UCRL-98450
PREPRINT

FROST AS A FIRST WALL FOR THE ICF
LABORATORY MICROFUSION FACILITY

Charles D. Orth

This paper was prepared for submittal to
the Eighth Topical Meeting on
the Technology of Fusion Energy
October 9-13, 1988
Salt Lake City, Utah

Received 10/13/88

DEC 3 1988

November 15, 1988

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**FROST AS A FIRST WALL FOR THE ICF LABORATORY
MICROFUSION FACILITY**

UCRL--98450

DE89 004013

Charles D. Orth, Lawrence Livermore National Laboratory
L-481, P. O. Box 5508, Livermore, CA 94550
(415)-422-8665

ABSTRACT

We introduce the concept of using frost as the first wall of the ICF Laboratory Microfusion Facility being designed to produce 200-1000 MJ of thermonuclear yield. We present one design incorporating 2 cm of frost deposited at 0.1 g/cm³ on an LN-cooled fiber-reinforced polymer substrate. We calculate that such a frost layer will protect the substrate from ablation by target x rays and debris, and from shock-induced spallation. Postshot washdown with water should permit low-activation operation, and should preserve the original wall properties. We expect the impact of the frost on laser optics to be minimal, and expect the preshot lifetime of thermally unprotected cryogenic targets to be extended by operating the wall at 100-150 K. Moreover, we believe that such a frost first wall will involve little technical risk, and will be inexpensive to construct and operate.

THE DESIGN PROBLEM

The Laboratory Microfusion Facility (LMF) is being designed to produce 200-1000 MJ of thermonuclear yield from an Inertial Confinement Fusion (ICF) target. We have assumed here that the maximum design yield is 1400 MJ, to include a margin of safety. We anticipate that such a target will emit approximately 500 MJ in x rays and debris. These emissions will vaporize approximately 1 kg or more of any first wall material at a practical radius from the target (e.g., 5-10 m). The rapid surface heating and the vaporization momentum transfer (ablation impulse) will generate a shock wave in the wall that can either damage the front surface directly or spall material off the back side or both. Representative DYNA2D computer calculations¹ with aluminum, ice, and carbon suggest that both types of damage are likely for materials at normal densities and small thicknesses (thicknesses that are insufficient to allow the rarefaction wave to catch up to the shock). To avoid rear-surface damage, three approaches have been suggested: (1) use renewable-wall materials at reduced densities, such

as foams (which generate lower shock pressures), or (2) use very large thicknesses (which allow attenuation of the shock pressures, but may increase site radioactivity through neutron activation), or (3) stop the front-surface ablation (possibly with an x-ray/debris shield²).

After the vaporized material expands away from the wall, it cools by converting its thermal energy into kinetic energy as it fills the target chamber. Upon reaching the center of the chamber, it rethermalizes by converting its kinetic energy back into thermal energy, radiating to the wall, and expanding outward. After many reverberations, the vapor reaches thermal equilibrium at 1/3 to 1 eV, having transferred most of its energy to the wall. This heat transfer vaporizes additional wall material (if the time scale is too short to allow wall heat conduction, almost ten times more wall mass can be vaporized than that removed by the x rays). Material will also be vaporized from other sources such as the target, target mounts, cryogenic equipment, diagnostics, experimental apparatus, etc. The vaporized material condenses after tens of milliseconds on any surfaces exposed to the inside of the target chamber, including optics and diagnostics. If any condensates are naturally radioactive (e.g., absorbed unburned tritium) or have been activated by fusion neutrons, then all chamber surfaces become radioactive. Such radioactivity might be embedded to depths of tens to hundreds of micrometers or more in the wall if the radioactive products condense before the vaporized wall material. Cleaning and deactivating a permanent first wall can thereby be a tedious and expensive process, and might exclude certain target materials or impose other materials constraints on the system.

We believe that a first wall composed of a replaceable frost layer on a fiber-reinforced polymer substrate may alleviate many of these problems. Vaporization of the frost would not cause permanent damage, condensation of the vaporized frost would not permanently alter other surfaces, and the

substructure would not absorb unburned tritium or accumulate activated materials because condensates would form on the residual frost and could be washed away after a shot. Such a wall would have insignificant activation by fusion neutrons, so its use would not hinder scheduled operations or personnel entry for repairs or equipment setup. A frost wall would even offer a slight degree of shrapnel protection.

In this paper, we discuss the concept of using frost as a first wall in the LMF, and present one possible target-chamber design incorporating this concept. We are currently developing completely different target-chamber designs employing frost layers, through research at the Lawrence Livermore National Laboratory and through subcontract with K. Schultz and B. Bourque at General Atomic working with both us and the Energy Technology Engineering Center (ETEC). These other designs will be discussed elsewhere.

THE FROST FIRST WALL AS ONE DESIGN SOLUTION

Figure 1 shows a preliminary layout of a modular target chamber incorporating a frost layer.

Each module contains: (1) 2 cm of frost at 0.1 g/cm³ and 100-150 K, (2) a liquid-nitrogen (LN)-cooled substrate consisting of either an unspecified thickness of a carbon-fiber-reinforced polymer such as an epoxy or a polyimide (the preferred option), or 3 mm of aluminum, (3) at least 0.2 m of thermally insulating material, and (4) 1.5 m of water (for neutron moderation and absorption) in its own fiberglass water jacket. The vacuum seal (not yet specified in detail) occurs at the outside mating surfaces between adjacent modules, thus creating a thick fiberglass vacuum vessel with many easily accessible vacuum seals. Several different types of modules are required: one through which laser beam lines enter the chamber, another with diagnostic ports, and others for the remaining spherical surface. Separate cryogenic plumbing is incorporated for each module, so repair or replacement of one module would require decoupling that module's LN plumbing, draining of its water jacket, and removal of the module.

A. Frost Layer

The frost layer shown in Fig. 1 at a radius of 5 m represents about 630 kg (175 gallons) of water. Calculations with our code PROFILE³

suggest that a 1400-MJ target will vaporize and partially dissociate about 260 μm (8 kg) of frost on a time scale of nanoseconds, assuming 500 MJ in x rays and debris, and half of that in x rays. After the vapor expands to fill the chamber and reaches thermal equilibrium, at most 160 kg of frost could be vaporized (ignoring dissociation and thermal transport through the chamber wall). We calculate that the optimum radius of the chamber is between 3 and 5 m based on preliminary engineering analysis of (1) neutron heating of the frost as a function of chamber radius, (2) vaporization of up to a maximum of 10 cm of frost by the x rays alone, (3) buckling stress on the target chamber, (4) hoop stresses due to the peak chamber pressure and the ablation impulse, and (5) the tradeoff between minimum overall size (cost) and the need to make the target chamber large enough to include defense-applications experiments up to 0.5x0.5x1.0 m. In a target chamber of radius 5 m (Fig. 1), the maximum amount of frost that could be vaporized (160 kg) has a thickness of 0.5 cm. To have a margin of safety, and to ensure the presence of some liquid water or residual frost during vapor condensation, we have chosen to use 2 cm of frost.

ETEC is under contract to measure the mechanical properties of the different types (morphologies) of frost available, as well as how long it takes to grow 2 cm of thickness. ETEC has found that the most-stable morphology has dendritic ice crystals resembling truncated hexagonal pyramids. This frost grows on an LN-cooled substrate if the vapor pressure of water at the tips of the ice crystals is between a minimum value and a maximum value. The minimum value is the saturation vapor pressure of solid ice at the temperature of the tips. The vapor pressure must be at some value (yet to be determined experimentally) above the minimum to avoid producing a needle-like morphology. The maximum value (less than 5 Torr) is the vapor pressure of liquid water supercooled to the temperature of the tips. The maximum-pressure requirement is necessary because (low-density) frost must be grown from the vapor phase of water, not from the liquid phase. The temperature gradient along the ice crystals is also important because larger gradients increase the size of the pyramidal bases of the crystals (because water vapor tends to deposit on the coldest surfaces). Large gradients are beneficial in growing frost with sufficient mechanical strength. To maintain large gradients during frost growth, the total chamber pressure (of air, water vapor, etc.) must not exceed roughly 100 Torr in order to avoid excessive thermal transport in the gas between the base and the tips of the crystals.

ETEC has grown 1 cm of dendritic frost in about 45 minutes in an evacuated bell jar containing water vapor at about 4.5 Torr. For later

times, the growth rate reached an asymptote of about 6 mm per hour. The resulting frost had a density between 0.09 g/cm³ near the surface and 0.12 g/cm³ near the substrate, and was the morphology most resistant to loss of adhesion (big chunks falling off the wall due to jarring).

The scenario for growing frost in the LMF would be to grow 2 cm of frost within several hours at the appropriate water vapor pressure, then to cool it to roughly 130 K, at which the vapor pressure from the frost would be 10^{-10} Torr. The cold wall would aid in achieving the desired chamber vacuum (10^{-5} Torr is thought to be adequate for diagnostics) through condensation (cryopumping) of all substances that vaporize above 130 K. In addition, the heat load on a cryogenic target from a 130-K wall with 300-K laser beam ports would be lower by a factor of about 10 than that from a room-temperature wall.

We have made DYNA2D computer code calculations to ascertain the probability of rear-surface spall for an aluminum substrate. Results indicate that a 1000-MJ shot will create a pressure pulse in the frost that is orders of magnitude lower than that created in either full-density ice or bare aluminum. The porosity of the frost reduces the maximum tensions in the substrate to only about 10^5 Pa, which is about a factor of 100 less than the anticipated damage threshold. Similar results are expected for the fiber-reinforced polymer substrate. Studies are under way to examine our assumptions regarding the strength of the frost (measured by ETEC to be about 10^5 Pa), the "crush curve," other Hugoniot and equation-of-state parameters, and the anticipated density gradient in the frost.

During postshot vapor condensation, which lasts at least tens of milliseconds, the residual frost or liquid water on the wall will not move much, several millimeters under the action of gravity. We assume that condensates will form directly on this frost/water, and not on the substrate. These condensates will include any activated target materials or fissionable materials from defense-applications experiments. We therefore assume that postshot warm up of the wall followed by a water spray and pumping will remove essentially all condensates and vapors, leaving the chamber in the same condition as it was before the shot. Exterior radioactive waste-handling and tritium scrubbing systems will be required.

B. Cryogenic Substrate

Figure 1 shows the substrate to be either a fiber-reinforced polymer (e.g., an epoxy or a polyimide with embedded radial carbon fibers) with embedded channels or aluminum tubes carrying LN, or 3 mm of low-activating aluminum alloy with

LN cooling tubes fastened to the back. TART computer code calculations⁴ indicate that the design using 3 mm of low-activating aluminum (with physical properties similar to Al-5083) will produce only 2.5×10^{-4} Sv/hr (25 mrem/hr) six days after a 1000-MJ shot conducted in a series of one such shot per week for 10 years. The activation arises partly from the neutron activation of the aluminum, which produces ^{24}Na , and partly from the activation of impurities. Use of this aluminum allows high-yield shots to occur once per week with chamber entry after 6 days, and low-yield shots producing up to 10 MJ of fusion energy to occur once per day with chamber entry after about 1 day. Thus, an aluminum thickness of 3 mm, which is the estimated minimum thickness for mechanical rigidity, would not compromise the desirable feature of manned entry before every shot with shots occurring at these frequencies (except that low-yield shots could not begin until one week after a high-yield shot if chamber entry were required to convert to low-yield status). Also, unlike most other materials, aluminum alloys with 5083 characteristics become more ductile at low temperatures, and are hence good materials for cryogenic applications.

The fiber-reinforced polymer substrate would produce significantly less radioactivity than the 3-mm-aluminum design, even though it might have embedded aluminum LN tubes. It would also reduce any gamma-ray (EMP) burst caused by neutrons interacting with the aluminum. The fiber-reinforced polymer substrate is thus preferable if it can be developed.

C. Thermal Insulating Region

Designing the region behind the substrate is difficult. This region must thermally isolate the cold first-wall and substrate structure from the room-temperature water-containing structure at larger radii in order to minimize cool-down expense. To decrease the stress on the cryogenic plumbing, the insulating region must absorb the kinetic energy (damp any ringing) of the frost-substrate structure when the ablation impulse accelerates it outward at about 10 m/s. The materials used in this region must maintain their mechanical properties over many shots (e.g., to avoid compression, which would create gaps in the frost covering), and must not degrade under the facility-lifetime neutron bombardment of roughly 2×10^{23} neutrons per 4 π steradians.

A preliminary design for this region is merely to use 0.2 m of polyimide with embedded voids, as is being done for the Torus-II tokamak facility in France, or to use 0.2 m of CH or CH₂ foam. A concern with these materials is whether they will survive the cumulative neutron fluence without a change of mechanical properties (strength, elasticity).

D. Outer Structure

Outside the thermally insulating layer is the vacuum vessel, which is a fiberglass water jacket. TART calculations to specify the exact thickness of water required to moderate and absorb fusion neutrons have not yet been conducted. However, calculations for reactor designs suggest that 1.5 m should be adequate, so this thickness of pure water is assumed here. We do not yet know what additional exterior structure might be needed for support against earthquake accelerations, etc. A ground-based conical foundation is one possibility for exterior chamber support, not shown in Fig. 1, but additional support concepts need investigation.

E. General Comments

The frost concept involves a simple extrapolation of known technology. The ability of frost to reduce shock strengths is supported by many calculations and experiments for other materials fielded at densities well below normal. Therefore, at least conceptually, a frost first wall is expected to be feasible and reliable with little technical or physics risk.

An overall construction and fabrication cost goal for the target chamber is \$5-\$10 million, and estimates based on the preliminary design of Fig. 1 suggest that this goal is credible. The operational expense to cool down the chamber interior for one shot is estimated to include less than \$2000 of LN.

The frost wall offers a slight degree of shrapnel protection, because its column density of 0.2 g/cm² will stop particulates traveling at most any speed and having a column density of roughly one-fourth to one times this value (cf. Fermi's Law). For example, the frost should stop equi-axed grains of iron with diameters less than 100-200 μm . On the other hand, the existence of LN tubes or channels in the first wall creates a vulnerability to shrapnel exceeding perhaps 0.1 g/cm² in thickness.

Frost does not produce high-speed particulates or opaque condensates, so the design of the optics-protection systems should not be made more complicated by deposition of material from the first wall. Although water may affect some diagnostics, the vapor is present only during frost growth and immediately after a shot. It is also possible to put frost part way up the laser beam pipes to avoid condensate collection there.

A modular construction has advantages. It facilitates chamber fabrication, assembly, and repair. It permits flexibility in configuration after construction. It also provides a water-jacket structure that precludes a large hydrostatic load.

The failure modes for the frost first-wall concept include: (!) inadequate pre-shot frost

thickness, (2) large chunks of frost falling off preshot because of vibrations, (3) failure of the thermally insulating region (e.g., loss of adherence, or loss of elasticity), and (4) impingement of shrapnel larger than about 0.1 g/cm^2 . These failures might necessitate down time to repair or replace components.

WORK IN PROGRESS AND ASSUMPTIONS NEEDING VERIFICATION

The most important feature of a frost first wall is that it should mitigate shock damage to the substructure. Although this claim is verified by calculations, we are working to verify it experimentally.

We know that 2 cm of frost can be grown in well under 3 h in the laboratory, but we do not yet know the exact pressure and temperature constraints that allow dendritic frost to be grown in the laboratory, nor whether such growth conditions will scale to the large size of the LMF chamber. Experimental verification of the scaling is essential to check growth, adherence, stability, and thickness uniformity at LMF scale. In particular, it is critical to know whether there is a practical way to design a source of water vapor that supplies enough vapor to maintain the vapor pressure at the tips of the ice crystals above the minimum required to form the dendritic morphology. Experiments are in progress to check the mechanical stability of the frost against jarring. Experiments must be conducted to determine the maximum thickness of frost that will adhere in a stable manner to the substrate; thicknesses greater than 10 cm might be possible, thereby allowing the target chamber to contain a shot considerably above 1400 MJ. We must also determine whether the frost morphology changes with time to determine frost stability during shot delays.

Experiments are necessary to verify the maximum density to which the frost is compressed upon shock transit. This information would help to define the "crush curve" assumed in the DYNA2D calculations, and ascertain whether we need to include ice phases more dense than ordinary ice in our computer models (current calculations exclude other ice phases because the peak density is less than 1 g/cm^3). We must measure the frost density profile for a 2-cm layer, and calculate its effect on the shock propagation.

In addition, we should determine whether the frost morphology, as a three-dimensional mixture of full-density ice crystals with intervening voids, has any significant effect on either the shock pressure in the frost or the ablation impulse to the wall. Three-dimensional effects might reduce the shock pressure below the low value already established

by a uniform frost density of 0.1 g/cm^3 , because the shock propagates by ice spalling off the back side of one crystal, propagating through a void, and striking the surface of the next crystal. Such effects are probably not significant, however, because a uniform-density frost already reduces the shock pressure to a level that is well below the minimum for substrate damage. On the other hand, we expect some of the vaporized frost to condense on nearby cold crystals before leaving the surface. This condensation will reduce the ablated mass while increasing the velocity of the vaporized material (by energy conservation), thereby reducing the ablation impulse. Because the ablation impulse for frost (ignoring molecular dissociation) is comparable to that expected for high-Z wall materials, but roughly 50% larger than that expected for aluminum,³ any reduction in impulse and the associated chamber hoop stress could be beneficial. For the frost design presented here, however, the dominant overall chamber stress is likely to be the buckling stress. If this is the case, reduction of the ablation impulse due to vapor condensation might be of consequence only if the beam and diagnostic ports cause the ablation impulse to excite chamber vibration modes that constructively interfere and dominate the peak stress. It is primarily for this reason that the three-dimensional effects of both the frost morphology and the chamber stresses should be investigated.

A system must be developed to verify preshot that all surfaces are covered by frost with the minimum thickness and to the required uniformity in thickness. This might be done by viewing black spots painted on the substrate and illuminated with a light source.

We must complete our investigative program with ETEC to determine the charges in the chemical states of the water with time after vaporization. Chemical states are important because the water molecule absorbs considerable energy upon dissociation ($\sim 53 \text{ MJ/kg}$), so more dissociation means less energy in the vapor and thus lower ablation impulse and lower peak pressure in (and lower hoop and bending stresses on) the vacuum vessel. ETEC is calculating the effects of the dissociation of the water vapor into H , O , OH , etc. Preliminary results indicate that dissociation limits the peak equilibrium vapor temperature for a 1400-MJ target in a 5-m-radius chamber to 4200 K (0.36 eV) assuming no energy loss through wall heat conduction. If this is true, the peak internal pressure would be less than $8 \times 10^4 \text{ Pa}$, and the chamber would always be in compression (because the external atmospheric pressure is $1 \times 10^5 \text{ Pa}$). The amount by which dissociation reduces the ablation impulse is not yet known, but we expect it to be significant (i.e., the impulse is probably reduced

to a level comparable to or less than the impulse expected for an aluminum wall).

We have assumed that additional experimental apparatus can be protected from condensates (if necessary) by allowing a frost layer to be deposited on their surfaces, but this needs verification. We must also develop an operations plan describing the sequence of pre-shot events (e.g., when target alignment occurs in relationship to the growth of the frost). We must also verify that a postshot washdown will in fact remove (radioactive) residue that might form on the substrate due to non-wall condensates that fail to be washed away with the melted frost.

For the fiber-reinforced polymer substrate, it is essential to determine: (1) its neutron and gamma-ray damage limits (especially whether cracks will occur and disallow the use of LN channels built into the substrate); and (2) its thermal fatigue under temperature cycling (caused by the differential expansion of the carbon fibers and the polymer, or by [crazing] stresses arising from nonuniform cooling). If thermal fatigue is a problem, we need to assess whether it is possible to control the thermal transients during chamber cool down to avoid material failure. In addition, we must make shock calculations for the fiber-reinforced polymer substrate using DYNA2D.

We have assumed that the thermally insulating layer does not compress with time, is not damaged by the cumulative neutron fluence during the lifetime of the facility, and remains in mechanical contact with both the water jacket and the substrate even after many temperature cycles to nearly 70 K. We must verify that such performance is possible.

A detailed plan for cost-effective waste disposal must be developed. We have assumed that the tritiated water formed when unburned tritium combines with the water vapor created by a shot can be disposed of inexpensively, by putting it in drums and transporting it to a burial site if by no other means. The tritium concentration is probably too low to warrant the cost of removing the tritium.

Although the modular mechanical design offers many advantages, it involves many points of vacuum seal. Although the exterior placement of these seals allows easy access and easy vacuum-leak fix through application of sealant, we must verify the reliability of a design involving so many points of seal. In addition, the modular design offers many virtual vacuum leaks (i.e., inter-module cracks difficult to pump). How the module sidewalls should be constructed to avoid pumping delays has not been determined. Moreover, it is not clear that a modular concept is feasible with many beam lines. Also, we need TART calculations to verify that

neutrons do not preferentially transport up the adjoining water-jacket walls between adjacent modules. We are currently assessing the feasibility of exchanging wall modules with diagnostic modules to switch from high-yield to low-yield shots in an LMF with just one target chamber.

Detailed mechanical designs are lacking for all chamber components. A stress analysis must be performed, with special consideration given to the external clamping joints where the vacuum seals occur, and to the associated flanges where bending stresses may be large.

CONCLUSIONS

We have introduced the concept of using frost as the first wall of the ICF Laboratory Microfusion Facility, and have presented one target-chamber design incorporating 2 cm of frost deposited at 0.1 g/cm³ on an LN-cooled fiber-reinforced polymer substrate. We calculate that a replaceable frost layer will protect the substrate against permanent damage due to ablation by target x rays and debris, and from shock-induced spallation. In addition, the frost need not permanently deposit on any surfaces, so the wall operation should have minimal impact on the other target-chamber systems (e.g., optics). Moreover, the unvaporized frost acts as a cold surface for the condensation of all other condensable materials. We therefore assume that a postshot warm up of the wall followed by a water spray and pumping will remove all condensates and vapors, thereby leaving the target chamber in the same condition after a shot as it was before a shot. In particular, frost prevents the buildup of radioactive condensates or tritium compounds on the wall and offers a clean contaminant-free "dirt"-free environment conducive to personnel entry, if required.

Because a frost wall maintains the substrate in its original condition, free of all radioactive condensates (even from defense-applications experiments), a frost wall permits low-activation operation and thus maintains a high degree of operational flexibility without significant added cost or schedule delays. With a fiber-reinforced polymer substrate, activation of the target chamber could be low enough to permit nearly unrestricted access. Even with a 3-mm-thick aluminum substrate, entry inside the target chamber is permitted 1 day after shots with yields below 10 MJ, and 6 days after any high-yield shot. Although chamber entry may not be required for most shots, entry would be possible for repairs or equipment setup without waiting for more than one week for the dose rates to drop to acceptable levels.

In short, we believe that a replaceable frost first wall will: (1) prevent front-surface erosion,

interior damage, and rear-surface spall of the permanent wall; (2) avoid the buildup of all condensates including (radioactive) contaminants and tritium compounds on diagnostics, optics, and the permanent wall; (3) provide a target-chamber interior conducive to personnel entry because it is free of contaminants and "dirt"; (4) permit low-activation operation and thus maximum operational flexibility; (5) accommodate target yields above 1400 MJ, if desired; (6) extend the preshot lifetime of thermally unprotected cryogenic targets; (7) involve little technical or physics risk; and (8) be rather inexpensive.

ACKNOWLEDGMENTS

We acknowledge considerable technical and experimental support from N. Hoffman of ETEC pertaining to the physics and chemistry of frost for this application. We thank L. Glenn of LLNL for theoretical advice, K. Sinz of LLNL for the DYNA2D shock calculations, M. Tobin of LLNL for the TART neutron-activation calculations, R. Warren and G. Bradley for thermal analysis and mechanical design, D. Young of LLNL for helpful comments, and colleagues in the LLNL ICF Applications Group and the LMF Design Team for helpful suggestions. Work was performed under the auspices of the U. S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

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