TARGET SURVIVAL DURING INJECTION IN AN
INERTIAL FUSION ENERGY POWER PLANT

by
D.T. GOODIN, R.W. PETZOLDT, A. NIKROO, E. STEPHENS,
N. SIEGEL,† N.B. ALEXANDER, T.K. MAU,‡ M. TILLACK,‡
F. NAJMABADI,‡ and R. GALLIX

This is a preprint of a paper to be submitted to Nuclear
Fusion.

†Virginia Polytechnic Institute and State University
‡University of California, San Diego, California

Work supported by
the U.S. Department of Energy under
Contract No. DE-AC03-98ER54411 and
Subcontract No. N00173-01-C6004

GENERAL ATOMICS PROJECT 30007
APRIL 2002
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 reactor chamber. Driver beams of laser or heavy-ions converging at the center of the chamber (CC) 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. In certain reactor designs 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. Detailed results of parametric radiative and convective heating calculations are presented for direct-drive targets during injection into a dry-wall reactor 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.
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 center of the capsule. The target is injected into the reactor chamber at high velocity at a rate of about six per second (Fig. 1). When the target reaches the chamber center (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 Ref. [1].

Figure 2 illustrates schematically a distributed radiator, heavy-ion driven, indirect-drive IFE target design [2]: 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 center of the chamber. Therefore, the fuel remains at ~18 K during injection for a wide range of operating conditions.

Figure 3 shows the design, optimized for implosion physics, of a radiation preheat, direct-drive IFE target consisting of five parts [3]: 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 vapor.

Fig. 1. Target injection schematic.
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 reactor concepts. The coordinated design of the chamber and the targets must ensure that heating during injection does not excessively affect target uniformity.

This article presents detailed results of heating analyses of the direct-drive target design shown in Fig. 3 during injection into the 6.5 m radius chamber of the Sombrero reactor concept [4], as well as recent target thermal protection developments, aimed at establishing integrated design parameter windows for target survival.
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. 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 Fig. 4. Considering all the uncertainties inherent to this analysis, the total heat flux absorbed by the target should be in the range of ~0.5 to 1 W/cm² to avoid extensive phase changes in the DT for an injection velocity of ~400 m/s, considered to be near the maximum practical velocity.

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

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 (< ~2 μm RMS) at the inner surface of the DT ice, then cooled down to ~18 K before injection. During "layering" and cooling experiments [5] 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 [6] indicate that the polymer capsule 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 reactor chamber, as the polymer capsule and the outer layer of frozen DT are heated up very rapidly\(^1\) 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 [6] 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

Convective heating. The Sombrero chamber utilizes rarefied xenon fill gas to attenuate x-rays and debris emanating from the target explosion, in order to limit wall temperature excursions and wall ablation. The fill gas is at roughly the same elevated temperature as the chamber wall. 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 [7]. The magnitude and distribution of the heat flux around the surface of the target were obtained, as illustrated in Figs. 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 Fig. 7 as a function of chamber gas temperature for two injection velocities. It should be noted that a lower velocity decreases the convective heat flux but increases the heating time, resulting in a slightly higher total heat load.

It has recently been noted that chamber gas temperature is likely much higher than the chamber wall temperature due to the short time available for gas cooling between shots. This effect is currently under investigation.

Radiative Heating. During injection the target is exposed to a uniform heat flux \(q = \sigma T^4\) W/cm\(^2\) from the hot chamber wall radiating as a black body at absolute temperature \(T\), where \(\sigma\) is the Stefan-Bolzmann constant. For \(T = 1758\) K (1485°C) and 1273 K (1000°C), \(q = 54\) and 15 W/cm\(^2\) respectively. The heat flux absorbed by the target, \(q' = (1-\rho)\sigma T^4\) W/cm\(^2\), is reduced by the reflectivity \(\rho\) of its surface. A very reflective target surface is clearly required to keep the total absorbed heat flux between ~0.5 and 1 W/cm\(^2\). A surface reflectivity of about 98% \(^1\)Transit time across a 6.5 m radius chamber is about 16 ms at 400 m/s.
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.
Fig. 7. Peak convective heat flux absorbed on the target surface during injection.

Fig. 8. Radiative heat flux absorbed on the target surface during injection versus chamber wall temperature.

**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 that the total heat flux absorbed by the target must stay below ~1 W/cm² for the DT to avoid extensive phase changes. Calculations were performed for the Sombrero reactor design with a 6.5 m radius chamber, using a high 400 m/s injection velocity and a low 10 mTorr fill gas pressure (measured at 300 K). The results show that the chamber wall and gas temperature must not exceed ~1000°C with a 98% target surface reflectivity, or 800°C with a 96% target surface reflectivity.
These plant parameters represent a marked reduction from the 1485°C chamber wall temperature and 500 mTorr fill gas pressure of the reference Sombrero reactor design in [4], indicating that the issue of target survival of heating during injection is critical to the design of both the target and the chamber. The following section presents recent developments and proposed solutions for target survival.
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 Fig. 9. For the gold coating thickness of interest for the target design (about 325 Å) and for a chamber temperature of ~ 700 to 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 Fig. 10. 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

![Graph](image)

Fig. 9. Calculated hemispherical reflectivity of flat gold coatings of various thickness versus chamber wall temperature.
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. 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 Fig. 11. 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 Fig. 12.

![Graph showing pressure in mTorr versus time for uncoated, palladium-coated, and gold-coated shells.](image)

Fig. 12. Time required for D₂ to diffuse through coated and uncoated polymer shells was tested by measuring the pressure increase in a vessel containing a filled shell versus time.

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 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 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:

1. Providing a sacrificial layer of frozen gas (e.g., Xe, Ne, D₂, DT) on the target surface.
4. CONCLUSIONS

Results of experiments and calculations to date show that there are operating regimes that would allow successful target injection into IFE power plants, albeit at reduced chamber wall temperature\(^2\) and fill-gas pressure for reactor designs using direct-drive targets. The effects of such reductions on plant energy efficiency and maintenance cost must be taken into account in optimizing the plant design and driving the continuing development of target design and testing. While the first approach to target survival is to provide inherent protection by coordinating chamber parameter selection and target design, there are many other methods that can be developed if needed. However, alternate concepts which would add complexity and risk to the power plant design and operations should be considered only if target designs with inherent survival features cannot be achieved within a reasonable time span.

\(^2\)Fortunately, much of the fusion energy absorbed by the chamber is due to neutrons which are deposited over the ~1 m thick first wall; thus a small penalty in overcooling the inner surface of the first wall can substantially reduce the radiation heat load on the target.
REFERENCES


ACKNOWLEDGEMENTS

This work has been supported by the U.S. Department of Energy under Contract No. DE-AC03-98ER54411 and the Naval Research Laboratory under Subcontract No. N00173-01-C-6004.