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USING THE NOVA TARGET CHAMBER FOR HIGH-YIELD TARGETS

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Using the Nova Target Chamber for High-Yield Targets*

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Abstract

The existing 2.2-m-radius Nova aluminum target chamber, coated and lined with boron-seeded carbon shields, is proposed for use with 1000-MJ-yield targets in the next laser facility. The laser beam and diagnostic holes in the target chamber are left open and the desired 10^{-2}-Torr vacuum is maintained both inside and outside the target chamber; a larger target chamber room is the vacuum barrier to the atmosphere. The hole area available is three times that necessary to maintain a maximum fluence below 12 J/cm^2 on optics placed at a radius of 10 m. Maximum stress in the target chamber wall is 73 MPa, which complies with the intent of the ASME Pressure Vessel Code. However, shock waves passing through the inner carbon shield could cause it to comminute. We propose tests and analyses to ensure that the inner carbon shield survives the environment.

Introduction

The next laser facility beyond Nova will illuminate inertial-confinement-fusion targets with 10 to 12 MJ of energy and produce yields up to 1000 MJ. In the interest of economy when building the next laser facility, we propose using the existing 2.2-m-radius Nova aluminum target chamber lined and coated with boron-seeded carbon shields, as shown in Figure 1. The carbon lining inside the chamber moderates and absorbs 14-MeV neutrons emanating from the fusion reactions to reduce activation of the aluminum vessel wall. The carbon coating outside the chamber shields personnel from activation in the aluminum so they can return to the target chamber shortly after an experiment.

In contrast to Nova, the laser beam and diagnostic holes in the target chamber are open—no glass or other material is used over the holes. The desired 10^{-2}-Torr vacuum is maintained both inside and outside the target chamber; a separate target chamber room is used as a vacuum barrier to the atmosphere, as proposed by Sooy.[1]

In our proposal, the target chamber is a convenient means of supporting the carbon shields allowing carbon to be placed at a smaller radius than without a containing structure. This reduces the volume and, therefore, the expense of the carbon necessary for shielding. Optical components, diagnostics, and the target positioner would be supported from structures outside of the target chamber and so would not impose additional constraints on the target chamber as they do in Nova.

Because both the target chamber and the target chamber room are initially in vacuum, high-pressure gases produced inside the target chamber will jet out through the open laser-beam and diagnostic ports. These jets will spread dramatically once outside the target chamber in a fashion similar to a rocket jetting into the vacuum of space. The optics and diagnostics are positioned in a direct line-of-sight from the target and the dramatic spreading (initially about a 85° half angle) reduces the amount of material impacting them. Hence, less protection of the optics and diagnostics is needed.

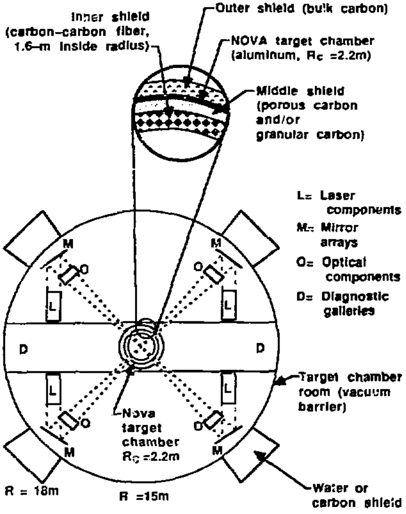

Figure 1. Sooy's High-Gain Test Facility concept revised to use the Nova target chamber.

Carbon Shielding

We propose three layers of carbon shielding; the outer layer surrounds the target chamber while the middle and inner layers line the inside of the target chamber. The inner shield has an inside radius of 1.6-m and is made of boron-seeded carbon-carbon fiber composite blocks to withstand the high-temperature, high-thermal-shock environment. The blocks are shaped so that they form a self supporting bridge or roof, similar to a Roman stone bridge or an Eskimo igloo. The blocks have an essentially zero coefficient of expansion in the circumferential direction. This zero coefficient reduces macroscopic thermal stress and thermal shock problems; however, some microscopic thermal stress will exist between the carbon matrix and the carbon fibers.

The middle shield is made of boron-seeded carbon foam and/or granular carbon material that dissipates shock waves caused when x-ray and debris energy is

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deposited at the inner surface of the shield. No shock waves reach the target chamber wall.

The outer shield is made of the inexpensive bulk carbon material, again seeded with boron, because it has near-zero stress and does not require much strength. All shield material has conical holes matching those in the target chamber so that the laser beams can illuminate the target.

Boron-seeded carbon is used for each shield because it moderates and absorbs 14-MeV neutrons, has good high-temperature properties necessary to avoid excessive ablation at the inner surface of the shields, and does not activate significantly itself. Tobin[2], in a companion paper, calculated the activation for shields with a variety of dimensions and boron seeding. Even with shielding, activation of the Nova target chamber aluminum wall may require excessive time delays before reentry into the laser facility. If reentry restrictions are too severe, the methodology outlined here can be applied to other target chamber designs such as those made of low-activating, carbon-carbon fiber composites rather than aluminum.

Area Available for Laser Beam Penetration

The existing 2.2-m inside-radius Nova target chamber has 20 entrance holes specifically manufactured for laser beam penetration, each hole being 0.91 m in diameter. The projected area of these 20 holes at 10-m radius is 270 m². In addition, there are two 1-m-dia holes on the horizontal centerline. The combined projected area at 10-m radius is 310 m². For a total laser beam energy of 12 MJ and a maximum fluence of 12 J/cm² with 0.35-μm laser light[1,3], the required area (the quotient) is 100 m². Hence, we have at least 2.7 times and if necessary up to 3.1 times the required area for laser beam penetration if the optics are located at 10-m radius.

Target Chamber Wall Stresses

Both the pressure produced inside the target chamber and the momentum imparted to the inner shield cause stress in the target-chamber wall. The largest stress is caused by the internal pressure.

Pressure stresses

Although specific hydrodynamic calculations are required for an exact solution, an approximation can be made using Glenn's[4] analysis of the pressure produced by a nuclear explosion inside a spherical chamber with holes in its surface. For a 1000-MJ-yield shot, Orth[5] found that about 300 MJ of x-ray and debris energy reside in the ablated carbon. He estimated the ablated mass, m, as

$$m = W/h_s = 300\ \text{MJ} / 60\ \text{MJ/kg} = 5\ \text{kg} \qquad (1)$$

where W is the x-ray and debris energy in the ablated mass, and h_s is the sublimation energy for monatomic carbon.[6] Next we calculated the period[7] of the Nova aluminum target chamber, T, as

$$T = 2\pi R_c[2E/\rho(1 - \nu)]^{-0.5} \qquad (2)$$

where R_c is the radius of the target chamber, and E, ρ, and ν are Young's modulus, density, and Poisson's ratio for aluminum[8] (69 GPa, 2700 kg/m³, and 0.33). Nova has an R_c of 2.2 m, which results in a period, T, of 1.6 ms.

We then used results for a chamber initially at vacuum (Glenn's Figure 1 in Ref. 4) for various values of R_c and for the shield inner radius, R_o. Glenn shows results for a hole fraction of the chamber surface area of zero and of one-half. We interpolated between these results because Nova has a hole fraction equal to about one-quarter. Next, we averaged the pressure, P, over a time equal to the chamber period, T. Finally, we calculated the wall stress due to this pressure, σ_p, as

$$\sigma_p = PR_c/t \qquad (3)$$

where t is the thickness of the target chamber wall (0.12 m for Nova). Note that this equation gives a value of σ_p twice that for a statically loaded spherical vessel. This is because the pressure loading is applied over a short time and the peak dynamic stress is double that of static conditions.[9]

We used an allowable strength for aluminum[10] of 72 MPa and calculated the required chamber wall thickness. Note that fatigue is not important because the number of high-yield targets expected to be tested in the next laser facility is only about 1000--less by at least an order of magnitude from conditions where fatigue life becomes limiting. Figure 2 shows the variation of chamber wall thickness required to satisfy the ASME Pressure Vessel Code[10] as a function of R_c and R_o. For a given value of R_c, the required wall thickness decreases as R_o increases (and the thickness of the inner plus middle shields, $R_c - R_o$, decreases) because there is more volume into which the ablated material can expand. The selection of R_o is based on the required shielding thickness and the required wall thickness. For the Nova target chamber ($R_c = 2.2, t = 0.12$ m), the minimum value of R_o is 1.6 m.

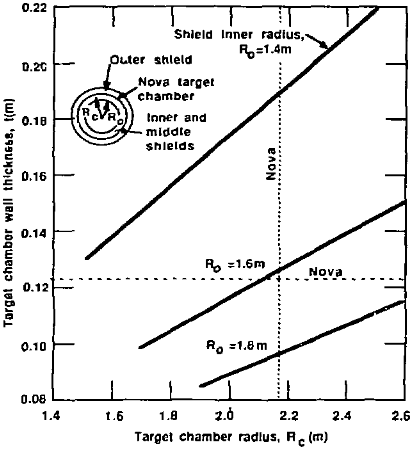

Figure 2. Interrelation between the shield inner radius, and the target chamber radius and wall thickness. The aluminum wall allowable stress for ASME compliance is 72 MPa.

Tobin[2] calculated variations in dose with thickness of the carbon shields. He found that for carbon seeded with 10-wt% boron and $R_0 = 1.6$ m, the dose one hour after a 1000-MJ shot is 60 mSv/h if there is no carbon external to the target chamber, and only 25 μSv/h if there is 700 mm of external carbon.

Figure 3 plots the weight of the inner plus middle carbon shields and the weight of an aluminum target chamber for various values of R_c, and of the inner plus middle shield thickness. Note that the target chamber weight, and hence the cost, increases as R_c decreases, but that the weight of the inner plus middle carbon shields decreases more rapidly. (Our carbon material is also more expensive than aluminum.) Hence, for a given thickness of shielding, the cost of the complete target chamber including shielding decreases as R_c is reduced. As a result, it is desirable to use a target chamber even smaller than Nova's. However, as the chamber becomes smaller, stresses in the inner carbon shield increase. Before proposing a target chamber smaller than Nova's, or even using the Nova target chamber, specific hydrodynamic calculations and experiments are needed to determine a minimum size where the carbon will not comminute excessively.

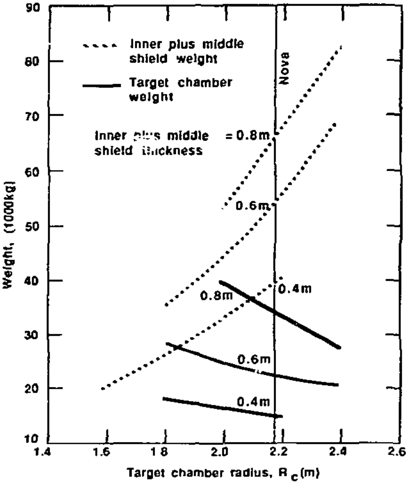

Figure 3. Variation of inner plus middle shield and target chamber weights with target chamber radius and shield thickness.

Ablation generated stresses

Momentum generated when carbon is ablated from the inner surface of the shield is transmitted to the target chamber and produces stress in the wall, σ_m, equal to[11,12]

$$\sigma_m = \mathcal{M} \, [E/2\rho(1 - \nu)]^{0.5}/t \qquad (4)$$

where $\mathcal{M}$ is the momentum generated per unit area. Orth[6] calculated the momentum generated if a 1000-MJ fusion target exploded inside target chambers of various radii when the inside surface was carbon, aluminum, and solid nitrogen. Orth found that the momentum per unit area reaching the Nova target chamber was 300 kg(m•s)$^{-1}$, which resulted in a value of σ_m equal to 11 MPa--approximately 15% of the magnitude of 73 MPa for σ_p. Therefore we conclude that the pressure generated stresses dominate our target chamber design.

The momentum is generated mainly by ablation of the inner shield and not from the explosion of a high-yield target at the center of the target chamber. Hence application of Glenn's momentum results (his Figure 4 in Ref. 4) is not appropriate for our conditions, and in fact would give too large a magnitude for the momentum generated.

Jet Spreading

Using Glenn's Figure 1 from Ref. 4, we calculated that the material vaporized from a shield having an inside radius of 1.6 m produces a pressure inside the Nova target chamber, P, of about 4 MPa. This vapor jets out of the holes in the target chamber at supersonic speed. Because the exterior of the target chamber is in vacuum, dramatic spreading of the jet occurs. We calculated the initial spreading assuming isentropic expansion of a perfect gas with Prandtl-Meyer flow.[13] The initial exterior pressure, P_∞, is 1.3 Pa. The pressure ratio is related to the external Mach number, M_∞, by

$$P/P_\infty = [1 + (\gamma - 1)M_\infty^2/2]^{\gamma/(\gamma - 1)} \qquad (5)$$

where γ is the ratio of specific heats (5/3 for our monotonic gas). The Prandtl-Meyer expansion half angle, υ, for γ = 5/3 is

$$\upsilon = 2\tan^{-1}[M_\infty^2 - 1)/4] - \tan^{-1}[M_\infty^2 - 1] \qquad (6)$$

In our case, $M_\infty = 34$ and $\upsilon = 85°$. The boundary of the jet would curve as shown schematically in *Figure 4 but the specific profile remains to be* accurately calculated. However, it is clear that extensive spreading of the jets will occur.

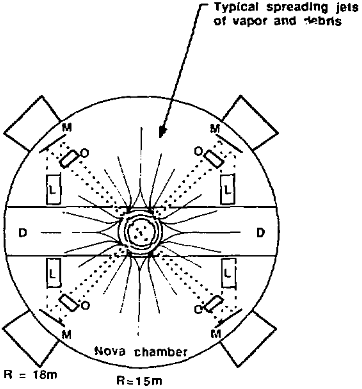

Figure 4. Spreading jet pattern of vapor and debris leaving the Nova target chamber after a shot.

Optical components placed at 10-m radius would still need to be protected from debris and from condensation of vapors by either a gas puff and/or a blast shield, but the amount of material directed toward the optics will be reduced substantially because of the jet spreading.

Remaining Issues

Two issues remain to be resolved. First, we need to determine the minimum radius of the inner carbon shield that would survive the environment following a 1000-MJ-yield target shot (the equivalent energy of detonating 480 pounds of TNT at the center of the Nova target chamber!). We are concerned that if the inner radius of the shield is too small, the carbon material will comminute too quickly due to thermal-shock loading. We don't know how carbon composite materials behave under conditions of rapid, nonuniform energy deposition. Hence, hydrodynamic calculations and experiments are needed to assure that the inner shield will survive the loading conditions. We propose that some carbon-carbon fiber material be obtained to conduct laboratory tests and to line a scaled tank simulating the Nova target chamber. We would then explode a few pounds of TNT inside the tank. We would compare experimental results to hydrodynamic calculations, determine the equation of state for our material, and evaluate how well the carbon shield survived. We could also illuminate carbon material with lasers, electron beams, or ion beams, and observe how it ablates and transmits shock waves, or we could conduct split Hopkinson bar tests to determine some carbon shock propagation properties. It is only through a combination of analysis and experiment that we believe a reliable inner shield design will be obtained.

Second, although the Nova target chamber already exists, estimates of the cost of the carbon shields range from $1M to $20M. It may be less expensive to build a new, and possibly even smaller, target chamber made of low-activating material rather than use the existing aluminum Nova target chamber, thereby reducing the amount of carbon shielding.

Conclusions

In summary, we suggest that 1) using the Nova target chamber with carbon shields for the next laser facility has the potential of reducing cost and yet of satisfying most if not all of the stated target-chamber objectives, 2) the concept of a carbon shield is applicable to target chambers in general and has the advantage of protecting the target chamber itself without producing excessive activated material, and 3) a program of hydrodynamic calculations coupled with experiments is necessary to determine the lifetime of the inner shield.

Acknowledgments

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