Lead-Bismuth-Eutectic Spallation Neutron Source for Nuclear Transmuter

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Abstract

A lead-bismuth eutectic (LBE) spallation target design concept has been developed for the subcritical multiplier (SCM) design of the accelerator-driven test facility (ADTF). The design is based on a coaxial geometrical configuration, which has been carefully analyzed and designed to achieve an optimum performance.

The target design description, the results from the parametric studies, and the design analyses including neutronics, heat transfer, and hydraulics analyses are given in this paper. A detailed MCNPX geometrical model for the target has been developed to generate heating rates and nuclear responses in the structural material for the design process. The beam has a uniform distribution of 600 MeV protons and 5-MW total power. A small LBE buffer is optimized to reduce the irradiation damage in the fuel elements from the scatter protons and the high-energy neutrons, to maximize the neutron yield to the SCM, and to provide inlet and outlet manifolds for the LBE coolant. A special attention has been given to the target window design to enhance its lifetime. The window volumetric heating is 766 W/cm^3 relative to 750 W/cm^3 in LBE for a 40-μA/cm^2 current density. The results show that the nuclear heating from the proton beam diminishes at about 32 cm along the beam axis in the LBE target material. The neutron contribution to the atomic displacement is in the range of 94 to ~100% for the structure material outside the proton beam path. In the beam window, the neutron contribution is ~74% and the proton beam is responsible for more than 95% of the total gas production. The proton contribution to the gas production vanishes outside the beam path. The LBE average velocity is ~2 m/s. The heat transfer and the hydraulics analyses have been iterated to reduce the maximum temperature and the thermal stress level in the target window to enhance its operating life.

I. Introduction

A lead-bismuth eutectic (LBE) spallation target design concept has been developed for the subcritical multiplier (SCM) design of the accelerator-driven test facility (ADTF). The ADTF is a major nuclear research facility that will provide multiple testing and production capabilities. The main ADTF mission includes the capability to assess technology options for the transmutation of spent nuclear fuel and nuclear waste through proof-of-performance demonstrations; the ability to operate as a user facility that allows testing advanced nuclear technologies and applications, material science and research, experimental physics, and conventional nuclear engineering science applications; the capability through upgrades to demonstrate tritium production for defense purposes, if it is required; and the capability, through upgrades to produce radioisotopes for medical and commercial purposes.

Multiple experimental target stations are envisioned to accommodate the above mission. The principal target station consists of a spallation target and a SCM with a power rating up to 100 MW. This SCM will provide the prototypic environment necessary to support the transmutation proof of performance. In addition, a target and material test station will be used to test a wide range of target designs, fuels, and coolants, which will help developing components for the SCM. The work presented in this paper is intended to study and design an LBE target for the SCM.

The spallation target design is based on a coaxial geometrical configuration to satisfy the SCM configuration requirements and to minimize the space requirements. The target is installed vertically along the SCM axis. The inlet and the outlet manifolds and the proton beam are entered from the top above the SCM. The flow cross-section area is maintained at a constant value along the axial direction to obtain a constant average velocity, which improves the target hydraulics design. The geometrical configuration has been carefully designed to insure flow stability and adequate for cooling the structure material. Target design objectives and constraints were defined and utilized in the design process. Physics analyses were performed using the Monte Carlo code MCNPX [1] to account for the geometrical details, the spallation process, and the transport of the different spallation products. Parametric analyses were performed to study the neutron yield, the neutron energy spectrum, the buffer size between the target and the subcritical multiplier, and the nuclear responses in the beam window. Also, the neutronic performance of the SCM with MK-III EPR-II fuel was analyzed with the target to define the fast neutron flux and the energy deposition in the system. The fast neutron flux is a key performance parameter for testing nuclear fuel. The energy deposition is calculated to check that the fuel is operating within its design window. Thermal hydraulics analyses were performed to define the flow stability and the velocity distribution of the LBE and the temperature distribution in the target structure. Also, the hydraulics results were used to update the geometrical configuration to improve the flow stability. The design constraints and the analyses performed to reach the current design are discussed in this paper. Also, the design and its parameters are presented.

II. Target Design Objectives and Constraints

The main objective of the target design is to generate the required neutron source to operate the SCM. The neutrons are generated from the spallation process driven by the 600-MeV proton beam. The beam has a total power of 5 MW and it has a uniform spatial distribution over the beam cross-section area. The SCM design requires a small target diameter to simplify the fuel and the target replacement procedures, to reduce the neutron losses in the vertical direction, to reduce the shield volume, and the required number of the SCM fuel assemblies for a specific power level. On the other side, the structural material and the heat transfer considerations require a large beam diameter to reduce the power and the irradiation damage densities in the beam window. A 40 μA/cm^2 current density was selected as a compromise to satisfy the engineering requirements for the window design and to extend its operating live without a significant impact on the SCM design. The other main objectives for the target design are to protect the SCM from the high-energy protons and neutrons, to contain the spallation products, to contribute for achieving the availability goal of the facility, and to fail safe to avoid long shut down time for target replacement. Also, the target has to generate a uniform neutron source along the SCM axis as much as possible to minimize the SCM power peaking.

Several design constrains are imposed on the target design process to satisfy different engineering requirements and to minimize the design development time and cost. Existing structural materials, ferritic steel (HT-9) and type 316 stainless steel are used for the target design. LBE is used as a target material and coolant to simplify the design. The surface temperature of the structural material in contact with the LBE is limited to less than 550 ºC to avoid any corrosion problem. This temperature limit assumes that the coolant chemistry is closely controlled to maintain an oxide layer on the structural surface for corrosion protection. The stress analysis of the irradiated structural materials limit the maximum temperature to less than 550 and 600 ºC for HT-9 and type 316 stainless steel, respectively. Also, the average coolant velocity is limited to ~2 m/s based on the current database to avoid any erosion/corrosion problems. Also, the coolant pressure is minimized to avoid high primary stresses in the structural material. The coolant inlet temperature is 200 ºC, which provides adequate design margin above the LBE melting point of 129 ºC. The outlet temperature is constrained by the maximum allowable temperature for the structural material. Heat conduction to the SCM sodium coolant and/or natural convection are used for decay heat removal as much as possible. These objective and constraints are utilized to develop the current LBE target design presented in this paper.

III. Target Design Description

The target beam has a total current of 8.33 mA distributed uniformly over a circular cross section. The beam radius is 8.14-cm with a current density of 40 μA/cm^2. The beam tube has 10-cm radius to accommodate the halo current. The target window has a conical shape with a rounded tip. However, a hemispherical target window is also under consideration and more discussions about the performance difference are given in the section V. The target tube is enclosed inside two coaxial tubes to provide inlet and outlet manifolds for the LBE target material. The LBE act as a target material and coolant to simplify the design. The radii of these tubes were adjusted to achieve the same average velocity in the inlet and the outlet manifolds. Also, the edge of the inside tube between the inlet and the outlet flow is terminated with a rounded fairing to improve the flow stability. The fairing is tangent to the inlet side surface of the middle wall and extends into the outlet flow field. The geometrical details of the target design are shown in Figure 1. A guard tube is used to enclose the target design. It provides a confined space to check and contain any LBE leakage. Also, this space provides a buffer between the SCM sodium coolant and the LBE. He gas or NaK at low pressure are under consideration to fill this space. Pressure and/or chemical monitors will be used to check for LBE and Na leakage. Ferritic steel (HT-9) is the selected structural material and type 316 stainless steel is the backup. The LBE maintains oxygen concentration in the range of 10^{-4} to 10^{-6} at% to avoid corrosion problems.

IV. Physics Analyses

A detailed MCNPX model was developed that includes the target, the SCM, and the sodium pool to perform target, buffer, parametric, and SCM design analyses. Mark-III EBR-II fuel is used for the SCM. In this model, all the secondary particles are transported and the nuclear responses are tallied. In all the calculations, the fuel loading was adjusted to achieve a total power of 100 MW. The proton beam power is 5 MW and the proton energy is 600 MeV. The beam window has a current density of 40-μA/cm^2.

The first step in the analyses is to define the required target length to stop the protons and the axial energy deposition profile. The calculated energy deposition profile is shown in Figure 2 as a function of the distance alone the beam axis with 0.5 cm thick steel window. The required target material length is 32-cm to stop the 600 MeV protons. The peak energy deposition is 796 w/cm^3 at 1.75 cm from the LBE surface. Table 1 gives the nuclear responses in the target window for iron. In the beam window, the neutrons are responsible for 68% of the atomic displacement and the protons are generating more than 96% of the gas production rate.

The same MCNPX model was used to define the target buffer design taken into consideration the total neutron yield from the target, the SCM neutron utilization, the spallation neutron leakage, and the nuclear responses in the structural material. The analysis was performed as a function of the buffer thickness. The cross section areas required for the inlet and the outlet manifolds define the minimum buffer thickness, which is 7-cm. The results show that the number of spallation neutrons per proton has small sensitivity to the buffer size as shown in Figure 3. It reaches a saturation value at a buffer thickness of ~40 cm. However, the number of spallation neutrons reaching the multiplier is significantly reduced as the buffer thickness is increased. This is shown in Figure 4 where the number drops from 7.8 neutrons per proton with 7-cm buffer to ~3.3 neutrons per proton with 40-cm buffer (the radial component). The neutron leakage is increased as the buffer thickness is increased. This requires the target design to use a minimum buffer thickness. The nuclear responses in the structural material outside the buffer zone are shown in Figure 5 as a function of the reciprocal of the outer buffer radius for a 100-MW SCM power level. These results show that the 7-cm buffer thickness protect the structural material form the radiation damage for more than a full power year. The actual lifetime will depend on the operating temperature of the structural material.

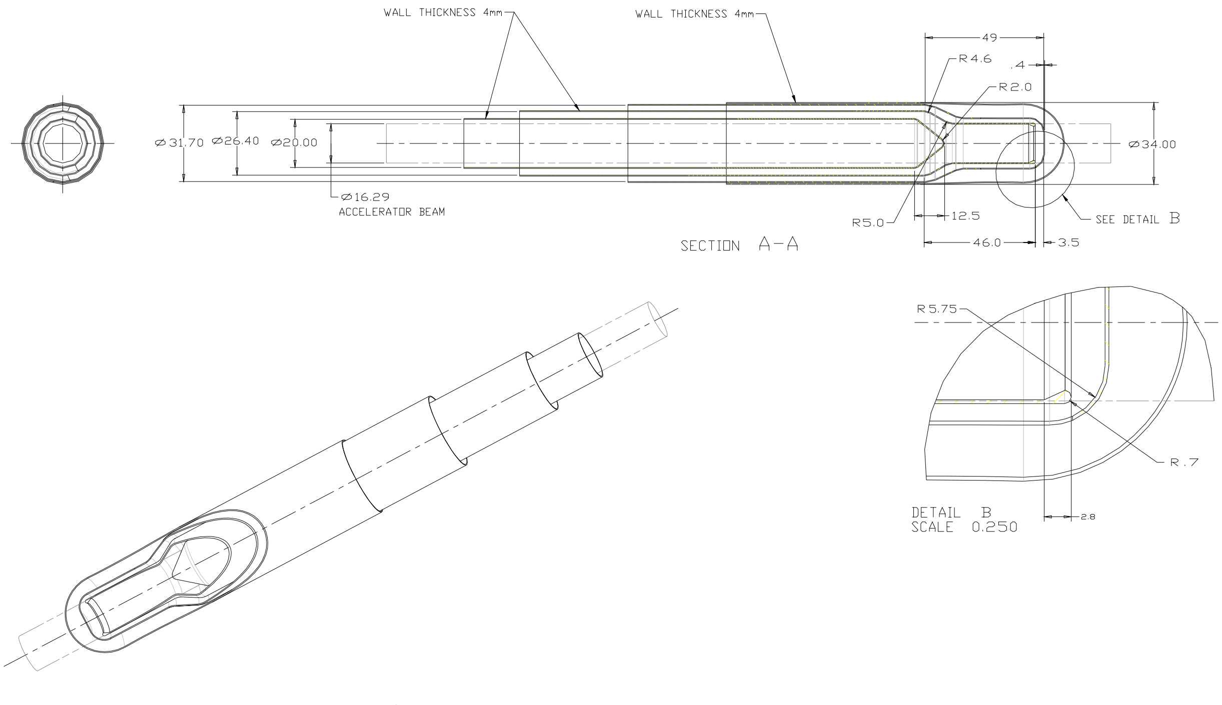

Figure 1. Lead-bismuth eutectic target design

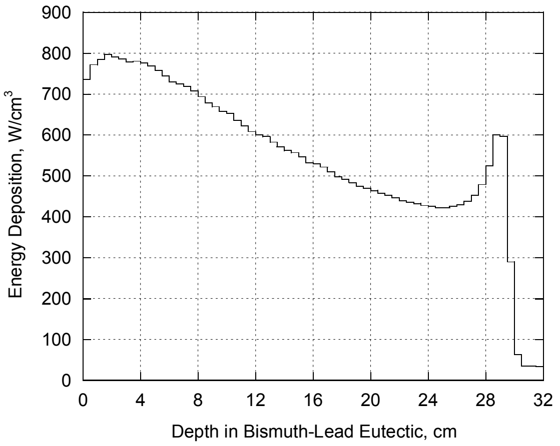

Figure 2. LBE axial energy deposition

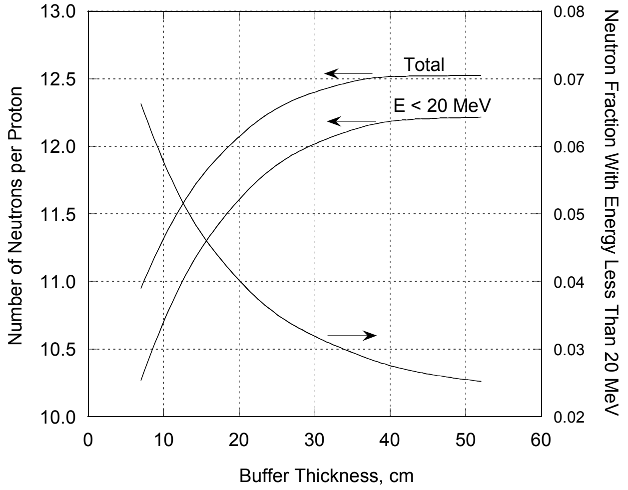

Figure 3. Number of neutrons per proton as a function of the LBE buffer

Table 1. Target Window Nuclear Responses

Energy deposition, W/cm^3	766.49
Atomic Displacement, dpa/y	
Neutrons	46.2
Protons	21.1
Total	67.4
Helium Production, appm/fpy	
Low energy neutrons < 20 MeV	5.7
High energy neutrons > 20 MeV	50.2
Protons	1437.3
Total	1493.2
Hydrogen production, appm/fpy	
Low energy neutrons < 20 MeV	6.3
High energy neutrons > 20 MeV	1010.1
Protons	26753.1
Total	27769.5

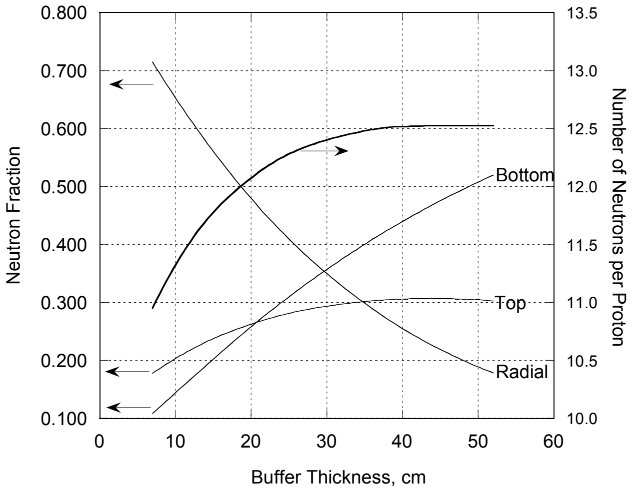

Figure 4. Neutron distribution as a function of the LBE buffer size

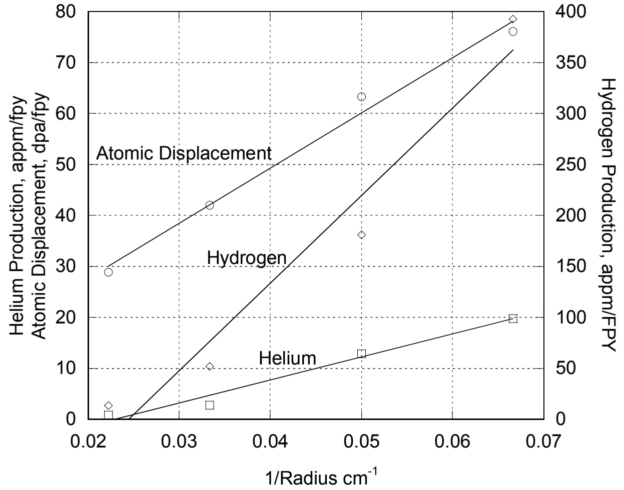

Figure 5. Maximum nuclear responses in the outer buffer iron structure as a function of the outer LBE buffer radius

The target design with the 7-cm buffer is used to calculate the energy deposition distribution for the 100 MW system. Figure 6 shows the power density distribution in the target and the MK-III EBR-II fuel. The beam and the target radii are 8.14 and 15-cm, respectively, which can be seen from the energy profile of Figure 6. The maximum energy deposition is about the same for the target and the fuel. Figure 7 shows the fast neutron flux distribution in the energy range of 0.1 to 20 MeV. The peak fast neutron flux is about 3 x 10^{15} n/cm^2.s, which satisfy the ADTF design requirements.

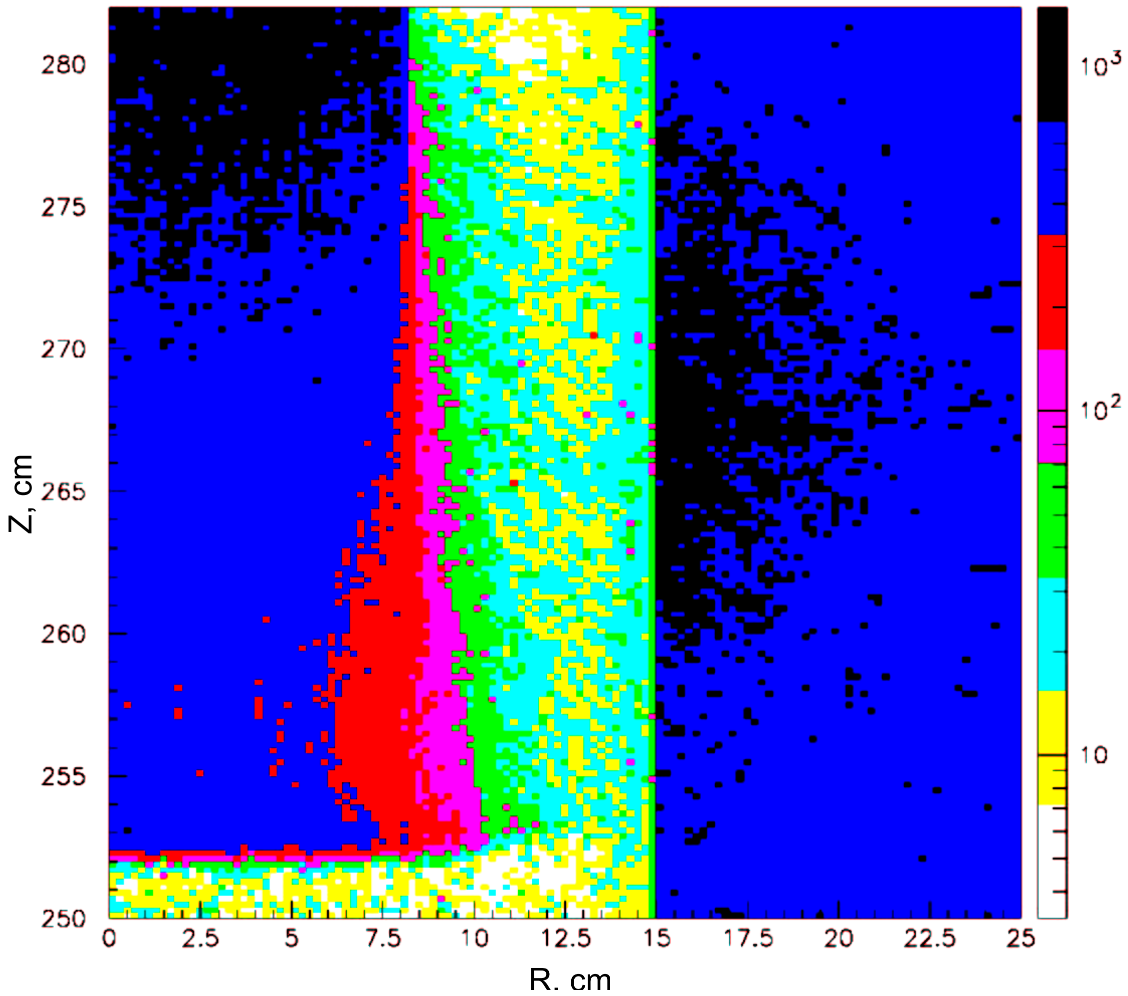

Figure 6. SCM-100 Power Distribution, W/cm^3

V. Thermal Hydraulics analyses

Thermal hydraulics analyses have been performed for the target design using the commercial Computational Fluid Dynamics (CFD) software package Star-CD [2], the geometrical configuration shown in Figure 1, and the heat dissipation distribution calculated by MCNPX. The analyses are based on an axisymmetric model with a total length of 127 cm, which provides a sufficient inlet/outlet length to insure fully developed turbulent flow. The inlet temperature for the target section used in the analyses is 220°C. The heat source is specified in an external user subroutine and it is based on the energy deposition obtained from the MCNPX analyses. The computational mesh is sufficiently refined for accurate prediction of the structural material temperature. The target model consists of three concentric 0.5-cm thick tubes separating two annuli for forced LBE circulation. The LBE flows downward in the outer annulus (inflow), and returns upward in the inner annulus (outflow). The LBE is heated in the spallation zone during its return by the proton beam. Near the spallation zone, the middle and outer tubes get narrower for optimized cooling of the beam window. An inlet average velocity of 2 m/s has been used. Surface temperature exceeding 550°C is considered unacceptable due to increased rate of corrosion. Parametric studies have been performed to minimize thermal stresses that could build up at the beam window.

Alternative configurations have explored including variations in the inlet temperature, the average inlet velocity, a reversal of flow direction, and geometric configurations with varying angles for the conical region of the beam tube. All the results are from converged steady state solutions subject to the boundary conditions.

The calculations used the PISO solution algorithm and upwind differencing methodologies with 50000 cells. The structural material is HT9. The results of the CFD evaluation are shown in Figure 8 as a series of contour plots. The peak temperatures on the adiabatic and wetted surface of the beam window are 696.7°C and 291.5°C, respectively. The peak surface and internal temperatures on the middle wall, or turning baffle, are 310.5°C and 438.4°C, respectively. The mean fluid temperature in the portion of the target considered is 246.9°C. The vector velocity predictions indicate the development of a recirculation zone near the tip of the middle wall, which is eliminated by the use of a rounded fairing at the tip as shown in Figure 1 detail B. For 4 mm thick window structure, the maximum temperature is 548°C, which is quite satisfactory. The final dimensions for the structural material will be based on the stress analyses, which is the subject of another study. The total pressure drop in the target is 32 psi including the contribution from the inlet and the outlet manifolds. The LBE outlet temperature is 280°C.

As an alternative configuration, the cone shaped beam window is replaced with a hemispherical beam window. The computational model is similar to the cone shaped design. The obtained results are compared and the differences are insignificant between the two configurations. Except the cone tip temperature is ~100°C less than the corresponding point for the spherical case. Again, the stress analyses will be used to make the final selection.

VI. Conclusions

An LBE target design has been developed successfully for the SCM station of the ADTF. Target design objectives and constraints were defined and utilized. The design uses a coaxial geometrical configuration. The physics analyses show that the window volumetric heating is about 766 W/cm^3 relative to 750 W/cm^3 in the LBE for the 40-μA/cm^2 current density. The nuclear heating from the proton beam diminishes at about 32 cm along the beam axis of the LBE target material. The neutron contribution to the atomic displacement is in the range of 94 to ~100% for the structure material outside the proton beam path. In the window, the neutron contribution is about 74% and the proton beam is responsible for more than 95% of the total gas production. The thermal hydraulics analyses show that the outlet temperature of LBE is 280°C for an inlet temperature of 200°C. The total pressure drop is 32 psi. The peak temperatures on the adiabatic and wetted surface of the beam window are 548°C and 291°C, respectively, for the 4-mm thick beam window.

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2. Star-CD Version 3.1B, CD-Adapco Group.

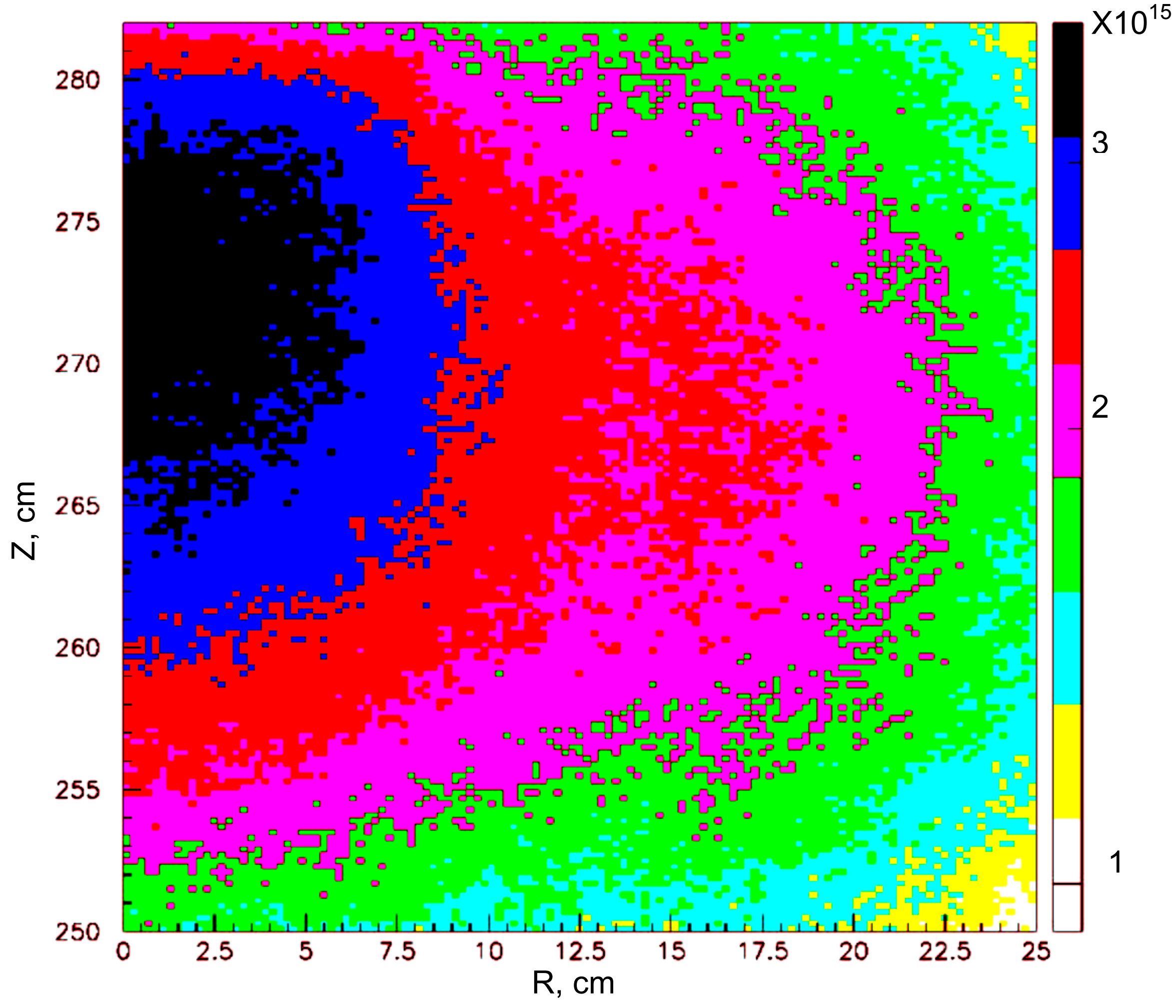

Figure 7. SCM-100 Fast Neutron Flux (0.1 to 20 MeV), n/cm^2/s

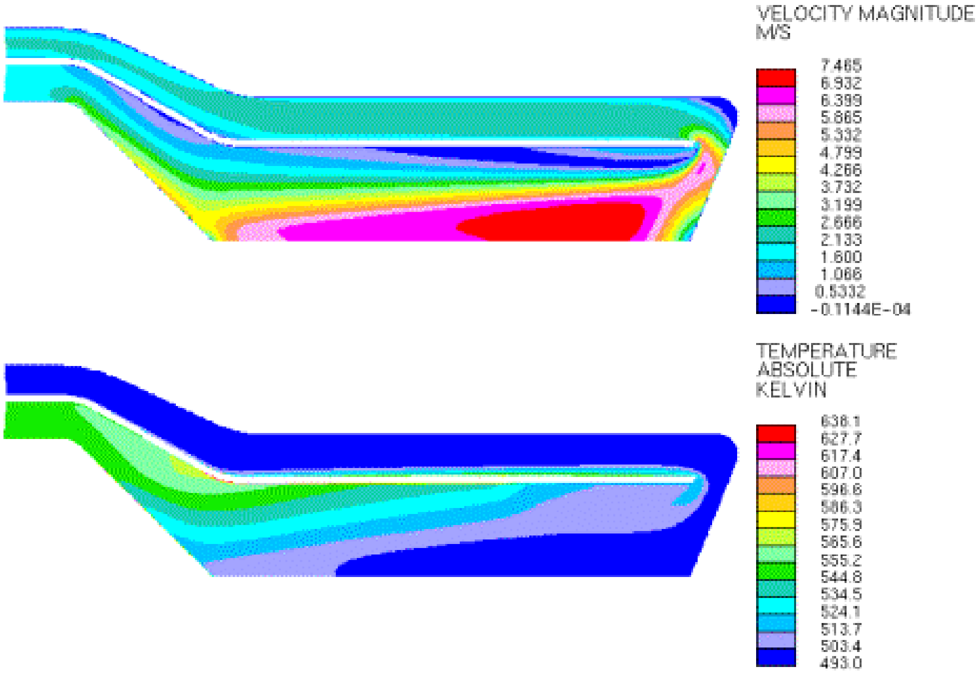

Figure 8. Velocity and temperature Contour plots of CFD results for the LBE