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ABSTRACT

Fueling of a commercial Inertial Fusion Energy (IFE) power plant consists of supplying about 500,000 fusion targets each day. The most challenging type of target in this regard is for laser-driven, direct drive IFE. Spherical capsules with cryogenic DT fuel must be injected into the center of a reaction chamber operating at temperatures as high as 1500°C and possibly containing as much as 0.5 torr of xenon fill gas. The DT layer must remain highly symmetric, have a smooth inner ice surface finish, and reach the chamber center at a temperature of about 18.5 K. This target must be positioned at the center of the chamber with a placement accuracy of ± 5 mm. The accuracy of alignment of the laser driver beams and the target in its final position must be within ± 20 μm. All this must be repeated six times per second. The method proposed to meet these requirements is injecting the targets into the reaction chamber at high speed (~400 m/s), tracking them, and hitting them on the fly with steerable driver beams. The challenging scientific and technological issues associated with this task are being addressed through a combination of analyses, modeling, materials property measurements, and demonstration tests with representative injection equipment. Measurements of relevant DT properties are planned at Los Alamos National Laboratory. An experimental target injection and tracking system is now being designed to support the development of survivable targets and demonstrate successful injection scenarios. Analyses of target heating are underway. Calculations have shown that the direct drive target must have a highly reflective outer surface to prevent excess heating by thermal radiation. In addition, heating by hot chamber fill gas during injection far outweighs the thermal radiation. It is concluded that the dry-wall, gas-filled reaction chambers must have gas pressures less than previously assumed in order to prevent excessive heating in the current direct drive target designs. An integrated power plant systems study to address this issue has been initiated.

1. INTRODUCTION AND BACKGROUND

At the heart of an Inertial Fusion Energy (IFE) power plant is a target that has been compressed and heated to fusion conditions by the energy input of the driver beams. For direct drive, the target consists of a spherical capsule that contains the DT fuel. For indirect drive, the capsule is contained within a cylindrical or spherical metal container or "hohlraum" which converts the incident driver energy into x-rays to implode the capsule. The target must be accurately delivered to the target chamber center at a rate of about 5-10 Hz, with a precisely predicted target location. The fragile targets must survive injection into the target chamber without damage.

An example of a recent direct drive IFE target is shown in Fig. 1. The target consists of four parts: a gold-coated polymer capsule of thickness ~1μm, a DT filled CH foam ablator, a layer of solid DT fuel, and a core containing DT vapor. The target design gain is 125 using a 1.3 MJ KrF laser [1].

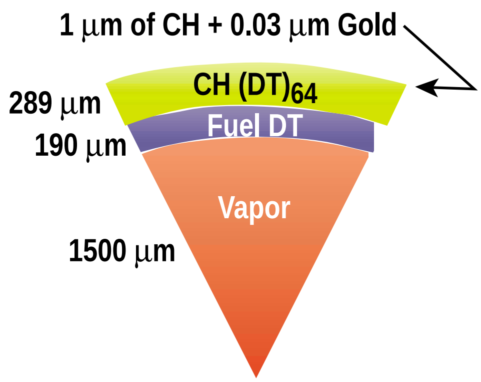

Fig. 1. Direct drive target concept for IFE designed at NRL.

Shown in Fig. 2 is an example of a close-coupled, heavy-ion indirect drive target proposed by LLNL [2]. The DT fuel is contained in the central capsule supported by a polymer membrane attached to the hohlraum casing. The interior geometry consists of beam blocks and converters constructed from low density metals and polymers. The design yield of this target is 436 MJ with a gain of 133.

While IFE power plant design studies [3, 4] have suggested potentially plausible scenarios for both direct drive and indirect drive target injection, the purpose of the development program described in this paper is to provide the detailed scientific basis that will be necessary for fueling of future IFE power plants.

This paper presents the requirements and key issues that have been identified for IFE target injection, summarizes the modeling and analyses that have been done, and presents the development program that is planned to assure that target injection can be successfully accomplished.

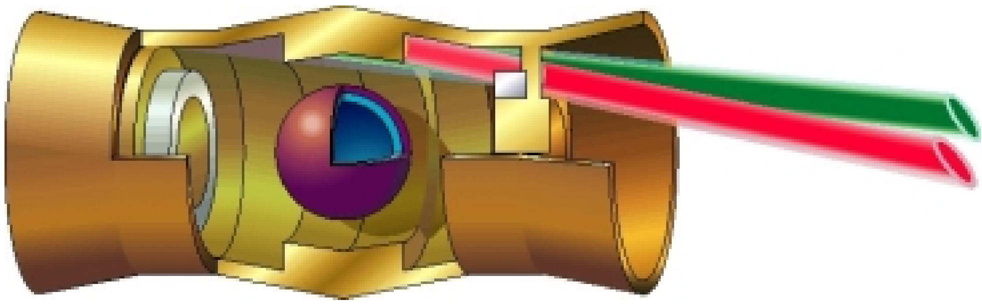

Fig. 2. Close-coupled, heavy-ion indirect drive target concept for IFE designed at LLNL. The length of the target is 20 mm and the average radius is ~5 mm. The central fuel capsule is ~4.7 mm in diameter and consists of a 0.2 mm thick bromine doped beryllium ablator followed by a solid DT fuel layer of 0.32 mm thickness.

2. DEVELOPMENT PROGRAM

2.1. Key Technical Issues

The top-level critical issue for target injection and tracking is the ability to accurately and repeatedly place a target filled with DT ice at ~18.5K, and meeting precise geometric requirements, at the center of a high-temperature target chamber at a rate of 5 to 10 Hz.

Key issues associated with demonstrating a successful IFE target injection methodology are:

1. Ability of targets to withstand acceleration into chamber
2. Ability of targets to survive chamber environment (heating due to radiation & gases)
3. Accuracy and repeatability of target injection
4. Ability to accurately track targets.

2.2. Target Injection Requirements for IFE

Target injection systems for IFE power plants must place about 500,000 cryogenic targets each day (at a rate of 5 - 10 Hz) into a target chamber operating at 500 - 1500°C. This must be done with high precision, high reliability of delivery, and without damaging the mechanically and thermally fragile targets. Target placement must be within ±5 mm of a specified point at the target chamber center. In addition to the placement, target tracking must be accurate enough to enable precise alignment of the driver beams with the actual target position. The accuracy requirements for indirect drive targets is alignment of the driver beams and the targets to within ±0.1 mm perpendicular to the injection axis and about ±0.3 mm along the injection axis. The relaxed requirement along the injection axis is due to the narrow angle from which the beams approach along this axis. Direct drive targets will require alignment of the centerline of the driver beams with the centerline of the target to within about ±0.02 mm. Greater position measurement accuracy is required in order to be able to predict target position with the above accuracies. Target position prediction must be accomplished early enough to allow time for beam steering.

2.3. Prior Work

Design studies of target injection were done as part of the several IFE power plant studies completed in the early 1990's. A gas gun system was proposed for injection, along with target tracking and beam steering. More recently, a gas gun indirect drive target injection experiment has been constructed and operated at LBNL [5] (Fig. 3). The results showed that relatively simple gas gun technology could repeatably inject a simulated indirect drive target to within about 5 mm of the driver focus point, within the range of laser or beam steering mechanisms to hit, but not sufficient to avoid the need for beam steering. Results from this 3 m coasting distance experiment extrapolate to ±0.2 mm target position prediction accuracy at power plant size. This work has recently been extended to show similar results for low speed (~70 m/s) injection of simulated direct drive targets (solid plastic spheres) at room temperature, using a sabot.

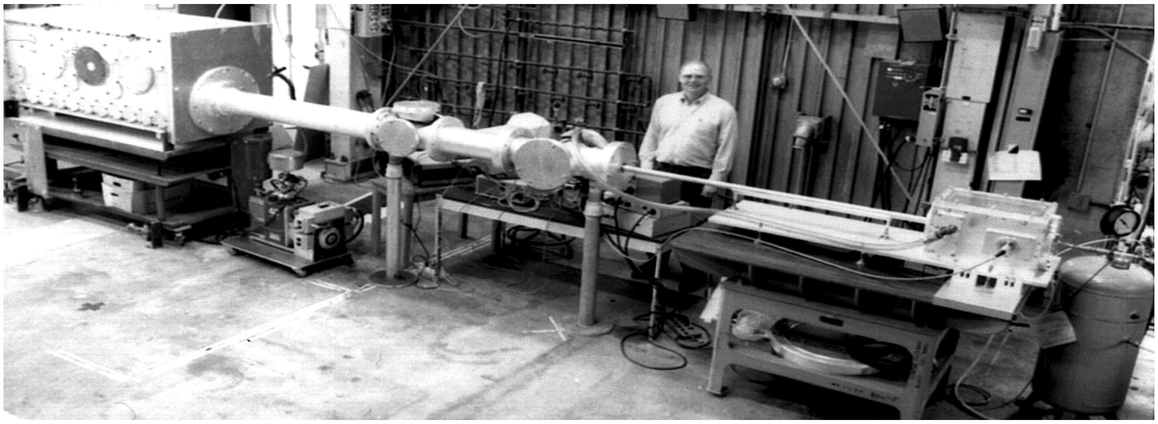

Fig. 3. IFE Target Injection Experiment at LBNL.

2.4. Approach to Resolution of Issues

Development issues for target injection will be addressed with a combination of analyses and experiments. Since the development pathway for IFE is anticipated to take several decades and span more than one generation of scientists and engineers, a well-documented and scientifically sound basis to address the key issues is needed. Modeling of basic phenomena and supporting analyses are an inherent part of this development strategy. However, the ultimate goal must be to demonstrate successful injection under prototypical conditions to prove the viability of IFE. For this purpose, an experimental target injection and tracking system is being designed (see Section 4).

Significant overlap exists between the technology development programs for ion driven (typically indirect drive targets) and laser-driven (typically direct drive targets) inertial fusion. This overlap includes the areas of target fabrication, tritium fueling, cryogenic handling, high-rate injection, and tracking. Many of the material and equipment development needs for direct drive and for indirect drive targets are closely related, if not identical. Thus, a common R&D program is planned to address these development areas.

Even more essential for a successful development program, is a close integration of the target fabrication and injection/tracking development tasks, coupled with an ongoing coordination with IFE target designers. It is crucial to assess the effects that proposed changes in one area have on the other, closely related, areas of target fabrication, injection, and physics.

3. RESULTS OF ANALYSES

3.1. Target Heating During Injection

Following acceleration inside the injector, the target will enter the reactor chamber and coast to the center at which point the driver energy is applied and the target is imploded. While coasting through the chamber, the target is exposed to a heat flux from two sources: thermal radiation emitted by the chamber walls and convection resulting from the interaction between the target and a chamber fill gas (if present). The heat which is applied at the target surface conducts into the portions of the target containing DT.[1] Once this occurs, the target can be damaged either by melting of the DT or by yielding of the DT due to thermal stresses. For current direct drive target concepts it has been calculated that the target can tolerate less than a 0.8 K temperature increase in the outermost DT layer before the yield strength is exceeded. Another potential temperature "limit" during injection is reaching the triple point of DT at 19.79 K.

An IFE reactor such as the Sombrero design [3] with a chamber wall temperature of around 1760 K (~1485°C) would emit 54 W/cm^2. A reactor with a cooler wall temperature of ~900 K (~630°C) such as the Osiris design [3] would emit 3.7 W/cm^2. By using highly reflective coatings on the targets, the amount of radiation absorbed at the target surface can be reduced to about 2% of the incident radiation. It is recognized that achieving a target design with 98% surface reflectivity in the infrared will be challenging.

Assuming that a highly reflective coating is used, the thermal radiation heat flux in even the Sombrero chamber can be reduced to ~1 W/cm^2. Then the bulk of the heating load on the target during injection results from the interaction between the target and low-density chamber fill gas.[2] Since the fill gas is rarefied, continuum regime heat transfer relations cannot be directly used to evaluate the convective heat transfer. Instead, a correction factor accounting for rarefied flow effects (non-continuum boundary conditions) is used to adjust the continuum equations (Eqs. 1–2) [6,7]. For injection at 400 m/s and a steady state gas temperature of 1760 K, the heat flux incident on the target surface due to convection is calculated to be ~13 W/cm^2. Assuming symmetric heating for the moment, the convective heating can be calculated with the following equations.

$$q''_{conv} = Nu_{slip}\frac{k}{D}(T_{gas} - T_{target}) \quad , \tag{1}$$

[1]Calculations show that current designs of indirect drive targets [2] injected into liquid wall chambers [3] do not show any significant heating of the DT ice. This is a result of protection provided by the low thermal conductivity materials used in the hohlraum construction.

$$Nu_{slip} = \frac{Nu_{cont}}{1+\zeta} = \frac{2 + (0.4\,\mathrm{Re}^{1/2} + 0.06\,\mathrm{Re}^{2/3})\,\mathrm{Pr}^{0.4}\left(\frac{\mu}{\mu_s}\right)^{1/4}}{1.255\sqrt{\gamma}\,\frac{2-\alpha}{\alpha}\,\frac{2\gamma}{\gamma+1}\,\frac{Ma}{\mathrm{Re}\cdot\mathrm{Pr}}} \quad . \tag{2}$$

Where q''_{conv} is the convective heat flux, k is the thermal conductivity of xenon, D is the target diameter, T_{gas} is the fill gas freestream temperature, T_{target} is the target surface temperature, Re is the Reynolds number, Pr is the Prandtl number, Nu_{slip} is the rarefied flow (corrected) Nusselt number, Nu_{cont} is the continuum flow Nusselt number, γ is the specific heat ratio, α is the accommodation coefficient, μ is the freestream viscosity, and μ_s is the viscosity at the target surface temperature. These adjusted continuum equations are used to provide an estimate of the convective heat flux on the target during injection in near-continuum through transition regimes. (Near continuum, or slip flow regime, = Knudsen numbers up to ~0.1).

A computational fluid dynamics program, ANSYS FLOTRAN, was used to determine the distribution of the convective heat flux along the target surface in the near-continuum regime [8]. The reactor environment conditions were: gas temperature of 1760 K, fill gas pressure of 0.5 torr. The analysis was done at three injection velocities: 100, 200 and 400 m/s.[3] The results of the analysis (Fig. 4) show that a major asymmetry is present at injection speeds of 400 m/s. This is a significant issue since asymmetric heating will cause the density of the solid DT fuel near the target surface to vary around the circumference, leading to hydrodynamic instabilities during target implosion. Reducing the injection speed does reduce the asymmetry, but leads to higher overall heating as the time of exposure is extended. Integrating the FLOTRAN near continuum results for 400 m/s injection speed leads to a calculated total convective heat flux of ~13 W/cm^2, in good agreement with the estimates obtained by using Eqs. (1) and (2). If the heating is assumed to be uniform, the total heat flux absorbed at the target surface due to both thermal radiation and convection can be calculated with Eqs. 1–2 and standard thermal radiation heat transfer theory. These results are shown in Fig. 5 as a function of injection velocity and fill gas pressure.

To evaluate the allowable heat flux, the finite element code ANSYS was used to calculate the temperature rise in the outer DT ablator of the Ref. 1 direct drive target for different surface heat fluxes as a function of injection time (Fig. 6.) For injection at velocities of 400 m/s or less, the allowable amount of heat flux absorbed at the target surface must be less than ~1 W/cm^2 in order to prevent the outer DT ablator from exceeding the DT triple point temperature during injection. Since this level of heat flux is imposed by thermal radiation alone in a Sombrero dry wall chamber, this means that the convective heating component must be reduced to negligible levels for target survival. The most straightforward methods to reduce the total heat flux are to reduce the chamber fill gas pressure and/or reduce the chamber operating temperature.

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[2]The fill gas, xenon, is present in the chamber to attenuate x-rays and slow debris ions before they reach the first wall. The SOMBRERO reactor design, which is representative of a class of dry-wall reactors, contains 0.5 torr of xenon (pressure specified at 300 K.)
[3]FLOTRAN is a Navier-Stokes solver. For this reason only continuum/near continuum flows can be modeled. At a temperature of ~1500°C and 0.5 torr fill gas pressure, the flow is at the limit of the solver's capabilities.

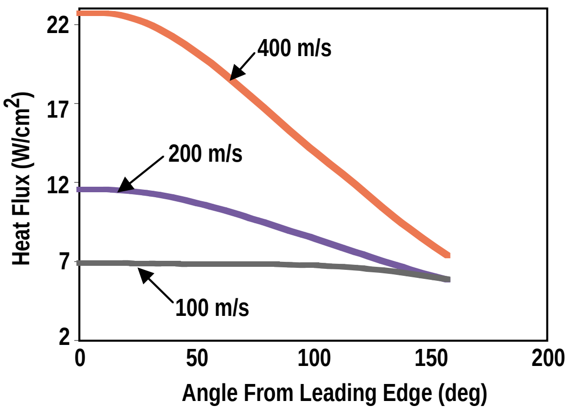

Fig. 4. Convection heat flux distribution over the surface of a direct drive target.

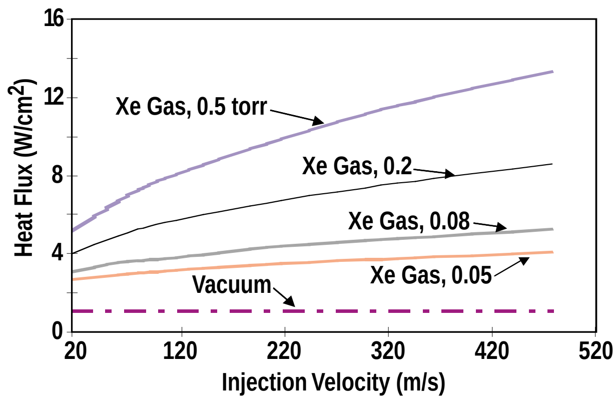

Fig. 5. Total uniform heat flux on a direct drive target during injection into a dry-wall chamber operating near 1485 °C.

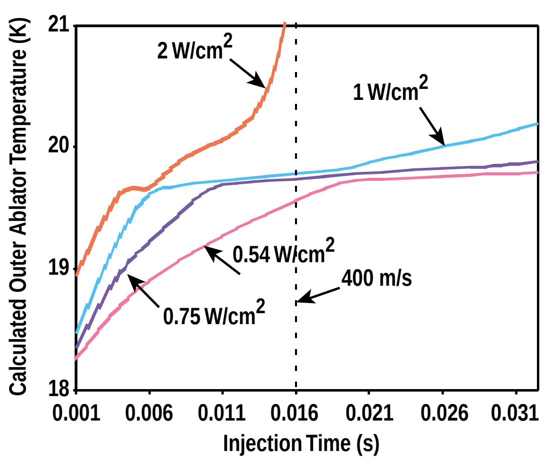

Fig. 6. Finite element results showing the temperature rise in the outer DT ablator as a function of uniformly distributed surface heat flux and injection time (time in the target chamber).

A parametric finite element analysis was performed in order to evaluate the design envelope for a dry wall, gas-filled target chamber under a variety of different operating conditions. The parameters included fill gas pressure, chamber wall and gas temperature, and injection velocity. The results of the analysis are summarized in Fig. 7.

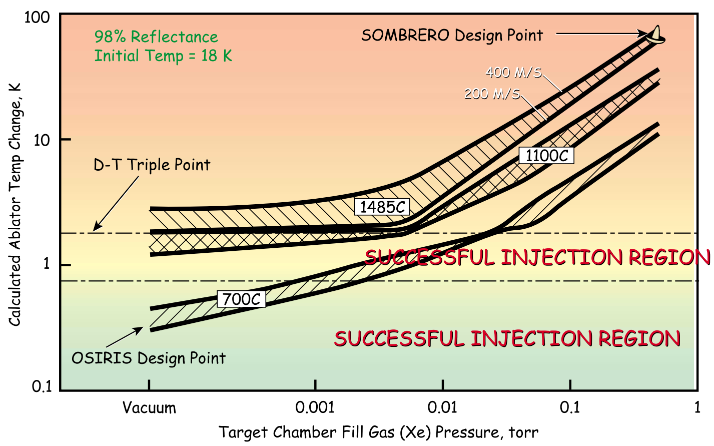

Fig. 7. Calculated outer DT ablator temperature following injection. A temperature < 18.8 K is considered to be successful injection; T > 19.8 K is excessive heating during injection.

The precise point of failure of the target due to heating is not known. Thus, an "at risk" region is defined when the calculated thermal stresses in the DT exceed the yield strength. For injection at 18 K, this criteria is met at a delta T of ~0.8 K. Calculations show that injecting the target at lower temperatures actually reduces the time for reaching the yield stress in the DT. This is due to the lower heat capacity of the DT as the temperature is reduced. Once the outer ablator of the target reaches or exceeds the DT triple point (19.79 K), melting and or vaporization will begin which will most likely affect the implosion stability of the target and lead to failure ("excessive heating" region).

Indirect drive targets are significantly more resistant to heating due to the high thermal resistance of the hohlraum materials. For the close-coupled design [2] shown in Fig. 8, heat is deposited on the surface of the target and must conduct through ~3 mm of low density, low thermal conductivity materials before reaching the central fuel capsule. (Also included in Fig. 5 is a Flibe layer that is assumed to encase the outer surface of the Ref. 2 target during injection. This outer Flibe layer is a structural material which provides strength for the target during the injection process.)

A finite element analysis was performed on the close-coupled target to determine the temperature rise in the DT fuel during injection. The results show that the DT effectively remains at the initial injection temperature of 18 K. Figure 9 shows the calculated temperature distribution in the close-coupled target from LLNL during injection. The curve begins at the outer surface of the Flibe casing. There is no significant temperature change in the DT ice.

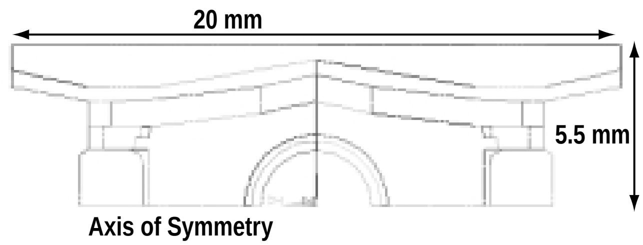

Fig. 8. Indirect drive close-coupled IFE target design [2].

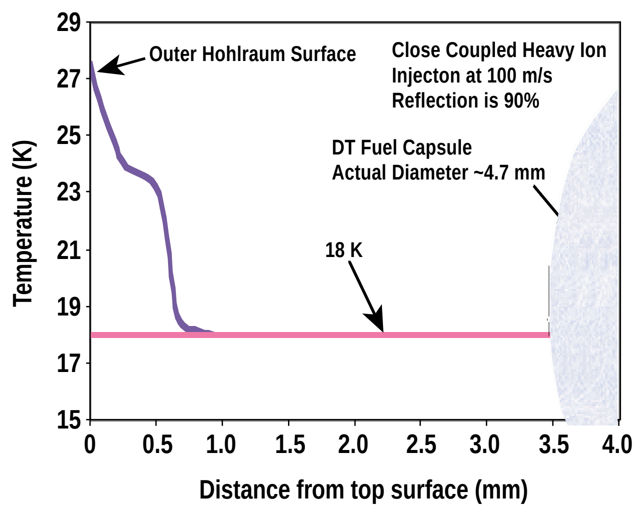

Fig. 9. Temperature distribution in close coupled indirect drive target. Injection speed is 100 m/s and reactor temperature is 930 K. Surface reflectivity of the target is assumed to be 90% and the reactor chamber is assumed to be evacuated.

The key issue of target survival in the high temperature chamber environment is being addressed initially by development of a modeling capability as described in this section. It is expected that modeling of the injection environment will be used to work with target designers and iteratively develop targets that are more resistant to thermal damage. Then it will be necessary to demonstrate successful target injection under prototypical conditions. For this purpose, an experimental target injection system is being designed — as described in the next section.

4. DESIGN OF AN EXPERIMENTAL TARGET INJECTION SYSTEM

4.1. Selection of the Injector

Most IFE design studies have assumed that a light gas gun would be suitable for target injection. A detailed review of this assumption in light of current injection system was conducted. Light gas guns, electrostatic accelerators, and a variety of magnetic accelerator options were considered. Electrostatic accelerators could be suitable for the low mass of direct drive targets but are limited to an acceleration of about 1000 m/s^2 (and consequent long injection system lengths). They are not suitable for the higher-mass indirect drive targets. Magnetic systems are capable of accelerating both direct drive and indirect drive targets at accelerations and velocities that are limited only by the structural capabilities of the targets. However, the light gas gun was determined to be the simplest and lowest cost option that met all the system requirements. Consideration of target heating, maximum velocity, barrel swelling due to neutron damage, target chamber products in the barrel, barrel wear, gas injection into the target chamber, and cycle time factored into the evaluations. While a primary use of the current experimental system will be as a tool in developing successful targets for IFE and developing target tracking capability, it is fully expected that the light gas gun injection technology will also be suitable for use in an IFE production plant environment.

4.2. Design of a Gas Gun Injector

An overview of the injection system is shown in Fig. 10. The experimental facility consists of a gas supply and control system, a target loading system, a gas removal system, a sabot removal system, a target tracking system, and a simulated target chamber. While the facility will be operated first at room temperature, it is designed for later upgrades to accept cryogenic targets and inject them into a simulated target chamber at up to ~1760 K. The capability to provide chamber fill gas pressures up to 0.5 torr will also be incorporated. The design of the injector is underway (Fig. 11). The system includes a series of pressure-reducing expansion chambers to remove the injection gas prior to reaching the target chamber. The gas gun will operate at a pressure of up to 2.8 mPa and accelerate targets at up to 50,000 m/s^2 to a velocity of up to 400 m/s. The capability to inject up to 12 targets in a 2 s test is included.

During operation, the injector produces a gas flow into the system of up to 9400 Pa-m^3 of helium. The bulk of this gas must be removed or prevented from reaching the exit of the injection system where the allowable pressure increase is set at ~0.01 Pa. This is accomplished by injecting the target through a series of individual expansion chambers, separated by rotating shutters, which are each connected to evacuated reservoirs (Fig. 11). The reservoirs take the place of high-capacity, continuous-flow pumps that would be utilized in a power plant configuration. The shutters are designed to allow the target to pass through while minimizing the amount of gas moving from one chamber to the next. Figure 12 shows the calculated pressure rise in each chamber during a two second test. The pressure rise in the last chamber (#5), for 0.5 m^3 expansion volumes, is 0.1 mPa, less than the required value of 0.01 Pa.

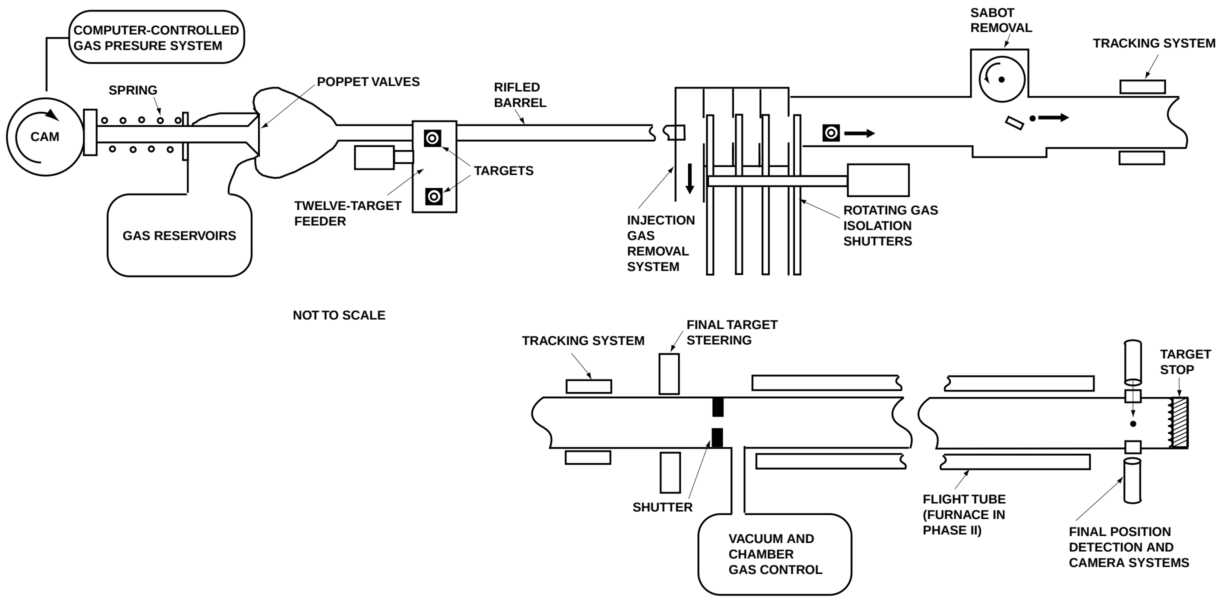

Fig. 10. Overview of experimental target injection and tracking facility.

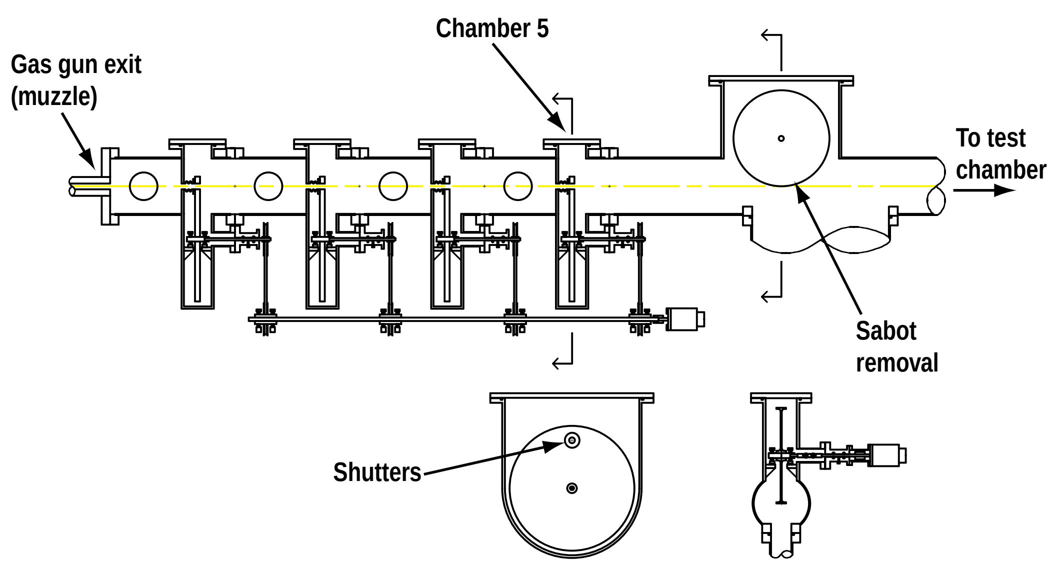

Fig. 11. Pressure reduction and sabot removal sections of the experimental injection and tracking system. The evacuated reservoirs are not shown.

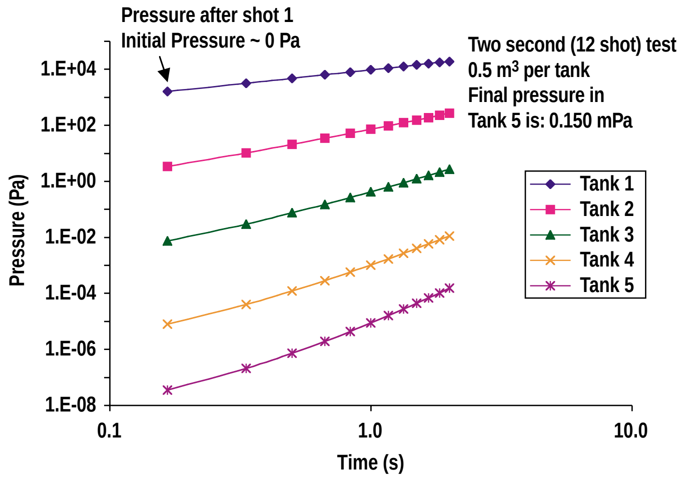

Fig. 12. Pressure rise in the expansion chambers during a 2-second (12 shot) test. If the shutters remain active after the test, the pressure in all chambers will eventually reach an equilibrium value of ~4700 Pa.

4.3. Target Protection in a Gas Gun

Direct drive targets, especially those with DT near the outer surface, must be isolated from the propellant gas during injection with a gas gun. The gas will exist both behind and in front of the projectile as well as beyond the end of the barrel during the injection process. Providing this isolation while providing an effective release mechanism that does not adversely affect the target trajectory is a challenge. One potential sabot design with a pressure released latch is illustrated in Fig. 13. The sabot is loaded and latched into the revolver. Firing gas pressure releases the latch and accelerates the sabot forward. To assist the latch release, a lubricant may be necessary to reduce friction between the latch and leading surface of the sabot. Gas flow into the sabot is minimized during acceleration by the chevron seal formed between the two halves of the sabot. Any gas that makes it in to the vicinity of the capsule will be cooled in transit to the sabot temperature.

The spring will be held in compression by the inertia of part 2 of the sabot during acceleration. The spring force of this design is limited to the force required to accelerate part 2 of the sabot. The capsule will roll back in it’s cavity during acceleration. The two halves of the sabot will be of roughly equal mass of order 1 g each.

After the sabot is clear of the barrel, the two halves begin to separate. Full separation is timed to occur after the injection gas is removed in the expansion chambers. After the sabot is clear of the capsule, target tracking can begin. After the sabot is well clear of the capsule, the sabot halves may be deflected away from the reaction chamber opening.

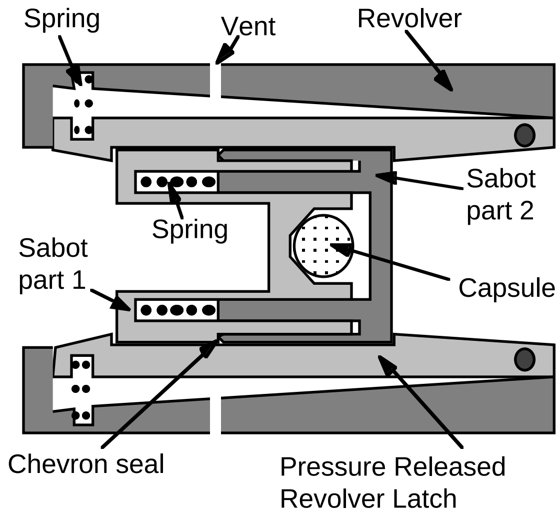

Fig. 13. The sabot isolates the capsule from warm propellant gas during acceleration and separates due spring force after leaving the barrel. The spring is compressed and the sabot is latched in the revolver.

A system such as this will enable the use of a gas gun for direct drive target injection. The required thickness for a plastic sabot to keep heat from the capsule is about 1 mm. The exterior of the sabot is calculated to reach ~100 K in the barrel. Using a typical linear temperature coefficient 10^{-5}/K, the thermal expansion will be ~10^{-3}. If the barrel is a constant diameter, this may imply a looser fit in the early part of the barrel. One may also consider a gradient in the barrel diameter or temperature to match the target thermal expansion.

4.4. Experimental Plans

The experimental target injection system described in this section will directly address the key issues of accuracy and repeatability of injection, as well as accuracy of tracking. This will be done initially at room temperature, then the system will be upgraded to cryogenic targets and a high temperature (simulated) target chamber. This final configuration of the system will then address the issues of target survival under acceleration and in the high temperature chamber environment.

5. DT MATERIAL PROPERTIES EVALUATION

Modeling of target behavior during acceleration and exposure to thermal stresses requires suitable material property data. A key parameter to address the issue of target survival under acceleration is the strength of DT ice at the temperature conditions of target injection. The currently available data are extrapolations, and indicate acceleration near 10,000 m/s^2 may be applied during injection. However, these data are measured with deuterium at 16.4K and no data are available for DT ice at 18.5K. Indeed, the DT properties are changing rapidly in this temperature range because it is approaching the triple point. In addition, the strength for DT may be a function of time due to buildup of He-3 from tritium decay. Thus, measurements of DT ice strength are planned at Los Alamos National Laboratory (LANL). These data, coupled with analytical evaluations to calculate the stresses imposed during acceleration, will be used to initially determine the DT ice survivability. In subsequent years, the experimental target injection system will be used to verify survivability during acceleration with prototypical targets. This issue is much less critical for indirect drive targets since the presence of the surrounding hohlraum provides thermal radiation protection which, in turn, results in significantly lower injection velocities and accelerations.

Additional tritium compatibility tests for target materials, and material property data will be acquired as needed. Analytical evaluations will be used to calculate stresses imposed on structures other than DT ice (*e.g.*, within indirect drive targets).

6. CONCLUSIONS

Target injection and tracking is recognized as a crucial element of the development plans for inertial fusion energy. A number of key issues associated with target injection and tracking have been identified, and a development plan has been assembled to address these key issues. The development plan for target injection consists of a combination of analysis and modeling, measurements of key material property data, iteration with target physics designers and plant systems evaluations, design of experimental equipment, and – ultimately – demonstration of target survival during injection under prototypical conditions.

A close interaction with target designers, target fabricators, chamber designers and safety/environmental specialists is underway. Design of a target injection and tracking experimental system to be used as a developmental tool has been initiated. The first data on accuracy and repeatability of injection will be at room temperature. Upgrades to cryogenic targets and a high temperature chamber will take place as the target designs evolve to those that can be fabricated and that have the potential to survive injection. Initial modeling results are already guiding the target design efforts and are being used in integrated power plant systems evaluations.

ACKNOWLEDGEMENT

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