LA-UR-16-21214
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Title: Conjugate Heat Transfer and Thermal Mechanical Analysis for Liquid Metal Targets for High Power Electron Beams.

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Intended for: Report

Issued: 2016-02-26

Conjugate Heat Transfer and Thermal Mechanical Analysis for Liquid Metal Targets for High Power Electron Beams.

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Objective

A conjugate heat transfer and thermal structural analysis was completed, with the objective of determining the following: Lead bismuth eutectic (LBE) peak temperature, free convective velocity patterns in the LBE, peak beam window temperature, and thermal stress/deformation in the window.

Conjugate Heat Transfer Analysis

Computation fluid dynamics (CFD) techniques were used to solve the conjugate heat transfer problem using ANSYS CFX. LBE fills the stainless steel reservoir; in addition to the 'hot' and 'cold' legs from the reservoir to the LBE window target region. The overall height of the target apparatus is 68 cm, while the stainless steel reservoir has a height of 17 cm, see Figure 1. A temperature of 140°C was used as a fixed temperature boundary condition in the cold leg and LBE reservoir. A sample of the mesh is shown in Figure 2. The assembly was meshed using approximately 2.6 million nodes.

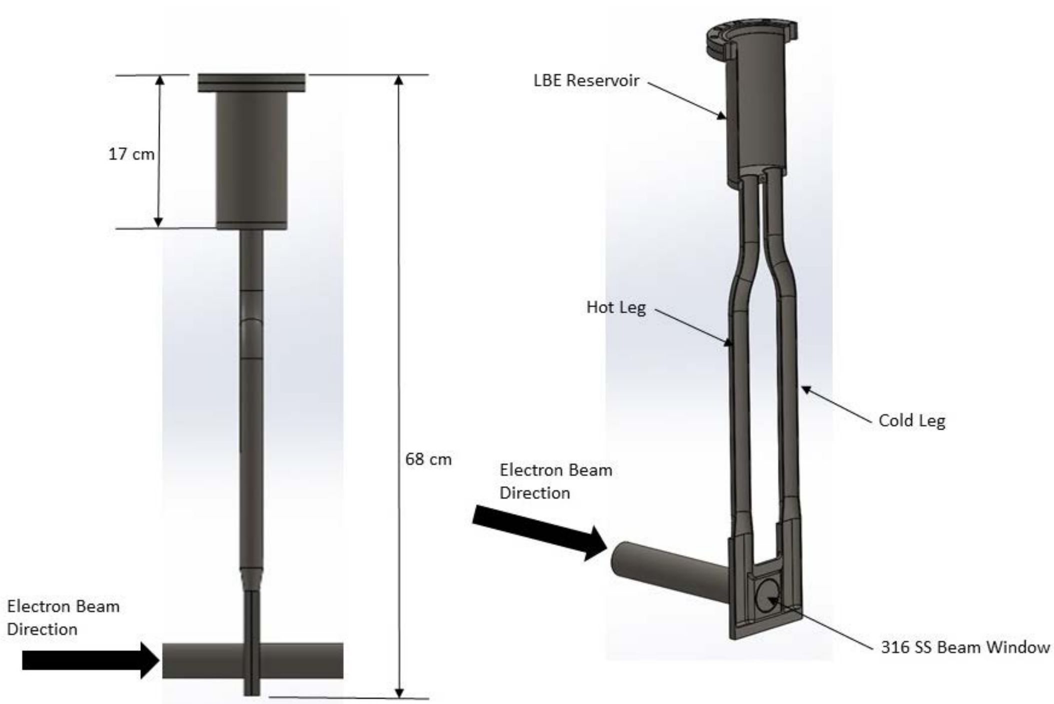

Figure 1. Liquid Metal Target.

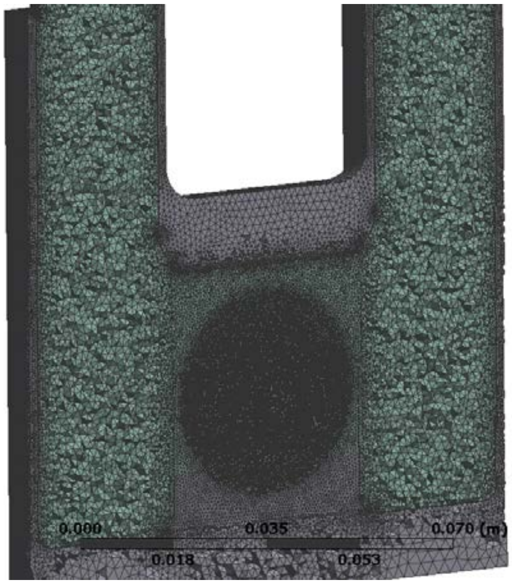

Figure 2. Liquid Metal Target - Mesh.

MCNPX was used (Niowave) to generate volumetric heating in the LBE as a function of radius and axial depth (beam direction) in the LBE domain space, as it is shown in Figure 3.

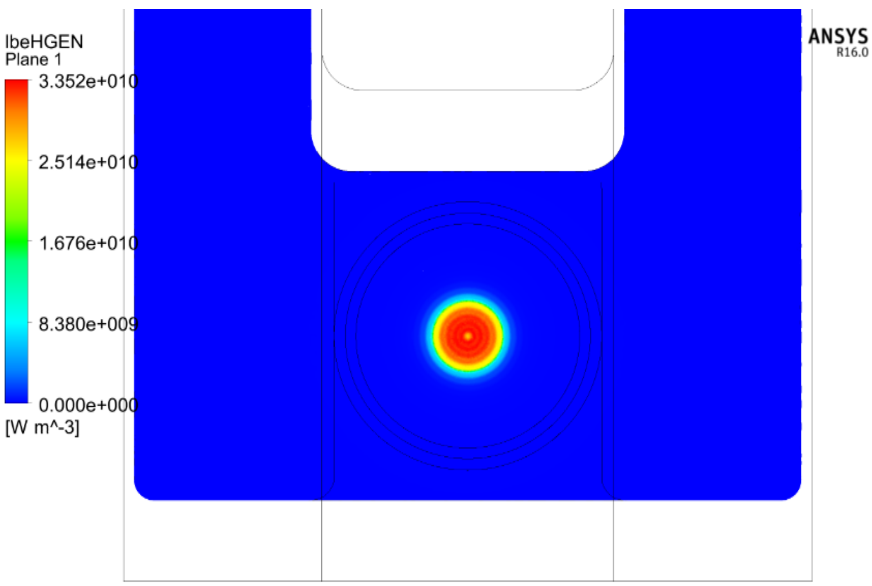

Figure 3. Internal Heat Generation @ 10 MeV and 1 mA.

Results of the LBE Liquid Metal Target CFD analysis are shown in subsequent figures. Figure 4 shows the velocity vectors on the yz plane, while Figure 5 illustrates the velocity streamlines. Regarding convergence, these buoyant flows often don't have purely steady results. Steady state buoyance flows produce a time-averaged solution. In addition to monitoring residual convergence, user defined monitor points were setup to monitor, peak LBE temperature, LBE velocity at points of interest, and heat loss. These additional monitor points aided in determining stable flow conditions. The temperature profiles in the LBE is illustrated in Figure 6 in yz plane. The temperature profile of the stainless steel beam window and vacuum tube are presented in Figure 7.

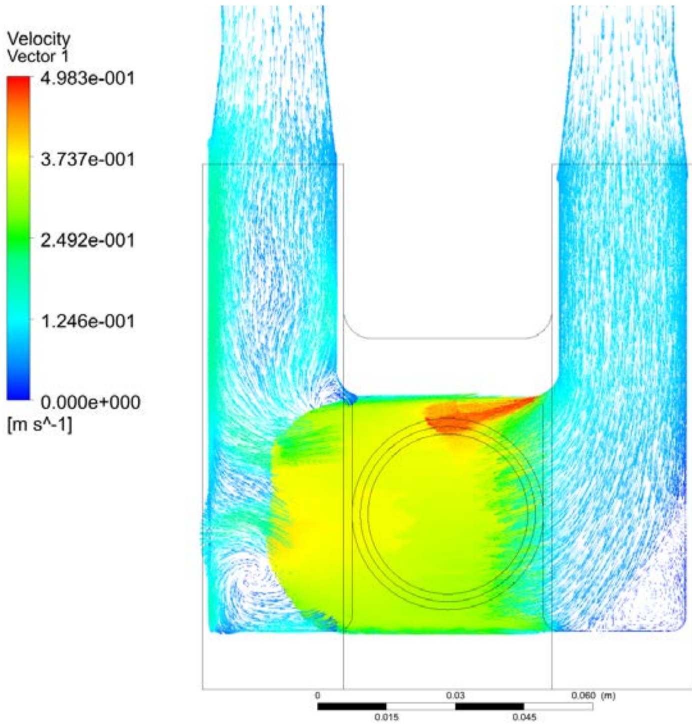

Figure 4. YZ Plane Velocity Vector Plot.

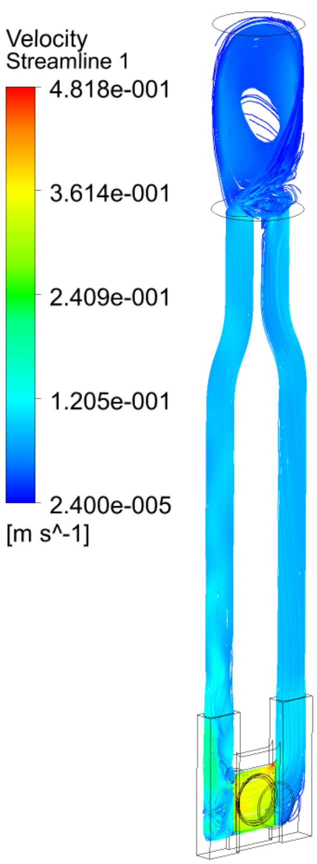

Figure 5. Velocity Streamline Plot.

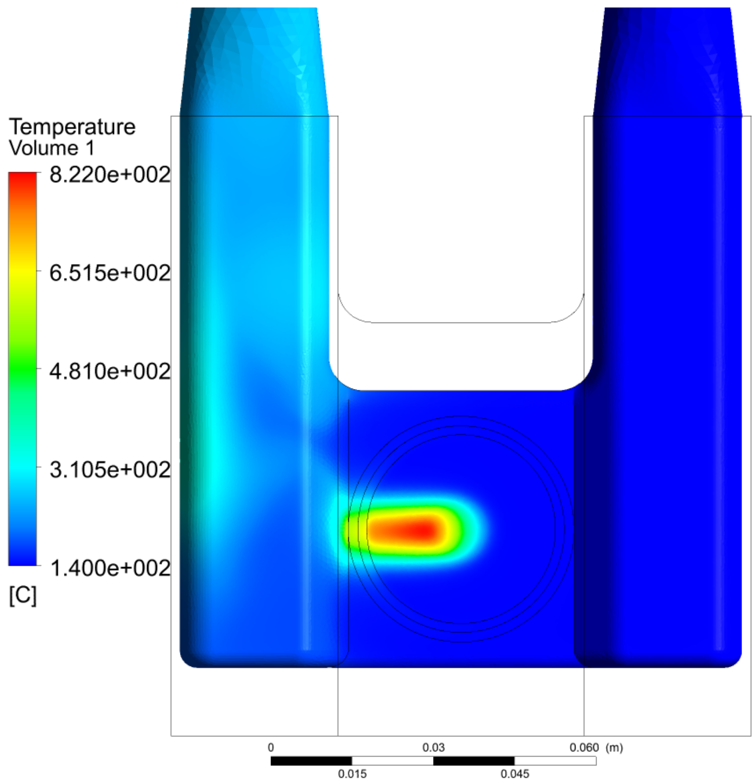

Figure 6. Liquid Metal Target - Temperature Plot.

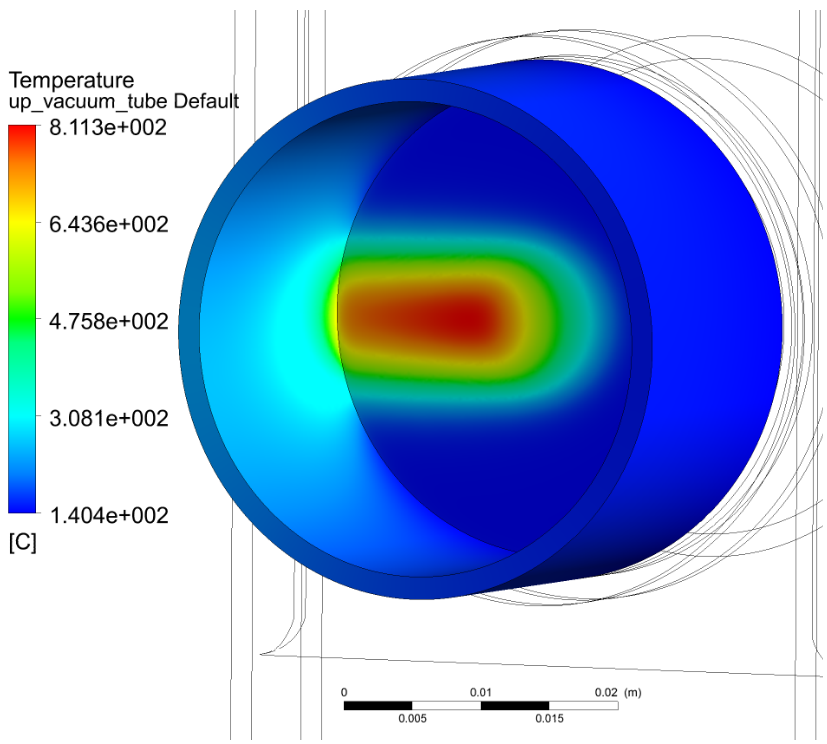

Figure 7. Fast Spectrum Neutron Source - Beam Window Temperature Profile.

300 series stainless steels (austenitic) are ruthlessly attacked by lead-bismuth through depletion of nickel. The oxide layer formed on 300 series stainless steels have the following potential structures[1]:

1. For temperature below 500°C, the oxide layer is very thin and is composed of the single-layer Fe-Cr spinel, which can prevent direct dissolution.
2. For temperature around 550°C, the oxide layer can have either duplex- or single-layer structure, depending on the surface and operating conditions. The duplex-layer oxide can prevent steel component dissolution, while heavy dissolution is observed when the single-layer oxide forms.
3. For temperature above 550°C, heavy dissolution occurs.

Thermal Mechanical Analysis – Beam Window

The strength of 316 stainless steel is quite low above 800 C (Table 1 and Figure 8). Pressure vessel code has an allowable stress for 316 at 1500 F (815 C) of 10 kPa. 316L is much weaker, but most steel is duel certified. Check your material certification. Thermal structural results for the beam window are shown in Figures 9 and 10.

Table 1. Elevated Temperature Mechanical Properties – 316L Sheet Specimen

Temperature °F (°C)	UTS ksi (MPa)	0.2% YS ksi (MPa)	Elongation % in 2in (50.8 mm)
68 (20)	88.2 (608)	43.8 (302)	56
200 (93)	78 (539)	36.6 (252)	49
400 (204)	69 (476)	32.4 (223)	37
600 (316)	67.4 (465)	28.1 (193)	33
800 (427)	66 (455)	26.7 (184)	33
1000 (538)	63.3 (444)	25.9 (179)	36
1200 (649)	54.2 (374)	25.3 (174)	28
1400 (760)	42 (290)	22.1 (152)	25
1600 (871)	26.9 (185)	168 (116)	50

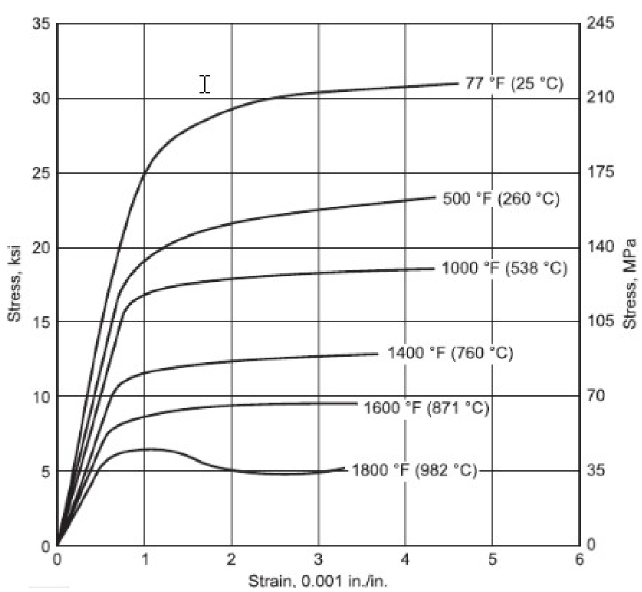

Figure 8. 316 SS Typical Stress-Strain Curves at Room and Elevated Temperatures.

[1] Zhang J., N. Li, J.S. Elson, *Progress in Materials Science, 2004.*

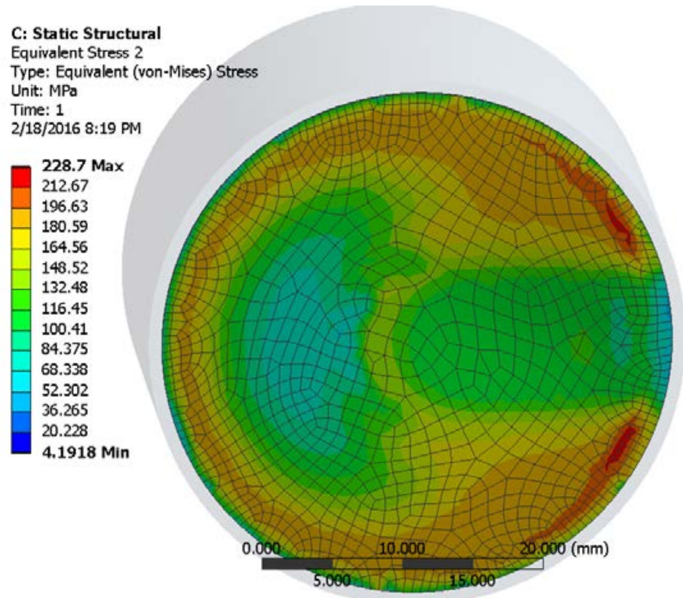

Figure 9. Thermal Structural Results: Coupled Thermal Stress.

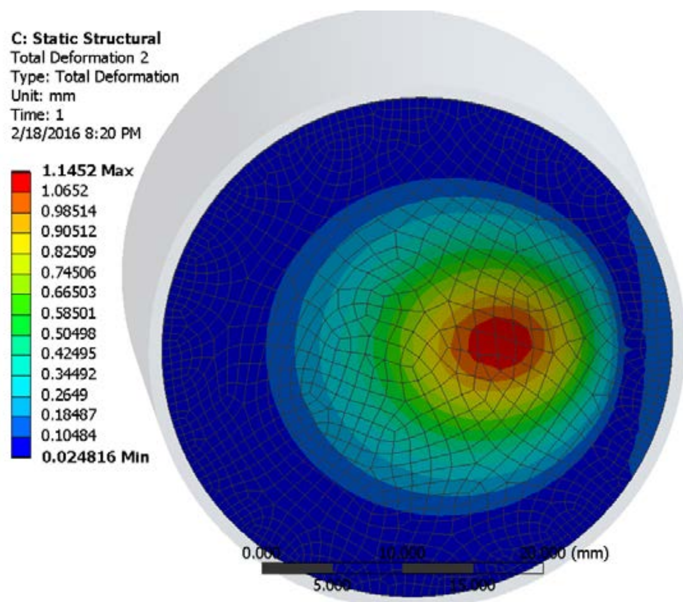

Figure 10. Thermal Structural Results: Total Deformation..

While the pressure induced stress on the window is low and allowing that the secondary thermal stresses may be acceptable for a short time, it is nonetheless strongly advised to reduce the beam current to the point of maximum temperature 550 C or less. This will virtually eliminate any possibility of failure for a short duration test. An IR camera looking at the back side of the target may be the best way to insure the temperature is not excessive. If that is not possible or convenient, perhaps a thermocouple spring loaded against the back side will be sufficient. Please note that reducing current in proportion to the desired temperature decrease is not an accurate guide because the free convection cooling is temperature gradient dependent and does not scale linearly with the heat load.

Summary

An engineering study was done on the Liquid Metal Target assembly to determine flow characteristics; in addition, to determining steady state temperature profile in the 316L SS beam window. Lastly, stress analysis was completed to determine the thermal stress response due to beam heating. The target window is over 800 C. This is a dangerous condition because of both corrosion and lack of material strength. The beam current should be reduced to lower the window temperature to 550 C or below. Window temperature measurement by IR camera or a thermocouple is advised. Thermocouple attachment is problematic in these situations. The window may survive the short duration of the test at 815 C, but the consequences of window failure must be acceptable. If a low current, short duration test provides useful data and satisfies milestone requirements, it is advised to lower the current and repeat the analysis until an acceptable temperature is achieved. Optionally, the experiment could be reconfigured for forced convection.