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THIN FILMS FOR REDUCING TAMPING GAS CONVECTION HEAT TRANSFER EFFECTS IN A NIF HOHLRAUM

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The effects of natural convection in the tamping gas in a vertical hohlraum on the heat flow from a frozen layer of deuterium and tritium (D-T) on the inner surface of a target capsule is investigated numerically. The energy released from tritium decay within the capsule is transferred through the tamping gas to the cooling rings on each end of the hohlraum. The thickness of the frozen layer must be uniform. This means that the heat flow from it to the capsule must be spherically symmetric, and that the temperature of the inner surface of the deuterium-tritium layer will be uniform and in equilibrium with its vapor. The objective of this study was to determine the combination of boundary conditions and thin films for restricting convection in the tamping gas, which satisfy these requirements. With the capsule mounted between two thin plastic films, clockwise-flow convection cells form in the upper and lower gas regions. When this flow contacts the capsule, the temperature variation along the inner surface of the D-T layer was as great as 3 mK. This was reduced to 180 ∝K by introducing thin films to isolate the capsule from the convection cells. Further reduction of this value to about 50 ∝K was achieved by modifying the boundary conditions.

I. INTRODUCTION

The indirect-drive targets for initial testing in the National Ignition Facility (NIF)[a] will consist of a fuel-filled spherical capsule centrally mounted in a vertical circular cylinder or hohlraum (Fig. 1a). In a generic unit the capsule will be a thin-walled spherical shell ⊕ 2 mm in outside diameter. This shell consists of an outer region (⊕0.160 mm thick), which forms the ablator, and an inner frozen layer of a 50-50 atomic% mixture of deuterium and tritium (D-T) about 0.080 mm thick. A primary requirement is that the thickness of this layer be uniform. The hohlraum (approximately 5.5 mm in diameter and 9.5 mm long) will be filled with a nominal 50-50 atomic % mixture of hydrogen and helium gas, whose purpose is to impede the expansion of the plasma formed when the laser beams strike the hohlraum wall. This tamping gas is also important in controlling the solid D-T layer thickness distribution because it will serve as a medium for

[a] Currently being constructed at the Lawrence Livermore National Laboratory. The NIF will be a 192 beam frequency-tripled Nd-glass laser system with on-target energy and power of 1.8 MJ and 500 TW, respectively.

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transferring the heat released during tritium decay to the hohlraum wall. This heat and any auxiliary heating supplied will flow through the hohlraum wall to cooling rings attached to each end of the hohlraum.

The generic target illustrated in Fig. 1a shows the capsule mounted between thin plastic films, and also includes what are called equalizer rings around each end of the hohlraum. These devices are needed to assure uniform axial heat flow along the hohlraum wall. This effect is achieved by channeling the heat flow through many equal thermal resistance paths. Heat is then transferred through small-diameter sapphire support rods to a liquid-helium-cooled heat sink. This target assembly is positioned at the center of the 10-m-diameter containment chamber.

I.A. Conduction heat transfer study

The anticipated temperature distribution and heat flow throughout the hohlraum was first studied by assuming conduction only through the "transfer" (a more appropriate description than "tamping" in this study) gas surrounding the capsule, and by specifying a uniformly thick D-T fuel layer. In an actual hohlraum the resistance to heat flow from the capsule to the hohlraum wall is lowest at the mid-plane and increases toward the poles. The mean temperature of the D-T layer in the mid-plane region would then be lower that at the poles. This would result in a non-uniform thickness layer due to movement by sublimation of the D-T from the pole regions and condensation in the region around the mid-plane in order to achieve thermal equilibrium between the vapor and the solid. External heating of the hohlraum was imposed to correct for this effect. The results, which are described in detail in Ref. 1, showed that it was possible to obtain very close to spherically uniform heat flow from the fuel layer by providing optimal uniform heating on the outside wall of the hohlraum. With a hydrocarbon capsule the layer thickness can be controlled to about $\pm$ 0.5 ∝m. Less variation can be achieved with higher thermal conductivity capsules. For example, with conduction heat transfer only, results indicated that the D-T layer thickness could be controlled to about $\pm$ 0.2 ∝m if the capsule were made from copper-doped beryllium. Additional calculations showed that concentrated ring heating (such as shown in Fig.1b) would also yield acceptable control of layer thickness. From a practical point of view it is much easier to provide ring heating. For this reason it was decided to assume the use of ring heating for the studies involving convection reported herein.

II. CONVECTION FLOW IN TRANSFER GAS

II.A. Local and overall heat transfer from the capsule

With a typical transfer gas density of 1.25 mg/cm^3 Raleigh numbers estimated from the gas properties, dimensions and temperature differences in the hohlraum are in the range of 50 to 500. Extrapolating the curves correlating experimental data for horizontal and vertical surfaces into this range indicated that free convection would reduce the heat transfer resistance with only conduction by less than 5%. A change of this magnitude would not have a major effect. However, the important question in this system is what local variations in heat transfer the convective flows along the capsule and hohlraum walls will introduce. Also the convective flow and local heat transfer will vary differently along the top and bottom of the capsule because the gravity force in the upper region is opposite in direction to heat flow to the cooling ring and in the same direction in the lower region. A numerical model, which consisted of upper and lower gas regions separated by a thin film at the mid-plane, was first developed to investigate these effects. This geometry was identified as a two-gas region model. Results for the flow and heat transfer are described in the following section.

III. TWO-GAS REGION MODEL

III.A. Capsule at center of hohlraum mid-plane

The system investigated consisted of a capsule mounted between two Formvar films[b] as shown in Fig. 2a (This figure also shows isotherms for conduction through the transfer gas, which is discussed below). A capsule is placed at the center of one film supported on a ring and is then enclosed (i.e., "tented") from the top with a second layer. The two films are then shrunk around the capsule. Hohlraum halves with flanges are brought from above and below and glued to the two layers. The result is a hohlraum with equal gas volumes above and below the capsule.

With the capsule located at the center of the hohlraum the combination of capsule and hohlraum will be axially symmetric about the vertical axis. The system can therefore be modeled by zoning one half of a vertical section. A grid with quadrilateral elements was developed. Typical element dimensions in the 0.080 mm D-T fuel layer and capsule were 0.020 mm. Gas element dimensions were on the order of 0.020 to 0.030 mm except around the capsule where they were 0.003 mm in the radial direction. The mid-plane divider consisted of two films each about 0.1 µm thick. Since elements of this size would be eliminated during the zone meshing process, the films were specified as 0.003 mm thick, and their properties based on the fractions that were gas and plastic respectively. Fortunately the thermal resistance of the films is very small, so that they had a negligible effect on thermal transfer. The final grid had over 43,000 elements.

Since temperature changes throughout the capsule and hohlraum are only a little greater than 0.1 K, it is reasonable to assume constant average thermal properties. Assuming a mean temperature of 19.5 K thermal conductivities (all in mW/mm K) were $8.0\text{x}10^{-2}$ for the D-T vapor[2], 0.294 for the D-T solid [3], 0.022 for the transfer gas[2,4] (consisting of a 50-50 atomic % mixture of H_2 and He), and $1.0\text{x}10^{3}$ for the hohlraum[5], respectively. The capsule was assumed to be a hydrocarbon (CH_X) since it will then be possible to load a D-T fuel charge by diffusion through the wall. The particular material will probably be a polyimide because of superior strength. A representative value of 0.15 mW/mm K was taken for the thermal conductivity[6]. The tritium decay heat release rates were $5 \text{ x } 10^{-5}$ and $4.91 \text{ x } 10^{-2}$ mW/mm^3 in the D-T vapor and solid, respectively[2].

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[b] Formvar is a polyvynal resin marketed by the Monsanto Chemical Co. Films were formed by suspending a microscope slide vertically in a solution of Formvar and methylene-chloride. As the solution level is lowered a thin layer on the order of 500-800 Angstroms thick forms on the slide surface. After the solvent has evaporated, the layer of Formvar is floated off the slide onto a water surface. It is then lifted off the water surface onto a wire ring larger in diameter than the diameter of the hohlraum.

III.B. Conduction only through transfer gas

As a basis for evaluating the effects of convection, the temperature distribution throughout the D-T vapor and solid, the capsule, the transfer gas, and the hohlraum wall was first calculated assuming only conduction heat transfer through the transfer gas[c]. The symmetrical boundary conditions specified were 19.5 K over each cooling ring and 1.3 mW/mm^2 to the 0.75 mm wide heaters on the outer surface of the hohlraum. The purpose of these external heaters is to reduce the heat flow from the capsule to the hohlraum in the mid-plane region so that the radial heat flow from the capsule is spherically uniform[1]. An isotherm plot of the conduction results is shown in Fig.2b. Since a uniform thickness D-T layer was specified, the critical test for radial flow only is whether the temperature distribution along the inner surface is uniform. In Figure 2b there is an increase of about 20 μK above and below the mid-plane. Beta layering[1] would cause sublimation from these locations and condensation elsewhere until equilibrium between the vapor and solid was achieved. Based on non-uniform thickness layer results presented in Ref. 1 the resulting thickness variation for the boundary conditions for Fig. 2b would be less than 0.1 μm. Also, note that the overall temperature change from the center of the vapor to the cooling rings was 123 mK. The radial-symmetrical temperature decrease through the vapor, solid D-T, and capsule wall is 4.55 mK. The temperature decrease from the outer surface of the capsule through the transfer gas to the cooling rings is therefore 119.5 mK

III.C. Convection in transfer gas

The velocity and temperature fields for the two-gas region model were obtained with the Flow Plus module incorporated in the COSMOS/M program[7]. Results are shown in Fig. 3a for the velocity distributions in the gas regions[d], and in Fig. 3b for the temperature distribution in the capsule region. Heat transfer in the DT vapor was assumed to be by conduction only. Fig. 3a shows that clockwise flow cells are generated in each half. However, the peak velocity of 1.170 mm/s along the axis in the upper region is about twice that in the lower region. This difference between the upper and lower regions is due to the downward flow along the capsule wall in the upper region being in the direction of increasing temperature while that in the lower region is along a wall decreasing in temperature. The former has a downward buoyant effect, while the latter has a stabilizing trend. The gas in the upper region is heated as it flows downward along the hohlraum wall. As it turns and flows over the capsule, a boundary-layer-like region occurs along the capsule wall. The result is a higher gas temperature over the top of the capsule compared to conduction. The effect is to increase the resistance to heat transfer, which is also indicated by the peak temperature in the vapor occurring close to the upper pole.

The isotherms in the vapor in Fig. 3b show a downward temperature gradient in the center. However, they turn upward toward the solid D-T layer. The heat flow rate down

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[c] The second order partial differential equation governing conduction was solved numerically with version 2.7 of the COSMOS/M Fast Finite Element Analysis Program (Ref. 7). Special formatting changes were incorporated to provide eight significant digit output, which was needed to identify temperature changes along the D-T surface.

[d] A value of 2.7×10^{-6} g/mm s was used for the viscosity of the H_2 –He gas mixture at 19.5 K (calculated from data in Refs. 2 and 4)

across the mid-plane of the D-T layer was estimated to be about 0.1 ∝W. This is only around 0.25% of the heat released in the Layer. Hence, the downward heat flow can be considered negligible, and the heat flow to the capsule to be essentially radial. The symmetric radial temperature decrease through the solid D-T layer and the capsule wall is about 3.85 mK. Subtracting this from the overall decrease of 125 mK indicated in Fig. 3b gives the temperature difference from the upper pole region to the cooling ring as 121.2 mK. The symmetric radial temperature drop in the vapor is around 0.5 mK. The comparable value for conduction only would be 123 - 4.6 = 118.6 mK. These values suggest that the resistance to heat transfer is increased by about 2% in the upper region and decreased by about 2% in the lower. The critical effect, however, was the development of an unacceptable temperature variation (2.85 mK) along the inner surface of the D-T layer (Fig. 6). .

IV.THREE-GAS REGION MODEL

IV.A. Model of tented capsule in a hohlraum

The next system investigated was with the capsule mounted between two Formvar films as illustrated in Fig. 1b. Again a capsule is placed at the center of one film mounted on a ring and enclosed (i.e., "tented") from the top with a second layer. Hohlraum halves with flanges are brought from above and below and glued to the two layers. In this case the films are not shrunk, resulting in a hohlraum with relatively large gas volumes above and below the capsule and a much smaller volume enclosed between the films. This was designated a three-gas region model. With the same boundary conditions listed above results for the flow and temperature fields and for the temperature distribution throughout the capsule are plotted in Figures 4a and b.

IV.A. Three-gas region convection patterns

The clockwise circulation patterns in the upper and lower regions are similar to those in the two-gas region model, although the peak velocity of 1.0035 mm/s in the upper half is about 14 % lower. As in the two-gas region model the peak flow magnitude in the lower region is about one half that in the upper region. Peak velocities in the tented region are on the order of 0.12 mm/s. The indicated overall temperature decrease between the capsule center and the cooling rings is 123 mK, which is the same as with only conduction. Note however, that the highest temperature still occurs above the center of the capsule, and that the 19.623 K temperature occurs twice in the spectrum. This means that the highest temperature is a fraction of a mK greater than 19.623 K, and that the resistance to heat transfer in the upper region is still slightly higher that in the lower region.

The important change from the two-gas region model is that the temperature variation along the inner D-T surface is decreased to about 2 mK. This can be attributed to improved separation of the capsule from the warm gas coming from the hohlraum wall both in the upper and lower regions. The reduction in the magnitude of the temperature variation along the inner D-T surface by surrounding part of the capsule with a low velocity region suggested the addition of additional films to further isolate the capsule. This was achieved by dividing the upper and lower halves of the hohlraum into two parts and inserting films during assembly. An additional set of flanges in both the upper and lower halves were required as has been indicated in the models already considered. This modification led to a five-gas region model.

V. FIVE-GAS REGION MODEL

Arrows showing the velocity distribution in the five-gas region model are plotted in Fig. 5a. Fig. 5b shows the isotherm distribution in the capsule region. The peak velocities in both the upper and lower regions are now comparable, about 0.24 mm/s. This is a substantial reduction from values in the two-gas and three-gas models. More important is that the additional films isolate the capsule from the main clockwise-flow cells. Velocities in the inner regions are almost negligible, so that heat transfer approaches the conduction mode. The overall result is that the variation along the inner D-T surface decreased to about 180 μK (Fig. 6). Further reduction in the D-T surface temperature variation could be achieved by installing another set of films. However, changing the boundary conditions was a more convenient solution.

V.A. Optimizing boundary conditions

The objective was to determine values for the ring temperatures and the auxiliary heaters that will cause the heat flow from the capsule to be spherically uniform. The heat flow from the D-T layer will then be spherically uniform and the temperature around the inner surface will be uniform and in equilibrium with the D-T vapor. To achieve this condition it was necessary to lower the upper hohlraum end temperature and increase the lower end temperature. Although this is an iterative process, the final magnitudes of the required changes can be quickly estimated by assuming linear variations based on one initial calculation. Optimum ring temperatures were found to be about 19.494 K and 19.506 K for the upper and lower rings, respectively, and with auxiliary heating of 1.43 mW/mm^2 for both the upper and lower hohlraum side heaters. Figure 7 shows an expanded view of the isotherms in the central region for these boundary conditions. The inner D-T surface temperature variation was reduced to around 50 μK. Redistribution of the solid D-T to achieve equilibrium with the vapor is estimated to result in a D-T layer thickness variation of less than 0.5 micron.

VI. CONCLUSION

When the solid D-T layer thickness in a capsule mounted at the center of the hohlraum is assumed uniform, the predicted effects of convection are to

a) increase the resistance to heat transfer from the capsule to the cooling ring in the upper half of the hohlraum by about 2% over conduction, and
b) decrease the resistance in the lower half by about 2% compared to conduction.

The effects of convection can be greatly reduced by the installation of thin films in both the upper and lower halves. These films isolate the capsule from the convective flow coming from the hohlraum walls. Specifically the inner D-T surface temperature variation is reduced from 2.8 mK to about 180 μK. Additional improvement in reducing the surface temperature variation can be achieved (to about 50 μK) by modifying the temperature and heat flux boundary conditions.

ACKNOWLEDGEMENT

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LIST OF FIGURES

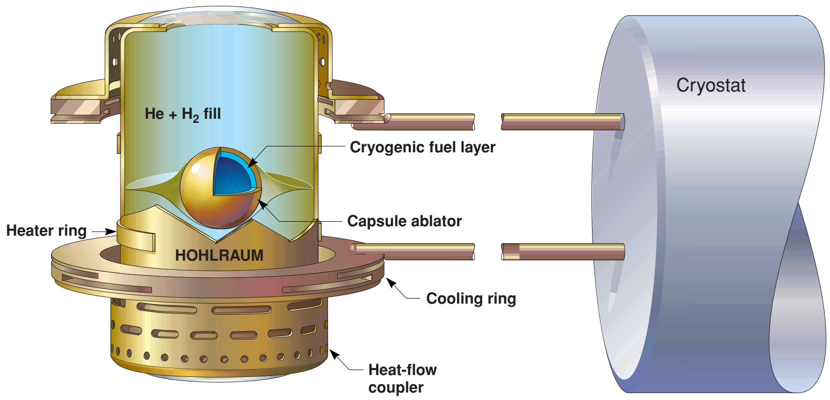

Figure 1a **Generic target for the National Ignition Facility.**

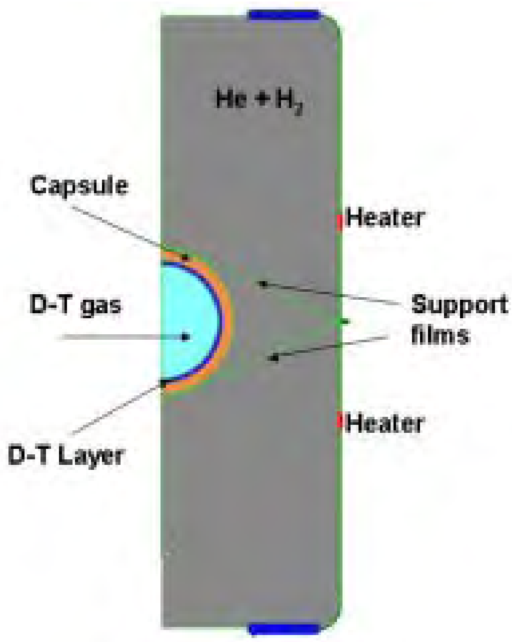

Figure 1b **Axisymmetric model of capsule in hohlraum**

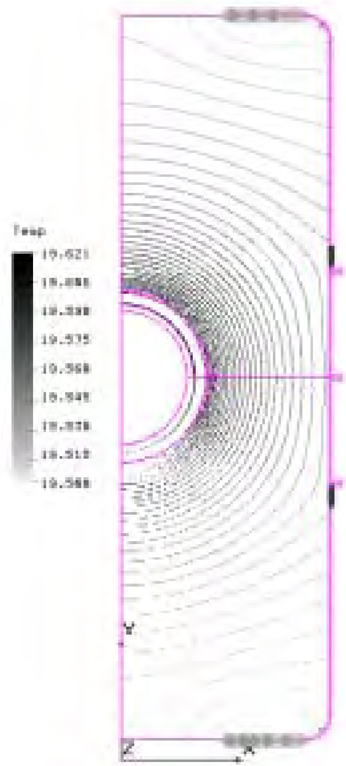

Figure 2a **COSMOS/M Program solution for isotherm distribution throughout capsule, transfer gas and hohlraum assuming conduction only (cooled ends at 19.5 K, ring heating of 1.3 mW/mm^2)**

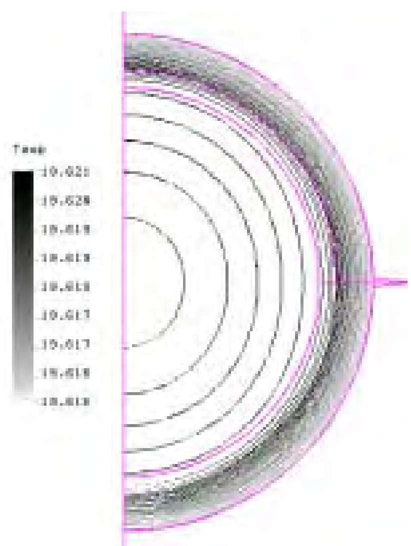

Figure 2b **Isotherm distribution in D-T vapor, solid layer and capsule (from Figure 2a)**

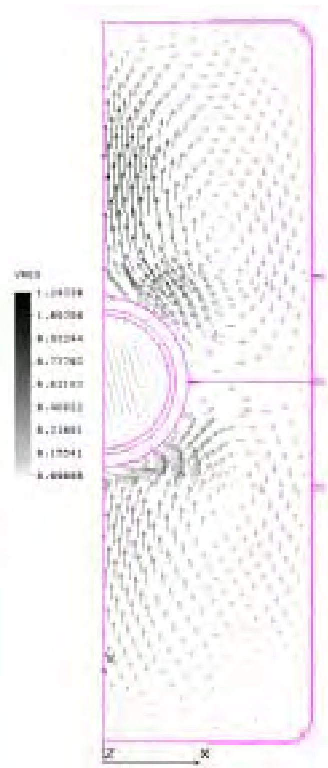

Figure 3a **FLOW PLUS Program solution for velocity distribution in two-gas region model (cooled ends at 19.5 K and ring heating of 1.3 mW/mm^2)**

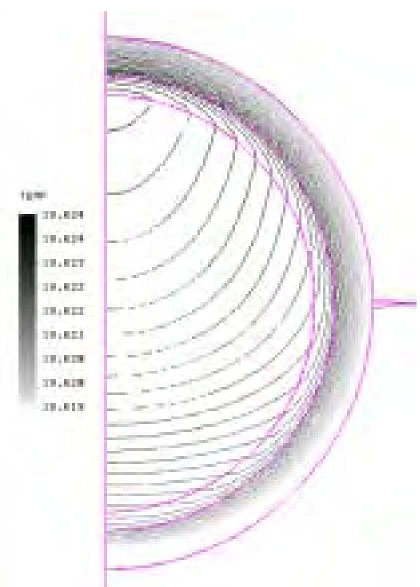

Figure 3b **Temperature distribution along inner surface of D-T layer**

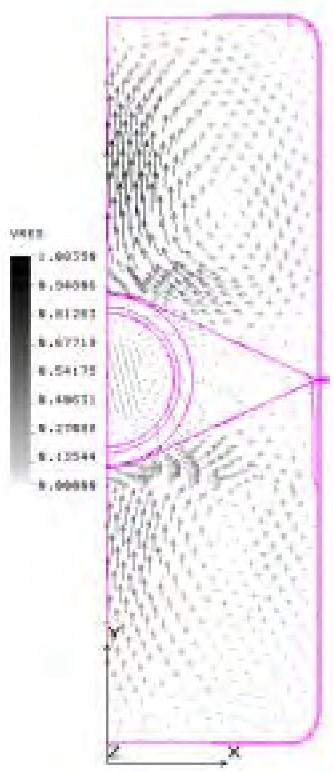

Figure 4a Velocity distribution in transfer gas of three-gas region model (cooled ends at 19.5 K and ring heating of 1.3 mW/mm^2)

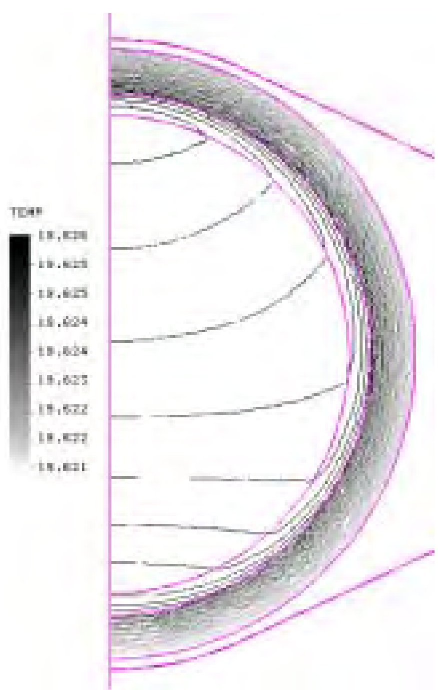

Figure 4b Isotherm distribution in D-T vapor, solid layer and capsule of a three-gas region model

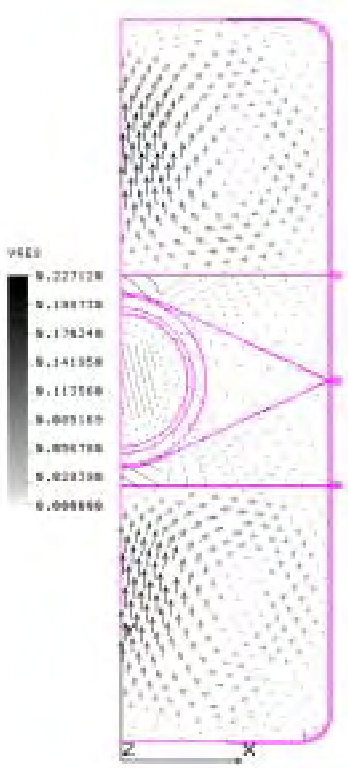

Figure 5a Velocity distribution in transfer gas of five-gas region model (cooled ends at 19.5 K and ring heating of 1.3 mW/mm^2)

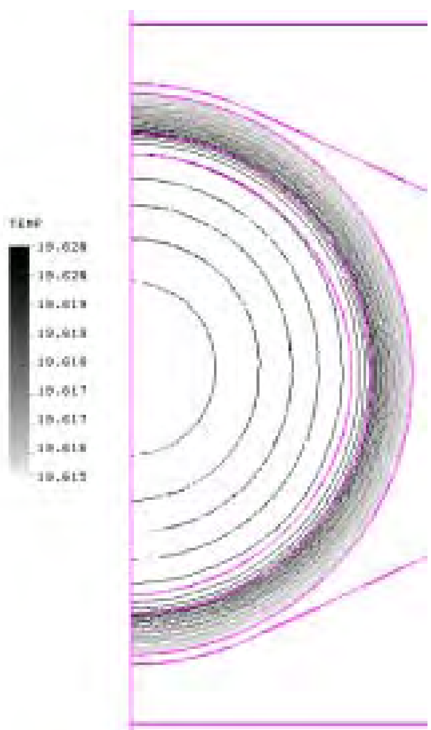

Figure 5b Isotherm distribution in D-T vapor, solid layer and capsule of five-gas region model

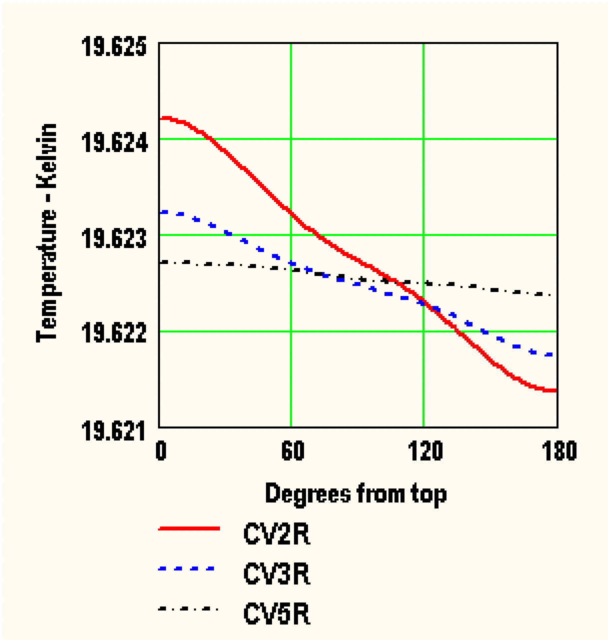

Figure 6 Temperature distribution along the inner surface of D-T layer in two-, three- and five-gas region models (cooled ends at 19.5 K and ring heating of 1.3 mW/mm^2)