JP0150614

JAERI-Conf 2001-002

ICANS-XV
15th Meeting of the International Collaboration on Advanced Neutron Sources
November 6-9, 2000
Tsukuba, Japan

21.6 Conceptual Design Studies of a Neutron Source at the BNL-HFBR Facility

H, Ludewig*, J. Hastings, P. Montanez, and M. Todosow

Brookhaven National Laboratory, Upton, New York 11973
*E-mail: ludewig@bnl.gov

Abstract

Following the shutdown of the High Flux Beam Reactor (HFBR) it has been proposed to substitute the reactor based source with a CW accelerator driven source. Both sub-critical assemblies and spallation sources have been explored. The accelerator driven sub-critical assemblies include a spallation neutron source surrounded by a sub-critical blanket. The neutron source is a bed of randomly packed ^{184}W spheres cooled by heavy water. The sub-critical blanket consists of a co-axial bed of randomly packed coated graphite spheres, which have been infiltrated with uranium carbide. The uranium is 20 % enriched, and has a volume averaged density of 1.0 g/cc. The spallation source only option consists of a target design which is conceptually the same as the neutron sources, described above, used in the driven sub-critical sources. The surrounding reflector in both cases consists of an inner Be/D_2O volume and a larger D_2O outer volume. Both volumes are co-axial with the source.

A series of calculations was carried out for the driven sources in which the proton energy was varied (500 MeV<Ep<1000 MeV) and the power adjusted to achieve a thermal neutron flux of 10^{15} n/cm^2-s in the outer reflector volume. The flux level and total power are comparable to the original HFBR operating point. The spallation only source was limited to an accelerator power of 10 MW and a proton energy of 1000 MeV.

The shielding surrounding the target was also investigated. The existing HFBR facility shielding was compared to shield designs consisting of light water and stainless steel, with an inner and outer lead layer.

Introduction

The High Flux Beam Reactor (HFBR) at Brookhaven National Laboratory (BNL) was permanently shutdown in 1999. This reactor was a steady state neutron source used to carry out a variety of fundamental experiments in physics, biology etc., and when operating at its rated power of 60 MW, was able to generate a peak thermal flux in the reflector (useful to experimenters) of approximately 10^{15} n/cm^2-s [1]. In addition to thermal neutrons, cold neutrons thermalized in a cryogenic moderator (liquid hydrogen) were also available. A vertical section through the reactor and shield is shown on Fig. 1. Since its shutdown a variety of accelerator driven replacement sources have been studied. These include sub-critical targets driven by a spallation source, and a spallation only source. Advantages of a driven sub-critical source are:

1) It is easier to control compared to a critical reactor (no control system etc.),

2) Since it is significantly sub-critical, criticality initiated and driven accidents can be ruled out,

3) Due to the source multiplication effect, a less powerful accelerator is sufficient for this application compared to that required for a spallation only source, for the same performance. This has cost, materials, and source brightness implications.

However, despite the above advantages essentially the same mass of fission products will be generated compared to a critical reactor, since the sub-critical blanket is expected to operate at similar power and power density as a critical system. The spallation only source has the unique advantage of generating essentially no fission products (fission being a rare event in a spallation target at the proposed proton energy). However, spallation products will be generated, which are similar in nature to fission products but have advantages regarding decay heat production and decay time.

All the spallation targets to be considered below consisted of randomly packed beds of ^{184}W spheres cooled by D_2O, contained in a stainless steel vessel. The target cross section in the direction of the proton beam was sized to be approximately consistent with an average proton current per unit window area of 0.2 A/m^2. This criterion could not be satisfied for all cases, since the accelerator power requirements to achieve the desired performance goals out grew the window size. This degradation in performance will be discussed below. The sub-critical blanket consisted of a randomly packed bed of coated graphite spheres, infiltrated with uranium carbide. The uranium is assumed to be enriched to 20 % in the fissile isotope ^{235}U, in order to render it acceptable as a non-proliferative fuel form. There are several coating layers on the surface of the fissile material containing graphite kernels. The most likely combination would consist of a pyrolytic carbon layer followed by a layer of silicon carbide. The blanket is configured as a coaxial volume which contains the coated graphite spheres and surrounds the spallation source. It is cooled by D_2O flowing radially through the bed from the outside to the inside and out past the outside of the spallation source. The blanket and spallation source are assumed to have separate cooling loops. In all cases the neutron generating volumes are surrounded by an inner and an outer reflector. The inner reflector consists of a mixture of beryllium spheres and heavy water, and the outer reflector consists of pure heavy water. In one case (spallation only) the source was surrounded only by heavy water, as a comparison to the two stage reflector concept.

In order to judge the performance of the existing HFBR shield, and alternative shield concepts, the dose due to neutron and gamma-ray leakage from the source in rads/s deposited in water at the outer edge of the shield was determined. The unacceptably high dose for accelerator driven targets shielded by the currently installed concrete shield necessitated the use of alternative shield concepts. In the current study a stainless steel water mixture (35 % H_2O - 65 % stainless steel) surrounded by an additional 10 cm of lead, was considered for the case using a spallation only neutron source. The acceptable performance of this concept would require the removal of the existing concrete shield and indicates that acceptable shield concepts for this application are possible.

All the calculations reported in this paper were carried out using a combination of LAHET 2.8.3 and MCNP-4B, or MCNPX [2,3,4]. These code packages are compatible and the individual application was based on convenience. The heat transfer and fluid dynamic estimates were carried out using correlations for pressure drop and Nusselt number in randomly packed beds of spheres. The heat deposition in the target, window, and blanket were determined by the above code packages.

Driven Sub-Critical Blanket Systems

As described above these systems all have a centrally located spallation source surrounded by a sub-critical blanket and a reflector. In order to determine the size of the system the following steps had to be carried out:

1) Determine the window area assuming an accelerator power, proton energy, and a window current density limited to an average of 0.2 A/m^2,

2) Configure the spallation source diameter, length, and composition. This step also includes any structural size and material definitions,

3) Configure the surrounding blanket consisting of fissionable material, coolant, structural material, and reflector arrangement, and

4) Determine the multiplication factor (k_e) of the entire system.

Steps 3 and 4 will generally need to be carried out several times until an acceptable value of k_e is achieved for the entire system. In the configurations of interest in this study a value of k_e = 0.975 was used. This required a blanket with a volume of 30 litres with an inner diameter of 17.5 cm, an outer diameter and height of 36.7 cm. The fuel consists of graphite spheres with uranium carbide infiltrated into the naturally occurring void spaces in the graphite. The spheres will be coated with an appropriate layer which is impervious to the transport of fission products. Pyrolytic carbon applied by the chemical vapor deposition method has been used in the past for this purpose, and could be used in this application as well. Finally, a coating of silicon carbide will be applied to the outside to act as a final fission product barrier, and as a pressure vessel to contain any build up of pressure due to the generation of volatile fission products. This pressure is not expected to be very high in this particular application since there is a substantial void in graphite (~ 25 %), and this can be increased by various means to further reduce the internal pressure from fission product generation. The spallation source consisted of a cylindrical shape 10.0 cm in diameter and 54.0 cm long. The inner reflector extended out to a diameter of 90.8 cm and had a height of 88.8 cm. The proton beam was brought in from the bottom. Finally, the heavy water reflector extended out to a diameter of 200 cm. The entire assembly was surrounded by a 20 cm thick inner lead shield, to reduce the gamma-ray heating on the outer shield. This was followed by either the, currently in place HFBR concrete shield, or an alternative light water and stainless steel shield followed by a 10 cm thick lead shield. The latter lead shield is used to attenuate the 2.2 MeV capture gamma-ray resulting from neutron captures in the hydrogen of the light water. Fig. 2 shows a vertical section through a typical source.

Three systems, assuming proton energies of 1000 MeV, 750 MeV, and 500 MeV respectively were investigated. The overall goal was to achieve a thermal neutron flux of 10^{15} n/cm^2-s in the outer (heavy water) reflector. This performance is comparable to the HFBR operating at full power. In addition, the current density on the window of the spallation target was limited to an average of 0.22 A/m^2. The results given in Table 1 satisfy the current density requirement, while the results given in Table 2 show the implications of requiring the thermal flux goal to be satisfied. Table 3 shows the radial variation of the thermal neutron flux at selected locations at the blanket mid-plane. The position of these locations pass through both the inner (Be-D_2O) and outer (D_2O) reflectors. The first practical location for a beam tube would in all likelihood be the first radial position (50.7 cm) in the outer reflector. Irradiation thimbles could be placed at closer locations in the inner reflector.

Table 1 - Results for cases with same proton current density on window
(Average current density = 0.22 A/m^2)

Case number	1	2	3
Proton Energy (MeV)	1000	750	500
Accelerator Power (MW)	1.52	1.14	0.76
Target thermal power (MW)	0.77	0.7	0.56
Blanket Power (MW)	60.2	43.1	24.5
Max. Thermal Flux (n/cm^2-s)	10^{15}	$7.2x10^{14}$	$4.1x10^{14}$

The results shown in Table 2 assume a constant maximum thermal flux in the outer (heavy water) reflector

Table 2 - Results for cases with constant maximum thermal neutron flux
($\phi_{max} = 10^{15}$ n/cm^2-s)

Case number	1	2	3
Proton Energy (MeV)	1000	750	500
Accelerator Power (MW)	1.52	1.59	1.87
Target thermal power (MW)	0.77	0.98	1.37
Window Current Density (A/m^2)	0.22	0.31	0.54
Blanket Power (MW)	60.2	60.2	60.2

The thermal neutron flux at selected radial positions from the proton beam centerline in the inner and outer reflector are shown in Table 3. These values all assumed an average proton window current of 0.22 A/m^2.

Table 3 - Cell averaged thermal neutron flux as function of radial distance from beam centerline (n/cm^2-s)

	Case			
Mean Radius	1000 MeV	750 MeV	500 MeV	Reflector
32.9	1.8(15)*	1.3(15)	7.2(14)	Inner
50.7	1.0(15)	7.2(14)	4.1(14)	Outer
60.5	7.2(14)	5.2(14)	2.9(14)	Outer
71.5	4.9(14)	3.5(14)	2.0(14)	Outer
82.5	3.1(14)	2.3(14)	1.3(14)	Outer
94.0	1.7(14)	1.2(14)	7.1(13)	Outer

* 1.8(15) = 1.8×10^{15}

The power distribution in the fissile blanket will be approximately dish shaped, with a peak around the outside circumference of the co-axial shaped volume, a minimum at an intermediate radius and a less pronounced peak along the inner circumference of the volume. The average power density in the blanket is 2 MW/liter. The highest power density will occur along the inlet surface where the coolant temperatures are the lowest and the pressures are the highest (T_{sat} at this location will be furthest from the particle surface temperature), thus boiling is less likely. At the outlet the temperatures are the highest and the pressures are the lowest and it is here were the possibility of coolant boiling will be investigated. Based on values measured at the HFBR the peak/average power can be expected to be approximately 3. Thus, the power density along the outside of the blanket will be approximately 6 MW/liter, and along the inside it will be close to 2 MW/liter.

In determining the parameters of a particle bed the particle size and coolant velocity are primary values from which the bed pressure drop and surface film temperature drop can be determined for a given coolant type. It is important to minimize the pressure drop (to reduce the forces, and the implied loads on the structural components), and simultaneously to minimize the film drop in order to avoid coolant boiling at the particle surfaces. Boiling can be suppressed by operating at elevated pressures. However, this option is not very desirable, since pressure vessels would require thicker walls in this case, which implies added radiation heat deposition, and increased thermal stresses. The coolant velocity is determined by the requirement to remove the heat generated in the volume. Assuming inlet and desired outlet conditions the enthalpy rise per unit mass of coolant can be determined and given the total power the mass flow rate and the velocity follow. Based on known correlations it can be shown that for a bed of randomly packed particles the pressure drop [5] and film temperature drop [6] vary in the following ways as functions of particle diameter and velocity.

$$\Delta p \sim V^2/d_p$$
$$\Delta T \sim d_p^{5/4}/V^{3/4}$$

where

Δp = Pressure drop across bed
ΔT = Film temperature drop between coolant and particle surface
V = Average coolant velocity
d_p = Particle diameter

The above relationships indicate that it is not possible to simultaneously minimize both the pressure drop and film temperature drop, and thus a compromise is required.

The average coolant mass flow rate, particle diameter, and operating points for the highest power density blanket (60 MW), and spallation neutron source (1.52 MW) are given below.

Blanket Parameters

Coolant mass flow rate (kg/s)	361.2
Particle diameter (mm)	3.0
Inlet temperature (^{0}C)	20
Inlet pressure (bar)	19
Outlet temperature (^{0}C)	60
Outlet pressure (bar)	6
Outlet film drop (^{0}C)	26.3
Outlet particle surface temperature (^{0}C)	86.3
Outlet condition saturation temperature (^{0}C)	158

In the case of the spallation targets the dominant power variation will be assumed to be axial along the direction of the proton beam. This maximum occurs approximately 4 cm from the window for the case that will be considered (although this case is not a likely practical configuration due to the high average proton beam current per unit area of window). The implied power density at this location for this case is 0.66 MW/liter. The coolant mass flow, particle diameter and operating parameters are given below.

Spallation Target

Coolant mass flow rate (kg/s)	9.15
Particle diameter (mm)	5.0
Inlet temperature (^{0}C)	20
Inlet pressure (bar)	7
Outlet temperature (^{0}C)	60
Outlet pressure (bar)	6
Outlet film drop (^{0}C)	30
Outlet particle surface temperature (^{0}C)	90
Outlet condition saturation temperature (^{0}C)	158

The above operating points indicate that in both cases the particle surface temperature is well below the saturation temperature, thus avoiding the onset of coolant boiling. The complications associated with coolant phase change are not desirable, and can lead to undesirable mechanical loads. Notice that particle diameter used in the fissile blanket is smaller than the diameter used in the spallation source. This reduction in diameter is necessitated by the requirement that the particle surface temperature be below the saturation temperature at all locations within the bed. Since the power peaks on the outer edge of the blanket the highest film drop occurs at this location. However, the coolant temperature and pressure are at inlet conditions at this location (lowest temperature and highest pressure), thus the saturation temperature will be the highest value, and that a large film drop can be tolerated before the onset of boiling. The reduction in particle diameter implies a higher pressure drop across the blanket, and to result in reasonable conditions at the outlet a higher inlet pressure is implied. The coolant outlet conditions are essentially the same for the blanket and the spallation source.

The proton window will be a double walled structure of Inconel, with a separate cooling channel between the walls. This design is used at other accelerator facilities, and thus with an average current density of 0.22 A/m^2 a practical design should be possible. Higher current densities (significantly higher than the current accelerator experience) or different window materials (beryllium or carbon/carbon) will require a window development program.

Spallation Target System

The spallation source remains in the same location, and the fissile blanket is replaced by an extended inner reflector. In all these systems it was assumed that the accelerator has a power of 10 MW, the proton energy is 1000 MeV, and that the average proton window current is limited to 0.2 A/m^2. The target is assumed to be rectangular in shape, and thus the other parameters of interest are the aspect ratio of the rectangular shape, and the particle diameter. Once these parameters are fixed the pressure drop and film temperature drop can be determined, and finally the system pressure can be specified, the magnitude of which has to be sufficient to prevent boiling on the particle surfaces.

Based on the above window current limit, proton energy, and accelerator power the beam footprint on the window will be 500 cm^2. Two target configurations will be examined in this study. The first will be rectangular with dimensions of 10 cm x 50 cm, and the second will be essentially square with dimensions of 20 cm x 25 cm. The coolant flow is arranged to flow across the shortest distance in both cases, and thus for the same particle diameter and flow rate the first configuration will have half the pressure drop of the second configuration. In a practical sense it will be possible to place beam tubes closer to the target in the second case than the first case, and thus it should be possible to achieve higher thermal neutron fluxes in the second configuration. However, it might be possible to arrange for irradiation ports close to the target in the first case. Fig. 3 shows a vertical section through the 20 cm x 25 cm source.

Results of the thermal flux calculations carried out for the above targets are shown on table 4, as a function of radial position and azimuthal angle.

Table 4 - Thermal flux as function of radial position and azimuthal angle for three spallation source configurations.

Radius/Azimuthal angle	Target description 10 x 50 Inner: Be/D_2O Outer: D_2O	20 x 25 Inner: Be/D_2O Outer: D_2O	20 x 25 Inner: D_2O Outer: D_2O
27.7/0°,180°	-	7.474(14)*	6.874(14)
27.7/90°,270°	-	6.628(14)	6.142(14)
38.9/0°,180°	4.858(14)	4.852(14)	5.412(14)
38.0/90°,270°	4.753(14)	4.720(14)	5.210(14)
50.7/0°,180°	3.022(14)	2.987(14)	3.80(14)
50.7/90°,270°	3.323(14)	2.951(14)	3.741(14)
60.5/0°,180°	2.30(14)	2.262(14)	2.873(14)
60.5/90°,270°	2.554(14)	2.249(14)	2.844(14)
71.5/0°,180°	1.638(14)	1.616(14)	2.027(14)
71.5/90°,270°	1.810(14)	1.60(14)	2.018(14)
82.5/0°,180°	1.106(14)	1.089(14)	1.354(14)
82.5/90°,270°	1.214(14)	1.079(14)	1.354(14)
94.0/0°,180°	6.325(13)	6.238(13)	7.685(13)
94.0/90°,270°	6.884(13)	6.173(13)	7.690(13)

* 7.474(14) = 7.474×10^{14}

The above results indicate that the azymuthal variation of the thermal neutron flux is only significant at the first radial position. At this point the azymuthal change is approximately 10 % and then decreases quite rapidly. The highest practical thermal neutron flux is seen to be approximately 30 % below that of the HFBR when it is operating at full power. Methods of increasing this flux have not been explored, and it felt that it should be possible to further increase the flux by using a target material which has lower parasitic neutron absorption, or using a two stage target with an inner high production volume (large n^0/p^+) surrounded by a volume with a lower parasitic capture cross section, but still capable of producing neutrons.

The maximum axial power density in the targets considered in this section are of similar magnitude as those determined for the targets discussed above. The maximum power density is 625.0 W/cm^3, which is essentially the same as for the spallation source outlined above. This is a reasonable result, since the average window current density is essentially the same, and thus one would expect that the spallation rate behind the window would be the same, assuming the same target material. Since it was possible to cool the above mentioned targets, this target should also be cooled, using the same parameters as the shown in the table above. The window cooling should also not be any different, since the average current density, material, and material thickness are all assumed to be the same. More detailed analyses will be carried out in the next stage of the design.

Shielding Study

Shielding which surrounds the HFBR core and reflector, and is currently in place, consists of an inner lead layer (~ 25 cm) which protects the remaining shield from the leakage gamma-rays , and a thick (~ 225 cm) concrete layer to attenuate any neutrons leaking out. The performance of any alternative designs will be measured relative to the performance of this configuration. At this stage there is only one alternative concept, which consists of a mixture of stainless steel and light water (35 % H_2O/65 % stainless steel), and an additional lead (10 cm thick) layer placed around the outside. The thickness of the water/stainless steel layer must be determined. It is expected that the light water will reduces the energy of the leakage neutrons, which are then absorbed by either the iron in the steel or the hydrogen in the water. The outer lead layer is there to ensure that any of the capture gamma-rays generated in the shield are attenuated before they have a chance to leak out.

A series of shield calculations was carried out using the configuration consisting of a centrally located spallation neutron source surrounded by a blanket. All these estimates used the existing HFBR shield, the only variable being the energy of the incoming proton. The measure of performance in all shield comparisons was the dose in rads/s expected on the outer periphery of the shield. This determination was made by estimating the dose in a layer of light water immediately surrounding the shield at this location. Furthermore, this location corresponds to the experimental floor, and is thus a measure of the expected human dose on the experimental floor.

The results of this first series of calculations is given below for three proton energies.

Table 5 - Dose as a function of proton energy for the existing HFBR shield (rads/s)

Proton energy (MeV)	Accelerator power (MW)	Shield description	Dose (n^0 and γ)
1000	1.52	25 cm Pb/225 cm Concrete	0.015
750	1.59	Same	0.012
500	1.87	Same	0.006

These results indicate that the dose is unacceptably high, and since the shield configuration yields acceptable dose values for reactor conditions, the significant doses with a spallation source are due to high energy neutron leakage. However, they indicate quite clearly that the dose is reduced by reducing the proton energy.

A comparison between the existing HFBR shield and the alternative shield configuration described above was carried out using the 1000 MeV spallation only source.A total accelerator power of 10 MW was assumed for all these cases. The results are given below in table 6:

Table 6 - Comparison between current and alternative shield designs (rads/s)

Shield description	Dose (n^0 and γ)
Current design (20 cm Pb;225 cm Concrete)	0.267
Alternative (20 cm Pb;225 cm Steel/water)	0.001
Alternative (20 cm Pb;380 cm Steel/water;10 cm Pb)	

It is seen that the dose from a 1000 MeV spallation only source surrounded by the standard HFBR shield is extremely high. However, substituting the stainless steel/light water combination in place of the concrete reduces the dose, and increasing the thickness of the steel/water region to 380 cm essentially eliminates the dose. This extended shield configuration can be constructed in the existing facility, provided that the exiting concrete shield is removed.

This is not the only alternative design of the shielding and a more exhaustive study would consider other designs.

Future Work

Described above are two possible conceptual designs of possible replacements for the steady state neutron source supplied by the HFBR. In these studies no effort has been made to optimize the design in any way. Only broadly defined limits were put on the designs in order to ensure that they were practical from both a neutron flux, and an engineering point of view. Future work will include studies on the following topics.

1) Spallation targets

The spallation target assumed above could be replaced by either a liquid metal target (Pb/Bi eutectic), or a two stage target consisting of an extremely dense core (W spheres cooled by liquid metal); surrounded by a less dense volume with lower parasitic absorption. The first target would be an alternative for relatively low proton energies since the liquid density ~ 11.5 g/cm^3, and the implied nuclide number density is ~ 0.033 atoms/b-cm. The second configuration would be better suited to a higher proton energy, since the average density is expected to be ~ 16.3 g/cm^3. Heat removal will play a pivotal role in choice of target configuration.

2) Blanket fuel management

The fissile material will be depleted at the rate of approximately 60 g fissile material/day (assuming 1 MW ~ 1 g ^{235}U per day). In addition, the mass of fission products increases monotonically with time. The loss of fissile material and the increase in fission products both tend to decrease the value of the multiplication constant (k_e). The fissile material must therefore be continually replaced, or following a prescribed reduction in the value of k_e the source is shutdown and a fresh fissile load is introduced. The management of the fissile material in the blanket has not been addressed in this paper, and will be the subject of the next phase of the study.

A variety of possibilities for managing the coated fissile graphite particles exist. First the continual replacement of the particles will be studied, this is not different, in principle, from the method used in the demonstration reactor AVR. Second, the batch replacement of the entire particle load is comparatively easy since the particles could be removed and added hydraulically, implying an extremely short shutdown of the source for re-fueling.

3) Window design concepts

Currently designed windows consist of a two walled structure (generally of Inconel-718), with demineralized water coolant flowing between the walls. As the pressure of the target volume increases it becomes necessary to increase the wall thicknesses, leading to increased heat deposition in the walls and increased thermal stresses, which add to the mechanical stresses. An alternative concept consisting of an outer wall of a low "Z" material (to minimize heating) followed by alternating layers of coolant (water) and Inconel, which carries the load, will be investigated. In this manner the layer which is only cooled on one face would have a minimum of heating and the thicker load bearing layers would be cooled on both faces. The final metal layer could again be made of low "Z" material, depending on the details of the target internal design.

4) Alternative shield concepts

The shield which is in place at the HFBR facility was designed to shield against radiation leaking out of a reactor based source. This is limited to well thermalized neutrons and gamma-rays with a peak at approximately 1 MeV. In the case of spallation based sources there is a high energy neutron flux, well beyond the energy of neutrons leaking from reactors, which require special attention. Generally these neutrons are shielded by thick (~ 5 m) iron shields surrounded by concrete (~ 1 m). In the exploratory study outlined above an alternative shield composition consisting of a water and stainless steel mixture showed positive results with significantly thinner shields. The thickness of the shield is an important factor in this application, since the facility already exists, and for selected applications distance from the source reduces the brightness of the source. In addition to this concept other concepts will be investigated for application to this problem.

Finally, a sub-critical blanket source driven by a neutron source which is not based on the spallation reaction will be investigated. It is possible to generate neutrons using photons with energies above ~ 8 MeV from most nuclides; except Be and D which require photons of ~ 1.7 MeV and 2.2 MeV respectivly. It is possible to generate photons of the appropriate energy by impinging high energy electrons on a heavy target (i.e. Ta). The neutron source has an energy spectrum very much the same as fission neutrons, and thus the existing shield at the HFBR facility could be used. The disadvantage of this type of source is the relatively short stopping distance of electrons in a heavy metal target, implying extremely high power densities. In addition the neutron production (n^0/e^-) is relatively inefficient, thus requiring an extremely high electron current to generate sufficient neutrons to drive the sub-critical blanket. This situation could be ameliorated by operating the blanket at a higher value of k_e ($k_e = 0.985$), but this possibility is limited by the desire to stay sufficiently below unity to rule out any safety hazard. This option will also be studied as an alternative to the shielding problem; and to determine the maximum possible neutron flux, and target heat removal.

Conclusions

The following conclusions can be drawn from this preliminary study:

1) It is possible to design a steady state neutron source to match the performance of the HFBR using an accelerator with a power less than 2 MW driving a target surrounded by a fissile blanket,

2) A spallation only based source will require an accelerator power equal to or greater than 10 MW to achieve the same performance as the HFBR,

3) The shielding currently in place at the HFBR is optimized for a reactor based source and will have to be removed and re-constructed if a spallation based source is used, and

4) Alternative solutions to the short coming posed by the current shield are possible within the HFBR facility.

Acknowledgements

This work was performed under the auspices of the U.S. Department of Energy.

References

[1] J.M. Hendrie, "Final Safety Analysis Report on the Brookaven High Flux Beam Research Reactor", Brookhaven National Laboratory, Upton, New York. BNL-7661 (1964).

[2] R.E. Prael and H. Lichtenstein, *"User Guide to LCS: The LAHET Code System"*, Los Alamos National Laboratory, Los Alamos, NM, LA-UR-89-3014 (1989).

[3] *MCNP-A General Monte Carlo N-Particle Transport Code Version 4A*, J.F. Breismeister, ed., Los Alamos National Laboratory, Los Alamos, NM, LA-12625-M (1993).

[4] *MCNPX Users Manual - Version 2.1.5*, L.S. Waters, ed., Los Alamos National Laboratory, Los Alamos, NM, TPO-E83-G-UG-X-00001 (1999)

[5] S. Ergun (1972) In: Analysis of Heat and Mass Transfer, (B.J. Clark and M. Eichberg, eds.), pp. 413, McGraw-Hill Book Co., New York.

[6] E. Achenbach, "Heat Transfer and Pressure Drop of Pebble Beds up to High Reynolds Numbers", Proc. 7th Int. Conf. Heat Transfer, Vol. 6, Munich, Germany (1982).

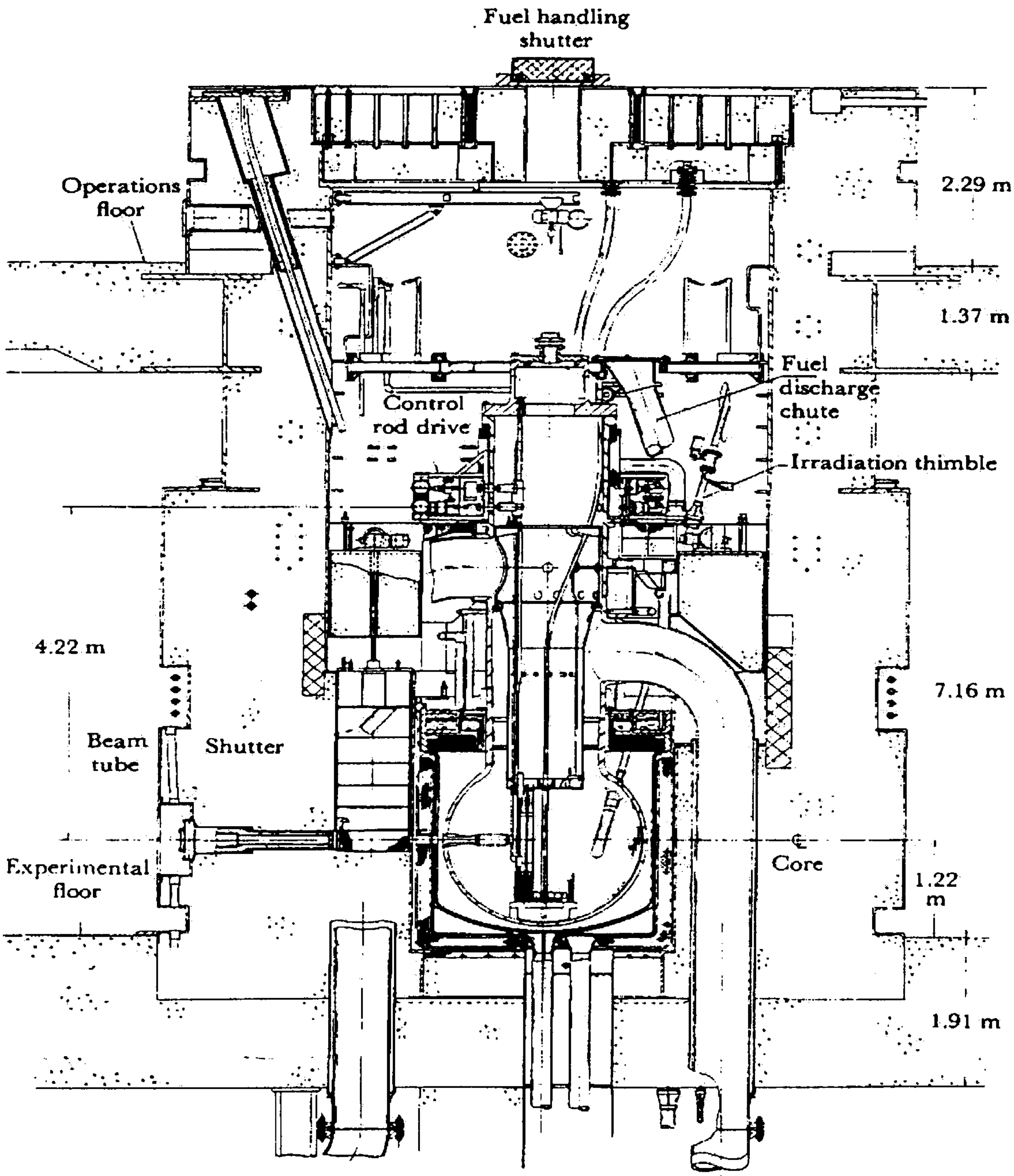

Figure 1: Elevation of the Reactor Vessel Shielding,
Showing a Typical Beam Tube, Shutter, and Thimble

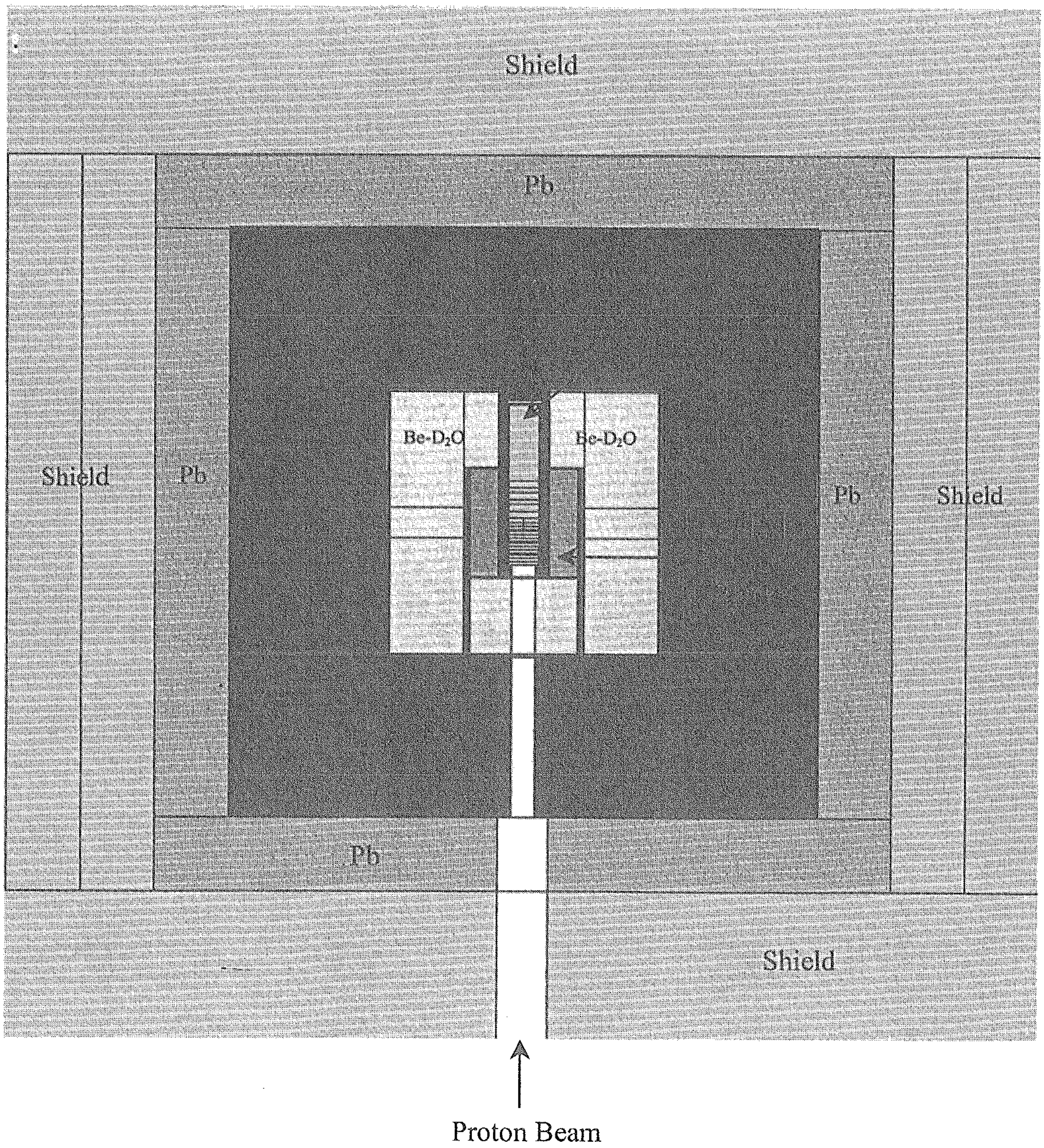

Figure 2: Spallation Neutron Source Surrounded by a Fissile Blanket

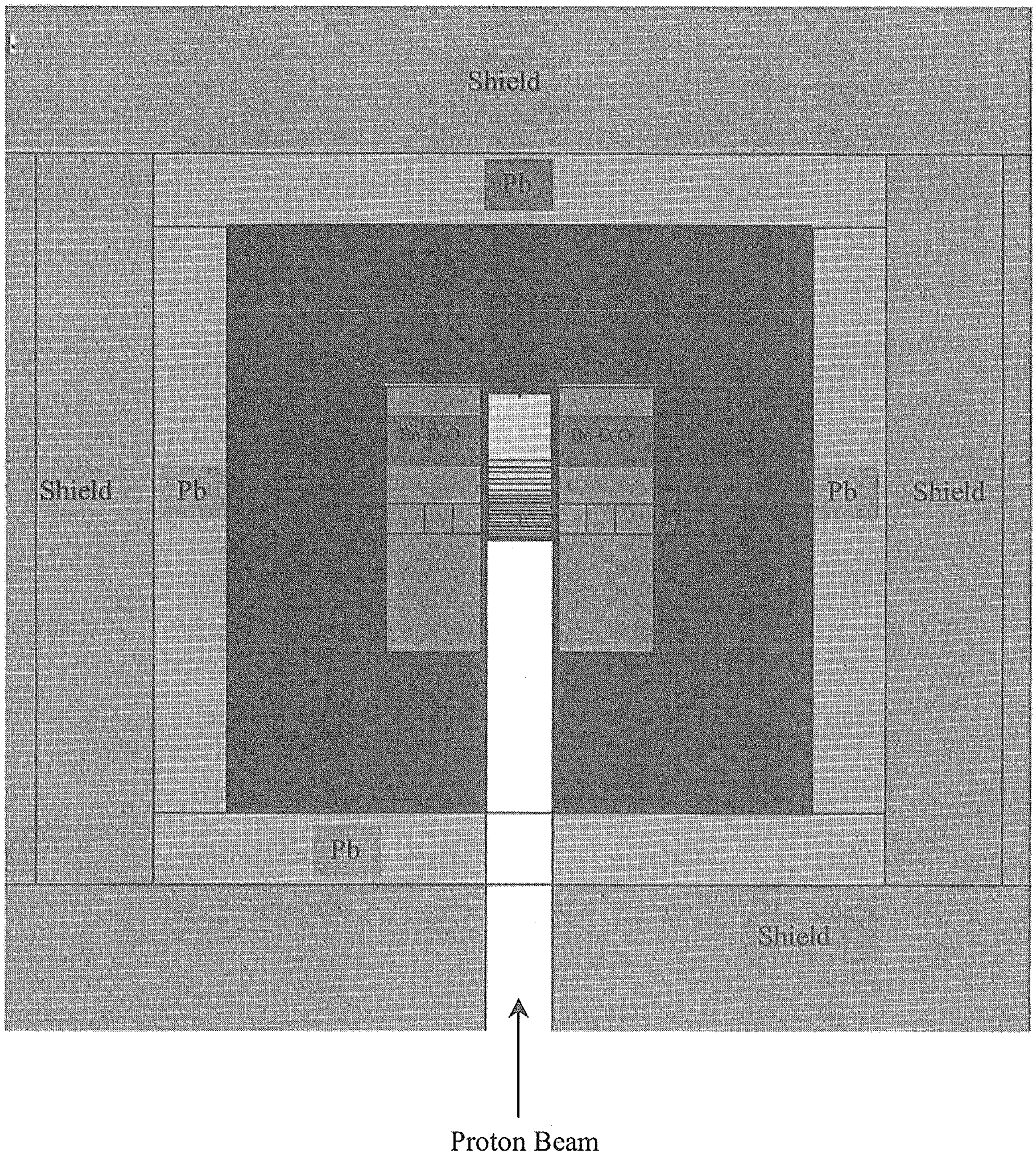

Figure 3: Spallation Only Neutron Source