliability, maintainability, gamma dose, etc., may outweigh differences in beam current performance.

All analyses to be presented in this paper were carried out using the MCNP Monte Carlo code.[9] This code uses combinatorial surface/cell representation to describe the problem geometry, and a point-wise cross section description. This allows the geometry of the various designs to be described with no simplifying assumptions, and removes uncertainties regarding nuclear data commonly encountered in preparing group averaged cross section libraries.

In the case of the initial NIFTI-1 targets, the source is placed immediately behind the iron filter that covers the treatment port at the front face of the assembly. A thick neutron reflector 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 of the outer cylindrical surface of the assembly. It was assumed that the diameter of the treatment port is 11 cm. The remainder of the front face of the assembly is covered by a layer of lithium hydride, which acts as a neutron absorber (boron carbide could also have been used). The addition of this layer to the front face reduces the radiation dose to the patient. Results for four different NIFTI-1 cases indicate that:

1. Neutron utilization efficiencies of ~10% are possible using iron filters 10 cm thick.
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, and
3. The lithium hydride absorber layer substantially reduces neutron leakage through the front face. However, to further reduce leakage to acceptable levels a more effective absorbing layer will be required. This can be achieved by enriching the lithium in ^{6}Li, or by using a boron containing layer enriched in ^{10}B.

The iron filter is very effective since virtually all the exiting neutrons are below 25 keV, with an average of approximately 12 keV. The addition of a thin moderating layer would reduce the average energy even more.

The angular orientation of the neutron source in the NIFTI assemblies also affects both the neutron utilization efficiency and the spectral distribution of the neutrons leaving the treatment port. For the NIFTI-1 cases, the orientation of the source substantially affects the fraction of source neutrons that exit the treatment port. If the source points toward the port the neutron utilization efficiency is 10.7%, while if it points parallel to the port the neutron utilization efficiency drops to 7.6%. In the case of the NIFTI-2 assembly the effect of the source orientation is less pronounced. If the source points toward the port the efficiency is 11.6%, while if the source points away from the port the efficiency drops to 9.4%.

For NIFTI-1 mechanical designs favor having the proton beam parallel to the filter assembly to accommodate a multi-layer thin foil target through which the beam passes. In NIFTI-2 mechanical designs favor having the proton beam impacting normal to a thick lithium target which is immediately behind the fluoride-iron assembly; this is also the most efficient direction.

To investigate the effect of various thickness of iron and lead fluoride four NIFTI-2 designs were analyzed. The NIFTI-2 geometry is similar to the NIFTI-1 geometry, except that the neutron source is located inside the lead fluoride region. Most of the high energy neutrons generated in the source are degraded in energy by inelastic scattering with fluorine. Results of this study show that:

1. Neutron utilization efficiencies of ~ 10% can be achieved with a lead fluoride inelastic scattering material and an iron filter.
2. Titanium is not as effective a reflector material as lead for NIFTI-2.
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. For this design an enriched absorber may be desirable.

A substantial fraction (~50%) of the neutrons are at an energy above 26 keV. A polyethylene layer 0.6 cm thick substantially softens the spectrum (only 38% above 26 keV). Increasing the port diameter from 11 cm to 18 cm shows a small effect on the neutron utilization efficiency. Thus, the diameter of the treatment port should not be an important determinant for optimizing NIFTI-2 designs.

The neutrons leaving the ^{7}Li(p,n)^{7}Be based source interact with the surrounding materials of the target/filter assemblies. These interactions produce photons of various energies by a variety of mechanisms. As the photons transport through the target assembly, a fraction of them eventually leaks out of the patient treatment port, irradiating the patient with photons. This photon dose is undesirable, since it increases the dose to normal tissue.

A coupled neutron/photon transport calculation was carried out for selected cases. The coupled calculation determines the relative neutron and photon leakage through the patient treatment port. The number of photons leaking from the assembly should be small compared to the neutrons leaking from the assembly, since there is a large amount of self shielding in the target design, resulting from the high "Z" materials in the target.

Estimates of the fraction of neutrons and photons escaping from the patient treatment port were made for one of the NIFTI-2 cases described above. In this estimate a non-isotropic, non-uniform energy distribution neutron source generated by 2.1 MeV protons impinging on a thick lithium target was used. The resultant neutrons have a maximum energy of 350 keV, and are distributed over all angles, with a forward bias. The 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 indicates that the dose due to photon leakage should be acceptably low for NIFTI designs. The leakage of both neutrons and photons is affected by orientation, being approximately 18% lower if the source points away from the port instead of towards it. For mechanical and proton beam design reasons, it is desirable that the source point towards the port; while there is a slight disadvantage to this, the effect will not be significant in terms of patient dose. Residual activity levels in NIFTI targets will be low because:

1. Neutron source strengths are relatively low ($\sim 10^{12}$ n/s), and
2. The fraction of neutrons captured which lead to residual activity is low.

Most neutron capture reactions with target materials lead to either stable isotopes, or to radioactive isotopes which have relative short half lives ($^{19}F \rightarrow ^{20}F$), or decay without significant external radiation ($^{54}Fe \rightarrow ^{55}Fe$).

^{59}Fe is the only long-lived isotope produced in the target materials. However, only about 1×10^{-3} of the neutrons are absorbed in iron that lead to ^{59} Fe. Since only a small fraction of the total neutrons absorbed in a NIFTI target are absorbed in iron, and because the duty cycle for the target will be low, the residual activation will be negligible. It is estimated that for a 10% duty cycle and a source strength of 10^{12} n/s, the residual activation from ^{59}Fe would be only 20 micro-curies.

In addition to the neutron induced activation, there will be some residual activity due to ^{7}Be which has a half life of 53.3 days. The steady state activation of ^{7}Be will be directly proportional to the neutron generation rate and the daily cycle. For the above example, approximately 3 curies of ^{7}Be will be present in the facility. The gamma ray decay energy of ^{7}Be is 0.477 MeV. The gamma dose to the patient is negligible compared to that from other reactions.

3. NIFTI-1 PRELIMINARY DESIGN

Figure 4 is an illustration of the NIFTI-1 design concept. The proton beam is assumed to enter the target area 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. Table 1 summarizes the output performance parameters. Two cases were analyzed for the NIFTI-1 concept: the first with a neutron moderating layer in place, and the second without the layer. The moderating layer consists of a 1 cm thick layer of water just behind the iron filter (i.e. between the filter and the DISCOS target). A proton energy of 1.889 MeV to 1.904 MeV is assumed, with the beam losing 5 keV as it passes through 1 foil of the multi-foil DISCOS target. The resultant neutron source energy and angular distribution caused by the proton impacts on lithium are taken from kinematic calculations of the Li(p,n)Be reaction.

The neutron utilization efficiency for the NIFTI-1 designs is very high, in the range of 12% to 18%. That is, 12% to 18% of the source neutrons generated in the target leave through the treatment port. Of the total number of neutrons that escape through the front face of the assembly, approximately 70% escape through the treatment port.

Without a moderating layer the average output neutron energy is 18.4 keV, which appears acceptable. For treatment where lower energy neutrons are desired (less penetration), one could use a moderating layer, to reduce the average energy to 11.6 keV. This could be done simply by filling the 1 cm thick moderating cavity with water.

The design is very flexible and would have a readily adjustable capability to deliver neutrons over a range of 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. This results in a very low proton current requirement (~ 2 mA to 3 mA). Determination of the optimum number of sheets will require more detailed study.

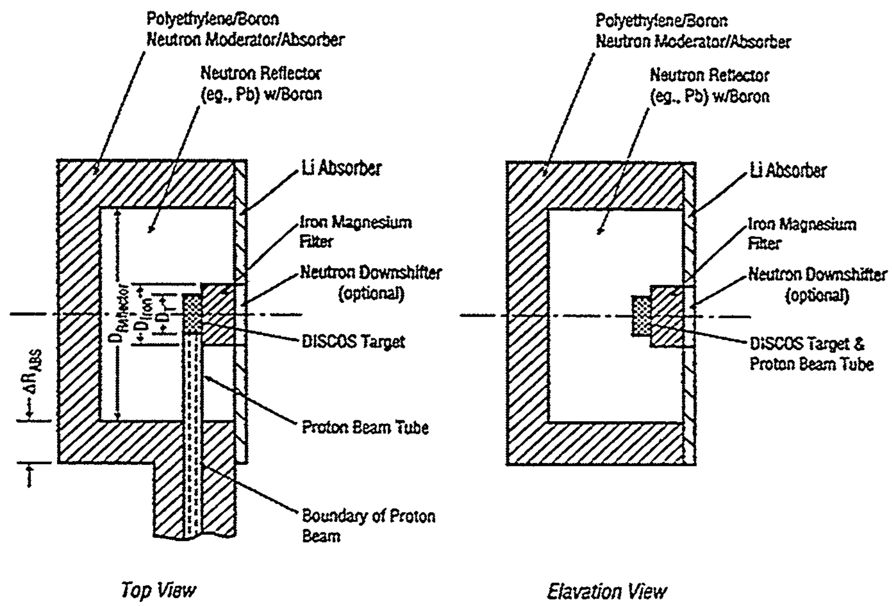

Figure 4. Geometry for NIFTI-1/DISCOS Preliminary Designs.

Table 1. Performance parameters for NIFTI-1/ DISCOS conceptual design

Proton Energy	1.9	1.9
1 cm Hydrogeneous Polyethylene "Down-shifter" Included	No Downshifer Present	Downshifter Present
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, mA	175* / 2.2**	273 / 3.4

* 1 sheet DISCOS (5 keV energy loss)

** 80 sheet DISCOS (400 keV energy loss)

4. NIFTI-2/FIXED TARGET PRELIMINARY DESIGN

Figure 5 shows the geometry for the NIFTI-2 preliminary design, based on the parametric studies carried out in the previous sections. A thick lithium target is assumed. Two fluoride layers (beryllium fluoride and lead fluoride) degrade the source neutrons by inelastic scattering. The outer iron filter impedes transmission of the neutrons until they drop into the 24 keV iron window.

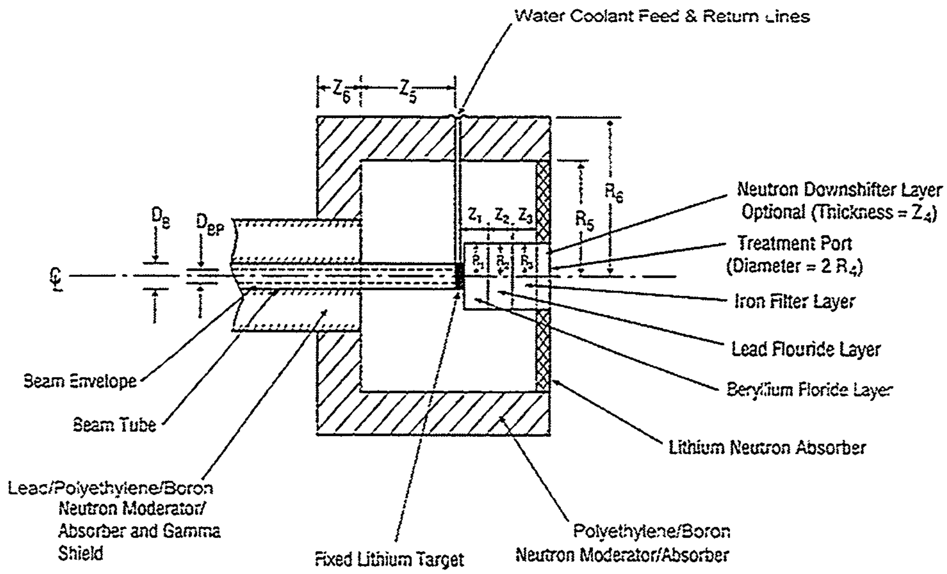

Figure 5. Geometry for NIFTI-2/Fixed Target Preliminary Design.

The proton beam enters the rear of the assembly and impacts on the lithium layer located immediately behind the fluoride region. This arrangement minimizes neutron leakage. At the relatively high proton energies used with the NIFTI-2 target approach, the angular spectrum of the source neutrons is nearly isotropic with a forward bias, so that target orientation does not have a significant effect. The diameter of the treatment port is increased to 18 cm compared to the 11 cm used in the scoping studies.

Cooling of the fixed target appears to be relatively simple. The total thermal power deposited by the beam is approximately 10 kW, or ~ 0.5 kW/cm^2 of target area. The corresponding temperature drop through the lithium film and copper support plate is modest, about 40^0 C. One millimeter diameter water coolant passages are provided 2.5 mm below the Li/Cu interface with a coolant flow rate of 100 cm^3/s. The water temperature rise across the target will be approximately 25^0 C. The film temperature drop in the water coolant is also modest, being approximately 20°C. Water velocity in the coolant passages is estimated to be 4 m/s, resulting in a pressure drop of approximately 10 psi. The total volume of water in the target region is equivalent to a disc 5 cm in diameter and 0.05 cm thick, for a total volume of approximately 1 cm^3. This is too small to have an appreciable effect on the neutron energy spectrum. The maximum temperature of the lithium layer is estimated to be 100°C, well below the melting point (179°C).

Table 2 summaries the resultant output performance parameters. The effect of two proton beam energies (2.1 MeV and 2.5 MeV) is examined, together with the effect of a 1 cm moderating layer located between the iron and fluoride layers. This results in four cases.

First consider those cases without the moderating layer. Increasing the proton energy from 2.1 MeV to 2.5 MeV reduces the required beam current (based on an exit neutron flux of 10^9 n/cm^2-s) from 11.8 mA to 2.42 mA. This results from the ~ 5 fold higher neutron yield at the higher energy. The average output energy increases from

20.4 keV to 37 keV when increasing the proton energy from 2.1 MeV to 2.5 MeV. A 37 keV neutron beam is probably still acceptable for treatment, as discussed below. However, if it proves desirable to have a lower average energy, one of the following three options can be used to achieve this:

1. Optimize the NIFTI-2 neutron conditioning zones,
2. use a thin moderating layer, and/or
3. operate at a somewhat lower proton energy.

Table 2. Performance parameters for NIFTI-2 conceptual design

1 cm "Downshifter" Included	no	yes	no	yes
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 (n/cm^2 - 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 n/cm^2 - s at Port, mA	11.3	16.8	2.42	3.3

These options can be implemented separately or in combination. Option 1 probably involves increasing the thickness of the fluoride and iron layers, to further soften the spectrum. Option 2 appears very attractive. As shown in Table 2, adding a moderating layer for the 2.5 MeV case increases the beam current from 2.42 mA to 3.3 mA, and decreases the average neutron energy from 37 keV to 31.5 keV. The fraction of the input source neutrons that leave through the treatment port is in the range from 5% to 8%. Finally, the relative fraction of gamma rays escaping from the treatment port is small (approximately 1 - 4 photons per 1000 source neutrons).

Table 3 summarizes the technical performance parameters for the NIFTI-2/Fixed Target and NIFTI-1/DISCOS preliminary designs. Both achieve practical neutron currents at the treatment port using very low proton beam currents, i.e. a few mA. The NIFTI-1/DISCOS design requires operation with multiple target foils, to achieve low proton currents since the neutron yield for a single foil DISCOS is too low. The NIFTI-2/Fixed Target design favors operating at higher proton energies, i.e. 2.5 MeV, as compared to lower proton energy. The higher yield at 2.5 MeV reduces the proton beam current by a factor of five. The benefit of lower proton current is to some extent offset by the higher average energy for the output neutrons (37 keV without the moderating layer, 31 keV with the layer). However, optimization should further reduce the average neutron energy resulting from the 2.5 MeV proton beam.

Generally, the neutron utilization efficiencies for NIFTI-1 are substantially greater than those for NIFTI-2. This is expected, since the target is much closer to the treatment port for NIFTI-1. However, even for NIFTI-2 neutron utilization efficiencies are approximately an order of magnitude higher than those projected by previous studies.

Table 3. Summary comparison of performance parameters for NIFTI-2 and NIFTI-1/DISCOS conceptual designs

	1	2	3	4	5	6
Proton Energy (MeV)	1.9	1.9	2.1	2.1	2.5	2.5
"Down-Shifter"	no	yes	no	yes	no	yes
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)

The number of gamma photons leaking from the treatment port per epithermal neutron leaving is very low, ranging from ~ 0.02 to ~ 0.1. This range is primarily affected by the presence or absence of the hydrogenous moderating layer. This low gamma leakage minimizes background gamma dose to healthy tissue.

There do not appear to be any major technical issues for the NIFTI concepts. Because of the high neutron utilization efficiency, the required current is only a few milliamps. The corresponding thermal load in a fixed target is less than ten kilowatts. This thermal load can be readily handled by a target of several centimeters in diameter.

The neutronic behavior of NIFTI can be modeled in detail using Monte Carlo codes based on a combinatorial geometry representation of the configuration. However, before constructing NIFTI facility, it would be desirable to experimentally verify the neutronic performance using a representative neutron source. The beam power level would be small compared to that of the actual facility. Such neutronic validation would assist in the final optimization of the prototype facility and would validate the output energy and spatial distribution of the neutron beam used for patient treatment planning.

The design of a NIFTI target/filter combination can be improved by including a co-axial outer reflector shell around the fluoride/iron filter. The diameter of this reflector shell is defined by the treatment port diameter, and it extends axially from the lithium source to the front of the iron filter. Typically, it has an ID of 10 cm and a length of 10 cm - 15 cm. The thickness of the reflector shell is determined by the nuclear properties of the reflecting material, and the desired increase in intensity. Neutrons emitted from the lithium source preferentially travel in a cone shaped direction with an included angle of 120°. They thus first pass through the fluoride layer, in which their energy is reduced to approximately 100 keV, before entering the reflector. The reflector must be efficient at reflecting neutrons with an energy in the range 100 keV - 1 MeV, while not degrading their energy too much. It has been found that both beryllium and molybdenum have relatively high macroscopic cross sections in this range (0.54 cm^{-1} - 0.56 cm^{-1}). These values are higher than other potential materials in this energy range, with the exception of hydrogenous materials. However, hydrogenous materials were not considered since they would excessively degrade the average energy of the output neutrons.

Preliminary analyses were carried out using both beryllium and molybdenum as radial reflectors. In the case of beryllium, it was found that changing the thickness of the reflector from zero to 7.5 cm increased the total flux in a test volume in front of the treatment port by approximately 25%, while the average neutron energy decreased from 13.5 keV to 2.5 keV. In the case of the molybdenum reflector the respective changes were not as dramatic; the flux increase in the test volume was 15%, and the average neutron energy decreased from 13.5 keV to 9.0 keV. It can be seen that inclusion of a radial reflector will both enhance the intensity of the neutron flux, and soften the neutron energy spectrum. A modular adjustable configuration composed of multiple layers of beryllium and molybdenum could be used to target tumors at different depths by altering the average neutron energy - a harder neutron spectrum will penetrate more deeply to reach the tumor. A dosimetry determination of this configuration is planned.

5. EFFECTIVENESS OF NIFTI SYSTEMS FOR BNCT TREATMENT

The effectiveness of a neutron beam generated by an accelerator driven target for BNCT treatment can be assessed using the following criteria:

1. Advantage Depth (AD)
2. Advantage Ratio (AR)
3. Treatment Time

Advantage depth is the depth in tissue at which the total dose to the tumor cells equals the background dose to healthy tissue at the skin surface. It thus measures the effective treatment depth. Advantage ratio is the ratio of dose to the tumor divided by total dose to healthy tissue, integrated from the surface to the depth of treatment. Figure 6 compares different BNCT neutron sources with regard to advantage depth and advantage ratio. High values of AD and AR are desirable. The values for 20 keV, 2 keV, etc.,[3] refer to ideal monoenergetic, monodirectional neutron beams, while the BMRR value refers to the BNL Medical Reactor. The illustrative NIFTI designs described here appear to have acceptable AD and AR performance. However, further optimization is necessary to improve the values. Acceptable treatment times of approximately 30 min. appear achievable with a proton current of approximately 5 mA.

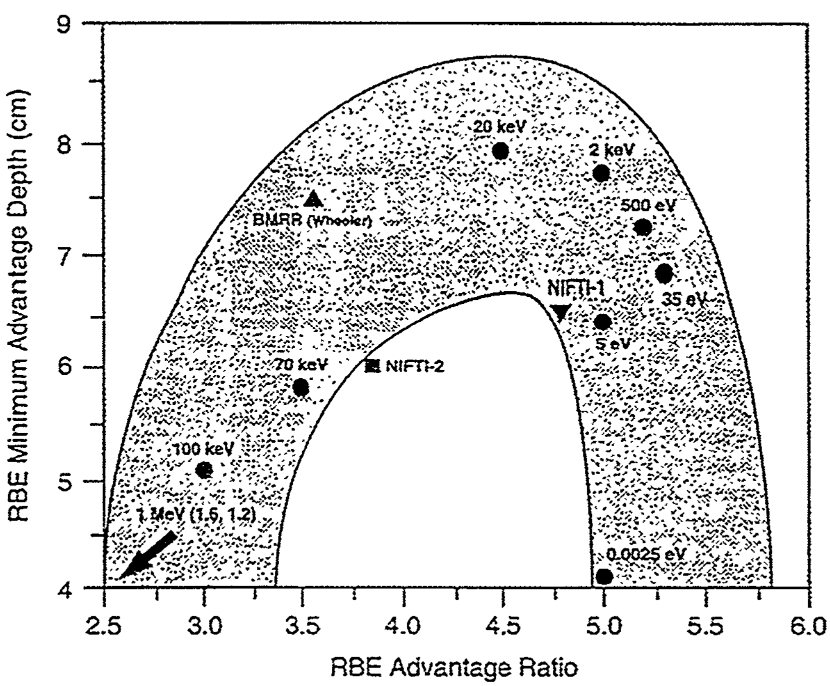

Figure 6. Advantage Ratio Versus Advantage Depth for Ideal Neutron Beams of Various Energies.

6. CONCLUSIONS

The NIFTI concepts appear very promising for accelerator based BNCT. They enable reductions of approximately an order of magnitude in the proton beam current required for patient treatment, while delivering epithermal neutron beams that have average energies in the range of 10 keV to 30 keV, depending on design. The low proton beam current makes it possible to use commercially available accelerators, thus avoiding an extensive research and development program.

The NIFTI-2 concept with a fixed target is the simplest and easiest to develop. It has a somewhat higher average output neutron energy than NIFTI-1 with a DISCOS target. The output neutron energy for the NIFTI-2 concept appears acceptable for treatment. Both target concepts should be further optimized to achieve their full potential.

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