Lead-Bismuth Spallation Target Design of the Accelerator-Driven Test Facility (ADTF)

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Abstract

A design methodology for the lead-bismuth eutectic (LBE) spallation target has been developed and applied for the accelerator-driven test facility (ADTF) target. This methodology includes the target interface with the subcritical multiplier (SCM) of the ADTF and the different engineering aspects of the target design, physics, heat-transfer, hydraulics, structural, radiological, and safety analyses. Several design constrains were defined and utilized for the target design process to satisfy different engineering requirements and to minimize the time and the cost of the design development. Interface requirements with the subcritical multiplier were defined based on target performance parameters and material damage issues to enhance the lifetime of the target structure. Different structural materials were considered to define the most promising candidate based on the current database including radiation effects.

The developed target design has a coaxial geometrical configuration to minimize the target footprint and it is installed vertically along the SCM axis. LBE is the target material and the target coolant with ferritic steel (HT-9 alloy) structural material. The proton beam has 8.33-mA current uniformly distributed and 8.14-cm beam radius resulting in a current density of 40 $\mu A/cm^2$. The beam power is 5 MW and the proton energy is 600 MeV. The beam tube has 10-cm radius to accommodate the halo current. A hemi-spherical geometry is used for the target window, which is connected to the beam tube. The beam tube is enclosed inside two coaxial tubes to provide inlet and outlet manifolds for the LBE coolant. The inlet and the outlet coolant manifolds and the proton beam are entered from the top above the SCM. The paper describes the design criteria, engineering constraints, and the developed target design for the ADTF.

Introduction

Design methodology and spallation target design have been developed to generate the required neutron source for the subcritical multiplier (SCM) 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 transmutation 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, fuel assemblies, and coolants for developing components for the SCM. The work presented in this paper is intended to cover the design methodology and to introduce the SCM lead-bismuth target design.

A design methodology was developed to guide the target design process and to satisfy the target design requirements. Different engineering constraints were also developed to insure satisfactory target performance based on the current experience and the existing database. The physics analyses were performed using the Monte Carlo code MCNPX [1] to account for the geometrical details, the spallation process, and the production and the transport of the spallation particles and the generated photons. The thermal hydraulic analyses were performed to define the velocity distribution and the flow stability of the lead-bismuth eutectic and the temperature distribution in the target structure and the target coolant. The analyses utilized the commercially available Computational Fluid Dynamics (CFD) software package STAR-CD [2] to account for the intrinsic feature of the target design. Structural analyses were performed in conjunction with the thermal hydraulics to check the design compliance with the stress and buckling design criteria developed for the Accelerator Production of Tritium project [3] and the International Thermonuclear Experimental Reactor [4] for irradiated structural materials. The results are used to select the shape and thickness of the beam window to maximize the engineering margins. Radiological analyses were performed to define the spallation products. These products define the radiological toxicity and the decay heat source from the lead-bismuth target material as function of the time after shutdown. The design analyses utilize the decay heat source to check the design performance during normal and abnormal conditions with respect to the maximum allowed temperature for the structural material. Also, the dose rate from the gamma rays of the LBE spallation products was calculated to define the required input for calculating the appropriate time and the shielding requirements for maintaining the target system. All these analyses were iterated to achieve a target design that satisfies the design constraints and the design requirements.

The spallation target design is based on a coaxial geometrical configuration to satisfy the SCM configuration requirements for minimizing the space requirements and to maximize the SCM utilization of the spallation neutrons. The target is installed vertically along the SCM axis. Lead-Bismuth Eutectic (LBE) is the target material and the target coolant. Ferritic steel (HT-9) alloy is the selected structural material for the target based on the current database and the design analyses. Austenitic steel (Type 316 stainless steel) is the second choice. A uniform proton beam is employed to perform the spallation process. The beam power is 5 MW and the proton energy is 600 MeV. The inlet and the outlet coolant manifolds and the proton beam are entered from the top above the SCM. The LBE flow cross-section area is maintained at a constant value along the axial direction to maintain a constant average velocity, which improves the target hydraulic design. The geometrical configuration has been carefully designed to insure flow stability and adequate cooling for the beam window and the structure material. Target design objectives were defined for the design process. Several design constraints are defined and used in the target design process to satisfy different engineering requirements, to minimize the design development time and cost, to insure a satisfactory operating performance, and to maximize the operating lifetime of the target structural material.

Design Requirements, Engineering Constraints, and Design Criteria

The main objective of the target design is to generate the required neutron source to drive 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 beam direction, to decrease the shield volume, and to lower the required number of the SCM fuel assemblies for a specific power level. However, the structural material and the heat transfer considerations require a large beam diameter to reduce the energy deposition and the irradiation damage densities in the beam window. A 40-$\mu A/cm^2$ current density was selected as a compromise to satisfy the engineering requirements for the window design and to extend it's operating life 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 help achieving the availability goal of the facility, and to reduce the shut down time for target replacement during normal and abnormal conditions. Also, the target has to generate a uniform neutron source along the beam axis as much as possible to minimize the SCM axial 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, HT-9 alloy is the selected structural material 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 reduce erosion and corrosion concerns. This temperature limit assumes that the coolant chemistry is controlled to maintain an oxide layer on the structural material surface for corrosion protection. The stress analysis of the irradiated structural materials limits the maximum temperature to less than 550 ºC for HT-9. The average coolant velocity is limited to ~2 m/s based on the current database to avoid erosion and corrosion concerns. The coolant pressure is minimized to avoid high primary stresses in the structural material. The selected 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 back shine shield in the beam tube, natural convection, and radiation to the sodium pool are used for decay heat removal. These objectives and constraints are utilized to develop the target design.

The ability of the target structure to withstand the mechanical and thermal loads is determined by comparing the induced stresses to allowable stresses based on the APT supplemental structural design requirements, the international thermonuclear experimental reactor, and the ASME Code. The allowable stresses take into consideration the change in the mechanical properties due to the radiation exposure. The ANSYS general-purpose finite element code [5] was used with a two-dimensional axisymmetric finite element model for the target. The LBE hydrostatic pressure load and the thermal stresses caused by the temperature gradient in the target structure were used in the ANSYS analysis. The buckling capabilities of the structure were initially evaluated using the ASME code. Then, a nonlinear buckling analysis was performed using ANSYS code.

Design description and Analyses

The proton 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. A hemi-spherical geometry is used for the target window, which is connected to the beam tube. The beam tube is enclosed inside two coaxial tubes to provide inlet and outlet manifolds for the LBE target coolant. The double function of the LBE as a target material and coolant does simplify the design. The radii of these tubes were adjusted to achieve the same average velocity in the inlet and the outlet manifolds. The outer manifold is used for the inlet flow for efficient beam window cooling. 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. It provides a confined space to check and contain any LBE leakage. Also, this space provides a buffer between the SCM sodium pool and the LBE. Helium gas at low pressure is used to fill this space. HT-9 alloy is the structural material. The LBE oxygen concentration is maintained in the range of 10^{-6} to 10^{-4} at% to avoid corrosion concerns.

The beam tube enters the subcritical multiplier building horizontally above the subcritical multiplier. Then the beam is bended 90º to reach the subcritical multiplier. The vertical section of the beam tube is ~14.1 m after the last bending magnet. The coolant manifolds have a vertical length of about 10.1 m before changing direction to connect horizontally with the external section of the LBE loop. Pressurized helium gas is used to heat the target tubes before the target is filled with the LBE material. Also, helium is utilized to drain the LBE using a small vertical tube(s) of ~1-cm diameter, which reaches the target bottom section. In the target replacement procedure, the LBE is drained before the target tubes are disconnected for removal. The overhead crane is used to pull the empty target structure inside a target replacement cask.

Inside the guard tube, chemical and pressure sensors are used to check for Na or LBE leakage to shut down the target operation. This early warning avoids the possibility of mixing the two fluids, which reduces the maintenance down time and improves the safety performance. The beam tube vacuum is also monitored to detect any LBE leakage through the beam window.

The target design analyses were iterated using the design methodology shown in Figure 2. A sample of the results is discussed to highlight the performance parameters of the target design. MCNPX computer code was utilized to calculate spatial neutron distribution shown in Figure 3 and the energy spectrum of the spallation neutrons, the energy deposition in the target material displayed in Figure 4, and the nuclear responses in the beam window given in Table 1. In this target design, the proton beam generates a total of10.3 neutrons per proton from which 7.8 neutrons are utilized for the SCM. In the beam window, the neutrons are responsible for 69% of the atomic displacement and the protons are generating more than 96% of the gas production rate. The neutron distribution peaks at ~12 cm from the upper surface of the lead-bismuth material while the high-energy neutrons (above 20 MeV) peak at ~14.5 cm. The peak to the average is 1.33 and the peak to the minimum is 4.11. The peak energy deposition value is 796 W/cm^3 at 1.75 cm from the LBE surface.

The thermal hydraulic characteristics of the evaluated target geometries were simulated using the commercially available CFD code STAR-CD and the temperature distribution of the target structure was transferred to the structural analyses. The simulation uses a uniform inlet velocity of 2 m/s and an inlet temperature of 220 °C. Sufficient inlet and outlet manifold length is included to insure fully developed velocity and temperature profiles. Velocity and temperature profiles are shown in Figure 5. The peak structural temperature is 501 °C and the maximum LBE interface temperature is 340 °C.

The ability of the target to withstand the mechanical and the thermal loads is determined by comparing the induced to allowable stresses. A stress analysis was performed to develop a beam window configuration, which would satisfy the stress and the buckling criteria. The ANSYS general-purpose finite element code was used with a two-dimensional axisymmetric finite element model for the target. The LBE hydrostatic pressure load and the thermal stresses caused by the temperature gradient in the target structure were used. The buckling capabilities of the structure were initially evaluated using the ASME code. Then, a nonlinear buckling analysis was performed using ANSYS code. Table 2 shows the calculated stresses during operation versus the allowable stresses for HT-9 with 72 dpa [6].

Radiological analyses were performed to define the spallation products. These products define the radiological toxicity and the decay heat source from LBE as function of the time after shutdown. The design analyses utilized the decay heat source to define the design performance during abnormal conditions with respect to the maximum allowed temperature for the structural material. Also, the dose rate from the gamma rays of the LBE spallation products was calculated to define the required input for calculating the appropriate time and the shielding requirements for maintaining the target system. The loss of flow analysis show that the management of the decay heat in the ADTF LBE target design does not require an active engineering system for the decay heat removal [6].

Conclusions

A target design methodology has been developed and successfully utilized for the LBE target of the subcritical multiplier station of the accelerator-driven test facility. In the design process, design objectives and engineering constraints were defined and satisfied. The target design has a coaxial geometrical configuration and HT-9 structural material, which achieves the ADTF design goals.

Acknowledgements

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Table 1. Beam window nuclear responses

Energy deposition, W/cm^3	766.49
Atomic displacement, dpa/y	
Neutrons	46.2
Protons	21.1
Total	67.3
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

Table 2. Calculated stresses and HT-9 allowable stresses for the 3.5 mm spherical beam window

Stress Component	Allowable stress	Calculated Stress (MPa)	HT-9 Allowable (MPa)	Temperature (^oC)
P_M	S_m	23.6	181*	277
P_L+P_B	K_{eff} S_m	24.3	--**	277
P_L+Q_L	S_e	56.9	181	417
P_L+P_B+Q+F	S_{d1}	423.5	--***	500
P_L+P_B+Q	S_{d2}	374.2	386	500

* The allowable is calculated at the maximum temperature (417 C) to be on the conservative side since the S_m value is not available at 277 C

** Larger or equal to Sm

*** Larger than S_{d2}

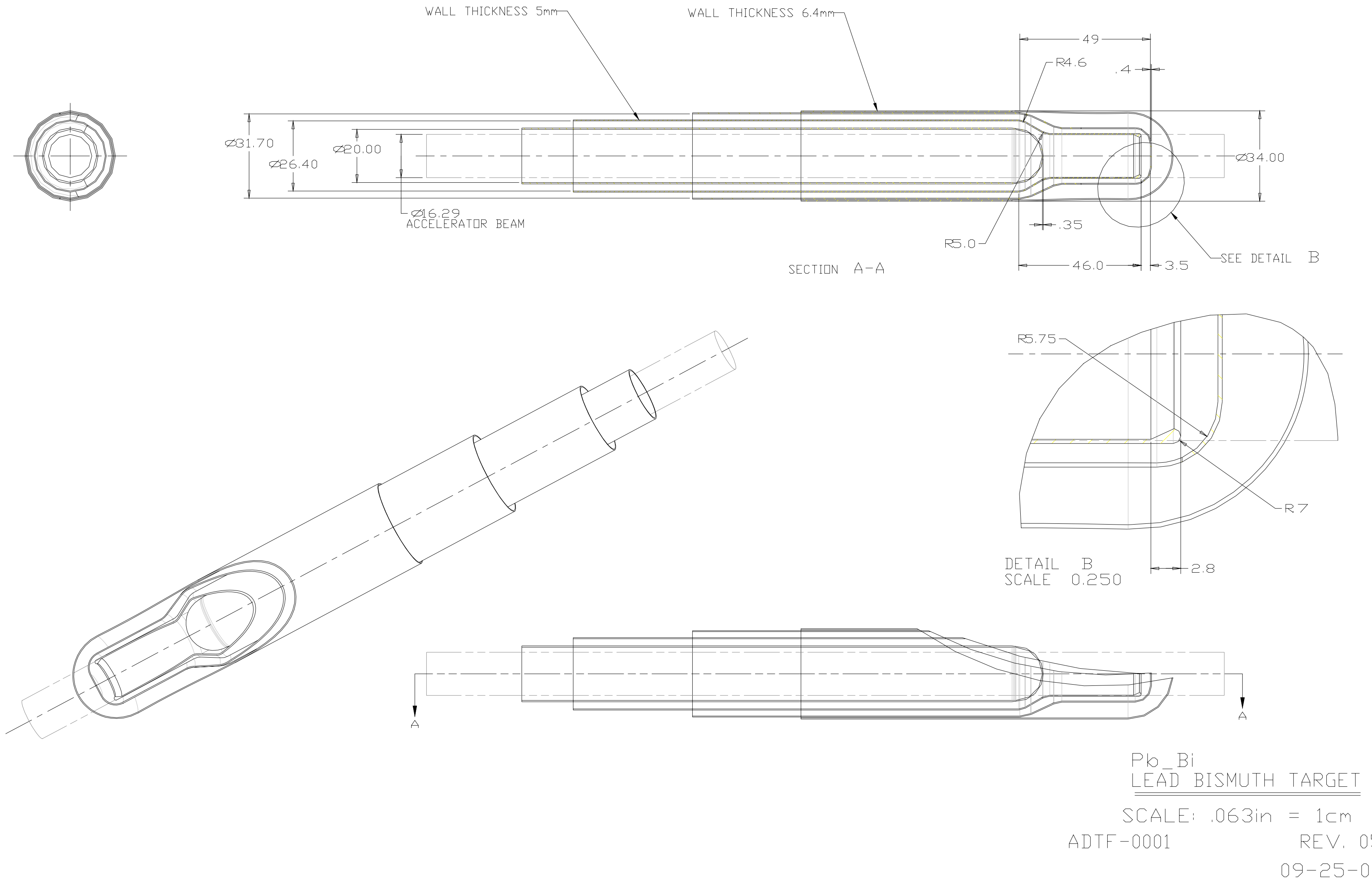


Figure 1. Lead-bismuth eutectic target design

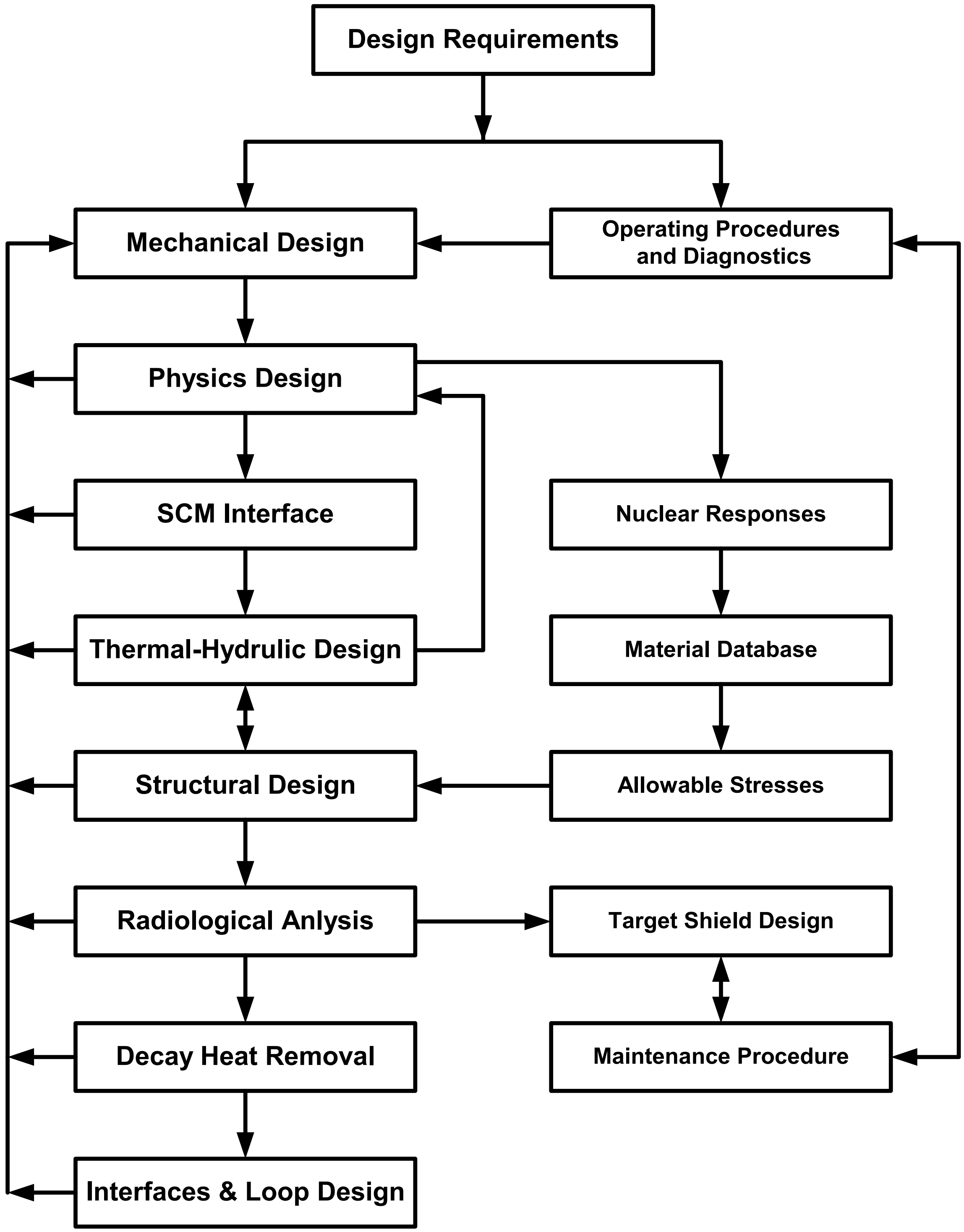


Figure 2. Target Design Methodology

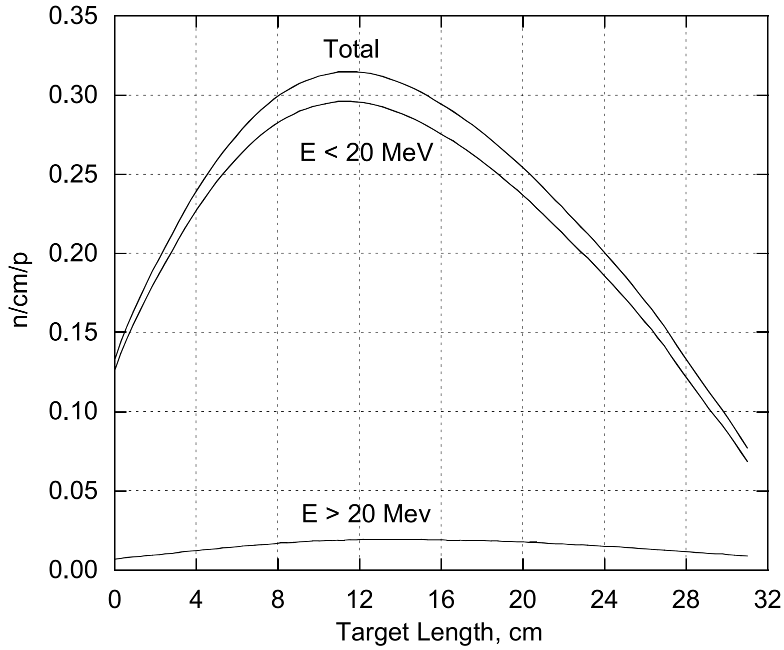


Figure 3. Spallation neutron distribution along the beam axis at the target boundary

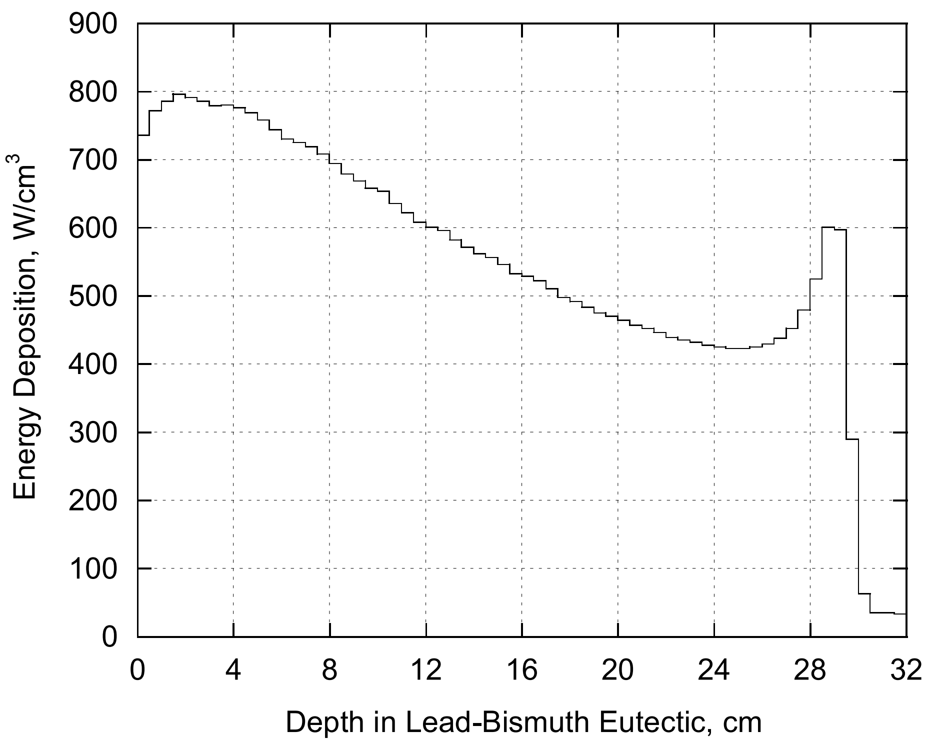
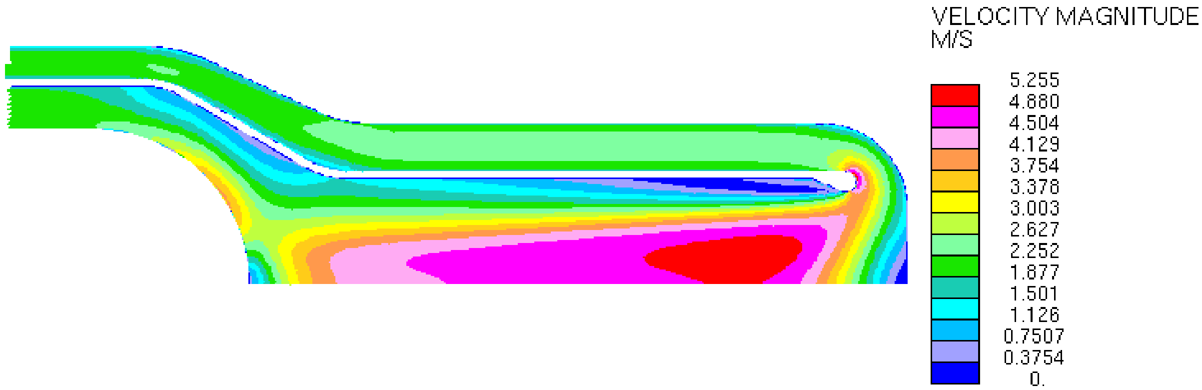
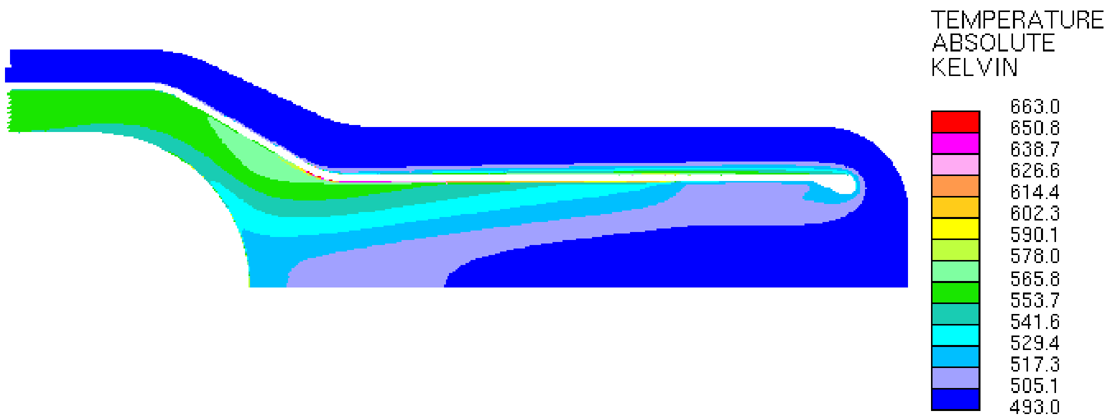


Figure 4. LBE axial energy deposition



(a)



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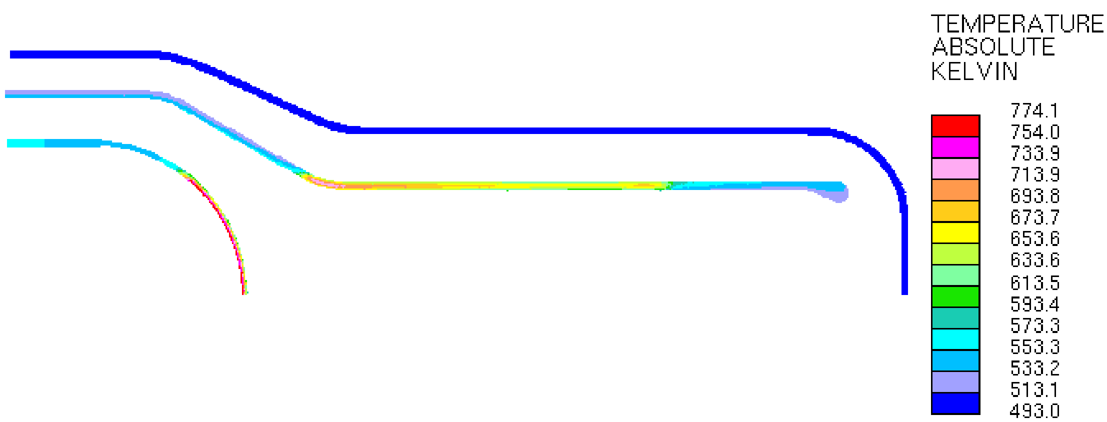

(c)

Figure 5. Lead Bismuth Eutectic Target Contour Plots Showing (a) Fluid Velocity, (b) Fluid Temperature, and (c) Structural Temperature Profiles