Comparison of 2 Lead-Bismuth Spallation Neutron Targets

Keith Woloshun, Curtt Ammerman, Xiaoyi He, Michael James, Ning Li, Valentina Tcharnotskaia, Steve Wender
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos. New Mexico, 87545
woloshun@lanl.gov

Abstract

In this paper, the results of a preliminary investigation of two liquid lead-bismuth eutectic (LBE) spallation target designs for accelerator transmutation of waste are presented and compared: 1) A right circular cylinder design, and 2) A conical target that allows for better axial distribution of neutrons and better overall neutron/proton ratio (n/p). The target designs are based on requirements set by preliminary blanket designs. These requirements are listed in the paper. Conceptual designs are presented, including scoping analysis of thermal/hydraulic performance and neutronic performance analysis (neutrons per proton and flux maps). The conical target out performs the cylindrical target in 3 significant ways: Reduced window heat flux and cooling problems, improved n/p, and improved axial distribution of neutrons.

I. INTRODUCTION

The Advanced Accelerator Applications (AAA) program, which encompasses the Accelerator Transmutation of Waste (ATW) project, is investigating the use of a high-power accelerator to produce neutrons that would then be used to drive a sub-critical multiplying assembly (blanket). Nuclear waste is transmuted to shorter-lived and less dangerous isotopes following neutron exposure in the blanket. The target couples the high-intensity proton beam to the sub-critical assembly and is a crucial part of the system. The target must convert the proton beam to neutrons (via spallation reactions) with good efficiency (n/p>>1) and produce a neutron spectrum that couples well to the blanket. The target is in an intense broad-spectrum radiation field at relatively high temperature. Heat produced by the incident proton beam must be removed at a rate sufficient to maintain the integrity of the target. The environment of the target is very stressful on the target materials.

Preliminary blanket designs have been developed for the US Transmutation of Waste program. These designs, although dissimilar in many respects, formed the basis for a single set of target requirements. Based on these requirements, a preliminary investigation of two liquid lead-bismuth eutectic (LBE) spallation target designs was conducted: 1) A right circular cylinder design, and 2) A conical target that allows for better axial distribution of neutrons and better overall neutron/proton ratio. These conceptual designs are presented in this paper, including scoping analysis of thermal/hydraulic performance and neutronic performance analysis (neutrons per proton and flux maps).

II. TARGET REQUIREMENTS

The requirements for the ATW target follow from the parameters of the accelerator and the blanket. The ATW Roadmap[1] guidelines are the basis for preliminary ATW blanket designs summarized below:

1) <u>LANL analysis of an LBE-cooled blanket:</u> The target is 50 cm in diameter and 55 cm long. If the current is adjusted to maintain constant power (840 MW), it must increase from 19 mA at beginning of cycle (BOC) to 67 mA at end of cycle (EOC).
2) <u>ANL analysis of LBE-cooled blanket:</u> The target is 16 cm in diameter with a buffer region (moderator) out to 80 cm in diameter. It is assumed that this 80 cm is LBE.
3) <u>ANL analysis of Na-cooled blanket:</u> The target is 16 cm in diameter with a buffer region out to 80 cm diameter. It is assumed that this 80 cm is LBE.
4) <u>LANL analysis of He-cooled blanket</u> The General Atomics reactor design geometry is used, which allows for a hexagonal target 14. 2” (40 cm) across the flats.
5) <u>ANL analysis of He-cooled blanket:</u> The General Atomics reactor design geometry is used, which allows for a hexagonal target 14. 2” (40 cm) across the flats. The blanket is 8 m in length with axial neutron distribution as uniform as possible.

The preliminary ATW target design requirements were based on these five blanket designs. The proton beam power at EOC for a typical burner is assumed to be 30 MW (30mA at 1GeV). The resulting beam current distribution is assumed uniform with a current density of 30 $\mu A/cm^2$. This beam current assumption results in a beam cross sectional area of 1000 cm^2. With an approximate energy deposition factor of 0.5, the resulting thermal energy deposited in the target is 15 MW.

It is desirable that the neutron distribution be axisymmetric and as uniform as possible over the length of the core to simplify core management issues. Typical core length is taken to be 2 m. The neutron spectrum should be appropriate to efficiently initiate a fission chain and drive a sub-critical assembly. In order to minimize beam power requirements, the target needs to have high neutron production efficiency. One of the blanket designs mentioned previously is based on 25 neutrons per proton (n/p). The ATW Roadmap specifies a neutron production efficiency of 27 n/p. For this study, therefore, the target design requirement is at least 25 n/p.

Based on a circular cross-section beam with an area of 1000 cm^2, a target diameter of approximately 36 cm is required. The target geometry has to provide for good coolant flow to remove the deposited thermal energy. Also, the target should be shaped to withstand thermal and mechanical stresses. The beam may be vertical or horizontal but it is assumed that the target is aligned axially with the beam. In addition, this target must be replaceable with remote handling equipment.

The desired operational life of the target has not been determined. At present, the ATW target should be designed to have the longest possible operational life. In order to extend the target service life, its design should utilize reliable components and materials. All instrumentation must be able to operate in beam for the projected life of the target. Backup instrumentation, pumps, and valves may be necessary. The structural design has to withstand thermal stress and thermal cycling. The geometry has to be optimized to provide sufficient coolant flow to remove the deposited heat.

Materials should maintain their integrity for the operational life of the target. All materials must perform under the proton and neutron radiation that will be present in the target. Typically, one would place the material radiation damage limit at 40-50 dpa, never to exceed 100 dpa. Based on fission irradiation experience and estimated radiation damage rates for different target materials, one can say that the lifetime of the target structure, particularly the window and the solid target material, is limited to less than 2 years. However, the spallation process produces hydrogen and helium at much higher rates than in the fission environment (up to 100 times faster). The exact response of materials to such radiation damage has just begun to be studied.

Spallation products have to be contained during and after operation. The target coolant also has to be contained. The target materials have to maintain their integrity for the life of the target. Adequate heat removal must be provided in the target and the auxiliary systems. If necessary, a decay heat removal system should be included in the target design. Adequate temperature measurement must be provided at critical points in the target system. Reliable monitoring of the coolant and cover gas conditions must be made, including pressure, contents, temperature, and flow speed. Backup equipment may be necessary to ensure reliable operation of the target. As mentioned earlier, remote handling of the target and its auxiliary systems is necessary.

III. LBE TARGETS FOR ATW

Because the thermal/hydraulic performance of LBE is excellent and LBE is both coolant and spallation target, the target design is an exercise in arranging the LBE in such a way as to provide optimum neutron production and distribution in a containment that is feasible to fabricate. The designs suggested below describe some possible configurations. These designs are not optimized. More detailed descriptions of these target designs, as well as sodium and helium tungsten targets, can be found in Reference 2.

Table 1. Advantages and Disadvantages of Lead-Bismuth Targets

Advantages	**Disadvantages**
1. Molten target, eliminates cooling problems and simplifies structure. 2. Good heat transfer properties. 3. Good neutron production/low neutron absorption. 4. Moderating properties. 5. Gamma shielding. 6. Low vapor pressure. 7. Excellent free convection potential for decay heat removal. 8. Solidifies on breach of target, minimizing spread of contamination. 9. Acts a beamstop with long grace time in loss-of-flow event. 10. Low pressure system.	1. Corrosion control requires passivation, technology well developed in Russia but unproven in US. 2. RCRA material. 3. Limited experience in the US with the design, operation, and maintenance of auxiliary systems. 4. Solid at room temperature. 5. No data on material compatibility with high-energy protons. 6. ^{208}Po spallation product (alpha emitter), and others.

LBE has very high useful neutron production efficiency from spallation reactions (30 neutrons per proton per GeV) and extremely low neutron capture cross section. The neutron transparency of LBE allows for a more widely spaced core with relatively low pressure drop and pumping power requirements. The coolant is also self-shielding against gamma radiation. Because of the unique nature of ^{208}Po (the most abundant lead isotope) and the high atomic weight and neutron transparency of both lead and bismuth, neutrons in LBE have a small average lethargy. LBE makes an ideal reflector and "storage medium" for neutrons and thus is ideally suited for transmutation applications. The integration of nuclear coolant, spallation target, and reflector using the same fluid in the ATW LBE target concept drastically simplifies the subcritical burner design by streamlining the flow configuration and by removing target and reflector structures.

The simplest target geometry is a cylindrical vessel with the axis of symmetry oriented along the beam line. A cylindrical target with a diameter of 40 cm and a length of 54 cm is consistent with the imposed requirements. LBE enters the target vessel near the window, flowing downward (assuming a vertically entering beam) across the window and into a central channel, which constitutes the body of the target. Return flow is through an annular space surrounding the target. Window cooling is accomplished by organizing the LBE flow to accomplish that task before entering the target proper. Alternatively, a double-wall window design could be used, comprised of two hemispherical segments separated by an appropriate gap that forms a coolant channel. The window coolant in this case need not be LBE, but LBE is an excellent heat transfer fluid and its use for window cooling eliminates the need to introduce another fluid and associated equipment. As will be discussed later, the neutron production efficiency for this geometry is about n/p=18.5. This is too low for ATW requirements; however, the design dimensions have not been optimized. A longer target of smaller diameter can be expected to increase the neutron production efficiency to acceptable levels. The flux maps below show high proton loss from the target, indicating poor conversion due to the geometry.

Neutronics performance can be optimized in a more elongated target, with reduced LBE thickness at any axial location. A conical target configuration meets this requirement in the simplest possible manner. As shown in Figure 2, the target is constructed of 3 nested cones, the outer and inner cones forming the containment boundaries of the target and the center cone providing a flow divider. The LBE flows in at the top, open end of the cones, then down the channel formed by the inner and central cones toward the apex of the inner cone. The central cone is truncated near the apex so that LBE can flow through the resulting opening and into the channel formed by the central and outer cones. The radius of the outer cone's apex has been increased to facilitate good LBE flow.

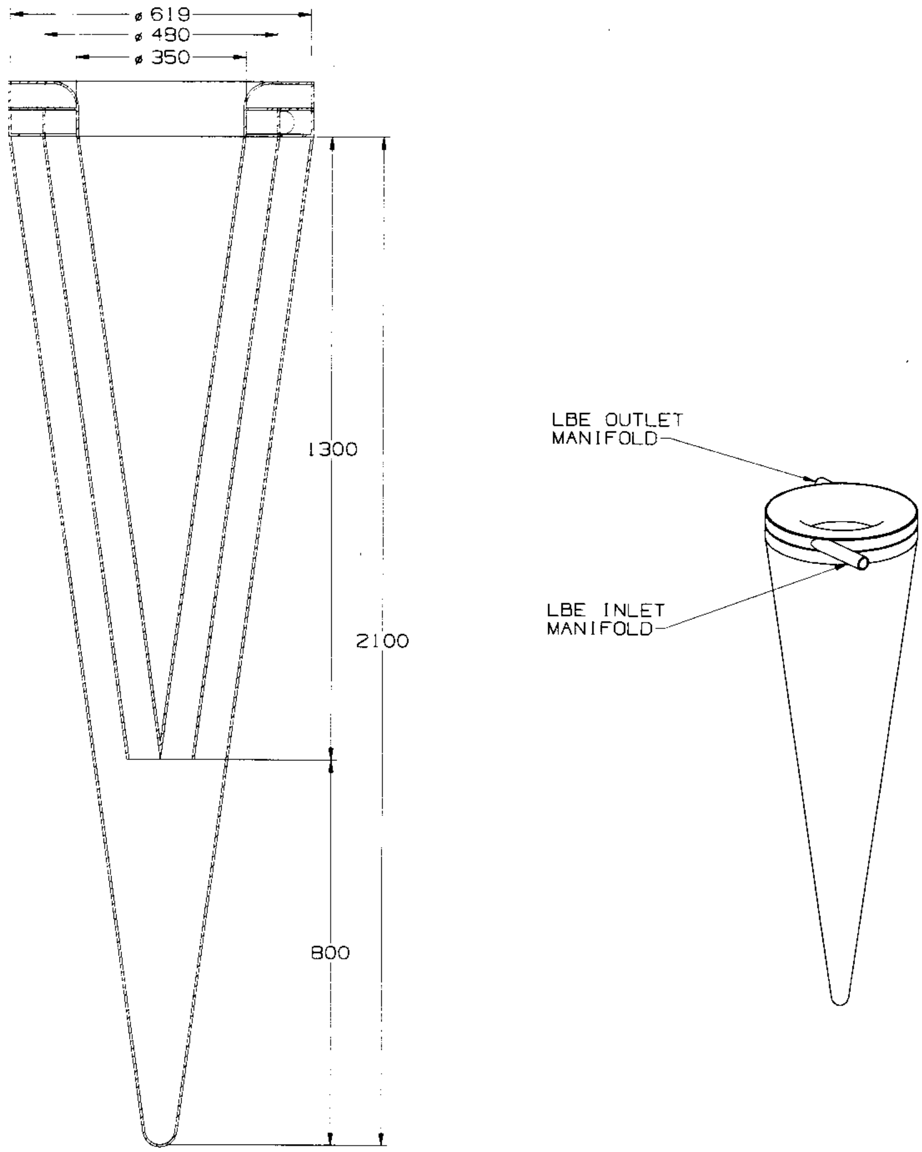

Figure 2. LBE Conical Target Configuration.

The cone angle is dictated, in part, by the neutron distribution requirements of the blanket. A 2.25-meter-long target is shown in Figure 2. The LBE thickness in the beam direction must be stopping length or more, while the thickness normal to the beam is kept small (by increasing cone angle) to minimize neutron absorption, but large enough to maximize utilization of protons. The target in Figure 2 has 100-cm target thickness in the axial direction and 10-cm radial thickness. The resulting neutron production efficiency is n/p=30. Again, this design has not been optimized.

The window of this target is the inner cone surface. A steep cone angle reduces the heat flux at the wall, reducing cooling requirements considerably. The coolant enters at a velocity of about 1 m/s and accelerates as it flows through the converging channel. In order to prevent excessive velocities near the apex of the target, some flow must be diverted to the outer, return channel through a hole pattern in the central, dividing cone. The simplified design shown schematically would need to be modified to prevent stagnation at the tip of the outer cone. Detailed design studies and experimental validation would be required. LBE velocity at the apex would be limited to about 3 m/s to avoid unnecessary pressure loss. Because of accelerating flow, boundary layers are never fully developed. This effect augments heat transfer so that standard correlations become bounding conditions. Experimental work would be necessary to establish effective heat transfer rates. In Table 2, characteristic design numbers for this conical target geometry are listed.

Table 2. Characteristic Conditions of a Liquid Lead-Bismuth Eutectic Conical Target (axial target thickness of 100 cm, radial thickness of 10 cm)

Total thermal power, maximum, MW	15
LBE inlet temperature, ºC	200
LBE outlet temperature, ºC	400
LBE density, kg/m^3	10400
LBE kinematic viscosity, m^2/s	1.5x10^{-7}
LBE specific heat, J/kg K	146.5
LBE mass flow rate, kg/s	512
LBE inlet mean speed, m/s	0.56
LBE mean speed near apex, m/s	3.5
Target max diameter, m	0.62
Target max cross sectional area, m^2	0.302
Target length, m	2.3
Nominal heat transfer coefficient, W/m^{2}K	5000
Peak volumetric heating, W/m^3	3.82x10^7
Estimated window heat flux, W/m^2	5.01x10^6
Peak ?T (target wall-to-fluid), ºC	140

It is expected that this conical target design can be modified for more uniform axial neutron production by replacing the conic sections by paraboloids, since a parabolic cross-section presents a constant target surface area to the beam. This enhancement would come at considerable fabrication complexity.

IV. NEUTRONICS OF LBE TARGETS

The neutron and proton fluxes from a non-optimized, cylindrical target are shown in Figures 4a and 4b. Neutron production efficiency for this geometry (54-cm long, 40-cm diameter) is n/p=18.5. Increased length would reduce proton streaming from the back of the target, and a smaller beam spot diameter relative to target diameter would reduce proton flux radially. Such a target could be optimized to meet or exceed ATW neutron production requirements.

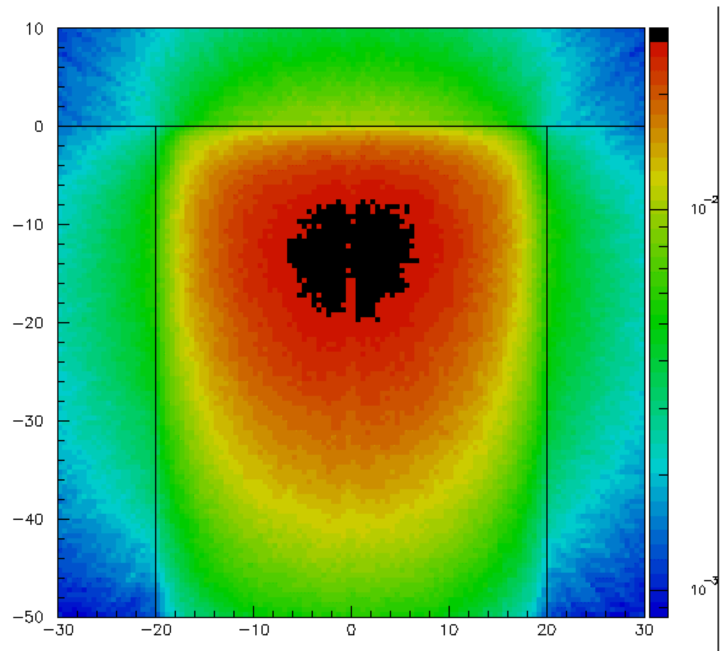

Figure 4a. Neutron Flux from a Cylindrical Target, 54-cm long and 40-cm diameter.

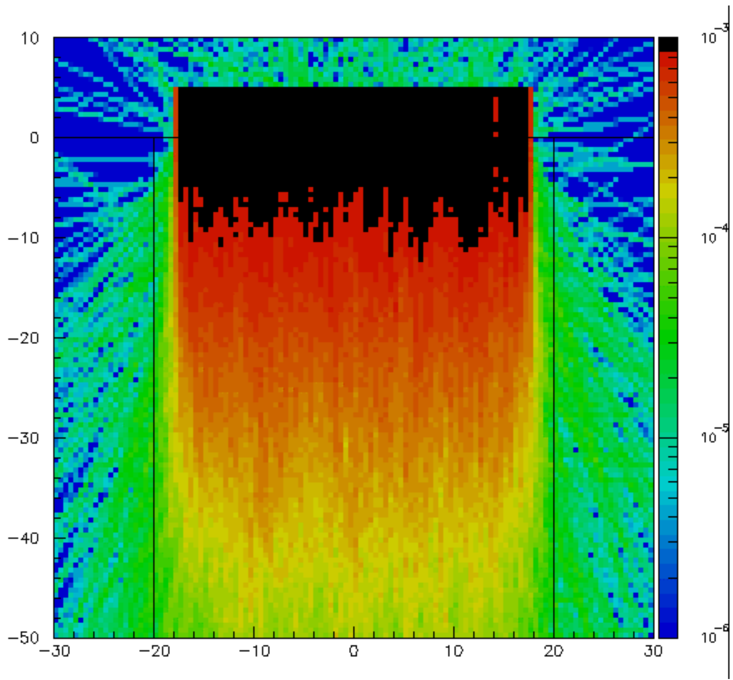

Figure 4b. Proton Flux from a Cylindrical Target, 54-cm long and 40-cm diameter. The large number of escaping protons suggests that geometric changes, such as smaller beam spot and longer target, will increase neutron production. Neutron production efficiency for this target is n/p=18.5.

The conical LBE target was also modeled. In a conical geometry, the source material is flowing between the nested cones. A cutaway view is given in Figure 5. This geometry distributes the neutron production along the length from a circular beam of uniform density. The neutron production efficiency for this geometry is approximately 30.2 n/p. The average flux leaving the cylinder surface at a radius of 30 cm is 6.966x10^{-4} n/cm^2 per proton. For a 30 mA source beam, this works out to 1.3x10^{14} n/cm^2/s. The spectra are given in Figure 6. The peak of the neutron energy distribution is at 2 MeV. Figures 7 and 8 illustrate the proton and neutron flux distributions from this conical target geometry.

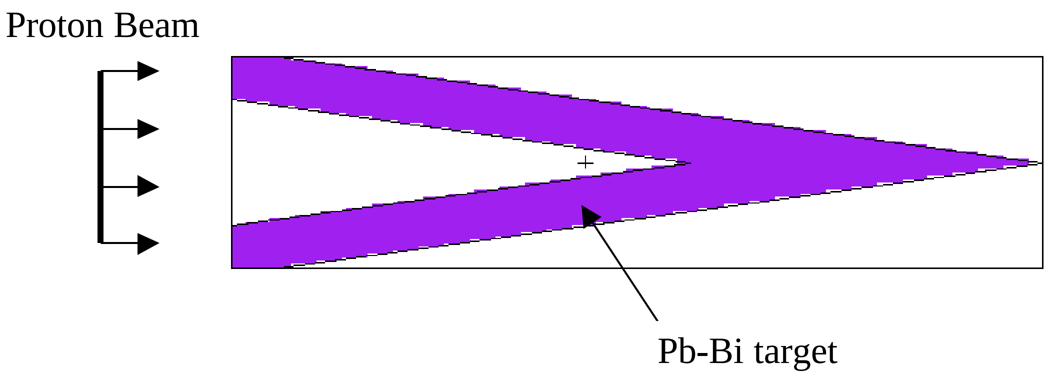

Figure 5. Pb-Bi Target Geometry Showing the Nested Cones that Contain the Target Material. No material is present outside of the cones.

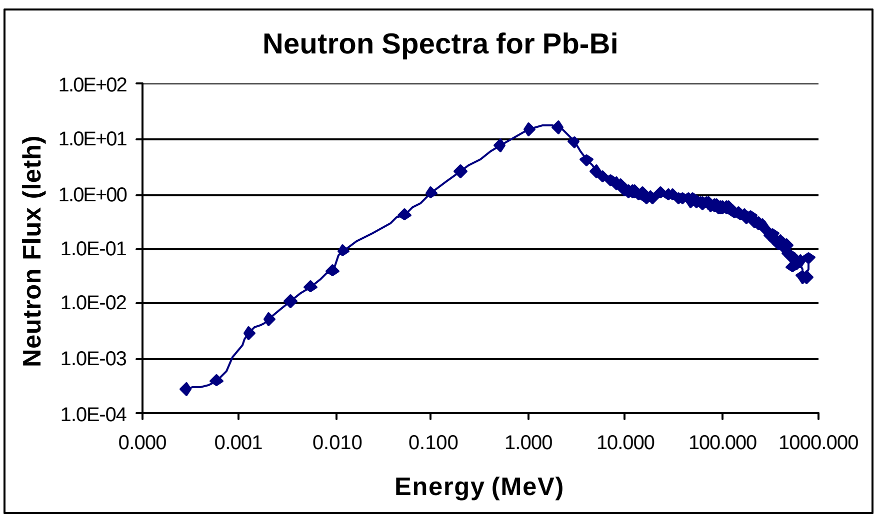

Figure 6. Neutron Spectra in Lethargy Units.

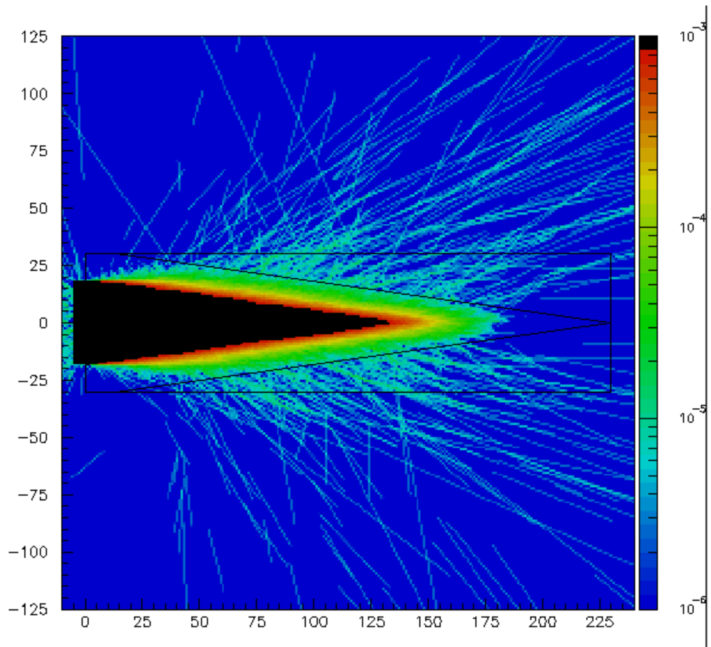

Figure 7. Proton Flux Distribution for Conical Pb-Bi Target.

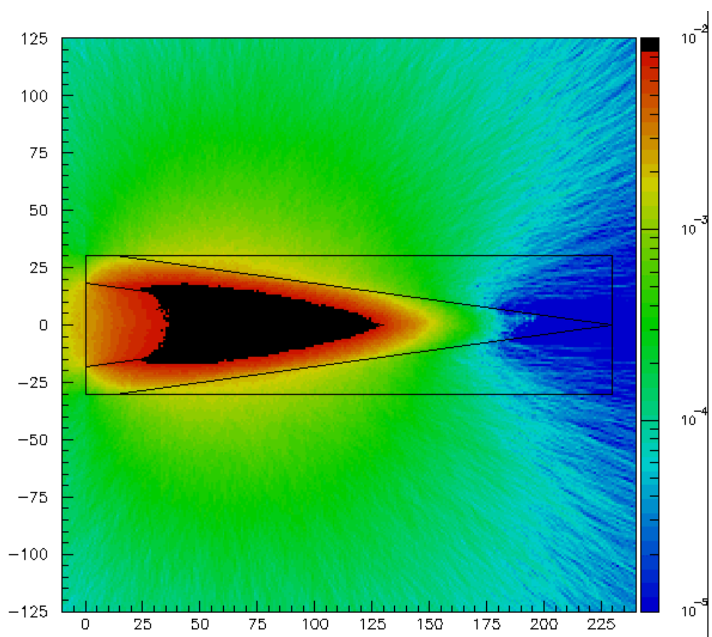

Figure 8. Neutron flux Distribution for Conical Pb-Bi Target.

References

1) "A Roadmap for Developing Accelerator Transmutation of Waste (ATW) Technology: A Report to Congress", October 1999, DOE/RW-0519.
2) K. WOLOSHUN, S. WENDER, et. al., "Preliminary Assessment of Spallation Target Options for Accelerator-Driven Transmutation" Los Alamos National Laboratory Report Number LA-UR-01-1634, March 2001.