Thermal Control Techniques for Improved DT Layering of Indirect Drive IFE Targets

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Fuel layering is an essential step for any of the target designs under consideration for Inertial Fusion Energy (IFE), both direct drive and indirect drive. The uniformity of the DT layer has a profound effect on the gain of the target.

Layering indirect drive targets with the capsule already assembled in the hohlraum would be advantageous. One way to accomplish this is to layer targets in controlled temperature tubes while they are being staged for feeding to the injection system. Successful layering requires maintaining a specially tailored temperature profile on the hohlraum surface. Tritium decay heat removal from the filled capsule depends upon the thermal properties of the tube material, the capsule material, and the other materials filling the hohlraum.

In this work we evaluate various techniques for achieving adequate thermal control during the in-hohlraum layering process. Results provide feedback to target designers on design techniques which will be important in order to make in-hohlraum layering possible.

1. Introduction

Currently demonstrated layering methods require placement of bare capsules in a "layering sphere" to control DT surface temperature uniformity to less than ~100 μK for times up to several hours. Staging individual capsules in layering spheres would require a prohibitively large number of spheres to produce targets at IFE rates (~500,000 per day). Controlled temperature tubes are one way to accomplish in-hohlraum layering while targets are being staged for feeding to the injection system.

Anisotropic material properties have been studied as a potential method for tailoring the profiles. This is especially important for high-conductivity materials such as gold, which interfere with external control techniques.

2. Thermal Analysis

2.1 Background

The objective of this work is to establish and demonstrate techniques which will allow adequate control over the temperature of the DT fuel such that the uniformity of the fuel under beta layering [1] will meet symmetry requirements imposed by the physics of target implosion. Recent analysis suggests that IFE targets are much less susceptible to DT ice roughness as compared with ignition targets (*e.g.*, NIF), especially for the low mode-number perturbations which arise due to temperature variations at the hohlraum surface [2]. Roughness values as high as 5-10 μm may be acceptable.

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The reference geometry for all thermal analysis performed here is the "distributed radiator" design of Callahan-Miller [3]. The target consists of a DT capsule surrounded by either a BeBr or plastic ablator, various low-density foams designs to absorb and re-radiate the ion beam energy, and a Flibe outer covering for mechanical stability and compatibility with the assumed chamber protectant.

2.2 Analysis of Targets with Uniform Boundary Temperature

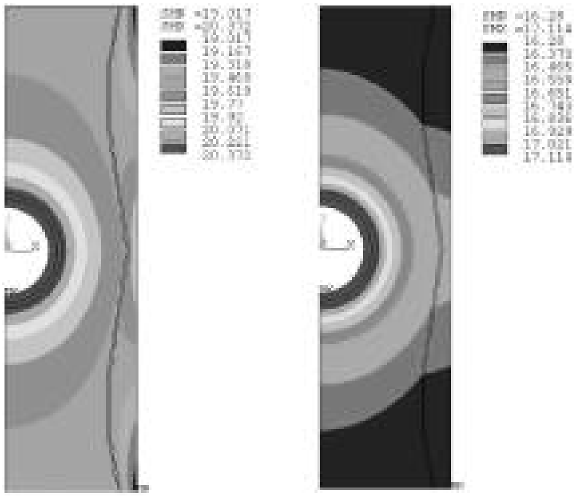
Several variations were analyzed in an attempt to determine the most effective technique for providing uniform layering: First, a uniform hohlraum boundary temperature was applied with BeBr and plastic capsules surrounding the DT fuel. The BeBr capsule has sufficient conductivity such that acceptable temperatures are achieved even in the case of uniform boundary temperature. Detailed comparisons were made with the work of Siegel [4] to establish the validity of the analysis technique. The case of a plastic ablator exhibited far greater non-uniformity in the fuel temperature, such that some form of thermal control becomes necessary.

2.3 Modification of the gold layer to allow thermal penetration

Initial attempts were made to reduce the temperature variation along the DT by imposing a spatially varying temperature along the outer surface of the hohlraum. Varying the hohlraum outer surface temperature as much as several degrees along the length of the hohlraum had little effect at the DT because the layer of AuGd in region B was masking any attempt to control the temperatures inside of it. The AuGd layer attempts to maintain an isotherm, in competition with the external control system. This problem was corrected by assuming that region B could be designed such that heat flux would flow easily across the layer and not along it (possibly by chopping it at small intervals or by manufacturing it with anisotropic properties). With anisotropic properties in region B, applied temperature profiles along the outer hohlraum surface were found to make profound differences in the temperature distribution at the DT. Figure 1 shows the hohlraum temperature distribution before and after segmentation of the AuGd layer. The results clearly show how segmentation allows penetration of the external temperature profile into the bulk of the hohlraum. Breaking the AuGd into segments or otherwise creating anisotropic conductivity was shown to be very effective. Manipulation of the low-density foams was explored as an additional technique. Anisotropic conductivity was applied to zones A, E, F, G, I, and J. This technique proved less effective than external temperature control.

2.4 Inverse Thermal Problem

The correct temperature profile to apply along the hohlraum surface could be determined by trial and error. However, a more efficient technique was used in order to obtain a relatively accurate "first estimate". A thick zone of material was added to the outer surface of the hohlraum in order to minimize the effect of the boundary. A fixed uniform temperature (equal to the desired temperature under ideal conditions) was applied to the DT outer surface, and a uniform heat flux boundary condition was applied to the outer boundary of the solution domain with a value consistent with the total volumetric heat generation in the DT. In this way, a temperature profile compatible with a uniform DT temperature naturally results on the hohlraum surface. This profile is not the exact solution for the thermal control system because the heat fluxes at the hohlraum surface are not the same; however, it provides a good first estimate which can be quickly optimized by iteration. In fact, this first estimate is sufficiently accurate to meet the requirements for DT thickness uniformity. Using the temperature solution along the hohlraum surface (see Figure 2) obtained in this way, the original thermal model was solved once again. The DT surface temperature variation was reduced from 10 mK to less than 200 μK. The corresponding fuel thickness variation, was reduced from 200 μm to under 5 μm. Further refinements to the imposed temperature profile reduced the variation to <100 μK.



Continuous AuGd *Segmented AuGd*

Figure 1. Effect of cutting the AuGd layer

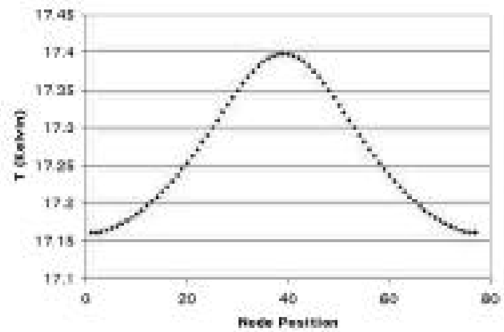


Figure 2. Input temperature profile

2.5 Analysis of the External Control System

Integrated analysis was performed on the hohlraum including the surrounding cryogenic pipe and thermal contact material in order to demonstrate the feasibility of the proposed final design solution. The reference technique for controlling the outer surface of the hohlraum includes coolers attached to a high-conductivity outer shell (which provides a defined isothermal region), a second interior layer with thickness designed to provide the required temperature variation on the hohlraum outer surface, and a thermal contact material to minimize variations in contact conductance between the control system and the hohlraum (see Figure 3). In order to obtain a first estimate of the insulator thickness required to map the constant copper temperature onto the desired hohlraum surface temperature, a simple estimate was made using the temperatures and heat fluxes determined in Section 2.4, and assuming one-dimensional heat flux in the insulator. The DT surface temperature variation is less than 1 mK. Further optimization of the insulator thickness profile is expected to reduce this.

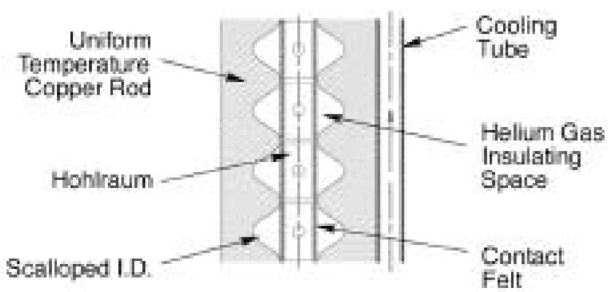


Figure 3. Configuration of the thermal control system

2.6 Sensitivity Studies

Variations in thermal conductivities of the hohlraum materials were found to have some effect on the DT surface temperature profile in Section 2.4. Region D is selected on one end of the hohlraum in order to vary its properties slightly from that of helium. A +/- 1 % change in thermal conductivity of Region D roughly doubles the temperature nonuniformity at the DT (Figure 4).

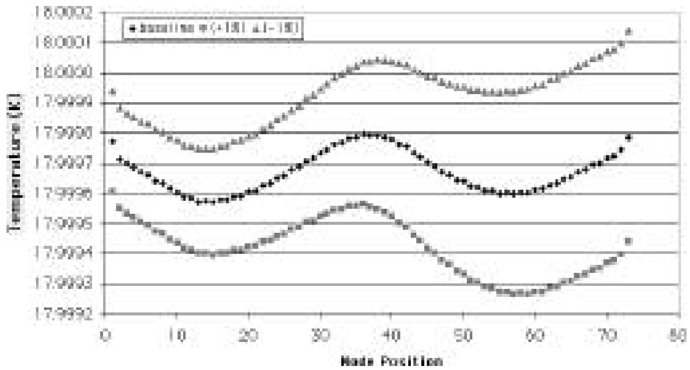


Figure 4. Baseline DT surface temperature distribution and sensitivity to variations in hohlraum material properties.

3. Conclusions

A uniform hohlraum surface temperature does not provide the needed temperature distribution for beta layering when a plastic capsule is used in place of BeBr. Therefore, some form of temperature control is necessary to make the DT surface temperature distribution acceptable for beta layering.

External thermal control is effective if the B layer within the hohlraum is modified to have anisotropic thermal conductivity. The segmented B layer allows the hohlraum outer surface to "communicate" with the capsule.

An applied temperature variation is determined using an "inverse problem" and is shown to reduce the temperature variation at the DT surface from 10mK to ~200μK. Tuning of the standard inverse problem input temperature profile results in temperature variation <100μK. Further optimization of the external thermal control profile is expected to reduce the DT surface temperature variation further.

The passive external thermal control system seems feasible, but requires optimization. The geometry of the insulator in the copper tube is a first order estimate and optimization of the scallop shape is being pursued.

Sensitivity studies show that variations in material properties must be kept below a few percent.

References

[1] J. K. Hoffer and L. R. Foreman, "Radioactivity Induced Sublimation in Solid Tritium," *Physical Review Letters* **60** (13) March 28, 1988.

[2] M. C. Herrmann, et al., "Surface Finish Requirements for IFE," presentation at the Indirect Drive Target Workshop, General Atomics, San Diego, May 1, 2001.

[3] D. A. Callahan-Miller and M. Tabak, "A Distributed Radiator, Heavy Ion Driven Target Driven by Gaussian Beams in a Multibeam Illumination Geometry," *Nuclear Fusion* **39** (7), July 1999.

[4] N. Siegel, "Thermal Analysis of Inertial Fusion Energy Targets," thesis presented to San Diego State University, Spring, 2000.