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Direct drive target survival during injection in an inertial fusion energy power plant

R.W. Petzoldt[1], D.T. Goodin[1], A. Nikroo[1], E. Stephens[1], N. Siegel[2], N.B. Alexander[1], A.R. Raffray[3], T.K. Mau[3], M. Tillack[3], F. Najmabadi[3], S.I. Krasheninnikov[3] and R. Gallix[1]

[1] General Atomics, PO Box 85608, San Diego, California, USA
[2] Virginia Polytechnic Institute and State University, Blacksburg, Virginia, USA
[3] University of California, San Diego, California, USA

E-mail: ronald.petzoldt@gat.com

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Abstract

In inertial fusion energy (IFE) power plant designs, the fuel is a spherical layer of frozen DT contained in a target that is injected at high velocity into the reaction chamber. For direct drive, typically laser beams converge at the centre of the chamber (CC) to compress and heat the target to fusion conditions. To obtain the maximum energy yield from the fusion reaction, the frozen DT layer must be at about 18.5 K and the target must maintain a high degree of spherical symmetry and surface smoothness when it reaches the CC. During its transit in the chamber the cryogenic target is heated by radiation from the hot chamber wall. The target is also heated by convection as it passes through the rarefied fill-gas used to control chamber wall damage by x-rays and debris from the target explosion. This article addresses the temperature limits at the target surface beyond which target uniformity may be damaged. It concentrates on direct drive targets because fuel warm up during injection is not currently thought to be an issue for present indirect drive designs and chamber concepts. Detailed results of parametric radiative and convective heating calculations are presented for direct-drive targets during injection into a dry-wall reaction chamber. The baseline approach to target survival utilizes highly reflective targets along with a substantially lower chamber wall temperature and fill-gas pressure than previously assumed. Recently developed high-Z material coatings with high heat reflectivity are discussed and characterized. The article also presents alternate target protection methods that could be developed if targets with inherent survival features cannot be obtained within a reasonable time span.

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1. Introduction and background

In an inertial fusion energy (IFE) power plant, the fuel is solid DT at ∼18 K encapsulated inside a target. This temperature is controlled to produce the desired gas density at the centre of the capsule. The target is injected into the reaction chamber at high velocity at a rate of about six per second (figure 1). When the target reaches the chamber centre (CC), it is compressed and heated to fusion conditions by the energy input of converging driver beams. Requirements and key issues related to target injection and tracking developments for various IFE plant designs were reported in [1]. Power plants chambers are designed to operate at high temperature for high thermal efficiency. They also often are designed with a fill gas (such as xenon at 0.5 Torr in the Sombrero design [2]) or wetted wall to protect the structural wall from x-rays and target ion debris. Some issues associated with target injection into a wetted wall chamber are reported in [3].

Figure 2 illustrates schematically a distributed radiator, heavy-ion driven, indirect-drive IFE target design [4]: the DT fuel is contained in the central capsule supported by a polymer membrane attached to the hohlraum casing which is made of low density metals and polymers and encased in ‘Flibe’, a F–Li–Be compound. Calculations show that the conductivity of the thermal path from the surface of the target to the capsule is so low that very little heat is transmitted to the DT fuel during the short transit to the centre of the chamber. Therefore, the fuel remains at ∼18 K during injection for a wide range of operating conditions and indirect drive targets are not discussed further in this paper.

Figure 3 shows the design, optimized for implosion physics, of a radiation preheat, direct-drive IFE target consisting of five parts [5]: a very thin coating of gold, a thin polymer capsule, a layer of DT-filled CH foam ablator, a layer of solid DT fuel, and a cavity containing DT vapour.

To optimize the energy yield of the fusion reactions, the targets must be very accurately delivered by the injector to the CC and the strict spherical uniformity of the capsules and the fuel they contain must be maintained to minimize hydrodynamic instabilities during implosion.

During their transit from the injector to the CC the targets are subjected to radiative heating from the chamber wall and convective heating by the rarefied gas that is present in the chamber of most power plant concepts. The coordinated design of the chamber and the targets must ensure that heating during injection does not excessively affect target uniformity.

Although there are plant efficiency and chamber wall protection benefits, high chamber temperature and even relatively low fill gas density may cause excessive target heating. Target heating during injection is critical to the design of both the target and chamber. This article presents detailed results of heating analyses of the direct-drive target design shown in figure 3 during injection, as well as recent target thermal protection developments, aimed at establishing integrated design parameter windows for target survival.

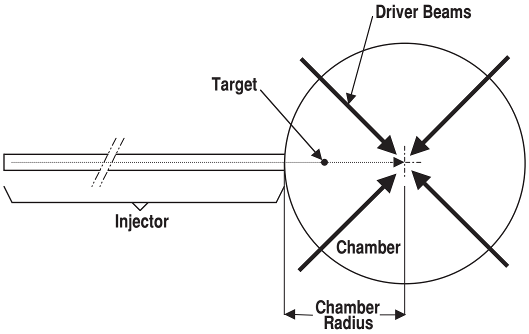

Figure 1. Target injection schematic.

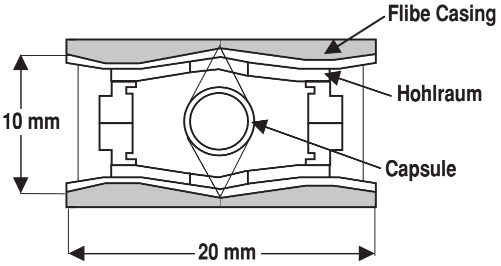

Figure 2. Lawrence Livermore National Laboratory indirect-drive target design [3].

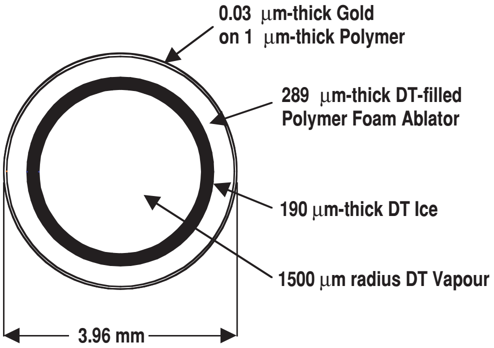

Figure 3. Naval Research Laboratory direct-drive radiation preheat target design [4].

2. Target heating during injection

2.1. Temperature limits

The target may suffer implosion instabilities if the outer surface of the frozen DT-filled ablator reaches the triple point (19.79 K) and gas bubbles begin to form inside the capsule. (The actual temperature at which gas bubbles form may be higher than the triple point because of superheating in the liquid and pressure increase beneath the outer membrane.)

The following assumptions were made in our target heating calculations. The same surface of the target faces forward throughout the injection process. The effects of target spin, other than to maintain the leading surface forward, are not expected to significantly affect the target heating. The target remains spherical (rigid). Heat is removed from the surface by conduction and transferred to the surface by contact with high temperature molecules. Condensation of gas on the target is not included in the calculations. DT thermal properties are taken from [6].

An axisymmetric finite-element model was used with the ANSYS code to calculate the temperature rise at the ablator surface as a function of injection time for a range of uniform heat flux values. The results are shown in figure 4. Considering all the uncertainties inherent to this analysis, the total heat flux absorbed by the target should be in the range of $\sim$0.5–1 W cm^{-2} to avoid extensive phase changes in the DT for an injection velocity of $\sim$400 m s^{-1}, considered to be near the maximum practical velocity.

Roughening of the target surface due to heating during injection may also lead to implosion instabilities, as explained below. Targets must be 'layered' just below the triple point to obtain the best smoothness ($<\sim 2\,\mu$m RMS) at the inner surface of the DT ice, then cooled down to $\sim$18 K before injection. During 'layering' and cooling experiments [7] the inner surface of the DT ice was observed to roughen again after layering when the temperature was decreased by about 0.5 K. Axisymmetric finite-element thermal stress calculations with the ANSYS code [8] indicate that the polymer capsule

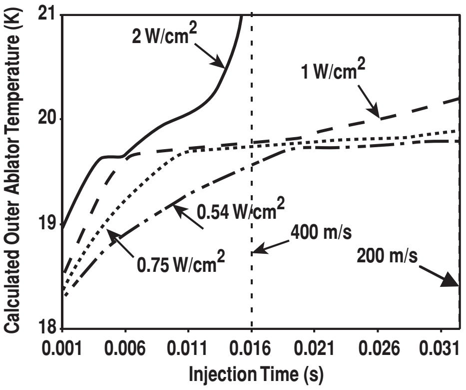

Figure 4. Temperature rise at the outer surface of the ablator versus injection time for a range of total heat fluxes.

contracts much less than the ice, putting the latter in hoop tension. The calculations also suggest that roughening of the inner surface of the DT ice occurs when its tensile hoop stress exceeds the estimated tensile yield strength of the ice.

Conversely, during target injection into the reaction chamber, as the polymer capsule and the outer layer of frozen DT are heated up very rapidly[4] from ~18 K, they are prevented from expanding freely by the still-cold inner region of the ice and they develop high hoop compressive stress. Similar ANSYS calculations [8] indicate that the estimated compressive yield strength of DT ice is reached when the temperature of the outer surface of the target reaches ~18.8 K during injection. Although the conclusions are not yet certain, this may cause a roughening of the outer surface of the target that could lead to implosion instabilities. Experiments are being planned at LANL to study the effect of rapid heating on representative layers of frozen DT-filled foam and DT ice, e.g. by forming such layers on the bore of a toroidal mandrel, thus exposing the frozen foam and ice surfaces to direct viewing through windows during rapid heating.

2.2. Parametric heating studies

2.2.1. Convective heating. Some chamber designs utilize rarefied xenon or other fill gases to attenuate x-rays and debris emanating from the target explosion, in order to limit wall temperature excursions and wall ablation. As the target traverses the gas at high velocity, its surface absorbs an asymmetric heat flux which is dependent upon its velocity and the temperature and pressure of the gas. The interaction of the gas with the target during injection was modelled at the molecular level by the direct simulation Monte Carlo (DSMC) method [9]. The magnitude and distribution of the heat flux around the surface of the target were obtained, as illustrated in figures 5 and 6. Parametric calculations of the peak convective heat flux, on the leading edge of the target, were performed. The results for 10 mTorr xenon pressure are shown in figure 7 as a function of chamber gas temperature for two injection velocities.

The above calculations assume that the gas atoms that hit the surface release most of their kinetic energy to the surface and are re-emitted at 18 K. These atoms form a partial barrier to further collisions of atoms with the surface, especially at higher pressure. If we make the assumption that all atoms stick to the surface, there is little heating difference at pressures below 1 mTorr gradually increasing to twice the heat flux (of the no condensation case) at 100 mTorr [10].

It has recently been noted that chamber gas temperature may be much higher than the chamber wall temperature due to the short time available for gas cooling between shots. While it is not our intent in this work to calculate chamber temperatures, this possibility is considered herein for its effect on target heating during injection. There may also be significant plasma remaining in the chamber at the time of target injection. The density of the gas atoms associated with a gas pressure of 10 mTorr at 300 K is 3×10^{20} m^{-3}. Even if the gas density can be reduced to 10^{20} m^{-3}, the mean free path between collisions given by

$$\lambda = \frac{1}{\sqrt{2}\pi D^2 N}$$

is order of 1 cm which is much less than the chamber radius. Therefore, the majority of the gas atoms cannot directly transfer heat to the chamber walls by collisions with the wall. There are three main mechanisms for plasma/gas mixture cooling: (a) radiation, (b) conduction, and (c) convection.

(a) Line radiation can quickly lower the temperature to about 10 000 K (1 eV), but becomes negligibly small at lower temperatures [11, 12].

(b) The characteristic time $\tau \sim 3(\pi^2 R_{\mathrm{ch}}^2/\lambda V_{\mathrm{th}})$ for conduction processes to reduce gas temperatures in a large reaction

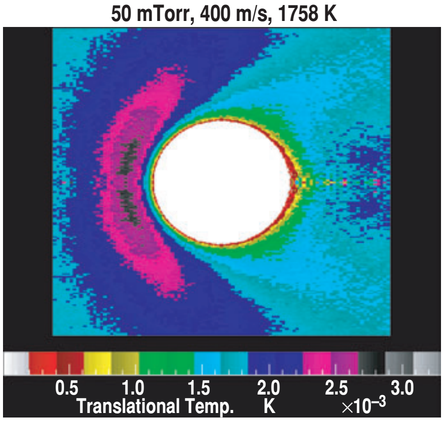

Figure 5. Asymmetric fill-gas temperature profiles during target injection (direct simulation Monte Carlo calculation).

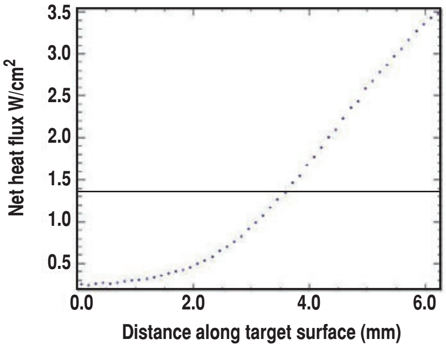

Figure 6. Asymmetric heat flux on the target surface during injection (direct simulation Monte Carlo method).

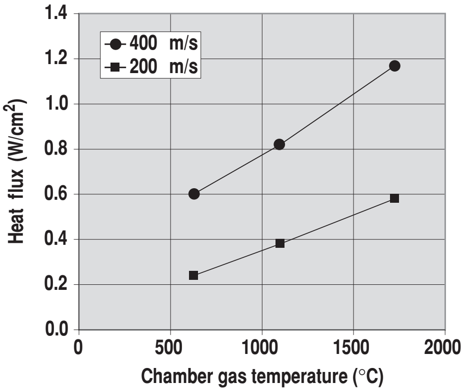

Figure 7. Peak convective heat flux absorbed on the target surface during injection.

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[4] Transit time across a 6.5 m radius chamber is about 16 ms at 400 m s^{-1}.

chamber are too large to reduce the gas temperature to a sub-eV level [12].

(c) Small-scale convection cells are expected to quickly damp leaving only convective cells of sizes comparable to the chamber radius. It may be possible to deliberately generate large convective cells in the chamber by off centre target explosions or asymmetric chamber design. These cells could potentially direct cool gas near the chamber walls into the target injection path [12].

Since the chamber gas temperature and plasma density are not well-defined at this time, we take a parametric approach to showing the effect on the target heating. The results can be used to evaluate potential chamber operating windows.

2.2.2. Radiative heating. During injection the target is exposed to a uniform heat flux $q = \sigma T^4\,\mathrm{W\,cm^{-2}}$ from the hot chamber wall radiating as a black body at absolute temperature T, where σ is the Stefan–Boltzmann constant. For $T = 1758$ K (1485˚C) and 1273 K (1000˚C), $q = 54$ and $15\,\mathrm{W\,cm^{-2}}$, respectively. The heat flux absorbed by the target, $q\prime = (1-\rho)\sigma T^4\,\mathrm{W\,cm^{-2}}$, is reduced by the reflectivity ρ of its surface. A very reflective target surface is clearly required to keep the total absorbed heat flux between ∼0.5 and $1\,\mathrm{W\,cm^{-2}}$. A surface reflectivity of about 98% for bulk gold for black body radiation at IFE power plant temperatures has been demonstrated. However, the direct-drive target specifications require a very thin (275–375 Å) coating of gold which can be expected to result in lower reflectivity. Figure 8 shows how the radiative heat flux absorbed by the target varies with chamber wall temperature, for 98% and 96%, reflectivity.

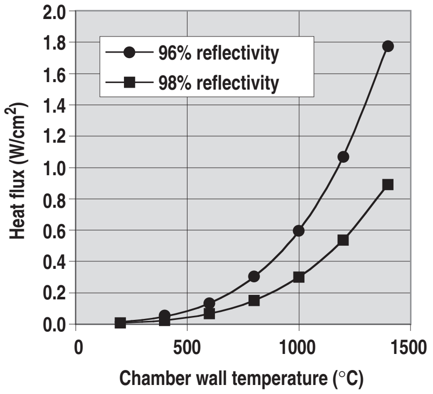

Figure 8. Radiative heat flux absorbed on the target surface during injection vs chamber wall temperature.

2.2.3. Total heating. The effects of convective and radiative target heating during injection were combined and parametric calculations of the temperature rise in the outer layer of the DT-filled, CH-foam ablator were performed for a range of first wall temperatures, chamber fill gas pressures, and injection velocities [1]. It is assumed for this analysis that the total heat flux absorbed by the target must stay below ∼0.5–$1\,\mathrm{W\,cm^{-2}}$ for the DT to avoid extensive phase changes. Calculations were performed with a 6.5 m radius chamber, using a high $400\,\mathrm{m\,s^{-1}}$ injection velocity, a target surface reflectivity of 96%, and a range of gas pressure of 0–50 mTorr (measured at 300 K), a range of wall temperatures for 400–1100˚C, and a range of gas temperatures from 400˚C to 2100˚C. The results are shown in figure 9. For gas temperatures equal to the wall temperatures, less than $1\,\mathrm{W\,cm^{-2}}$ heat load is calculated for temperatures below 800˚C at 10 mTorr. For gas temperatures 1000˚C over the wall temperature, less than $1\,\mathrm{W\,cm^{-2}}$ heat load is calculated for wall temperatures below 400˚C at 10 mTorr. At 800˚C wall temperature the gas pressure would have to be less than 5 mTorr.

If the gas temperature is much higher than the chamber wall with gas pressure more than a few millitorr, thermal survival of the targets will require changes in the target design or additional measures to provide thermal protection of the target. The following section presents recent developments and potential thermal protection methods for the target.

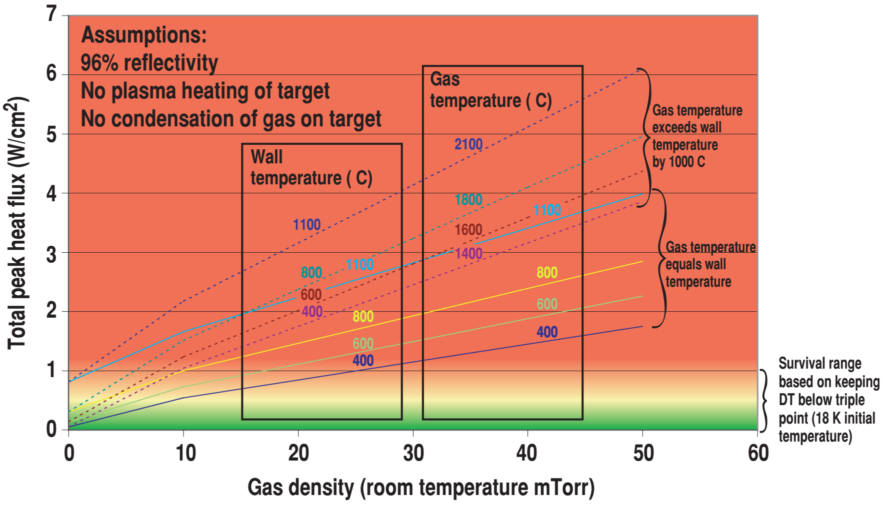

Figure 9. Total peak convective and radiative heat flux absorbed on the target surface vs gas density for several wall and gas temperatures.

3. Target protection developments

3.1. Reflective coating

A program was carried out to determine if a highly reflective layer of high-Z material could be deposited on the surface of a direct-drive target. Such a layer must be very thin, very uniform, stable through the target fabrication and staging process, and permeable enough to allow rapid target filling with pressurized DT gas.

Both gold and silver have the highest reflectivity over the temperature range of interest but gold was selected for the first coating experiments because silver presents activation issues under neutron irradiation. Thin (100–900 Å), smooth layers of gold were sputtered onto ~1 μm thick layers of CH polymer plasma-coated on silicon flats. The optical properties were measured with ellipsometry and the reflectivity was calculated as a function of wavelength, angle of incidence, and film thickness and the overall reflectivity was calculated for the blackbody spectrum over a range of potential chamber temperatures, as shown in figure 10. For the gold coating thickness of interest for the target design (about 325 Å) and for a chamber temperature of ~700–1100˚C, the integrated reflectivity was between 95% and 96%. Polymer shells were successfully gold-coated with the desired thickness, uniformity, and stability by the process illustrated in figure 11. The gold-coated shells were permeation filled with argon and helium without problem, but they took about ten times longer to fill than the uncoated shells. Slow permeation filling would lead to an undesirably large tritium inventory in the target filling station of an IFE power plant. It may be possible to significantly increase the permeability of the gold coating, e.g. by creating a columnar structure or pinholes in the coating.

Similar coating experiments were performed with palladium, another high-Z material known to be less reflective but more permeable than gold to hydrogen isotopes. Satisfactory palladium-coating of polymer flats and shells was demonstrated. The reflectivity of thin (390 Å), flat coating samples was determined as a function of wavelength independently by ellipsometry and by integrated direct measurement. The results were concordant and only slightly lower than for bulk palladium, as shown in figure 12. Based on the ellipsometry data for palladium coatings, the calculated normal-incidence reflectivity, integrated over wavelength in the black body spectrum, was ~83% at 627˚C, ~80% at 1000˚C, and ~76% at 1487˚C. The hemispherical reflectivity would be slightly higher. Tests demonstrated that permeation filling is much faster for palladium-coated polymer shells than for gold-coated ones, and only slightly slower than for uncoated shells, as shown in figure 13.

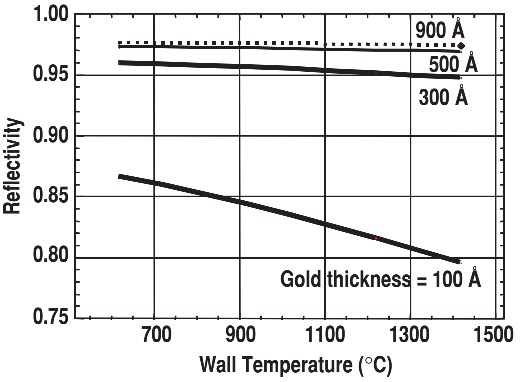

Figure 10. Calculated hemispherical reflectivity of flat gold coatings of various thickness vs chamber wall temperature.

Ways of combining the higher reflectivity of gold coating with the greater permeability of palladium coating, e.g. by coating with an Au–Pd alloy, are being investigated.

3.2. Other thermal protection methods

The main approach to ensure target survival during injection is to avoid complexity by providing inherent protection against overheating. This is done by selecting the lowest reasonable chamber temperature and fill-gas pressure compatible with the

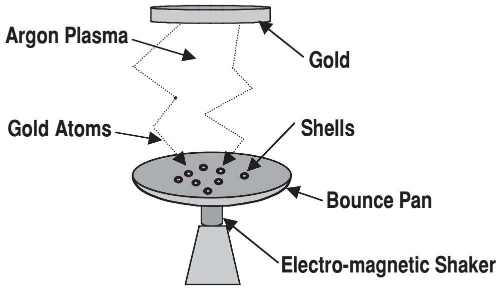

Figure 11. Gold-coating of target shells by sputtering.

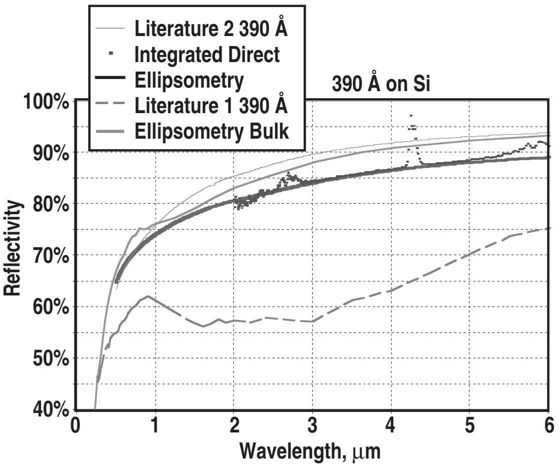

Figure 12. Palladium reflectivity vs wavelength for various samples.

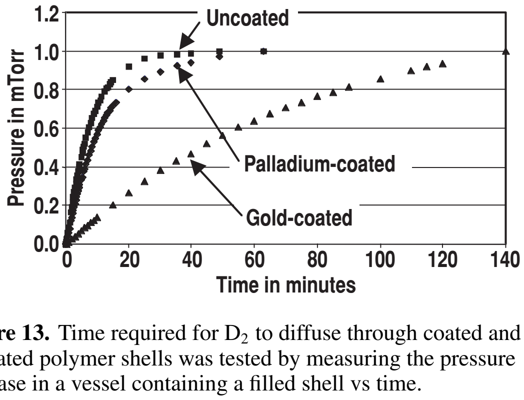

Figure 13. Time required for D_2 to diffuse through coated and uncoated polymer shells was tested by measuring the pressure increase in a vessel containing a filled shell vs time.

plant design, and by adjusting the target design parameters within the limits set by implosion physics and by the need to ensure target integrity. However, several additional methods have been identified that can be developed, if needed, to keep the temperature of the target below the limits described in section 2.1. Some of them are listed below:

(a) Providing a sacrificial layer of frozen gas (e.g. Xe, Ne, D_2, DT) on the target surface.
(b) Imparting a tumbling spin to the target around the axis perpendicular to the direction of flight to reduce the asymmetric convective heating, coupled with a sacrificial layer.
(c) Designing a target surface to foster random tumbling of the target to obtain more uniform heating ('comet' approach), coupled with a sacrificial layer.
(d) Using a target with an external foam layer. This layer may be filled with solid Ne or DT to provide strength during acceleration in the injector and evaporative cooling during transit in the chamber. Alternatively, the foam may be cooled by an external, solid Ne or DT layer.
(e) Co-injection of a sacrificial 'Wake Shield' to eliminate convective heating by clearing the fill gas ahead of the target 13].
(f) Using a sacrificial sabot [14] or a cooled radial tube inserted into the chamber to protect the target during most of its transit to the chamber centre.

For target designs without reflective high-Z coatings, take advantage of the fairly small absorptivity of DT in the infrared by designing a 'transparent' target with polymer materials tailored to minimize absorption for the given thermal radiation spectrum.

4. Conclusions

Radiation and convection heating during injection and its effect on survival of the cryogenic fusion fuel is an important issue for the direct drive IFE target. In order to optimize target chamber design conditions for an IFE power plant, estimates of target heating and the ranges of conditions for successful injection are needed. While experimental studies with cryogenic DT are planned, results are quite some time in the future. Thus, best estimates have been made of the temperature limits that will allow survival of the cryogenic DT. Survival is based on keeping the surface of the solid DT below the triple point, avoiding the potential formation of gas bubbles within the target which would adversely affect the implosion stability. On this basis, an upper limit of the heat flux to the target of about 0.5–1 $\mathrm{W\,cm^{-2}}$ is estimated.

Calculations of the heat fluxes generated by radiative heating and convective heating in the chamber over a range of temperatures and pressures have been performed. Assuming that 1 $\mathrm{W\,cm^{-2}}$ heat flux is acceptable and that the gas temperature is the same as the chamber wall temperature, successful injection is calculated for temperatures below about 800°C at 10 mTorr and below about 400°C at 25 mTorr. However, depending on the ultimate chamber design, the gas temperature may be significantly higher than the wall temperature during the time of injection. In this scenario, it is likely that changes in the target design or more drastic measures to provide thermal protection of the target during injection will be needed. While the desired approach to target survival is to provide inherent protection by coordinating chamber parameter selection and target design, there are many other engineered features that can be used to decrease the heat load to the target. As these add complexity to the target injection process they should be utilized only if inherent survival methods are found unworkable.

Acknowledgments

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