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**Analyses in Support of
the Laboratory Microfusion Facility
and ICF Commercial Reactor Designs**

**Final Report
Subcontract No. 2208703**

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OVERVIEW

Our work on this contract was divided into two major categories; two thirds of the total effort was in support of the Laboratory Microfusion Facility (LMF), and one third of the effort was in support of Inertial Confinement Fusion (ICF) commercial reactors. This final report includes copies of the formal reports, memoranda, and viewgraph presentations that were completed under this contract. The contents are summarized below beginning with the LMF work.

LMF STUDIES:

A Carbon-Carpet First Wall for the LMF

This is our final report on the first wall concept we invented for the LMF. We describe a passive, room-temperature first wall that conceptually solves the problem of survival under intense x-ray and ion loadings from ICF targets. The carbon-carpet first wall concept uses a clever configuration to overcome the limitations of material properties, and to reduce the mass loss per shot and the impulse delivered to the wall by more than an order of magnitude. The configuration provides an enormous surface area, within a small (3 in radius) chamber, for absorbing the x-rays and condensing the vapor generated by ablation. It does this in a way that minimizes the amount of ejected vapor, and thus, the net reaction force transmitted to the wall. The carbon that is vaporized protects the carpet from ionic target debris. Overall, we conclude that the carbon carpet first wall is an attractive option for the LMF. Further work on the chamber configuration, including the design of the neutron shield and the vacuum vessel wall, is needed.

Neutronics Analysis of the LMF

This paper, which was written for the Eighth Topical Meeting On the Technology of Fusion Energy, discusses a variety of neutronic and safety issues that have been addressed by the neutronics study group of the LMF design team. The main focus is on activation analyses and the resulting radiological hazards in and around the target chamber. Sodium-24, which is produced by high energy neutron reactions with Al, is a primary contributor to the radiation hazard for chambers with Al first walls.

Effects of Target pR on Neutron Activation

This memo reports the results of neutronics studies on the effects of the target pR on neutron activation of the first wall. For a constant yield, the production of activation products that are a major concern decreases with increasing target pR. However, when we consider the anticipated increase in neutron yield with increasing pR, we find that the net effect is an increase in activation with increasing pR.

Neutron Heating in Materials Close to the Target

This memo reports the results of neutronic calculations to determine the neutron heating of materials that are placed very close to a high yield target. We examined carbon, silicon, copper, iron, and aluminum. The calculated minimum inner radius to avoid melting, just due to neutron heating, ranges from 13 cm for SiC to 21 cm for Al.

An Experiment to Test the Carbon Carpet First Wall Concept

This memo provides our initial thinking an experiment to test the carbon carpet first wall concepts. The primary questions that such an experiment should address are 1) does the carbon carpet reduce the impulse and pressure transmitted to the support structure, and 2) is the damage rate to the carbon filaments and fibers acceptably low?

Gas Protection from Target Shrapnel

This memo addresses the question of whether the gas that is used to protect the final optics from x-rays and ions can also protect the optics from the shrapnel that may be generated from targets and diagnostics in high yield experiments. Simple drag calculations indicate that the gas will be effective only for particle sizes less than 6.5 μm in diameter. Since some larger particles are expected, a solid debris shield is recommended.

Gas Protection Against Debris Ions

This memo develops an equation for determining the amount of gas needed to stop energetic target ions. The stopping power equation is scaled for data on the ranges of various ions in air and is given as a function of the mass number of the stopping gas, the

ion energy, and the mass number of the ion. As an example, we calculate that 4.2 torr-meters of argon is required to stop 200 keV gold ions.

Gas-Breakdown Limit on Gas Protection to First Walls

This memo addresses the question of whether or not the first wall could be protect by filling the chamber with gas while avoiding laser-induced breakdown near the target. We conclude this is not a viable first wall protection scheme.

Concepts for the Final Optical System of the LMF

This viewgraph presentation to the LMF design team describes our ideas on the final optical system for the LMF. It provides an overview of the problems that must be addressed in the design of the final optical system, including protection from x-ray and debris damage and concerns about activation and maintenance. Several alternative design approaches and options are discussed.

Conclusions and Bibliography for the Optics Protection Work

Major conclusions from the optics protection work and a bibliography are given in this section.

The Analytic Hierarchy Process for Decision Making

This is a copy of a presentation made to the LMF study group on the AHP for decision making. The AHP provides a systematic approach to choosing between several alternatives when the relative comparisons are not necessarily quantitative. The process could be used to help choose between several LMF first wall concepts.

A Carbon-Fiber Brush-Like First Wall for the LMF

This is the presentation that was given at the Eighth Topical Meeting on the Technology of Fusion Energy at Salt Lake City. The presentation summarized the complete paper which was written for the meeting (see above).

COMMERCIAL ICF REACTOR STUDIES:

New Heavy-Ion-Beam Target Gain Curves for the SAFIRE Code

Algorithms for heavy-ion-beam target gain curves developed by LLNL were incorporated in the SAFIRE code, which is used for ICF economic studies. This report documents the modifications to the code, instructs users on how to use the new gain curves, and provides an example to compare with previously reported results.

Parametric Economic Studies for HYLIFE:

Implications for a New Molten Salt Reactor

One of the primary objectives of the HYLIFE-II reactor design study is to develop a concept that is more attractive than HYLIFE from an economic perspective. As a point of comparison, economic studies were carried out for the HYLIFE reactor to investigate the effects of various system parameters and design variables on the estimated cost of electricity. The implications for HYLIFE-II are discussed. For HYLIFE-II to be significantly less expensive than HYLIFE, the FLiBe hardware (pumps, pipes, heat exchangers, etc.) has to be much less expensive, and/or the total flow rate must be much smaller, and/or the intermediate loop must be very cheap or eliminated. A chamber pulse rate of a few Hz should be adequate. Lower driver costs and higher target gains would benefit HYLIFE as well as HYLIFE-II.

Review of HYLIFE Fluid Dynamics

This is a viewpoint presentation that was prepared for the ICF reactor studies group. We are investigating the possibility of modifying the HYLIFE reactor to use molten salt instead of lithium as the blanket material and primary coolant. This presentation provides an overview of the fluid dynamics of HYLIFE.

Preliminary Neutronics Considerations for HYLIFE-II

This presentation reported the results of neutronics calculations done for the molten salt version of HYLIFE, tentatively known as HYLIFE-II. We calculated the thickness of FLiBe required to provide adequate tritium breeding and neutron damage protection for the first structural wall. We found that about 50 cm of FLiBe is need to get a tritium

breeding ratio greater than one if all the breeding is done in the inner blanket. Only 30 cm of FLiBe is needed to reduce the displacement damage rate to an acceptable level for a 30 year wall life. The blanket thickness could be reduced to 40 cm if FLiBe is added to the reflector region for added tritium breeding.

A CARBON-CARPET FIRST WALL FOR THE LABORATORY MICROFUSION FACILITY

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ABSTRACT

A first wall concept for the Laboratory Microfusion Facility (LMF) that uses carbon fibers in a brush- or carpet-like configuration is described. This material and geometric configuration provide an extremely effective way of absorbing the intense burst of soft x-ray radiation from the fusion energy pulse without damaging the underlying structure. The 2-cm-long carbon fibers are pointed at the target so that the x-rays illuminate the sides of the fibers at a glancing angle. We describe how the carpet-like configuration reduces the impulse due to the blow-off of material vaporized by the x-rays. Resulting stresses in the support structure are low enough for the chamber radius to be brought in to 3 m, which is much smaller than a chamber with an unprotected first wall. We conclude that this is a viable and attractive concept for the LMF first wall.

INTRODUCTION

The ICF Laboratory Microfusion Facility (LMF) will be used to develop high gain targets, explore weapons physics, and conduct experiments relevant to the military and energy applications of ICF.¹ W.J. Schafer Associates is assisting the Laser Program at Lawrence Livermore National Laboratory (LLNL) in the design of the experimental chamber for the LMF.

Of all the products of the fusion microexplosion the x-rays are the most difficult to handle. To design a chamber with an inner radius of approximately 5 meters the first wall must withstand a fluence of 50-100 J/cm² (12-24 cal/cm²) and intensities up to 10¹⁰ W/cm² of x-rays. At such high intensities, even the best carbon-carbon or ceramic tiles would fail due to the enormous stress waves that are driven into the material in reaction to the fast vaporization during the 10 ns pulse of x-rays. To survive, a tile wall would have to stand back 15-20 m. In order to build a smaller chamber, the first structural wall must be protected in some way.

Other groups propose to solve this problem by one of two ways. First, one can employ a sacrificial inner layer of porous material on the first wall, which is inefficient at generating and transmitting x-ray driven shocks. Spraying a porous teflon coating on the wall, or refrigerating the wall to -200 °C and coating it with a layer of water frost, are two ideas proposed.² These schemes require the active establishment of a new inner wall layer on every shot by spraying or refrigeration.

The second strategy is to surround the target with a sacrificial x-ray shield, which explodes and converts x-ray energy into particulate kinetic energy.³ ICF proponents have long pointed out that one of the beauties of ICF was that you can get 1000 MJ out per shot, with only the blast of a cherry bomb. It is very unlike the blast of its energy equivalent, a quarter-ton of TNT. To solve the x-ray problem then by increasing the blast seems to remove this advantage. Access to the cryogenic target by 50 to 100 final optics and tens of diagnostics would be needlessly restricted by an x-ray shroud. In addition, the optics and diagnostics would unnecessarily be subjected to the blast loading.

In contrast to the above approaches, we sought a passive, room temperature first wall that didn't require active maintenance, didn't have blast effects like a chemical explosion, and didn't restrict target mounting, alignment, diagnostics or illumination. We propose using carbon fibers in a brush- or carpet-like configuration, called the Carbon Carpet First Wall (CCFW), as a solution to the first wall problem. In this paper, we describe the CCFW concept and how it works to reduce both the peak stresses in materials and the impulse on the underlying support structure. Our passive, room temperature CCFW successfully deals with the x-rays and ions and allows the chamber radius to be reduced to 3 m.

CARBON-CARPET FIRST WALL DESIGN

The CCFW surface is illustrated in Fig. 1. The approximately 2-cm-long carbon fibers are oriented radially so that the x-rays illuminate the sides of the fibers at a glancing (80 to 90° from normal) angle. With this configuration, the surface area over which the x-rays deposit their energy is increased by more than a factor of 15 compared to a solid at the same radius. This scheme also creates an effective x-ray absorption zone of 2 cm rather than 2 μm . The surface area available for condensing the vaporized carbon is increased by a factor of 40 or more. In one configuration that we are examining, the total condensing surface area is over 6000 m^2 , larger than the area of a football field. Each fiber making up the carbon carpet is 0.6 mm in diameter, and is in turn made up of 12,000 5- μm diameter filaments. The fibers are flexible and resilient, not brittle. The CCFW material is brush-like in that the fibers must be stiff enough to maintain their radial orientation and open enough to allow the x-rays to irradiate the sides of the fibers. On the other hand, it is carpet-like in that the fiber packing density is great enough that the support plate is not irradiated by the x-rays. We think the right construction is somewhere between a stiff, deep-pile carpet and a soft-bristle, dense-packed brush.

The carbon carpet type of material we propose for the first wall surface has in fact already been manufactured. It is made the same way as commercial household carpet, with multi-filament carbon fibers feeding the loom. For our application a carbon cloth backing is probably the best choice. We envision that the carbon carpet would be attached to panels of aluminum plate or perhaps a Kevlar composite armor plate. We are investigating various arrangements of carbon-carpet coated armor plates within the chamber to protect against x-rays, ions and even quite energetic shrapnel. One possibility is to construct an aluminum support frame in the shape of an icosahedron (20-sided polyhedron) with the triangular faces being 4 m on each edge. Each face could then be subdivided into 16 equilateral triangles that are 1 m on a side. The inner radius to the closest point would be 3 m. As shown later, this is an acceptable radius from the viewpoint of stresses that must be handled by a carpet support plate. The total flat-plate surface area of this geometric configuration is about 140 m^2 , and as previously stated, the total carbon fiber surface area is over 6000 m^2 .

The remainder of this paper is concerned with the analysis of the response of the carbon-carpet surface to the x-ray energy deposition. Other aspects of a complete chamber design, such as mounting the CCFW panels, design of the neutron shield, vacuum pumping and vacuum vessel design, etc., and analyses

Fig. 1 The carbon-carpet first wall is made carbon fibers, woven into a carpet, and cut to a length of 2 cm. Each fiber consists of 12,000 5- μm -diameter filaments. The fibers are grouped in tufts giving an overall packing fraction of 32%.

of remaining technical issues such as decontamination of the carbon carpet are outside the scope of this paper and will be the subject of future work. We do point out, however, that by using a CCFW attached to a Kevlar support plate we can eliminate the need for an aluminum wall in the high energy neutron flux. This significantly reduces the activation of Al to ^{24}Na , which is currently the dominant contributor to short term radiological hazard within the chamber. It is also a factor determining the shielding requirement to protect the outside of the chamber, where workers may be within a day of the shot. The CCFW offers the opportunity to build a truly low activation chamber, which is extremely important to operational safety and low operating cost, in addition to the low capital cost of a smaller chamber.

CCFW DYNAMICS

The impulse delivered to the structural wall from the absorption of high intensity x-rays is due to the reaction to rapid vaporization of the wall material. There is no impulse if the energy can be conducted into the wall rapidly enough by thermal conduction to avoid vaporization. The impulse generation process can be thought of in two complimentary ways, as the

integral over time of the vapor pressure pushing on the wall, or equivalently, as the product of the ablated mass and the characteristic velocity of escape. Both are approximations to the actual definition

$$I_m = \int_0^{\infty} (P + \rho u^2) A \, dt \quad (1)$$

where I_m = impulse, P = pressure, ρ = mass density, u = velocity, A = wall surface area, and t = time. The carbon carpet protects the wall from damage in the following ways 1) by absorbing the x-rays and reflected laser light over ten times the surface area on fibers having an incidence angle of $\theta = 85^\circ$ to the x-ray flux, 2) by reducing the wall pressure by spreading the plasma out over a very large region (the $H = 2$ cm carpet depth) compared to an absorption depth of $2 \mu\text{m}$, 3) by spreading out the interaction time from the 10 ns x-ray pulse-width to the 8 μs residence time of the plasma in the carpet, and 4) by condensing carbon atoms back onto the huge surface area of fibers before the vapor escapes from the carpet. The carbon carpet also protects itself and the supporting substructure from energetic target debris. The debris front arrives so late that is absorbed in the rushing carbon vapor and never reaches the carpet. The debris simply heats the vapor which then radiates to the carpet and causes more vaporization on a longer timescale.

Although the x-ray intensity on the fibers is an order of magnitude less than on a normal flat wall because of the 85° angle of incidence, the local peak compressive and thermal stresses can still exceed the ultimate stress on some fibers. For this reason we favor using carbon fibers which are each constructed of 12,000 $5 \mu\text{m}$ filaments. Even if some surface filaments break, the integrity of the fiber is not affected, and in no case is the structural integrity of the wall, or even the function of the carpet, compromised. In fact, many feel that because the tiny filaments are not much thicker than the x-ray absorption depth, any stress wave that forms would be quickly relieved from the sides, making the character of the energy addition much closer to that of volumetric heating.

It is easy to understand how the carpet reduces the pressure felt by the wall to safe values far below the material strength, by increasing the plasma volume and lengthening out the vapor residence time on the wall. Compare Cases A and B of Fig. 2. In case A the pulse lasts from the time vaporization commences until the end of the x-ray pulse; in case B the pressure isn't felt until the plasma fills the carpet, and it lasts until the pressure is relieved by the rarefaction wave which propagates in from the end of the carpet.

Fig. 2 The impulse is the area under the pressure-time curve. A flat plate experiences a peak pressures exceeding the material compressive strength. Without condensation, the impulse delivered to a carpet is the same as a flat plate, but the peak pressure is far lower. With condensation, the impulse can also be substantially less.

However helpful this time stretching may be, the total impulse would be the same were it not for the additional effects of thermal conduction and condensation. These two effects are the source of impulse reduction. The residence time of the plasma in the carpet ($\sim 8 \mu\text{s}$) is long enough, and the condensing area large enough (> 40 times wall area) that more than 90% of the vaporized mass can condense out on the fibers. All the vapor energy conducted into the fibers and all the vapor mass lost to condensation are unavailable to contribute to the momentum generation of inwardly directed gas. When a flat plate is irradiated by a 10 ns pulse there is no time for these mitigating processes. However, in the CCFW the interaction time is 800 times longer, allowing conduction and condensation to reduce the ejected momentum by a substantial amount. This is shown schematically by the area under the $P(t)$ curve in Case C of Fig. 2.

With this overall understanding, we can examine the impulse generation process in more detail. Instead of using an actual or projected ICF x-ray spectrum, we calculate a simpler fictional case using 200 MJ of monochromatic 1 keV x-rays, which impinge on first

walls located from 1 to 15 m from the source. The ions are of no consequence to us. They arrive so late that they are totally absorbed by the intruding carbon vapor that results from the x-ray deposition. The ions further heat the gas, which radiates away the energy to the walls by thermal radiation over a sufficiently long timescale that is not a hazard to the wall. Absorbing the 10 GW/cm² of x-rays is the problem.

The best way to understand the heating, vaporization, and condensation processes is to calculate and examine the relative timescales of the problem, which are shown in Fig. 3. The first important time duration is the x-ray pulse width, τ_x , which is 10 ns. Next is the time to begin vaporization, t_{bv} . By balancing the x-ray flux with the thermal conduction rate, we calculate that the time necessary to initiate vaporization varies from 10^{-10} s at 5 m to 4×10^{-9} s at 15 m. The time duration of the vaporization process is the difference between the x-ray pulse duration and the time to begin vaporization,

$$\tau_{vap} = \tau_x - t_{bv} \quad (2)$$

Next we calculate the time it takes for the blowoff plasma itself to become opaque to the incoming x-ray radiation. The time to become opaque is important because the vaporization due to x-ray absorption is shut off, and the vapor is heated, perhaps even to the point where it radiates away energy by thermal radiation. (In the closed geometry of a spherical chamber, prompt thermal radiation will just cause more vaporization however.) In Fig. 3 we have plotted the time required for the vapor to have a density-length product equal to twice the opacity of the solid,

$$t_{ba} = (2\lambda_a \rho_c H_v) / I_x(R) \quad (3)$$

where $\lambda_a = 2 \mu\text{m}$ is the absorption length of x-rays in solid carbon, $\rho_c = 2100 \text{ kg/m}^3$ is the density, $H_v = C_p T_v + L_v = 59.5 \text{ MJ/kg}$ is the total energy required to vaporize carbon, and I_x is the intensity of x-rays. To first order, this time is independent of the irradiation angle of the fiber.

The third line on the graph of Fig. 3 is the time for the vapor to fill the space between the fibers of the carpet, t_{fill} , approximately 2×10^{-7} s. This is really the earliest time that the wall can feel any pressure. The pressure pulse lasts for a time equal to the residence time of the vapor in the carpet,

$$\tau_{vb} = H / v \quad (4)$$

where H is the thickness of the carpet (2 cm), and v is the thermal velocity of the vaporized carbon ($2.5 \times 10^5 \text{ cm/s}$). While the vapor is in the carpet, it

Fig. 3 The key timescales of the problem: t_{bv} is the time to begin vaporization, τ_x is the x-ray pulse duration, t_{ba} is the time it takes for the vapor to become absorbing, t_{fill} is the time for the vapor to fill the carpet, τ_{cond} is the characteristic condensation time, and τ_{res} is the residence time of the vapor in the carpet.

condenses out with a characteristic time

$$\tau_{cond} = 4H(1 - \eta) / (\Omega S v) \quad (5)$$

where η is the packing fraction of fibers (0.32), Ω is the condensing area ratio (44), S is the sticking coefficient (0.2). The ratio of condensing surface area (of fibers) to the spherical first wall area is

$$\Omega = 1 + (4\eta H / d) \quad (6)$$

where d is the fiber diameter (0.06 cm). Using the base case values given in above in parentheses, gives a residence time τ_{res} of 8.0 μs and a condensation time of 2.5 μs . Since the residence time is more than a factor of 3 longer than the condensation time, we expect substantial condensation even though we are uncertain about many factors, particularly the value of the sticking coefficient.

The initial mass ablated off is approximately

$$m_0 = (I_x / H_v) A \Omega \tau_{vap} \quad (7)$$

where all the symbols have been previously defined. The amount of mass left after condensation is

$$m = m_0 \exp(-\tau_{res} / \tau_{cond}) \quad (8)$$

Fig. 4 The initial mass of carbon vapor vaporized by the x-rays and the final mass of ejected vapor. The difference is the mass condensed in the carpet.

The carbon atoms continue to condense out until a relief wave, propagating in from the inner surface of the carpet towards the wall, suddenly turns the thermalized plasma into a flow directed toward the center of the vacuum chamber. The pressure on the wall is thus shut off at time $\tau_{\text{res}} = H/v$. As the relief wave passes, and the gas expands into the vacuum, it is accelerated to a speed

$$v_{\text{esc}} = \sqrt{2E_p / m_c} \quad (9)$$

where E_p is the energy in the blowoff plasma.

We have plotted the initial ablated mass and the final mass ejected from the CCFW in Fig. 4. Note that over 95% of the vapor has condensed out during the residence time of the vapor in the carpet. We also expect that most of the carbon that initially blows into the center of the chamber (~0.13 kg) will eventually condense in the carpet, further reducing the net mass loss per shot. This is very favorable for the lifetime of the wall from the standpoint of erosion rate. It makes no difference if the condensed carbon takes the form of a uniform layer, or a snow-like soot deposit, or even diamond. On the next shot, the deposited carbon will again be recycled, and the majority of the material will stay in the carpet.

The final outward-directed impulse delivered to the wall is simply equal to the momentum of the inwardly directed vapor.

$$I_{\text{in}} = mv_{\text{esc}} = \sqrt{2m_0 E_p} \exp(-\tau_{\text{res}} / \tau_{\text{cond}}) \quad (10)$$

Fig. 5 The factor by which erosion is reduced by condensation, as a function of the length-to-diameter ratio of the carbon fibers shown for sticking coefficients ranging from 0.1 to 1.0.

The exponential reduction factor multiplies both the mass loss and the impulse. It is a function only of the carpet geometry and sticking coefficient, since

$$\frac{\tau_{\text{res}}}{\tau_{\text{cond}}} = \frac{\Omega S}{4(1 - \eta)} = \frac{S}{(1 - \eta)} \left[\frac{1}{4} + \frac{\eta H}{d} \right] \quad (11)$$

The exponential reduction factor is plotted in Fig. 5 for various sticking coefficients and fiber length-to-diameter ratios with a fixed fiber packing fraction of 0.32. The reduction factor is the key performance parameter in the geometrical design of the carpet. We see that one to two order of magnitude reductions in erosion and impulse can be achieved with realistic length-to-diameter ratios. Using the parameters for sticking coefficient and carpet dimensions given above, the ratio of residence time to condensation time is 3.2, resulting in a reduction of mass loss and impulse of 0.04.

In Fig. 6, we graph the impulse per unit area

$$J(R) = I_{\text{in}} / (4\pi R^2) \quad (12)$$

as a function of wall radius for our example case of 200 MJ of x-rays, and for both the CCFW and a flat carbon plate at the same radius. At $R = 3$ m, the impulse per unit area in the CCFW is about 4 Pa-s, corresponding to a wall pressure of 5 atmospheres for 8 μ s.

Fig. 6 A comparison of the impulse delivered to the first wall by x-rays on a carbon flat plate and a carbon carpet surface.

TRANSIENT STRESSES

To calculate the resultant stress due to the impulse, we need a first structural wall model. The best way to withstand a transient spherically symmetric load is with a perfect spherical shell, the unit stresses of which are all in simple uniaxial tension (hoop stress). Unfortunately this would be unacceptably idealistic since the model completely breaks down for a real sphere having large stress concentrations from the hundreds of holes that will be necessary for laser beams and diagnostics.

We believe that a more realistic model is that of a wall made of flat panels that are attached to a very rigid spherical space frame constructed inside a spherical vacuum vessel. The first wall would be tiled with these panels, which might have a characteristic size of 1 m across, and 1.0 cm thick. The carbon carpet would be attached to the inside surfaces. The panels could be square, rectangular or triangular, of either aluminum or a Kevlar-epoxy composite, and be either simply supported or have clamped edges. As long as these panels have approximately the same size and strength as our example, the details don't matter.

We shall model the first wall as 1 m x 1 m x 0.01 m aluminum flat plates, having a yield stress of 33 kpsi, and a design strength of one-half the yield stress. These plates would have their largest bending stress at the edges, if they were clamped, or at the middle, if simply supported, but of essentially the same magnitude. This transient stress is given by⁴

Fig. 7 Bending stress in an aluminum flat plate 1 m square and 1 cm thick due to the impulsive loading of 200 MJ of x-rays.

$$\sigma_p = 2\pi (b^2 / 2h^2 K_2) f_p J(R) \quad (13)$$

where b = plate size, h = plate thickness, K_2 is a shape factor that equals 1.62 for a square plate, and $f_p = 0.8$ kHz is the (lowest) vibrational frequency of the plate. For reference, the stress conversion factor is 6.9×10^6 Pa / kpsi. We have graphed this transient bending stress in Fig. 7, showing that it is below the design stress at all chamber radii greater than 2.31 m. We find that the minimum radius scales as the square root of the plate thickness; if we double the plate thickness to 2.0 cm, the chamber radius can be brought in to 1.63 m, while a 0.5 cm thick plate would require a radius of 3.26 m. We believe that, for the actual yield and target spectra of the LMF, an inner radius of approximately 3 m is achievable with a passive, room-temperature carbon-carpet first wall.

ISSUES AND POTENTIAL SOLUTIONS

One unresolved critical issue for the CCFW is its lifetime - how many shots will it last before it has to be replaced, as a function of the x-ray loading per shot? While experiments are needed to verify the lifetime properties of the carbon carpet, we expect that the carpet will have a reasonably long lifetime (hundreds of high yield shots) for several reasons. Some of the outermost filaments of exposed fibers (recall each fiber is a bundle of over 10,000 filaments) will be damaged on each shot due to vaporization and compressive thermal and ablation induced stresses. We do not, however, expect the shocks generated in the outer filaments to propagate

very efficiently to the underlying filaments since the fiber itself is similar to a compressible, porous material, and energy will be dissipated in filament motion and friction. The underlying filaments are thus protected, and the integrity of the fiber as a whole should not be seriously degraded.

In addition, condensation of vaporized carbon may reduce the damage to the outermost filaments on subsequent shots and thus extend the fiber lifetime. The nature of the condensation needs to be addressed experimentally. What if filaments or fibers are fused together by condensate? The fused areas may be separated by the subsequent shots or the process might continue and reduce the total fiber surface area available for condensation. We don't expect fusing to occur, because we expect the condensate to be more like soot than tar. LLNL will begin to investigate the survivability of various first wall concepts, including the CCFW, in experiments planned for Fall 1988.

Another issue that has been raised is that tritium and radioactive target debris might build up to an unacceptable level in the carbon carpet. The tritium build-up could be limited by adding a small amount (0.01 torr) of CO_2 to the chamber before each shot. The microexplosion would dissociate the CO_2 , and the unburned tritium would be tied up as T_2O and pumped out of the chamber so that it does not build-up. Proper selection of target materials will minimize the activation load from target debris. It is estimated that activated debris could accumulate for more than a couple of years before the design goal dose rate (100 mrem/hr 7 days after a high yield shot) would be exceeded.⁵

There is also some concern that vaporized carbon will contaminate the final optics. We don't expect this to be a significant problem. First of all, about 95% of the vaporized carbon condenses in the carpet before it has a chance to escape into the center of the chamber. Of the 130 g of carbon that is ejected into the vacuum chamber most of it (~98% or whatever the solid angle fraction of carpet coverage is) will expand back out into the carpet and have a high probability of condensing. The small fraction that expands out into the beam tubes should be stopped by gas that is puffed into the beam tubes or by the fast acting valves that are designed to stop shrapnel.⁶ The thermal velocity of the vaporized carbon (2.5 km/s) is in the range of the shrapnel velocities that the valves are being designed to handle (up to 10 km/s). If the optics can be protected from shrapnel, they will be protected from carbon condensate.

CONCLUSIONS

We have described a passive, room-temperature first wall that conceptually solves the problem of survival under intense x-ray and ion loadings from ICF targets. The carbon-carpet first wall concept uses a clever configuration to overcome the limitations of material properties, and to reduce the mass loss per shot and the impulse delivered to the wall by more than an order of magnitude. The configuration provides an enormous surface area, within a small (3 m radius) chamber, for absorbing the x-rays and condensing the vapor generated by ablation. It does this in a way that minimizes the amount of ejected vapor, and thus, the net reaction force transmitted to the wall. The carbon that is vaporized protects the carpet from ionic target debris. There is every indication that this concept will work as well on the hundredth shot as the first shot, but experimental confirmation is needed.

The use of low activation material and the possibility of eliminating Al from the high energy neutron flux reduces the short term radiation hazard. The CCFW does not require cryogenic cooling, does not need reestablishment or refurbishment between shots, and does not interfere with target alignment, mounting, irradiation and diagnostics. These factors should help minimize operation and maintenance costs. The use of commercially available materials in a compact chamber that can be operated at room temperature should help minimize capital costs. Overall, the carbon carpet first wall is an attractive option for the LMF.

ACKNOWLEDGMENTS

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NEUTRONICS ANALYSIS OF THE LABORATORY MICROFUSION FACILITY

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ABSTRACT

The radiological safety hazards of the experimental area (EA) for the proposed Inertial Confinement Fusion (ICF) Laboratory Microfusion Facility (LMF) have been examined. The EA includes those structures required to establish the proper pre-shot environment, point the beams, contain the pellet yield, and measure many different facets of the experiments. The radiation dose rates from neutron activation of representative target chamber materials, the laser beam tubes and the argon gas they contain, the air surrounding the chamber, and the concrete walls of the experimental area are given. Combining these results with the allowable dose rates for workers, we show how radiological considerations affect access to the inside of the target chamber and to the diagnostic platform area located outside the chamber. Waste disposal and tritium containment issues are summarized. Other neutronics issues, such as radiation damage to the final optics and neutron heating of materials placed close to the target, are also addressed.

INTRODUCTION

The Laboratory Microfusion Facility will be designed to contain target fusion reaction yields up to a nominal 1000 MJ. This corresponds to the production of 3.6×10^{20} D-T neutrons per shot peaked at 14.1 MeV. The radiological hazards, resulting from this burst of high energy neutrons and from the surrounding materials they activate, present a significant challenge to the facility designers. Neutrons must be moderated and absorbed, along with the secondary and decay gamma rays, in such a manner that the facility meets the U.S. Department of Energy (DOE) radiological siting requirements,¹ the International Commission on Radiological Protection (ICRP) (and DOE) public dose limits,² the DOE occupational dose limits,³ and the more stringent LLNL as low as reasonably achievable (ALARA) guidelines.⁴

The primary goal of the facility is to conduct some 1400 target experiments over a five-year period to demonstrate high gain in the laboratory. Projected yields for these experiments range from <10 MJ to ~1000 MJ. After high gain has been achieved, target yields above 100 MJ will be used to conduct weapons physics and weapons effects experiments. High gain experiments are expected to be conducted once per week. This will extend the facility lifetime to as much as 30 years.

We have set two design goals that minimize the affect of radiation hazards on the operation of the facility. The first is that LMF workers will have access to the diagnostic platforms outside the target chamber within 24 hours after a high-yield shot. This is required to retrieve data and set up for the next shot. Although it is possible that routine interior chamber operations will be done remotely, workers may occasionally require access to the inside of the chamber for nonroutine operations and maintenance. Therefore, the second design goal is that workers can safely enter the chamber for a short time 7 days after a high-yield shot. As quantitative measures of these two design goals, we have established dose rate limits of 2 mrem/hr outside the chamber 24 hours after a shot and 100 mrem/hr inside the chamber 7 days after a shot.

Several conceptual designs are currently being proposed for the LMF target chamber. All the designs include an inner first wall (aluminum, carbon, Kevlar epoxy, or fiberglass) that is protected from x rays with some other material (frozen nitrogen, a layer of ice or porous alumina, or a carbon carpet), a neutron moderator and absorber (water or borated graphite), and an outer structural wall (aluminum or steel). In this paper, we describe the results for a representative target chamber that consists of an inner 4-cm-thick aluminum wall, a 2-m-thick region of water, and an outer 4-cm-thick structural wall

also made of aluminum, and a concrete building as shown in Fig. 1. While this may not be the design chosen for the LMF, it serves as a useful example for discussing radiological issues, and it serves as a point of comparison for the other concepts being proposed. Where possible, we point out the anticipated impact of design modifications.

Note that although aluminum is generally considered a low-activation material, the ^{24}Na produced by (n, α) reactions with ^{27}Al is particularly troublesome for the first few days after a shot. The ^{24}Na has a half life of 15 hours and its decay yields two high energy gammas (2.75 and 1.37 MeV).

Our analysis includes: effects of leakage neutrons (from some 72 beam ports), materials impurities, nuclide buildup, and neutron scattering from concrete and beam tubes. Our estimate of the 24-hour dose rate at a diagnostic platform includes contributions from the activation of air, concrete, beam tubes, vacuum chamber, and interior chamber materials.

Two crucial design issues are the post-shot tritium recovery and radiation damage to final optics. We include data concerning the amount of tritiated waste and discuss means of handling and disposing of it. We also show that, at the projected radius of 25 meters, neutron damage to the final optics (degradation of transmission) will not impede LMF operations.

GENERAL NEUTRONICS ISSUES

The calculations performed for this paper were done using the computer codes TART,⁵ FORIG,⁶ and ORLIB.⁷ The neutron-photon transport code TART uses a Monte Carlo technique to determine the spatially- and energy-dependent fluences of neutrons and photons. ORLIB combines the neutron spectra from TART with our most current neutron cross section library to produce one energy group, spatially averaged, neutron activation cross sections. This information is then used by the nuclide generation-depletion code FORIG. Generally, TART was also used to determine the dose rates near activated surfaces using photon transport calculations and water to simulate tissue, as tissue is 71% water. Nitrogen, oxygen-like in absorbing decay radiation, is another 23%. Therefore water is an adequate model for 94% of the body.

The buildup of nuclides over time was considered in all the analyses using the equation

$$N = N_0 [(1 - e^{-\lambda n}) / (1 - e^{-\lambda t})],$$

where N is the number of curies of a given nuclide after n shots spaced t time units apart, N_0 is the amount of the nuclide produced on a single shot, and λ is the decay constant for the particular nuclide. The nuclide buildup approaches secular equilibrium

Fig. 1. Final optics protection and biological shield dimensions for activation analysis.

(where the amount that decays between shots is equal to the amount produced in a single shot). For example, at a shot rate of one per week, the buildup of ^{24}Na produced in Al after 500 shots is 1.00043 times the quantity produced in the first shot. For ^{54}Mn , which is produced from Fe and has a half-life of 312 days, the buildup is 64.9 times the quantity produced in the first shot.

The pr of the target (the density of the fuel region times its thickness) has a moderate effect on the activation of interior-chamber and first wall materials since it changes the neutron energy spectrum due to scattering in the fuel. The greater the pr of the fuel, the greater the neutron energy deposited in the fuel itself before the neutrons escape. A pr of 3 g/cm^2 will be the average fuel density achieved in LMF although some targets may achieve a pr of 5 g/cm^2 . The effect of the target's pr on material activation is expected to be greatest for those neutron reactions with thresholds (i.e., minimum neutron energy required to make the reaction energetically possible). For example, about 10% less ^{24}Na is produced in an Al first wall for a pr of 5 g/cm^2 target than for a pr of 3 g/cm^2 target, assuming the yield is the same in both cases. Implications of a range of pr values are being considered in the LMF design.

EXPERIMENT AREA DESIGNS

Two issues dominate the design of the EA: how to prevent or deal with the x-ray ablation of the first surface, and how to limit activation levels after high-yield shots to allow adequate accessibility.

The x rays will be dealt with in one or more of the following ways: with an x-ray and debris shield made of 15 cm of solid nitrogen or 0.25 cm of polyethylene at a radius of 20 cm (Ref. B); with a water frost layer condensed on an aluminum first wall⁹; with a sacrificial layer at the first wall made of alumina; with a carbon-carpet inner surface; or with pyramid-like carbon tiles.¹⁰

Limiting activation levels is done through careful material selection (high purity, low activating) and by providing adequate shielding to moderate and absorb the neutrons sufficiently to retard activation. The choice of low-activating aluminum allows re-entry into the chamber at the 7-day point (100 mrem/hr). For such a design, sufficient shielding must back this first Al wall to do two things: prevent activation of the second Al wall outside the shielding and attenuate the decay radiation from the first wall. This can be accomplished with 2 m of water. (see Fig 1.)

The 15-cm-thick x-ray and debris shield made of solid nitrogen provides not only a sink

for soft x rays and debris but also moderates and absorbs enough neutrons through (n, γ) captures to reduce the activation in an aluminum first wall by about 1/3 from the case with no debris shield. This reduces the time required for re-entry by half a day. The carbon-14 and tritium production from the nitrogen is insignificant.

Aluminum will be the material of choice over stainless steel for the frost condensing surface. Calculations using 3-mm-thick panels indicate that SS 304 would give an interior chamber dose rate 25 times greater than Al 5083 6 days after 500 full-yield shots (one-week spacing). This Al 5083 dose rate (40 mrem/hr) could be cut in half if a low-activation Al with similar properties to Al 5083 were used. The constituents of this low-activation aluminum are listed in Table 1 (Ref. 11).

The frost concept currently includes the idea of using fiberglass (located behind the aluminum condensing surface) as the vacuum vessel and as the container of the water used as the main neutron shield. The choice of fiberglass would result in an extremely low residual level of activation. Access to both the outer wall and the interior would be much less inhibited than with any other scheme proposed thus far. Detailed analysis of the performance of fiberglass in a radiation field is necessary. However, epoxy phenolics can generally withstand about 10^9 rad before experiencing significant weakening.¹² A 5-cm first wall of fiberglass would receive on the order of that dose during the LMF lifetime.

Proponents of the carbon-carpet first wall concept have also proposed using a Kevlar epoxy first wall, thus eliminating most of the Al (except for some support structures) from the high energy flux. This too would result in very low activation and good access to the interior of the chamber.

ACTIVATION OF ARGON GAS USED TO PROTECT FINAL OPTICS

Final optics must be protected from x rays and debris as well as shrapnel. Shown in Fig. 1 is

Table 1. Aluminum alloy with properties similar to Al 5083 but with lower impurity and activation levels.¹¹

94.999 wt%	Al
4.5	Mg
0.5	Si
0.001	Fe

a conceptual design of such a protection system.¹³ Of interest for neutronics analysis is the 24 Torr-m of argon intended to protect the fused-silica from soft x rays. A potential concern is the production of ^{41}Ar , both in the beam tube and in the surrounding ambient air, by the leakage neutrons. The concentration of ^{41}Ar in and out of the beam tubes were calculated. The ^{41}Ar concentration in a beam tube after a shot is at most $4 \times 10^{-3} \text{ Ci/m}^3$. Although this exceeds the allowable concentration for continuous exposure to workers, the concentration decays to $4.5 \times 10^{-7} \text{ Ci/m}^3$ at the 24-hour re-entry point, about an order of magnitude less than the allowable limit. Likewise, the concentration in the ambient air of the target chamber (due to the activation of the argon in the air) is $5 \times 10^{-5} \text{ Ci/m}^3$ after a shot and $6 \times 10^{-9} \text{ Ci/m}^3$ at the 24-hour point.

ACTIVATION OF BEAM TUBES

The activation of the aluminum beam tubes is also a major concern that could prevent re-entry into the EA within 24 hours after a maximum yield shot. Estimated to be 2 cm thick, the tubes are modeled as cylindrical tubes encasing each final focusing optic at the concrete wall and extending to the discrete port for beam entry at the chamber outer wall. This design, a cylindrical instead of tapered cone tube, uses the overlap around the actual beam hole as a shadow shield that effectively protects the beam tube from direct-shine neutrons. The actual beam hole at the chamber outer wall may be only 50 cm in diameter. The tube diameter is 1.4 m at the final optic, changing to 0.7 m at the second wall (see Fig. 1). The smaller radius is required at the chamber wall to provide adequate spacing for all 36 beam tubes in the designated solid angle of the sphere. Calculations indicate that the dose rate from the aluminum tube 24 hours after the five hundredth 1000-MJ shot is only 1.2 mrem/hr. A further step to minimize beam tube activation would be to line the interior of the tube with a thin layer (1 cm) of CH_2 . It is expected that those neutrons with a near grazing incidence to the beam tube material will see an effective thickness of moderator that will serve to further reduce neutrons to energies below the threshold for the (n,α) reaction in Al that nets the troublesome nuclide, ^{24}Na . Further work is required to establish the merit of this proposal and to see if normal Al 5083 could be used.

NEUTRON DAMAGE TO FINAL OPTICS

Final focusing lenses should be made of a material that is resistant to radiation damage and produces insignificant residual radiation. The leading material of choice is fused-silica. We have conducted a study of the

effects of 14-MeV neutrons in fused-silica when exposed to fluences that are predicted for the LMF final focusing lenses, which are currently set at 25 m from the target. The experimental fluence was $1.5 \times 10^{16} \text{ neutrons/cm}^2$, $\pm 20\%$. This is equivalent to ~3300 full-yield shots. This far exceeds the projected number of full-yield shots for the LMF lifetime covering high-gain development (100 full-yield shots), weapons physics experiments (1000 full-yield shots), and weapons effects experiments (100 full-yield shots). Including moderate- and low-yield shots, the equivalent number of lifetime full-yield shots will be 1600 (Ref. 14).

In this more recent experiment, a sample of fused-silica, 2.7 cm in diameter and ~1 cm thick, was irradiated using the Rotating Target Neutron Source (RTNS II) facility over a two-week period in May 1987. Spectrophotometry measurements made before and after the exposure indicated a change in optical density primarily below 400 nm with the peak at 215 nm. The baseline transmittance at 1ω (1.05- μm wavelength light) and 2ω (0.53 μm) was not altered. However, there was some degradation at 3ω (0.33 μm) and substantial reduction in transmittance at 4ω (0.26 μm). An earlier study showed no degradation in transmission at any wavelength for an experimental fluence level of $1.5 \times 10^{15} \text{ neutrons/cm}^2$. The final optical density measurements as a function of wavelength are given in Fig. 2.

The neutron-induced effects were largely reversible. Annealing of the sample at 400°C for two hours significantly recovered the transmittance. An additional 4-hour annealing had significantly less impact, suggesting a much longer required time to completely reverse the effects. Gamma spectrometry analysis indicated that there is a small amount of impurities in fused-silica, namely, Zn, Mn, Ce, Na, and Y. However, the resultant activation made no significant contribution to the residual radiation levels.

The degradation in transmission is assumed to be due to atomic displacements by neutrons. However, 5.5% of the total dose (1 Mrad out of 18.7 Mrad) to the silica is from secondary gamma radiation. There are indications that the gamma radiation threshold for damage is greater than 10 Mrad (Ref. 15). The degree to which electronic collisions may be reducing transmission will be explored later when a sample will be exposed to a comparable gamma dose and more spectrophotometry measurements are made.

AIR ACTIVATION

The activation of the ambient air in the concrete enclosed dome must not prevent access to the chamber at the 24-hour point for a full-yield shot. Calculations indicate that, a

day after a 1000 MJ shot, a 30-m-radius dome will contain 0.1 μCi of ^{41}Ar produced from the neutrons that get through the 2-m-thick shield. The contribution from the direct shine neutrons that escape through the 2 to 3% open solid angle and scatter off the concrete is 60 mCi of ^{41}Ar at this same time. The Derived Air Concentration (the allowable concentration for someone to continually breathe and not receive more than 5 rem in one year) is $3 \times 10^{-6} \text{ Ci/m}^3$ and is an order of magnitude greater than the actual concentration at 24 hours.

BIOLOGICAL SHIELD

Personnel must be protected from receiving excessive prompt doses of radiation from a high-yield shot, as well as from the residual radiation. Our results indicate that a 1.5-m-thick concrete wall enclosing the experimental area will reduce the prompt exposure immediately outside the EA building to less than 1 mrem/shot, or 50 mrem/yr, 1% of the allowable annual dose. An additional 0.7 m of

concrete (2.2 m total) will be required behind the final optics at the end of the beam ports (see Fig. 1).

The activation of the concrete presents a source of residual radiation that might constrain access to the diagnostic ports at the 24-hour point. The 72 beam tubes constitute clear paths for unmoderated neutrons to create "hot spots" in the concrete wall. Assuming that the inner radius of the concrete is 30 meters, the dose at the 7-m diagnostic ports at 24 hours is estimated to be about 10 mrem/hr. The overwhelming contribution to this dose rate is ^{24}Na production from (n,y) reactions with ^{23}Na in the concrete. The addition of boron to the concrete to suppress this reaction will be required, as well as some inelastic scattering shielding in front of or imbedded in the concrete. Adding 5 at.% boron to the concrete is estimated to reduce the activation by an order of magnitude. Further work is ahead to tailor the concrete shield to the specific LMF needs. We may also consider the use of "mobile shielding" to shield the diagnostic platforms from the concrete.

Final optics are set at 25 m from the target
Transmission (T) = 10^{-D} , D is optical density

Fig. 2. Neutrons and neutron-induced gamma rays cause insignificant transmission loss at 3ω in fused-silica for proposed LMF lifetime fluences ($7 \times 10^{15} \text{ n/cm}^2$).

NEUTRON HEATING CLOSE TO THE TARGET

We made a number of neutronics calculations to determine the neutron heating in materials positioned close to the target. These might include target-support structures, shrouds, irradiation samples, and perhaps even diagnostics. Calculations were done for Al, Fe, Cu, and SiC.

Our results show that all the materials will melt, sublime, or dissociate if placed within 10 to 20 cm of a 1000-MJ-yield target. Carbon and silicon carbide have comparable minimum inner radii at about 13 cm, while the three metals considered have minimum radii closer to 20 cm. Steel is slightly better than Al and Cu. Even if we can protect materials from x rays and debris, anything this close to the target must be considered sacrificial since it will be destroyed by neutron heating. The innermost 10 to 20 cm of the target support structure, for example, will have to be replaced for every shot.

INTERIOR DOSE RATE

The cumulative interior dose rate goal is <100 mrem/hr about seven days after a full-yield shot. The contributions to this dose rate come from the following: the target shroud and support mechanism, the ablated and recondensed first wall, the remaining tritium (internal dose), the sacrificial diagnostics, the first wall, and any materials introduced into the chamber as part of an experiment (e.g., military applications). The tritium will be rapidly pumped from the chamber within minutes, depending on the first wall construction. The target support components will be constructed from composite materials such as carbon-carbon or Kevlar to avoid the activation problem here. Sacrificial diagnostics will also be made of nonactivating materials. The first wall, if solid nitrogen, will not present any significant radiological hazard, nor will polyethylene or frost. The carbon will not have persistent activation products, as long as it is kept pure. A first wall, made of 4 cm of low activating Al (see Table 1) at a 5-m radius, will give 100 mrem/hr about seven days after five hundred 1000 MJ shots spaced one week apart, when the solid nitrogen shield is used (and a value one-third higher when it is not). For a 3-m-radius first wall (2-cm thick), 100 mrem/hr is attained at 7.5 days after the five-hundredth 1000-MJ shot. The longer time is required due to $1/r^2$ effects and the less self-attenuation of decay gamma rays in the thinner aluminum wall. Therefore, we feel that a dose rate of 100 mrem/hr at about the seven-day point is attainable. This rate will allow limited personnel access into the chamber at this time.

EXTERIOR DOSE RATE

Contributions to the exterior dose rate are: the first wall decay, the second wall decay, decay of impurities in the water that are activated, the concrete, and the beam tubes. As mentioned earlier, the dose rate from the first wall (5-m radius) outside the second wall (after 2 m of water) is 1 mrem/hr. The dose rate at this same point from the activated concrete (due to "through-the-shield" neutrons) is only 3 mrem/hr. However, the "hot spots" created by the direct shine (leakage) neutrons will contribute ~1 mrem/hr for a 5 at.% boron concentration in the concrete backing the final optics. Our water shield is not borated, both because a saturated solution of boric acid in the water (the simplest way to borate the water) does not introduce enough boron in the water to make a significant difference and because the boric acid or other boron compounds would introduce impurities into the water, most notably sodium. The contribution from activated beam tubes to the overall dose rate at the equator of the sphere is less than 0.1 mrem/hr. Since the goal is to limit the exterior dose rate to ~2 mrem/hr, a conceptual design with the features listed above can feasibly achieve the goal dose rate.

WASTE HANDLING

The expected tritium (liquid (<5 mCi/yr) and gaseous (<100 Ci/yr)) effluents will be many orders of magnitude below the maximum permissible concentrations and total quantities as given in DOE 5480.11. The design objective is to limit the facility's controlled releases to <100 Ci/yr. This value was easily met by the RTNS II facility, which had a somewhat higher tritium throughput. A typical high gain target will contain 10 to 50 mg of tritium. An estimated annual throughput then is 25,000 Ci. For an aluminum first wall, the residual tritium diffusing from the wall after the chamber is pumped out will not present a personnel hazard. For a frost first wall, the Sulzer process for tritium recovery would be used.¹⁶ This can involve cryogenic distillation, combined electrolysis catalytic exchange (CECE), water distillation, electrolysis, gettering, gas storage, and fixation. Here, the tritium could be recycled as it is currently worth \$20,000 per gram. The Sulzer process increases the tritium concentration in one stream while greatly reducing (by up to six orders of magnitude) the concentration in the other stream. After 20 years operation, the total volume for the highly concentrated tritiated water could be only 300 liters. Since this water can be easily doubly contained in certified stainless steel vessels, it presents no significant hazard. Any discharges will be many

orders-of-magnitude below the pertinent standards. At concentrations >1000 Ci per container, the waste must be handled as Class B, with the appropriate containers, etc. We estimate the total cost for waste disposal for the first ten years of operation to be roughly \$2M. By keeping the site tritium inventory to <30 g could ease siting requirements.

CONCLUSIONS

Facility and experimental goals for the LMF can be achieved through careful design of the experimental area. Our calculations show that careful design and material selection can minimize activation and that sufficient shielding can be employed to protect materials prone to activation. For a chamber that uses an Al first wall, ^{24}Na produced by (n,α) reactions with ^{27}Al is the design-limiting radiological hazard. In the case we examined, a 2-m-thick water shield was needed to reduce the dose rate at the diagnostic platform at the 24-hour point to an acceptable level. Reducing the amount of Al (or eliminating it) from the high energy flux would reduce the shielding requirements and allow earlier access to the inside of the chamber. Interestingly, ^{24}Na produced by (n,γ) reactions with ^{23}Na in the concrete walls of the experiment area also present some difficulties. This radiation hazard can be reduced by adding boron to the concrete. Neutron damage to final optics appears to be manageable and the effects of neutrons leaking through beam ports can be mitigated. The waste produced by the facility, predominantly tritium, can be safely and economically managed.

ACKNOWLEDGMENT

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March 24, 1988
SF-88-056

MEMORANDUM

To: Mike Tobin, Mike Singh
From: Wayne Meier
Subject: Effect of Target pR on Neutron Activation

As requested, I ran some TART calculations to determine the effect of the target pR on neutron activation in an aluminum first wall. The neutronics model consisted of a target at the center of a 5.0-cm-thick aluminum chamber located at 5.0 m. A 30-cm-thick borated water shield surrounds the chamber wall. The target pR was changed by changing the thickness of the source zone while leaving the material composition and density fixed. The three cases were run: pR of 3, 4, and 5 g/cm².

The production of ²⁴Na via ²⁷Al(n,α) reactions and the production of ⁵⁴Mn via ⁵⁴Mn(n,2n) reactions are of primary interest since the first dominates the short term hazard while the latter dominates the longer term (30 day) hazard. Both of these are threshold reactions, and we would therefore expect that increasing the target pR would decrease the number of reactions since more high energy neutrons will be moderated in the compressed fuel region. The reaction rates as a function of pR are tabulated below.

Burn zone pR	Reactions per source neutron	
	²⁷ Al(n,α) ²⁴ Na	⁵⁴ Mn(n,2n) ⁵⁴ Mn
3	2.710 E-2	2.922 E-4
4	2.557 E-2	2.660 E-4
5	2.380 E-2	2.403 E-4

These results are plotted in Fig. 1 normalized to the respective value at a pR of 3. The ^{24}Na production rate per source neutron is reduced by 12% as the target pR is increased from 3 to 5 g/cm³. The ^{54}Mn production rate per source neutron is reduced by 18% over the same range of target pR.

The above results are indicative of the effect of pR on activation only if the target yield does not change with pR (i.e., the source is constant). In reality, we expect the yield to scale as $\text{pR}/(\text{pR} + 6)$. This relationship is also plotted in Fig. 1. The yield at a pR of 5 is 36% higher than at a pR of 3. The product of target yield and reactions per source neutron gives the result we want. The normalized ^{24}Na and ^{54}Mn production rates as a function of pR are plotted in Fig. 2. The ^{24}Na production rate increases by 20% as the target pR is increased from 3 to 5. The ^{54}Mn production rate increases by 12%.

In summary, when we consider the combination of a reduction of activation per source neutron and an increase in the neutron yield with increasing target pR, we find that the net effect is an increase in production rate with increasing pR.

Fig. 1 Normalized target yield and normalized ^{54}Mn and ^{24}Na production rates per source neutron.

Fig. 2 Normalized ⁵⁴Mn and ²⁴Na production rates when neutron source increases with target yield.

April 14, 1988
SF-88-083

MEMORANDUM

To: Charles Orth
From: Wayne Meier
Subject: Neutron Heating in Materials Close to the Target

At your request, I have run a number of neutronics calculations to determine the neutron heating in materials positioned relatively close to the target. These might include target support structures, shrouds, irradiation samples, and perhaps even diagnostics.

MODEL

All of the calculations were done using TART. The reference case geometry consists of a rho-R 5 target at the center of a 1-cm-thick spherical shell of material with an inner radius of 10.0 cm. The shell is divided into three, 1/3 cm-thick zones. There is a vacuum between the target and the shell, and outside the shell is a leakage region (i.e., no backscatter). Calculations were done for Al, Fe, Cu, C, and SiC. For aluminum, calculations were done with the inner radius of the shell at 5, 10 and 15 cm in order to demonstrate the $1/R^2$ scaling of the energy deposition per unit mass (J/kg). For the other material the inner radius was 10 cm. Heating from neutrons and neutron induced gammas (i.e., from (n, γ) reactions) was determined. Gamma transport was included in the calculations.

TART RESULTS

The results for the Al shell at 5, 10 and 15 cm are given in Table 1. The energy deposition is given in MeV per source (14.1 MeV) neutron, while the energy density is given for a 1000 MJ yield. Note that the energy deposition per cm of material is approximately constant at 0.15 MeV per fusion neutron. As a result, the energy deposited per unit mass decreases as $1/R^2$, where R is the radius to the middle of the shell. This is illustrated in Fig. 1. The variation in energy density across the 1-cm-

thick shell is shown in Fig. 2 for the 10-cm shell. Extrapolating to the inner edge of the shell gives an energy density of about $2.5 \text{ E}+6 \text{ J/kg}$, which is 3% higher than the innermost zone and about 11% higher than the average for the entire shell. Results for the other materials are given in Table 2.

MINIMUM RADIUS

While it is interesting to compare energy densities, the more important issue is determining the radius at which the material melts, sublimes or dissociates. Using the specific heat data in Table 3 and using the $1/R^2$ scaling, the minimum inner radius to prevent melting is given in Table 4. I have used the energy density for the innermost zone (i.e., the 1/3-cm of the shell closest to the target) and assumed the initial temperature is 293 K. We simply solve the following for R_{min} :

$$C_p (T_L - 293) = E_{m1} * ((10.167)/(R_{min} + 0.167))^2 ,$$

where C_p = specific heat capacity (J/kg-K),
 T_L = limiting temperature (K),
 E_{m1} = energy density for innermost zone (J/kg), and
 R_{min} = minimum inner radius (cm).

CONCLUSIONS

As indicated in Table 4, all the materials will melt, sublime or dissociate if placed within 10 to 20 cm of a 1000 MJ target. Carbon and silicon carbide have comparable minimum inner radii at about 13 cm, while the three metals considered have minimum radii closer to 20 cm. Steel is slightly better than Al and Cu. Even if we can protect materials from x rays and debris, anything this close to the target must be considered sacrificial since it will be destroyed by neutron heating. The last 10 to 20 cm of the target support structure, for example, will have to be replaced for every shot.

Table 1. Heating rates in Al shells with inner radii of 5, 10 and 15 cm

Material = Al
Yield = 1000 MJ

Zone inner radius (cm)	Energy deposition (MeV/n)	Standard deviation (MeV/n)	Standard deviation (%)	Mass (kg)	Energy density (J/kg)
5.000	0.04953	5.06E-04	1.0	0.302	9.318E+06
5.333	0.04986	4.56E-04	0.9	0.342	8.278E+06
5.667	0.04819	4.57E-04	0.9	0.385	7.113E+06
Total	0.14758			1.029	8.147E+06
10.000	0.04986	7.67E-04	1.5	1.169	2.423E+06
10.333	0.05033	8.42E-04	1.7	1.247	2.293E+06
10.667	0.04860	6.05E-04	1.2	1.327	2.080E+06
Total	0.14879			3.744	2.258E+06
15.000	0.05144	9.22E-04	1.8	2.602	1.123E+06
15.333	0.05112	9.46E-04	1.9	2.717	1.069E+06
15.667	0.04896	6.70E-04	1.4	2.835	9.811E+05
Total	0.15152			8.154	1.056E+06

Energy deposition per unit mass, MJ/kg
 Material = Al
 Shell thickness = 1.0 cm
 Yield = 1000 MJ

Fig. 1. Energy density in Al shell as a function of shell radius. Results are plotted at the middle of a 1-cm-thick shell.

MJ/kg deposited in Al shell
 Inner radius = 10.0 cm
 Thickness = 1.0 cm
 Yield = 1000 MJ

Fig. 2. Variation in energy density for an Al shell with inner radius of 10 cm.
 Error bars are at +/- 2 standard deviations.

Table 2. Heating rates in Fe, Cu, C and SiC shells

Yield = 1000 MJ
Inner radius = 10 cm

Material	Zone Inner radius (cm)	Energy deposition (MeV/n)	Standard deviation (MeV/n)	Standard deviation (%)	Mass (kg)	Energy density (J/kg)
Fe	10.000	0.11393	2.96E-03	2.6	3.408	1.900E+06
	10.333	0.11015	2.53E-03	2.3	3.635	1.722E+06
	10.667	0.10034	2.59E-03	2.6	3.869	1.473E+06
Total		0.32442			10.912	1.689E+06
Cu	10.000	0.10497	2.30E-03	2.2	3.880	1.537E+06
	10.333	0.10372	2.08E-03	2.0	4.138	1.424E+06
	10.667	0.09133	1.75E-03	1.9	4.405	1.178E+06
Total		0.30002			12.423	1.372E+06
C	10.000	0.05687	4.82E-04	0.8	0.736	4.390E+06
	10.333	0.05634	5.20E-04	0.9	0.785	4.077E+06
	10.667	0.05470	3.73E-04	0.7	0.836	3.719E+06
Total		0.16791			2.357	4.048E+06
SiC	10.000	0.08663	8.88E-04	1.0	1.386	3.552E+06
	10.333	0.08574	8.45E-04	1.0	1.478	3.296E+06
	10.667	0.08234	6.05E-04	0.7	1.573	2.974E+06
Total		0.25471			4.437	3.262E+06

Table 3. Relevant physical properties (Ref. 1)

Material	Density (kg/m ³)	Specific Heat Cap. (J/kg-K)	Limiting Temperature (K)	Notes
Al	2700	962	855	(6061-T6 alloy)
Fe	7870	418	1783	(AISI C1020 steel)
Cu	8960	385	1355	
C	1700	690	3977	(sublimes)
SiC	3200	837	3033	(dissociates)

Ref. 1 Marks' Standard Handbook for Mechanical Engineers, McGraw Hill, NY, 8th Ed., pgs. 6-11, 6-61, 6-176 (1978).

Table 4. Minimum inner radii for the five materials

Material	Radius (cm)
Al	21.4
Fe	17.6
Cu	19.6
C	13.2
SiC	12.5

April 29, 1988
SF-88-095

To: Neil Frank, Dennis Slaughter
From: Michael Monsler
Subject: An experiment to test the carbon carpet first wall concept

I. Issues and Objectives

1) We know we're going to have vaporization and we can calculate the mass vaporized. Our model indicates it is the same as a flat plate. If we just want to verify vaporization dynamics, we could use a flat plate. Vaporization in itself is not a critical issue.

2) The real purpose of the CCFW is to lengthen the duration of the impulse resulting from the x-ray deposition, without damaging the underlying structure. The magnitude of the impulse itself is not an issue, since it is the same for a flat plate or a carpet. Too bad, because the impulse (integral of pressure over time) is easily measured with a ballistic pendulum. We really need to measure either the pressure or the duration (1-10 μ sec); then, knowing the impulse, we can get the other.

3) We must obtain realistic energy depositions, on both flat tile and brush-like samples. We must get the deposition length and timescales right.

4) The key issue and concern is survivability of the fibers and the support plate. We now suspect failure is due to compressive thermal stress in the individual filaments. The simulation must be able to determine if filaments have failed. Are they crushed by blow-off stress and or by thermal shock? The support plate has to be protected from direct exposure by proper design of the carpet. We have to show that the stress due to impulse on the support plate is acceptable.

Microscopic examination of the filaments after one pulse, and after 10 to 100 pulses, is desirable. So is a careful mass loss observation. It is desirable to distinguish between amounts of evaporation loss and of breakage. Does the damage extend beyond the first outer layer of filaments in each fiber? Again a flat carbon sample should also be irradiated as a control.

5) We suspect that the brush will recondense the vaporized material quicker than a flat plate. A comparison of weight loss should give some indication of the effectiveness. What does the recondensed carbon look like. Again microscopic examination is critical. For multiple shots, we should look to see if recondensed carbon protects the fibers on subsequent shots. The interpulse time must be long enough to allow the sample to return to ambient temperature between shots.

6) To reiterate, there are two key issues that an experiment must address.

- a) Does the CC work as advertised by stretching out the duration of the impulse?
- b) Is the total damage due to melting and breakage acceptable, such that the carpet does not have to be replaced very often?

II. Energy Source

1) What fluence do we need? A yield of 1000 MJ has 20% in x-rays. At 5 meters radius we get a fluence of

$$F = \frac{200 \text{ MJ}}{4\pi (5\text{m})^2} = 60 \frac{\text{J}}{\text{cm}^2}$$

Fluences of this order are needed to significantly exceed the vaporization threshold for carbon.

2) Spot size? A flat carbon surface has a blowoff layer that is 1 to 10 μm thick, so a spot size of 10-100 μm is adequate to achieve a one-dimensioned simulation. Our carbon brush surface is 1 cm deep, so to avoid the interference of edge effects we have to either have a 10 cm spot size or put a 1 cm sample in a stout cylindrical cup, so there will be no pressure relief from the edges.

sample constrained in cup

3) Background Pressure? A vacuum is needed, although not a very good one. The pressure of one atmosphere is well known to interfere with the experiment via laser supported detonation waves, which must be avoided.

4) Wavelength and Pulselength? The key lengths and timescales in the x-ray deposition process are the mean free path of 1 keV x-ray in carbon ($l=2\mu\text{m}$) and the x-ray pulse width (10ns).

Since the thermal diffusivity of carbon is about $K=0.2 \text{ cm}^2/\text{sec}$, the thermal conduction time required to transfer heat for distances of the order of the deposition zone depth is

$$t_c = \frac{l^2}{K} = \frac{(2 \times 10^{-4} \text{ cm})^2}{0.2 \text{ cm}^2/\text{sec}} = 200 \text{ nsec}$$

Thus the x-ray pulse deposits energy in a time short compared to the thermal conduction time, and so must the simulation. A laser or e-beam with a pulse width less than 100 nsec is ok.

The deposition depth must be realistic also. A laser of any wavelength is ok since energy will be deposited in depths less than $2\mu\text{m}$. An E-beam having an electron energy of 50 keV or less would be required to get a high enough energy deposition at depths of $2\mu\text{m}$ or less.

III. Target Samples

- 1) Both flat carbon samples and carbon carpet samples are required. It is desirable if they are close to the same kind of graphite. This may be impossible.
- 2) Carbon fibers must be of the compound filament type (10,000 filaments/fiber).
- 3) The cheapest way to prepare a few cm^2 sample carpet is to hand weave one, exactly as they make wigs. Bundles of fibers are sewn to backing fabric as shown in Figure 2a. Bundles are sewn tightly enough together so they stand up, shoulder to shoulder, as in Figure 2b they are then sheared off at an even height.

Figure 2a

Figure 2b

The sample is glued into the cylindrical cup in which it will be irradiated.

- 4) Some fibers should probably be irradiated separately at $\theta = 0^\circ$, i.e. sideways, and examined for damage mechanism.

IV. Data and Diagnostics

- a) Measure mass loss per shot and after 10 and 100 shots from both carpet and flat plate. Try to distinguish between vaporization and breakage.
- b) Measure impulse using a ballistic pendulum.
- c) Measure either the pressure or the duration of the blowoff. We don't know the best way to do this for timescales of 500 ns to 5 μsec . Would inserting a piezoelectric disk between the sample and pendulum give the desired $p = p(t)$?
- d) Examine filaments microscopically to determine damage mechanism and recondensation morphology. Look for evidence of vaporization, melting, thermal shock, spallation, etc.
- e) Observe gross changes in carpet - are fibers in tufts pushed aside, or smashed flat, etc.

V. Suggested Experiment

A 100 J Nd: Glass or CO_2 laser focused to a 1 cm^2 spot size would be great. The pulse width must be $< 100 \text{ ns}$ however, pulses of $1 \mu\text{sec}$ to 1 ms are way too long. Wavelength is not critical. The sample should be mounted on a ballistic pendulum in a small vacuum chamber, as shown in Figure 3.

Schematic of CCFW Experiment.

March 22, 1988
SF-88-055

To: Dave Nilson, John Woodworth, Charles Orth, Neil Frank
From: Michael Monsler
Subject: Gas Protection from Target Shrapnel

MEMORANDUM

Can the gas protection that we envision using to stop x-rays and ions also stop such large debris as particulates having a diameter of micron to a millimeter? To answer this we shall do a simple drag calculation.

Assume a target of mass M disassembles instead of vaporizes, such that N particles are formed, each of diameter D_p and mass m . These particles start out with a total kinetic energy E .

Then

$$E = N \left(\frac{mv_0^2}{2} \right), \text{ and}$$

$$M = Nm = N \rho_p \frac{\pi}{6} D_p^3 \quad \text{where } \rho_p = \text{particle density}$$

The initial velocity of each particle is:

$$v_0 = \sqrt{\frac{2E}{M}}$$

The particles decelerate by drag as follows:

$$m \frac{dv}{dt} = -C_D A \frac{1}{2} \rho_g v^2$$

We note that ρ_g = gas density, and C_D is the drag coefficient. Writing the particle mass m and the frontal area A in terms of the diameter D_p gives the velocity decay as follows:

$$\frac{1}{v^2} \frac{dv}{dt} = -C_D \left(\frac{3}{4D_p} \right) \frac{\rho_g}{\rho_p}$$

The best way to integrate this is to calculate the stopping distance L as follows:

$$L = \int_0^t v dt = - \frac{4D_p}{3C_D} \frac{\rho_p}{\rho_g} \int_{v_0}^{v_f} \frac{dv}{v} = \frac{4D_p \rho_p}{3C_D \rho_g} \ln \left(\frac{v_0}{v_f} \right)$$

Let's rewrite this to appreciate the relationship between the stopping power of the gas, $\rho_g L$ in gms/cm², and the areal density of the particle, $\rho_p D_p$.

$$\rho_g L = (\rho_p D_p \left(\frac{4}{3C_D} \right) \ln(V_o/V_f))$$

To evaluate this equation, imagine a target of mass $M = 1$ gm disassembles with a kinetic energy of $E = 100$ MJ. It's hard to imagine a larger energy than this because if this were to be a proper implosion, everything would vaporize and there would be no shrapnel. The initial velocity is then $V_o = 4.47 \times 10^5$ cm/sec. Assume we want to slow it down to $V_f = 1$ cm/sec. Then $\ln(V_o/V_f) = 13$. Fortunately the $\ln(V_o/V_f)$ logarithm is very insensitive to the assumptions. The drag coefficient for spheres at very high velocity varies from $C_D = 0.5$ just after the turbulent transition to $C_D = 2$ for Newtonian hypersonic flow. Let's simply take $C_D = 1.0$ since we don't know the true unspherical shape of the particle anyway. We then get

$$\rho_g L = 17.3 \rho_p D_p$$

for the required stopping power of the gas. Note that if both sides of the equation are multiplied by the frontal area of the particle, we get a rule of thumb that says that to stop the particle by aerodynamic drag, you need a mass of gas an order of magnitude greater than the mass of the particle.

To stop the x-rays we have previously calculated that we would need a density-length product of

$$(\rho_g L)_{x\text{-ray}} = 1.4 \times 10^{-3} \text{ g/cm}^2$$

This amount of gas protection will apparently stop all gold particles ($\rho_g = 19.3$ gm/cm³) in the diameter range $0 < D_p < 6.5$ microns. Larger particles will require either more gas, or a solid debris shield.

We do not know the expected particulate diameter distribution, integrated over time. The majority of particulates should be less than several microns, and the gas

protection will filter these out. However, since it is probable that there will be a few occasional particles in the range of 10 microns to 1 millimeter which the gas will not stop, it would seem wise to plan on using solid debris shields as well.

March 28, 1988
SF-88-057

To: Neil Frank, Dave Nilson, Charles Orth, John Woodworth
From: Michael Monsler
Subject: Gas Protection Against Debris Ions

MEMORANDUM

Because there are so many physical processes occurring during the deceleration of a fast ion in a neutral gas, it is best to not stray too far from empirical data. I have not found data tables for gold ions stopping in argon gas, but there are data for other heavy ions in air from which we can scale.

We shall fit a scaling law to a few representative data points that span the atomic weight range. The data are for stopping in air rather than in solids. Unfortunately the data are at higher energy, but that's all I have at the moment. In his book The Atomic Nucleus, R.D. Evans, discusses the stopping of both fission products and alpha particles in air at one atmosphere pressure. The data given in Table 1 that we shall scale from is taken from Evans, Chapter 22, "The Passage of Heavy Charged Particles through Matter".

Atom	Mass Number	Energy in MeV	Range cm
He	4	3.4	8.6
Sr	97	95	2.5
Xe	138	67	1.9

Table 1. Range of some ions in one atmosphere air.

To scale to the situation of laser fusion debris ions, we shall take the simple approach of creating a range-energy scaling relation that fits the data of Table 1. This will be adequate for engineering estimates.

A simple relationship for the range in one atmosphere air that fits the above data is:

$$R_o = (1.9 \text{ cm}) \left(\frac{E}{67 \text{ MeV}} \right)^{0.2} \left(\frac{A_i}{138} \right)^{-0.6}$$

where E is in MeV and the mass number of the ion is A_i . This holds in air of density $\rho_o = 1.23 \times 10^{-3} \text{ gm/cm}^2$ and an average mass number of $A_o = 14.6$

How do we scale to other media than air, at other densities? Evans (p653) says that the quantity $(R\rho)/\sqrt{A}$ is constant to within +/- 15% for heavy particles whose range has not been shortened by multiple scattering in high Z materials. We therefore set

$$\frac{\rho R}{\sqrt{A}} = \frac{\rho_o R_o}{\sqrt{A_o}}$$

and obtain for our stopping power in a gas

$$\rho R = (2.34 \times 10^{-3} \frac{\text{gm}}{\text{cm}^2}) \left(\frac{A_{gv}}{14.6} \right)^{0.5} \left(\frac{E_{im}}{67 \text{ MeV}} \right)^{0.2} \left(\frac{A_{im}}{138} \right)^{-0.6}$$

Now let's relate this to ICF by the following example. Imagine a gold target of mass 2 gm, having an energy in debris ions of 200 MJ. The energy per particle would be $E = 206 \text{ keV}$. Gold has a mass number of $A_i = 197$. Argon has a mass number of $A = 40$ and a standard density of $1.78 \times 10^{-3} \text{ gm/cm}^3$.

The stopping power of the argon is then $\rho R = 9.84 \times 10^{-4} \text{ gm/cm}^2$, or 4.2 torr-meters at 273K. Using twice this much gas should assure the safety of the optics.

April 5, 1988
SF-88-066

MEMORANDUM

To: Neil Frank, Dave Nilson, Dennis Slaughter, John Woodworth
From: Michael Monsler
Subject: Gas-breakdown limit on gas protection to first walls.

How much gas can be added to the entire chamber to protect the first wall by absorbing the x-rays and debris? One limit on the gas pressure would be the occurrence of laser-induced gas breakdown near the target. During Nova operation it has been noted that a very small amount of air (in the millitorr range) in a leaky spatial filter will block the beam at the focal point. To estimate the breakdown limit, we have found an excellent paper with experimental data in the correct wavelength and pulselength range. The reference is "Laser-induced breakdown in N_2 and rare gases at 0.53 and 0.35 micrometers", by D.I. Rosen and G. Weyl, J. Phys. D: Appl. Phys. 20, (1987), 1264 - 1276.

Rosen and Weyl provide a graph of argon breakdown as a function of pressure at $\tau_p = 15$ ns and a wavelength of 0.35 microns. Fitting their data, which is shown in the enclosed viewgraph, the breakdown threshold is

$$I_{bd} = (3.5 \times 10^{11} \text{ W/cm}^2) \left(\frac{P}{760 \text{ torr}} \right)^{-0.85} \left(\frac{\tau_p}{15 \text{ ns}} \right)^{-0.6}$$

Breakdown is defined as the appearance of a visible spark. At threshold, a variation of a factor of two in laser power changes the probability of occurrence of a spark from less than 0.5 to more than 0.9. The onset of average pulse energy attenuation greater than 5% correlated very well with the appearance of a spark.

Using the above fit to experimental data, and assuming that a 10 ns shaped ICF pulse has most of its power in the last 5 ns, we expect an average intensity at the target on each of two sides of

$$I = \frac{5 \text{ MJ}}{\pi (50 \mu\text{m} \times 30 \text{ m})^2 5 \text{ ns}} = \frac{10^{15} \text{ W}}{\pi (0.15 \text{ cm})^2} = 1.4 \times 10^{16} \text{ W/cm}^2$$

We assumed that the beams add linearly; there will certainly be intensity spikes larger than this.

Setting the breakdown flux equal to the expected intensity, and setting $\tau_p = 5 \text{ ns}$, gives a maximum allowed pressure of argon in the chamber of

$$p_{\text{max}} = 6.4 \times 10^{-3} \text{ torr}$$

This amount of gas, distributed throughout a chamber of $R = 5 \text{ meters}$, will provide only 0.032 torr - meters of protection. The stopping power of argon for 1 keV x-rays is such that 1.4 torr - meter of argon is needed to provide an attenuation of e^{-1} due to the photoelectric effect. An amount of gas that will just cause breakdown near the target is therefore very ineffective in protecting the wall. We plan on using at least 7 torr - meters to protect the optics.

One can operate somewhat above breakdown of course; most of the photons will probably still get on target. It would be very risky to go too much above breakdown, however, because of refractive effects in the plasma. To get appreciable protection one would have to operate at pressures of 50 times the breakdown threshold - an unlikely prospect. I conclude that gas protection is not a viable first wall protection scheme for laser fusion.

Laser-induced breakdown in nitrogen and the rare gases at 0.53 and 0.35 μm

D I Rosen and G Weyl

J. Phys. D: Appl. Phys. 20 (1987) 1264-1276.

Figure 2. The breakdown threshold in argon at $\lambda = 0.53 \mu\text{m}$: $\bullet$, $f/10$ optics, $r_f = 6.5 \mu\text{m}$; Δ , $f/30$ optics, $r_f = 19.5 \mu\text{m}$; --- corrected (see text) measured thresholds of Buscher *et al* (1965) with $\tau_p = 28 \text{ ns}$ and $r_f = 16 \mu\text{m}$.

Figure 3. The breakdown threshold in argon for $\lambda = 0.35 \mu\text{m}$: Δ , $f/14.6$ optics, $r_f = 6.4 \mu\text{m}$; $\bullet$, $f/30$ optics, $r_f = 7.7 \mu\text{m}$; --- corrected (see text) measured thresholds of Buscher *et al* (1965) with $\tau_p = 20 \text{ ns}$.

**Concepts for the Final Optical System of the
Laboratory Microfusion Facility**

**M. J. Monsler
W. J. Schafer Associates, Inc.**

February 16, 1988

There are many critical issues in protecting the final optics

- Can the final optic be protected, or need it be disposable?
- Should it be a mirror or a lens?
- It must either avoid or tolerate neutrons, ions, x-rays, incident & reflected laser light, and perhaps neutral particles & shock waves.
- Have minimum activation from radiation, tritium absorption
- Be accessible, easily replaceable.
- Have adequate optical quality.

The optical train must also

- Prevent tritium from migrating out of experimental area
 - normal operation
 - accident conditions
- Attenuate scattered neutrons along beam duct
- Ensure that laser building is kept safe, clean, radiation free
 - so it can be cheaper than experimental area.

We must protect both the final optical element and the laser itself from the radiation environment.

The critical objective is to protect the optical thin film coating (on mirror or lens) from excessive heat loading

San Francisco

- $\Delta T = 100^\circ\text{C}$ is considered the delamination limit —
Multilayer dielectric stack suffers unacceptable thermal stresses somewhere above this
- Allocate $\Delta T = 50^\circ\text{C}$ to each of dominant heating mechanisms
 1. absorbed laser light @ 350 nm
 2. absorbed x-rays @ $E \geq 1\text{ keV}$

that get through protective gas, shroud, etc.

- Absorbed laser light

Incident fluence $F = 5\text{ J/cm}^2$

Model optical coating as SiO_2

Absorption depth $\approx 5\lambda$

Absorption required is

$$\rho = 2.5\text{ g/cc}$$

$$C_p = 0.2 \frac{\text{cal}}{\text{gm}^\circ\text{C}} = 0.838 \frac{\text{J}}{\text{gm}^\circ\text{C}}$$

$$(1-R) = A = \rho \Delta x C_p \frac{\Delta T}{F} = 3.7 \times 10^{-3} = 0.4\% \quad \text{Reflectance} = 0.996 \quad \text{OK!}$$

How much gas protection would be needed to have the transmitted x-rays, which deposit in mirror, give $\Delta T \approx 50^\circ\text{C}$

• Flux of x-rays expected at mirror? $f_a = 0.20$

$$\frac{f_a E}{4\pi r_m^2} = \frac{(0.20 \times 10^9 \text{ J})}{4\pi (30 \text{ m})^2} = 1.77 \frac{\text{J}}{\text{cm}^2}$$

• What fraction of this can be allowed to deposit in mirror?

Mean free path of 1 keV x-rays in SiO_2 $\lambda_2 = 2.5 \text{ E-}4 \text{ cm}$
 $\rho \lambda_2 = 6.23 \text{ E-}4 \text{ g/cm}^2$ $\Delta T = 50^\circ\text{C}$

$$\text{Safe flux} = \rho \lambda_2 C_p \Delta T = 0.026 \text{ J/cm}^2$$

• Must attenuate 1 keV x-rays by factor $\frac{0.026}{1.77} = 0.015$
two orders of magnitude

• Let λ be mean free path of gas

$$e^{-L/\lambda} = 10^{-2}$$

$$\frac{L}{\lambda} = 4.6 \text{ mean free paths.}$$

The rare gases are excellent x-ray attenuators

- Temperature = 273 K
- Low energy cross-sections dominated by the photo-electric effect.

How much Argon would we need for gas protection?

^{40}Ar

$$\lambda_0 = 1.86 \text{ E-1 cm @ 1 keV}$$

$$\rho_0 \lambda_0 = 1.623 \text{ E-3 g/cm}^3 \quad \rho_0 \lambda_0 = 3.03 \text{ E-4 g/cm}^2 = \rho \lambda$$

$$\text{We need } L = 4.6 \lambda, \text{ or } \left(\frac{\rho}{\rho_0}\right) L = 4.6 \lambda_0 = 0.86 \text{ atm-cm}$$

$$= 6.5 \text{ torr-meters @ } 273^\circ\text{C}$$

All we need is a 13 meter region at half a torr, approximately.

$$\text{How much gas is this? } (1\text{m} \times 1\text{m} \times 15\text{m}) \times 0.5 \text{ torr} \times \frac{1 \text{ atm}}{760 \text{ torr}} \times \left(1.623 \text{ E-3 } \frac{\text{g}}{\text{cm}^3 \text{ atm}}\right)$$

$$= 16 \text{ gm Argon per beam}$$

How much debris is there per beam

$$10 \text{ gm} \times \frac{200 (.2\text{m})^2}{4\pi (30\text{m})^2} = .007 \text{ gm per beam}$$

The gas protection should also stop the debris.

Kinetic energy distributions of debris ions

• All the ions are likely
to have energies
 ≤ 500 keV

IMPROVED UNDERSTANDING OF FIRST-WALL
VAPORIZATION-CONDENSATION IN
INERTIAL CONFINEMENT FUSION REACTORS

UCRL-93899, Rev. 1

Charles D. Orth

August 1, 1986

Ion range in cold Argon & Xenon

San Francisco

Ref: D.K. Brice
 "Ion implantation
 range & energy
 deposition distributions"
 Vol I, IFI/Plenum
 N.Y. (1975)

James P. Reilly
W.J. Schaffer Associates
August 1983

EVALUATION OF WINDOW CONCEPTS FOR REPPED-PULSE CHEMICAL LASERS

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TRANSVERSE FLOW AERODYNAMIC WINDOWS SUPERSONIC FLOW

SUPERSONIC EXPANSION
AERO WINDOW

SUPERSONIC COMPRESSION
AERO WINDOW

TRANSVERSE FLOW AERODYNAMIC WINDOWS - SUBSONIC FLOW (LOW ΔP)

SINGLE LAYER
POTENTIAL VORTEX
SUBSONIC AREA WINDOW

(Refs. 11-13)

TWO-LAYER
POTENTIAL VORTEX
SUBSONIC AERO WINDOW

(Ref. 14)

AXIAL FLOW AERODYNAMIC WINDOWS

(Ref. 15)

(Ref. 16)

AEROWINDOW CONFIGURATION

SHOCK TUBE FLOW IS AN IDEAL TRANSIENT AEROWINDOW -
THE GAS IS INERTIALLY CONFINED DURING THE PULSE

San Francisco

- Shoot laser pulse
1. After disturbed gas exits into chamber
 2. After rarefaction waves have gone several diameters toward mirror
 3. Before protection gas strikes target at center
 4. Before rarefaction waves strike mirror

This report has
valuable experimental
data in it on
optical quality of
shock tube flow.
MM.

Final Report
PULSED AERODYNAMIC WINDOWS
FOR FUSION LASERS

for Period
November 1979 to December 1980

1 February 1981

Prepared for

Dr. C. Fenstermacher, L. Division
Los Alamos Scientific Laboratory

Under LASL Contract No. P.O. 4L20-8204K-1

by

V. Kulkarny, D. McGregor, J. Schwartz and R. A. Briones

TRW

DEFENSE AND SPACE SYSTEMS GROUP

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OPTICAL QUALITY IS A KEY CONSIDERATION

Phase difference between two optical paths

$$\Delta \phi(x,y) = \phi(x,y) - \phi(0,0)$$

$$\text{Phase } \phi(x,y) = k \int_0^L n(x,y) dz \quad k = \frac{2\pi}{\lambda_{vacuum}}$$

$$\text{- Index of refraction } n(x,y) = 1 + \underbrace{\beta_0 \left(\frac{\rho(0,0)}{\rho_0} \right)}_{n_0-1} \left(\frac{\rho(x,y)}{\rho(0,0)} \right)$$

Phase difference between two optical paths

$$\Delta \phi(x,y) = k \int_0^L \beta_0 \left(\frac{\rho(0,0)}{\rho_0} \right) \left[\frac{\rho(x,y) - \rho(0,0)}{\rho(0,0)} \right] dz$$

or more concisely

$$\Delta \phi = \frac{2\pi}{\lambda} \int_0^L \beta_0 \left(\frac{\rho}{\rho_0} \right) \left(\frac{\delta \rho}{\rho} \right) dz$$

$\uparrow$ ave. density level $\uparrow$ local level of fluctuations.

Ordered density fluctuations cause the beam to defocus

$$\begin{aligned} \perp \text{ Beam Quality} &= \frac{\text{Actual intensity at focus}}{\text{Diffraction limited intensity}} = \frac{I}{I_0} = \left| \langle e^{i\phi} \rangle \right|^2 \\ &= \frac{\text{Ideal spot area}}{\text{Actual spot area}} \approx 1 - \langle (\delta\phi)^2 \rangle - \langle \delta\phi \rangle^2 \end{aligned}$$

$$\frac{\delta\phi}{2\pi} = \frac{\Delta\lambda}{\lambda} = \text{number of waves of distortion} = \beta_0 \left(\frac{\rho_0}{\rho} \right) \left(\frac{\Delta\rho}{\rho} \right) \frac{L}{\lambda}$$

Example: $\lambda = 1.06 \mu\text{m}$ in air $\beta_0 = 2.76 \times 10^{-4}$ $\frac{\rho}{\rho_0} = 0.001$
 $\frac{\Delta\rho}{\rho} = 4\%$ $L = 10 \text{ meters}$

$$\frac{\Delta\lambda}{\lambda} = 0.1 \quad \frac{I}{I_0} = 1 - 2\pi^2 \left(\frac{\Delta\lambda}{\lambda} \right)^2 = 1 - 0.39 = 60\%$$

SPOT AREA INCREASES $\frac{1}{0.60} = 67\%$

Acoustic waves traveling in the x or y direction are examples of such ordered disturbances.

TURBULENCE SCATTERS ENERGY OUT OF THE BEAM

Light is scattered far out of focal spot, so turbulence can be treated as an extinction phenomenon.

$$\frac{I}{I_0} = e^{-\alpha L}$$

$$\alpha = \frac{\sqrt{\pi}}{2} k^2 \langle \delta n^2 \rangle \Lambda$$

$$k = 2\pi/\lambda$$

$$\delta n = \beta \left(\frac{f}{f_0} \right) \frac{\delta \rho}{\rho}$$

Λ = turbulent scale size

$$\alpha L = \frac{\sqrt{\pi}}{2} \left[\frac{2\pi}{\lambda} \beta \left(\frac{f}{f_0} \right) \frac{\delta \rho}{\rho} \right]^2 \Lambda L$$

In the shock tube window, the density disturbances are primarily random or turbulent.

- No shock or acoustic waves $\perp$ to laser beam
- No flow disturbances
- Rarefaction waves are very planar, travelling in beam direction
- Source of turbulence is breaking of diaphragm, but gas is then expanded to lower pressure
- Turbulent scale size that is characteristic, and most deleterious, is 10-30% of pipe diameter

• Let $\Lambda = 0.20 D = 0.2 \text{ meter}$

$$\left. \begin{aligned} \frac{P}{P_0} L &= 6.5 \text{ torr} \cdot \text{meters} = 8.6 \times 10^{-3} \text{ atm} \cdot \text{m} \\ \beta = n_0 - 1 &= 2.76 \times 10^{-4} \end{aligned} \right\} \text{ Argon}$$

$$\frac{P}{P_0} = \frac{0.5 \text{ torr}}{760 \text{ torr}} \quad \lambda = 350 \text{ nm}$$

Obtain $\alpha L = 25.5 \left(\frac{\beta P}{P} \right)^2$

For 5% extinction $\frac{\beta P}{P} = 4.4\%$ fluctuations are tolerable

OK, but short wavelength blue light makes optical quality, not stopping power, the key issue.

Which gas is "best"? — Has the highest x-ray stopping power and lowest index of refraction?

X-ray Stopping distance $\sim \frac{\rho}{\rho_0} \frac{L}{\lambda_0} = \lambda_0$ Phase distortion $\sim (n-1) \frac{\rho}{\rho_0} \frac{S}{\lambda_0} L$

Minimize the figure of merit F.O.M. = $(n-1)\lambda_0$ Small is beautiful.

Gas	$(n-1)10^4$	λ_0, cm @ 1 atm, 1 keV	F.O.M. $(n-1)\lambda_0$
He	0.36	86.	31
N ₂	2.96	0.47	1.4
Ar	2.81	0.18	0.506
Xe	6.80	0.14	0.952

← Smallest.

Argon is the best x-ray absorber for least optical distortion.
But, must also consider

- half life of activated isotopes
- cost of separation from tritium

The shock tube aerowindow has many advantages

1. No mass flow or pumping power is needed for operation
2. Bursting diaphragm is simple and inexpensive

- mylar sheet with crossed wires which are electrically exploded
- mechanical shutter may not be fast enough - needs to open in 20 ms.

3. Has the best potential for acceptable beam quality - critical at short wavelength.
 - high density gas is stationary, has no shocks or turbulence
 - turbulent interface gets blown out to low density
 - expansion waves are planar and perpendicular to flow after several diameters.
 - tube must be oversized to accommodate thermal boundary layers.

4. Very little gas consumption - 0.5 torr in each 15 m section times 200 tubes $\approx$ 3.5 kg $\leftarrow$ 1 gas bottle!

The neutron attenuation strategy uses distance, flux traps behind mirror, doglegs in optical train, large L/D ducts.

- Final mirror should be as transparent as possible to 14 MeV neutrons
- Flux trap behind mirror uses neutron absorber — lead acetate solution + borat for example
- Ducts of $L/D = 10-20$, with concrete shields
- Westinghouse found they could obtain attenuations of neutron flux of 10^4 /bend. Two bends should be OK
- What is proper biological hazard criterion? Where should it be applied?

Calculational Model of Westinghouse Blanket and Mirror Beam-Duct Configuration.

Ref: Neutron Attenuation in the laser ducts of an ICF Reactor, F. Augustine Jr., Westinghouse Electric Corp., Nov 1981, WFPS-TME-81-031

The interface between the laser and containment buildings

- Tritium, activated gases and debris must be prevented from contaminating the laser
- Windows located somewhere between the final optics and the beam tubes will provide a physical barrier
- An additional barrier will probably be required to prevent radiation leakage in the event of a window breaking
- Such a isolation system was designed for isotope separation experiments that required a beam penetration into the Pu building

Schematic of interface of line-of-sight vacuum pipe with Pu containment building B-332

Ball valves are used to prevent radiation leakage from the Plutonium building at LLNL

Requirements:

1. Redundancy of closure system (2 windows & 2 valves)
2. Valves close in event of:
 - power outage
 - fire alarm
 - criticality alarm
 - seismic signal
 - loss of pressure differential
 - manual override signal
3. Valves operated by pneumatic actuators
 - normally house air
 - nitrogen gas bottle back-up
4. Once closed, manual reset required to reopen
5. Valve indicators show open/closed status
6. Periodically tested with simulated signals
7. Earthquake certification comparable to critical nuclear reactor components
8. Minimal leakage in event of fire

Tentative layout of final optical system

Conclusions from Optics Protection Work

The major conclusions from our optics protection work are as follows:

1. Approximately 6.5 torr-m of argon gas at 273 K are needed to adequately protect the final optics against 1 keV x-rays. This corresponds to a 13 meter region of argon in each beam tube at a pressure of 0.5 torr, which seems quite feasible.

2. The above amount of argon corresponds to 16 gm of argon gas. If we imagine that the target can be represented by two grams of gold ions, having a total energy of 200 MJ, we would expect 0.007 g of ions to head up each beamline. Since there are 2000 times more argon than gold ions, the ionic debris should be stopped.

3. In a separate calculation using range data for heavy charged particles other than gold, and scaling formula to adjust for energy per ion and atomic mass number, we confirmed that 6.5 torr-m would confidently stop the ions.

4. From gas-breakdown data, using 350 nm lasers and rare gases, we project that breakdown will occur at pressures above 6.4×10^{-3} torr in the focused beam near the target. Since we plan to use 100 times this pressure to stop the x-rays, we recommended confining the argon to the beam tubes where the intensity is (relatively) low and breakdown is avoided. Breakdown may, in fact, not be harmful since the plasma will not be dense enough to go opaque; but since there is no need to have gas in the chamber itself, why borrow potential trouble?

5. A simple drag calculation was performed from first principles to determine that 6.5 torr-m of argon will stop all macroscopic particles (small shrapnel) in the diameter range $0 < D < 6.5$ microns. Larger particles do have a finite probability, and since doubling or tripling the quantity of gas will not solve the problem, we recommended the need for fast-closing shutters to stop large particles.

6. The outflow of the argon gas into the vacuum chamber, combined with the use of fast-acting valves to stop debris, is likely to also provide a barrier against tritium gas contamination of the final optics in normal operation. A shutter failure, of course, could lead to mixed gases reaching the final optics over larger timescales.

7. The argon gas used to provide protection against x-rays and ionic debris will not further degrade the optical quality of the beam.

8. The final optics are not protected from neutrons. We recommend using reflective optics, placed after the tripling crystals, so that no transmissive optics need be exposed to direct neutron radiation. Only the high-reflectance (HR) coatings would be affected, so the mirrors would have to be recoated occasionally. LLNL feels that HR coatings have unacceptable low damage thresholds, however, and that it is necessary to place the tripling crystals, lenses and transmissive coatings in the direct neutron flux. We have agreed to disagree on this point in the absence of better data.

9. While the above combination of argon gas and fast shutters provides the simplest solution, we have recommended that some attention be given to an alternate solution of a pulsed supersonic gas lens, which would bend each beam by one beam width, completely removing the final optics from the potential harm of x-rays, ions, neutrons or shrapnel. Perhaps this could be studied in future work.

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**The Analytic Hierarchy Process
for Decision Making**

W. J. Schafer Associates

April 6, 1988

Purpose:

To describe a systematic approach to choosing between several alternatives when the relative comparisons are not necessarily quantitative

Examples:

- rating the quality of wines**
- selecting members of a 4 x 100 relay team**
- selecting a college to attend**
- selecting a place for a vacation**
- selecting a first wall concept for the chamber**

Example hierarchy for choosing a vacation site

- 1) Establish the objective**
 - What do we need to do?**
- 2) Determine possible alternatives**
 - What are possible courses of action?**
- 3) Determine the criteria by which the alternatives will be compared**
 - What factors should influence our choice?**
- 4) Set priorities according to the importance of the various criteria**
 - What is the relative importance of each criteria?**
- 5) Choose best alternative or mix of alternatives**

- **Adaptable to a wide range of decision / selection type problems**
- **Useful when qualitative and subjective information must be taken into account**
- **Process of pairwise comparison simplifies the specification of weights or priorities**
- **Provides a method to check consistency without demanding a total self-consistent set of comparisons**

Scale for pairwise comparisons

Rating	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement moderately favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity is of the highest possible order of affirmation
2,4,6,8	Intermediate values	When compromise is needed

Reciprocals - If activity i has one of the above numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i.

Matrix of pairwise comparisons

Comparison of n objects, $A_1, A_2, \dots, A_n$,
according to their relative weights, $w_1, w_2, \dots, w_n$.

$A =$

	A_1	A_2	$\dots$	A_n
A_1	$\frac{w_1}{w_1}$	$\frac{w_1}{w_2}$	$\dots$	$\frac{w_1}{w_n}$
A_2	$\frac{w_2}{w_1}$	$\frac{w_2}{w_2}$	$\dots$	$\frac{w_2}{w_n}$
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
A_n	$\frac{w_n}{w_1}$	$\frac{w_n}{w_2}$	$\dots$	$\frac{w_n}{w_n}$

Given matrix A , there is a vector of relative weights, w , that satisfies

$$Aw = \lambda w$$

where w is the principal eigenvector and λ is the principal eigenvalue.

λ is used to check the consistency of the pairwise comparisons.

**The pairwise comparisons do not have to be totally self consistent.
With a reciprocal matrix there is a tendency to compensate.**

When a positive matrix of order n is consistent, the principal eigenvalue is equal to n . When it is inconsistent, λ exceeds n .

Improving consistency means that the ratio estimates in the matrix are closer to being logically related than randomly chosen.

The consistency ratio should be less than 10%

**The difference between λ and n serves as a measure of inconsistency:
Consistency index = $CI = (\lambda - n)/(n - 1)$**

Random consistency index = RI

$n =$	3	4	5	6	7	8	9
$RI =$	0.58	0.90	1.12	1.24	1.32	1.41	1.45

**Approximate fit to the above:
 $RI = \ln(n - 1) - 0.09(n - 2)$**

Consistency ratio = $CR = CI/RI$

If CR is not less than 10%, study the problem and revise the judgments

Example hierarchy for choosing a vacation site

Matrix of pairwise comparisons for the 6 criteria

	<i>MDT</i>	<i>CF</i>	<i>NA</i>	<i>RFE</i>	<i>CA</i>	<i>C</i>
<i>MDT</i>	1	1	7	5	3	1/3
<i>CF</i>	1	1	5	3	1	1
<i>NA</i>	1/7	1/5	1	1/3	1/7	1/9
<i>RFE</i>	1/5	1/3	3	1	1/3	1/3
<i>CA</i>	1/3	1	7	3	1	1/5
<i>C</i>	3	1	9	3	5	1

Solve $Aw = \lambda w$

A^b converges to w for large b . In this case,

$$A^b = \begin{bmatrix} 0.224 \\ 0.191 \\ 0.028 \\ 0.065 \\ 0.133 \\ 0.359 \end{bmatrix}$$

$$\lambda = 6.475$$

$$CI = (6.475 - 6)/(6 - 1) = 0.095$$

$$CR = 0.095/1.24 = 0.077$$

Consistency ratio is less than 10% as required

Matrices of pairwise comparisons of alternatives for each criterion

<i>Minimal Driving Time</i>	<i>SSR</i>	<i>MC</i>	<i>VR</i>	<i>Convenient Facilities</i>	<i>SSR</i>	<i>MC</i>	<i>VR</i>
<i>SSR</i>	1	1/7	1/5	<i>SSR</i>	1	9	5
<i>MC</i>	7	1	5	<i>MC</i>	1/9	1	1/9
<i>VR</i>	5	1/5	1	<i>VR</i>	1/5	9	1
<i>New Acquaintances</i>	<i>SSR</i>	<i>MC</i>	<i>VR</i>	<i>Relaxed Environment</i>	<i>SSR</i>	<i>MC</i>	<i>VR</i>
<i>SSR</i>	1	9	7	<i>SSR</i>	1	1/5	5
<i>MC</i>	1/9	1	1/9	<i>MC</i>	5	1	9
<i>VR</i>	1/7	9	1	<i>VR</i>	1/5	1/9	1
<i>Children's Activities</i>	<i>SSR</i>	<i>MC</i>	<i>VR</i>	<i>Cost</i>	<i>SSR</i>	<i>MC</i>	<i>VR</i>
<i>SSR</i>	1	9	5	<i>SSR</i>	1	1/7	1/9
<i>MC</i>	1/9	1	1/7	<i>MC</i>	7	1	1/5
<i>VR</i>	1/5	7	1	<i>VR</i>	9	5	1

Calculate the eigenvector (relative weights vector) for each criteria

Example for minimal driving time:

$$\begin{bmatrix} 1 & 0.143 & 0.2 \\ 7 & 1 & 5 \\ 5 & 0.2 & 1 \end{bmatrix} * \begin{bmatrix} 0.0668 \\ 0.7147 \\ 0.2185 \end{bmatrix} = 3.183 * \begin{bmatrix} 0.0668 \\ 0.7147 \\ 0.2185 \end{bmatrix}$$

Hence $w = \begin{bmatrix} 0.0668 \\ 0.7147 \\ 0.2185 \end{bmatrix}$ and $\lambda = 3.183$

Form the alternative weights matrix

96

		<i>Minimal Driving Time</i>	<i>Con- venient Facilities</i>	<i>New Acquain- tances</i>	<i>Relaxed Environ- ment</i>	<i>Chil- dren's Activities</i>	<i>Cost</i>
B =	<i>SSR</i>	.0668	.7107	.7511	.2067	.7219	.0510
	<i>MC</i>	.7147	.0462	.0436	.7352	.0510	.2271
	<i>VR</i>	.2185	.2431	.2053	.0581	.2271	.7219

Now multiply the alternative weights matrix
by the criteria weights vector

$$B * \begin{bmatrix} 0.224 \\ 0.191 \\ 0.028 \\ 0.065 \\ 0.133 \\ 0.359 \end{bmatrix} = \begin{bmatrix} 0.300 \\ 0.306 \\ 0.394 \end{bmatrix} = \begin{bmatrix} SSR \\ MC \\ VR \end{bmatrix}$$

Hence visiting relatives (VR) is the preferred vacation for the given criteria.

- 1) Establish the focus or objective
- 2) Develop the hierarchy including the alternatives
- 3) Develop the matrix of pairwise comparisons for the criteria
- 4) Calculate the eigenvector and eigenvalue of the criteria matrix.
This vector is the criteria weights vector.
- 5) Calculate the consistency ratio and revise judgments if necessary.
- 6) Develop the matrices of pairwise comparisons of the alternatives.
There is one matrix for each criterion.
- 7) Calculate the eigenvector and eigenvalue for each alternative vs
alternative matrix.
- 8) Calculate the consistency ratio and revise judgments if necessary.
- 9) Form a matrix of the alternative eigenvectors; it has $N(\text{criteria})$
columns and $N(\text{alternatives})$ rows.
- 10) Multiply the alternative eigenvectors matrix by the criteria weight
vector. The resulting vector gives the ranking of the alternatives.

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A CARBON-FIBER BRUSH-LIKE FIRST WALL FOR THE LABORATORY MICROFUSION FACILITY

**Michael J. Monsler and Wayne R. Meier
W. J. Schafer Associates, Inc.**

**Presented at the Eighth Topical Meeting on the
Technology of Fusion Energy
October 9-13, 1988
Salt Lake City, Utah**

The LMF first wall must withstand an intense x-ray pulse from the microexplosion

- Soft x-rays deposit energy near surface of material which can lead to:
 - melting or vaporization of surface layer
 - ablation driven shocks
 - front surface cracking or rear surface spallation
- Wall radius set by either local damage or impulse to structure
- An unprotected wall would have to stand back 15-20 m
- To build a smaller chamber, the first wall must be protected in some way

The carbon carpet is made of 2-cm-long fibers; each fiber consists of more than 10,000 5- μ m-diameter filaments

- absorbing the x-rays over ten times the surface area on fibers having incidence angle of 85° to the x-ray pulse
- reducing the wall pressure by spreading out the plasma over a larger volume (2 cm fiber height vs 2 μm absorption depth)
- spreading out the interaction time from 10 ns x-ray pulsewidth to 8 μs residence time of the vapor in the carpet
- reducing the total impulse by more than a factor of ten because the carbon vapor condenses back onto huge surface of fibers before it can escape from carpet
- absorbing energetic target debris in carbon vapor before it reaches the wall

The carbon carpet reduces the peak pressure and the impulse on the wall

The wall pressure history is stretched-out,
and the total impulse greatly reduced

- Initial vaporization moves perpendicular to fibers until inter-fiber space is filled
- Vapor moves radially to fill carpet region and begins to blow into center of chamber
- Wall does not feel pressure until vapor fills carpet, long after x-ray pulse has ended
- Plasma residence time is 3 times the characteristic condensation time
- Pressure decays as 90% of vaporized carbon condenses before it ever leaves the carpet region, greatly reducing the impulse

Key timescales for the vaporization and condensation of carbon in the carbon carpet first wall

The factor by which fiber erosion is reduced by condensation depends on the fiber L/D and the sticking coefficient

95% of the vaporized carbon condenses before it escapes from the carbon carpet

The carbon carpet reduces the impulse by more than an order of magnitude

Bending stress in an aluminum flat plate due to impulsive loading is less than the design strength for radii greater than 1.5 m

Plate is 1 m x 1 m x 2.5 cm
and supported at the edges

Lifetime of fibers -

- There are 10^4 filaments per fiber and only outer filaments are exposed to x-rays
- Filament diameter is about the same scale as x-ray absorption depth resulting in volumetric-like heating
- Material expands during 10 ns pulse time which reduces surface pressures
- Condensed carbon may protect filaments on subsequent pulse
- Modular design allows sections of first wall to be easily replaced if necessary
- Tests are needed and are being planned

Tritium absorption and build-up in carbon -

- Add 0.01 torr CO_2 to chamber
- Microexplosion dissociates CO_2
- Tritium tied up as T_2O and pumped out of chamber so that it does not build up

Carbon "soot" contamination of optics -

- Optics are separately protected by fast valves and gas flow
- More than 90% of carbon condenses before it leaves carpet
- Expect most of remainder to condense in carpet at later time

Shrapnel damage -

- Carpet backed by replaceable panels of "bullet proof" kevlar epoxy
- Function of carpet not harmed by small particulate damage

- Effectively deals with intense x-ray pulse from microexplosion
 - Net vaporization and impulse to structural wall reduced by more than an order of magnitude
 - Fiber micro-structure should reduce local damage due to x-ray induced shocks
- Self-protecting against target ions
- Chamber radius can be reduced to less than 2 m, other factors are likely to set size
- Uses low activation materials and can eliminate Al from high energy neutron flux which reduces short term radiation hazard
- Modular panels easily removed if necessary
- First wall protection scheme does not require cryogenic cooling (target cooling system still needed)
- Potential solutions have been identified for major issues

**New Heavy-Ion-Beam Target Gain Curves
for the SAFIRE Code**

W. R. Meier

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September 21, 1988

New Heavy-Ion-Beam Target Gain Curves for the SAFIRE Code

ABSTRACT

A new set of target gain curves for heavy-ion-beam drivers were developed by Lawrence Livermore National Laboratory. Algorithms for these target gain versus driver energy relationships have been incorporated into the SAFIRE code for economic evaluation of inertial confinement fusion electric power plants. This report describes the changes made to the SAFIRE code and provides instructions for using the new gain curves.

INTRODUCTION

Algorithms for calculating the target gain as a function of driver energy for heavy-ion-beam (HIB) drivers were developed by Roger Bangerter in late 1987. These algorithms have been incorporated into the SAFIRE code, which was developed to carry out economic analyses of inertial confinement fusion (ICF) electric power plants. The SAFIRE code is described in detail in Refs. 1-3. This report, which serves as a supplement to the previous SAFIRE reports, describes the changes to the SAFIRE code and how to use the new HIB target gain curves.

SUBROUTINE HIBGAIN

A single subroutine, HIBGAIN, was added to the code. This subroutine calculates the target gain as a function of the HIB driver energy for different types of targets and for different values of two parameters, the ion range and the beam spot radius. Inputs and outputs of the HIBGAIN subroutine are listed below. Default values, if any, are given in parenthesis.

INPUTS:

- ETA Switch for target type. The new curves are designated by ETA = 1, 2, 3, or 4. (The default is ETA = 0, which is a target gain curve for laser drivers; see Ref. 2).
- 1 = Base case, two-sided irradiation, single shell
 - 2 = Guess at single-sided
 - 3 = Polarized fuel, two-sided irradiation
 - 4 = Advanced concepts

TENERG Driver energy on target, MJ

TRADIUS Beam radius at the target, cm (0.25)

RANGE Ion penetration distance in target, g/cm² (0.1)

OUTPUTS:

TGAIN Target gain

TYIELD Target yield, MJ

The algorithms are valid over the following ranges:

$$TENERG \leq 15 \text{ MJ}$$

$$0.1 \leq TRADIUS \leq 0.5 \text{ cm}$$

$$0.025 \leq RANGE \leq 0.2 \text{ g/cm}^2$$

With the exception of TRADIUS, all of the above variables were previously defined and used within the SAFIRE code. References 2 and 3 list the common blocks and namelist groups that contain these variables.

TRADIUS is the same as RSPOT used in the McDonnell Douglas HIB driver model.³ With the previous target gain curves, RSPOT was calculated based on specified values the target gain parameter, $GAMMAH = RSPOT^{3/2} \times RANGE$, and either the ion range, RANGE, or the ion energy, EION. If EION was input, RANGE was calculated and vice versa. With the new curves, TRADIUS and RANGE must be input, and EION is calculated as a function of RANGE.

The McDonnell Douglas HIB model has an option to iterate on the ion energy to find the minimum cost accelerator. With the new gain curves, since EION is fixed based on the specified value of RANGE, it is not possible to iterate on EION. Therefore IFIXEI in NAMELIST HIB2NL must be set equal to 1 (see Ref. 3). Also note that if ETA = 2 (single-sided irradiation), we must set IRRAD = 1 and IACCNF = 2 in NAMELIST HIB2NL.

COMMON / TARI /

TRADIUS was added to common block TARI.

NAMelist / TASK /

TRADIUS and RANGE were added to NAMelist TASK. The additional options for the value of ETA are also specified in this NAMelist group.

EXAMPLES OF NEW GAIN CURVES

Figures 1-3 show the target gain as a function of driver energy for a representative set of target parameters. Figures 1 and 2 are for $\text{ETA} = 1$ and show the effects of varying TRADIUS and RANGE, respectively. Figure 3 compares the different target types, $\text{ETA} = 1-4$, with $\text{TRADIUS} = 0.25$ and $\text{RANGE} = 0.10$.

USING THE NEW HIB TARGET GAIN CURVES

The new HIB target gain curves can be used with the simple HIB driver model ($\text{IDRIVE} = 4$) or with the detailed McDonnell Douglas HIB driver model ($\text{IDRIVE} = 5$) by setting $\text{ETA} = 1, 2, 3$, or 4 in NAMelist TASK. TRADIUS and RANGE may also be specified in NAMelist TASK or allowed to default. If $\text{IDRIVE} = 5$, IFIXEI must be set equal to 1. If $\text{IDRIVE} = 5$ and $\text{ETA} = 2$, set $\text{IRRAD} = 1$ and $\text{IACCNF} = 2$.

An example input file for the Cascade chamber is shown in Fig. 4, and the corresponding output file is shown in Fig. 5. The beam radius and ion range were chosen to correspond to the example shown in Ref. 3 so that the effects of using the new base-case gain curve would be readily apparent. With these particular parameters, the new base-case target gain is somewhat lower than the gain in the example in Ref. 3. For both examples the pulse repetition rate was fixed at 5 Hz, and the net electric power was fixed at 815 MWe ($\pm 1\%$). With the previous curves, a driver energy of 4.2 MJ (giving a gain of 71 and a yield of about 300 MJ) was required to get about 815 MWe. With the new base-case gain curve, a driver energy of 5.9 MJ (giving a gain of 51 and a yield of 300 MJ) is required to achieve the specified net electric power.

REFERENCE

1. T. J. McCarville, W. R. Meier, C. C. Carson, J. D. Gordon, and B. B. Glasgow, "SAFIRE - A Systems Analysis Code For ICF Reactor Economics," Lawrence Livermore Laboratory report UCRL-15872, Vol. 1 (Jan. 1987).
2. B. B. Glasgow, and W. R. Meier, "SAFIRE User's Manual," Lawrence Livermore Laboratory report UCRL-15872, Vol. 2 (Jan. 1987).
3. W. R. Meier, "A New Heavy-Ion-Beam Driver Model for the SAFIRE Code," Lawrence Livermore Laboratory report UCRL-15872, Vol. 2, Sup. 1 (March 1987).

Figure 1. Target gain curves for single-shell HIB targets with two-sided irradiation ($\text{ETA} = 1$). Curves are shown for beam radii (TRADIUS) of 0.10, 0.25, 0.40, and 0.50 cm. The ion range (RANGE) is fixed at 0.1 g/cm².

Figure 2. Target gain curves for $\text{ETA} = 1$, $\text{TRADIUS} = 0.25$ cm, and $\text{RANGE} = 0.05, 0.10, 0.15$, and 0.20 g/cm².

Figure 3. Target gain curves for TRADIUS = 0.25 cm, RANGE 0.10 g/cm², and ETA = 1, 2, 3, and 4.

```

CASCADE REACTOR; SEPT 1988
IACCT=1,
IFLAG=1, PEFLAG=815.0, PEERR=1.E-2,
RPRATE=5.0,
TENERG=3.0, DTE=1.0, TEFLAG=10.0,
ETA=1.0,
TRADIUS=0.269, RANGE=0.144
$END
ICAVIT=9, NCAVIT=1
$END
IDRIVE=5
$END
NUNIT=1, NYEAR=1985
$END
IPRNT=1, IFIXEI=1
$END
      450.      1600.

```

Figure 4. Input file for Cascade chamber with the McDonnell Douglas HIB driver model (IDRIVE = 5) and the new target gain algorithm for single-shell HIB targets with two-sided irradiation (ETA = 1).

```

CHAMBER TYPE: CASCADE

DESCRIPTION:
  DRIVER TYPE: HEAVY ION BEAM
  GAIN CURVE: TWO-SIDED
  CHAMBER TYPE: CASCADE
  NUMBER OF CHAMBERS PER UNIT: 1
  NUMBER OF UNITS PER PLANT: 1
  NUMBER OF DRIVERS: 1
  NUMBER OF TARGET FACTORIES: 1

PLANT PARAMETERS:
  CHAMBER PULSE RATE (HZ): 5.00
  DRIVER ENERGY (MJ): 5.91
  TARGET GAIN: 51.4
  TARGET YIELD: 303.7
  THERMAL POWER (MWT): 1689.8
  THERMAL CYCLE EFFICIENCY (%): 54.0
  HEAT REJECTED (MWT): 777.7
  AVAILABILITY FACTOR (%): 70.0

ELECTRIC POWER BALANCE (MWE):
  GROSS ELECTRIC POWER: 912.1
  DRIVER POWER/UNIT: 82.7
  PUMPING POWER: 5.0
  OTHER BOP POWER: 10.0
  NET ELECTRIC POWER: 814.4

ECONOMIC FACTORS (%):
  ESCALATION RATE: 6.00
  GENERAL INFLATION RATE: 6.00
  AFTER-TAX COST OF MONEY: 9.00
  REAL COST OF MONEY: 2.83
  CURRENT DOLLAR FIXED CHARGE RATE: 16.22
  CONSTANT DOLLAR FIXED CHARGE RATE: 8.32

INDIRECT AND TIME-RELATED COST FACTORS:
  CONSTRUCTION SERVICES (F91): 0.200
  HOME OFFICE ENG. & SERVICES (F92): 0.150
  FIELD OFFICE ENG. & SERVICES (F93): 0.100
  OWNERS COST (F94): 0.070
  PROJECT CONTINGENCY (F95): 0.100
  CONSTRUCTION TIME (YR): 8.000
  ESCALATION DURING CONST. (FEDC): 0.323
  INTEREST DURING CONST. (FIDC): 0.420

```

Figure 5. Part of the SAFIRE code output for the input shown in illustration 1.

HEAVY ION BEAM DRIVER INFORMATION
BASED ON MCDONNELL DOUGLAS MODEL

FINAL TRANSPORT SUMMARY FOR DOUBLE-SIDED IRRADIATION:	
POLE TIP FIELD (T)	= 1.0000
ION ENERGY (GEV)	= 6.0376
ION MASS (AMU)	= 130.0000
ION CHARGE STATE	= 3.0000
GAIN PARAMETER (R*R**1.5)	= 0.0000
ION RANGE IN TARGET (G/CM**2)	= 0.1440
TARGET AVERAGE Z	= 13.0000
BEAM STIFFNESS (T-M)	= 43.0407
FINAL TRANSPORT BEND RADIUS (M)	= 21.5204
FINAL FOCUS CONVERGENCE ANGLE (RAD)	= 0.013337
CHAMBER RADIUS + STANDOFF (M)	= 7.0000
FINAL MAGNET LENGTH (M)	= 0.6836
FINAL MAGNET RADIUS (M)	= 0.5257
FINAL FOCUS SYSTEM LENGTH (M)	= 66.2031
FINAL SPOT SIZE (CM)	= 0.2690
BEAM POWER DENSITY (TW/CM**2)	= 1842.9443
FINAL PULSE LENGTH (NSEC)	= 14.0976
UNNORMALIZED EMITTANCE (UR-M)	= 33.89
BEAMLET PERVEANCE	= 0.000175
FINAL TRANSPORT SYSTEM LENGTH (M)	= 154.3705
DELAY LINE LENGTH (M)	= 0.0000
SWITCH YARD LENGTH (M)	= 0.0000
CURRENT PER BEAMLET (A)	= 1285.0181
NUMBER BEAMLETS IN FINAL TRANSPORT	= 54
ACCELERATOR SUMMARY:	
NORMALIZED ACCELERATOR COST (M\$)	= 809.94
ACCELERATOR REPETITION RATE	= 5.0000
ACCELERATOR EFFICIENCY (%)	= 35.7045
NUMBER OF BEAMS IN ACCELERATOR	= 16
ACCELERATOR LENGTH (KM)	= 1.4131
ACCELERATOR OPERATING SCENARIO	= SINGLE-PULSED
DRIVER COST SUMMARY:	
C27 DRIVER TOTAL DIRECT COST (M\$)	= 1079.90
C2701 ION SOURCE/PREACCELERATOR (M\$)	= 153.36
C2702 ACCEL MODULES AND PWR SUP (M\$)	= 766.79
C2703 PULSE COMPRESSION SYSTEM (M\$)	= 0.00
C2704 BEAM TRANSPORT SYSTEM (M\$)	= 43.16
C2705 FINAL FOCUS SYSTEM (M\$)	= 72.27
C2706 COOLING SYSTEM (M\$)	= 9.21
C2707 ACCEL AND TRANS VACUUM (M\$)	= 4.61
C2708 DRIVER MAINTENANCE EQUIP (M\$)	= 5.50
C2709 I&C (M\$)	= 25.00

Figure 5. (Continued)

ICF ECONOMIC EVALUATION FOR 1 UNIT POWER PLANT

ACCOUNT	ACCOUNT TITLE	M\$	
20	LAND AND LAND RIGHTS	5.0	
21	STRUCTURES AND IMPROVEMENTS	84.5	
22	REACTOR PLANT EQUIPMENT	284.0	
23	TURBINE PLANT EQUIPMENT	185.6	
24	ELECTRIC PLANT EQUIPMENT	70.8	
25	MISCELLANEOUS PLANT EQUIPMENT	16.3	
26	MAIN HEAT REJECTION EQUIPMENT	21.7	
27	DRIVER EQUIPMENT	1079.9	
28	TARGET FACTORY EQUIPMENT	86.4	
	TOTAL DIRECT COST	1834.2	
91	CONSTRUCTION SERVICES	366.8	
92	HOME OFFICE ENGINEERING AND SERVICES	275.1	
93	FIELD OFFICE ENGINEERING AND SERVICES	183.4	
94	OWNER'S COST	128.4	
95	PROJECT CONTINGENCY	278.8	
	TOTAL OVERNIGHT COST	3066.8	
		CURRENT\$	CONSTANT\$
96	ESCALATION DURING CONSTRUCTION	989.7	0.0
97	INTEREST DURING CONSTRUCTION	1288.1	286.5
	TOTAL CAPITAL COST	5344.6	3353.3
COST OF ELECTRICITY			
	CAPITAL	17.36	5.58
	FUEL	0.02	0.01
	O&M	5.73	1.84
	TOTAL	23.11	7.43

CONSTANT \$ RESULTS IN 1985 DOLLARS
CURRENT \$ RESULTS IN 1993 DOLLARS

Figure 5. (Continued)

**Parametric Economic Studies for HYLIFE:
Implications for a New Molten Salt Reactor**

**Wayne R. Meier
W. J. Schafer Associates, Inc.**

November 1, 1988

INTRODUCTION

Economic studies were carried out to investigate various aspect of a Heavy Ion Beam (HIB) driven HYLIFE reactor as a commercial electric power plant. The purpose of these studies was to gain an understanding of the factors that are most important in determining the cost of electricity for a reactor that scales like HYLIFE. This information can help guide our research on the molten salt version of HYLIFE, tentatively called HYLIFE-II. The results presented here thus serve as a point of reference as we begin our investigation of HYLIFE-II. I've evaluated the cost of electricity (COE) as a function of several system design parameters including: the characteristics of the target, which determine the gain versus energy relationship; the chamber pulse repetition rate; the net electric power per reactor; and the number of reactor units serviced by a single driver. The SAFIRE code, which is fully documented in Refs. 1-4, was used for this study. All costs are in constant, January 1988 dollars.

The base case power plant configuration is a single HIB driver operating a single HYLIFE reactor that produces a net electric power of 1.0 GW_e. The McDonnell Douglas (MDAC) cost-performance model for the HIB driver³ and the new HIB target gain relationships⁴ were used in these analyses. The focus of this study is on the reactor design and plant configuration, not on the driver design. The HIB driver was selected because it is the most detailed driver model in the SAFIRE code, and using it also gave me a chance to use the new HIB target gain relationships. The base case chamber pulse repetition rate is 1.5 Hz, and the corresponding target yield is 1660 MJ. The driver energy at this point is 8.5 MJ, and the target gain is 195. A list of system design parameters is given in Table 1. If only one value is listed, the quantity is held constant; if more than one value is listed, the quantity is either used as an independent variable or is varied as a parameter.

RESULTS

Target Parameters

New HIB target gain algorithms, developed by LLNL, were recently incorporated into the SAFIRE code.⁴ These algorithms give the target gain as a function of driver energy for four different types of target: 1) Base-case, two-sided irradiation, single shell; 2) Single-sided; 3) Polarized fuel, two-sided irradiation; and 4) Advanced concepts. For each target type there is a family of curves dependent on two parameters, the ion range

and the beam spot size (i.e., there is a unique gain versus energy curve each combination of ion range and spot size). A representative sample of curves is shown in Fig. 1, and Ref. 4 contains additional examples that show the variation with range and spot size. In general, the gain decreases with increasing spot size for a given range and decreases with increasing range for a given spot size. I originally intended to use the Base case, two-sided irradiation target, but found that the driver energy required to produce 1 GW_e at 1.5 Hz exceeded 10 MJ, and unfortunately the MDAC driver model is not valid above 10 MJ (some of the fitting routines it uses give non-physical results above 10 MJ). Therefore, the Advance concepts target, which is more optimistic, was selected for this study.

The COE from future coal and fission power plants (evaluated on the same economic basis as we use for ICF) is in the range of about 4 to 5 ¢/kW_eh. To be economically competitive, we would like to show that ICF can at least approach these electricity costs. The COE as a function of the beam spot radius is shown in Fig. 2 for three values of the ion range, 0.10, 0.15, and 0.20 g/cm². For the 130 amu, +3 ions used throughout this study, the three ranges correspond to ion energies of 4.73, 6.20 and 7.45 GeV. The results in Fig. 2 are for a single unit, 1.0 GW_e power plant with the chamber pulse rate fixed at 1.5 Hz. The COE is a minimum at the intermediate beam spot radius (0.25 cm) and decreases with increasing ion range. The minimum at 0.25 cm is the result of competing factors that influence the cost of the HIB driver. Increasing the spot size allows a higher beam emittance which reduces the driver cost. On the other hand, the target gain decreases with increasing spot size, and hence, more driver energy is required to get the yield necessary for the desired net electric power, and this increases the driver cost. The minimum at 0.25 cm is essentially a trade-off between driver energy and beam emittance. For the remainder of the analyses, the beam spot size and ion range are fixed at 0.25 cm and 0.20 g/cm², respectively. For the single unit, 1.5 Hz plant, the COE is 8.8 ¢/kW_eh with these target parameters, significantly higher than coal and fission.

HYLIFE Reference Case

The capital cost summary for the single unit HYLIFE plant is shown in Table 2. The total direct capital cost is \$2672 M, with the driver cost of \$1284 M being the largest single item. The driver energy is 8.5 MJ, so the driver has a direct capital cost of

\$150/J at this particular energy and pulse rate. The direct capital cost of the reactor (i.e., chamber plus balance of plant, accounts 20 through 26) is \$1305 M, with the reactor plant equipment cost of \$602 M accounting for 46%. Table 3 shows a breakdown on the reactor plant equipment, and we note that the heat transport system cost of \$484 M dominates this account. Table 4 shows the breakdown on the heat transport system cost. The recirculating jet array system, which includes all the large liquid metal pumps and associated piping needed to establish the flowing blanket, is the most expensive item at \$147 M. The sodium secondary loop equipment (including the intermediate heat exchanger) contributes a total of \$143 M.

If we postulate a reactor without the large flow rate of HYLIFE (i.e., no jet array) and without an intermediate coolant loop, we could save \$290 M and bring the cost of the reactor down to about \$1 B. Eliminating the recirculating and intermediate heat transfer loops would also reduce the size and cost of the containment building somewhat. A billion dollars is thus the probable minimum cost of a lithium cooled reactor, assuming that the intermediate coolant loop could somehow be eliminated. How will a FLiBe cooled reactor compare? The principal differences will be in the cost of the chamber and heat transport system. The cost will depend on whether or not a high flow rate blanket and an intermediate coolant loop are used. Even if HYLIFE-II does not use a high flow rate blanket, we need to determine the cost of FLiBe pumps, piping, heat exchangers, clean-up systems, tritium removal and containment systems, etc., and compare the FLiBe system costs to HYLIFE's lithium-primary, sodium-secondary heat transfer system. I propose to address these questions in the coming year as HYLIFE-II is better defined.

Dependence on Net Electric Power

Now let's turn our attention to some of the parametric studies with the HYLIFE reactor to see which system parameters and design variables are important in determining the COE. The COE as a function of the plant net electric power is shown in Fig. 3 for plants that are made up of a single driver and 1 - 4 reactor units rated at 0.5 - 1.5 GW_e each. The uppermost line is the COE for plants made up of 1 to 4 units each producing 0.5 GW_e, giving a total net power of 0.5 to 2.0 GW_e. The next line down is for plants with 1.0 GW_e units, and the dashed line is for 1.5 GW_e units. We note several things. A single 0.5 GW_e unit has a very high COE (13.5 ¢/kW_eh) since the investment in the driver can not be covered by such a small electric output. Driving four 0.5 GW_e units

with a single driver reduces the COE to 7.1 ¢/kW_eh. A plant with two 1 GW_e units has a COE of 6.2 ¢/kW_eh, which is 30% lower than the single unit 1 GW_e plant, but it is still higher than coal and nuclear. At 3 GW_e, there is little difference between a 2 or 3 unit plant. To produce 1.5 GW_e in a single reactor requires such a high yield and driver energy that the reactor economies of scale are essentially cancelled out. While a 3 GW_e plant has a lower COE than a 2 GW_e plant (5.4 compared to 6.2 ¢/kW_eh), the total capital investment is 28% higher (\$8.9 B compared to \$6.9 B). Three GW_e is also larger than current dual unit nuclear plants. Therefore, a 2 GW_e plant is probably a more appropriate choice when comparing to nuclear and coal plants.

Dependence on Chamber Pulse Rate

One important variable for the HYLIFE-II design team to consider is the chamber pulse rate. HYLIFE is by nature a low pulse rate (i.e., less than a few Hz) chamber because of the need to clear the chamber and reestablish the jet array between shots. A high pulse rate requires a high injection velocity and a high liquid metal flow rate. The injection velocity is provided by a head of Li on top of the injection plate, so increasing the injection velocity also increases the height of the vessel and the total Li inventory. On the other hand, for a fixed net power, a higher pulse rate corresponds to a lower target yield and smaller, less expensive driver. The driver power, however, will increase if the pulse rate increases faster than the driver energy decreases. It all depends on the shape of the gain curve at the particular design point and on the driver efficiency, which is also a function of the driver energy and pulse rate. Figure 4 shows the COE as a function of chamber pulse rate for single and dual unit power plants (1 and 2 GW_e net). The single unit plant is more sensitive to increasing pulse rate, decreasing from 9.4 to 8.5 ¢/kW_eh as the pulse rate increases from 1 to 3 Hz. The dual unit plant COE decreases from about 6.6 to 6.1 ¢/kW_eh over the same range of pulse rates with most of the decrease between 1 and 2 Hz. Therefore, for a dual unit plant, HYLIFE chamber pulse rates of 1.5 to 2 Hz are adequate. Note that this conclusion is based on the assumption that the Advance concepts targets will be available and perform as predicted.

Some of the HYLIFE design parameters are shown in Fig. 5 as a function of the chamber pulse rate. The chamber diameter decreases (from 11.6 m to 6.8 m) with increasing pulse rate, since the yield and resulting impact stresses on the wall are diminished. The lithium flow rate increases from 72 to 118 m³/s, and the required

injection head increases from 3.4 to 12.8 m. The chamber height is defined as the sum of the injection head plus 80% of the chamber diameter. This is the distance from the top of the lithium pool above the injection plate to the lithium pool at the bottom of the chamber. The vacuum vessel height will be a few meters more than this to allow for space above the injection pool and a region at the bottom to collect Li. As indicated the chamber height has a minimum of 11.3 m at 1.4 Hz and increases to 18.2 m at 3 Hz. At 3 Hz, HYLIFE would require a very tall vessel!

Allowable Reactor Cost for Fixed COE

None of the previous results with the HYLIFE reactor produced a COE less than 5 ¢/kW_eh. Using the same HIB driver cost model and target gain relationships as before, how much can the reactor cost if we want an ICF plant with a COE that is competitive with fission and coal? To answer this, I considered a dual unit plant with a total net power of 2 GWe. In this hypothetical example, the thermal conversion efficiency is fixed at about 37%. Figure 6 shows the direct capital cost of the driver and target factor. The driver cost decreases from \$1.6 B at a chamber pulse rate of 1 Hz to \$1.1 B at 10 Hz, and the driver energy decrease from 10.4 MJ to 4.6 MJ over this range. (Note that the driver pulse rate is twice the chamber pulse rate.) The direct capital cost of the target factory, which supplies both reactors, increases from \$0.1 B to \$0.2 B as the chamber pulse rate increases from 1 to 10 Hz. In our economics model, the COE is essentially directly proportional to the total capital cost. Therefore, for a fixed COE, the higher the sum of the driver and target factory costs, the lower the allowable cost for the two reactors making up the dual unit plant.

Figure 7 shows the allowable direct capital cost of the first reactor unit for a specified COE as a function of chamber pulse rate over the range of 1 to 10 Hz. The HYLIFE direct capital cost is shown for reference. (SAFIRE's costing for multi-unit plants is based on the cost of the first unit. The direct cost of the second unit is 80% of the first, and the indirect costs of the second unit are 60% of the first unit's indirect cost.) We see that it is advantageous to go from 1 to about 3 Hz, but there is little incentive beyond 3 Hz. To break below 5 ¢/kW_eh requires a reactor with a direct capital cost of \$0.94 B at 3 Hz, and to get down to 4 ¢/kW_eh requires a reactor cost of about \$0.59 B at 3 Hz. (Note that for every dollar that the reactor first unit direct capital cost exceeds the allowable cost given here, the driver direct capital cost must be reduced by a

\$1.73 in order to maintain the fixed COE). As previously stated, \$1 B is about the lower limit of a Li cooled reactor, and this may not be far off from what we will be able to do with a FLiBe cooled plant. It seems unlikely that 4 ¢/kW_eh is achievable with the current estimates for the HIB driver cost and target gain.

CONCLUSIONS

Various economic aspects of a HIB driven ICF power plant using a HYLIFE reactor have been investigated. The following points summarize the findings.

- 1) To get 1 GW_e in a single unit plant operating at 1.5 Hz with a driver energy less than 10 MJ requires target designs that are more advanced than the Base-case, two-sided, single shell targets. A gain of 166 is needed at 10 MJ, which is more than a factor of two higher than the Base case target gain of about 80 at 10 MJ (for ion range = 0.20 g/cm², spot size = 0.25 cm)
- 2) For the particular case examined, an ion range of 0.2 g/cm² and a spot size of 0.25 cm are the target parameters that result in the lowest driver cost and COE. HIB experts say that these parameters are very reasonable.
- 3) Eliminating the lithium pumps and piping required to maintain the jet array in the HYLIFE chamber, and eliminating the intermediate heat transfer loop, would reduce the direct capital cost of the reactor by 23% to about \$1 B. Costs estimates for FLiBe heat transfer components need to be made before we can determine whether or not a FLiBe cooled reactor will be cheaper than HYLIFE.
- 4) The COE decreases with increasing unit size and with increasing number of units per plant. A single unit, 1 GW_e plant is not economically competitive with coal or nuclear. A dual unit, 2 GW_e plant has a COE of 6.2 ¢/kW_eh, which is about 24% higher than coal fired power plants.
- 4) For the HYLIFE reactor, a chamber pulse rate of 1.5 to 2.0 Hz is adequate; increasing the pulse rate further does not reduce the COE significantly .

- 5) To reduce the COE to less than 5 ¢/kW_eh requires a reactor cost of less than \$1 B. A chamber pulse rate of about 3 Hz is desirable based on driver and gain considerations and not on reactor scaling.

For HYLIFE-II to be significantly less expensive than HYLIFE, the FLiBE hardware (pumps, pipes, heat exchangers, etc.) has to be much less expensive, and/or the total flow rate must be much smaller, and/or the intermediate loop must be very cheap or eliminated. A chamber pulse rate of a few Hz should be adequate. Obviously, lower driver costs and higher target gains would benefit HYLIFE as well as HYLIFE-II.

REFERENCES

1. T. J. McCarville, W. R. Meier, C. C. Carson, J. D. Gordon, and B. B. Glasgow, "SAFIRE - A Systems Analysis Code For ICF Reactor Economics," Lawrence Livermore Laboratory report UCRL-15872, Vol. 1 (Jan. 1987).
2. B. B. Glasgow, and W. R. Meier, "SAFIRE User's Manual," Lawrence Livermore Laboratory report UCRL-15872, Vol. 2 (Jan. 1987).
3. W. R. Meier, "A New Heavy-Ion-Beam Driver Model for the SAFIRE Code," Lawrence Livermore Laboratory report UCRL-15872, Vol. 2, Sup. 1 (March 1987).
4. W. R. Meier, "New Heavy-Ion-Beam Target Gain Curves for the SAFIRE Code," to be published as a UCRL, draft available on request.

Table 1. System Design Parameters

Target

Type	Advanced Concepts (Case 4 in Fig. 1)
Ion range, g/cm ²	0.10, 0.15, 0.20
Beam spot size, cm	0.15, 0.25, 0.35

Reactor

Type	HYLIFE, Generic
Thermal efficiency, %	41, 37
Chamber pulse rate, Hz	1 - 10
Net power per unit, GW _e	0.5, 1.0, 1.5
Units per plant	1 - 4

Driver

Type	HIB Induction Linac, Single pulsed
Ion mass, amu	130
Ion charge state	+3
Ion energy, GeV	4.73, 6.20, 7.45
Beam energy, MJ	≤ 10
Driver pulse rate, Hz	Varies
Efficiency	Varies

Table 2. Capital cost and COE summary for a single-unit, 1 GW_e HYLIFE power plant.

ICF ECONOMIC EVALUATION FOR 1 UNIT POWER PLANT			
ACCOUNT	ACCOUNT TITLE	M\$	
20	LAND AND LAND RIGHTS	5.0	
21	STRUCTURES AND IMPROVEMENTS	282.2	
22	REACTOR PLANT EQUIPMENT	602.9	
23	TURBINE PLANT EQUIPMENT	226.6	
24	ELECTRIC PLANT EQUIPMENT	91.7	
25	MISCELLANEOUS PLANT EQUIPMENT	59.9	
26	MAIN HEAT REJECTION EQUIPMENT	36.5	
27	DRIVER EQUIPMENT	1284.1	
28	TARGET FACTORY EQUIPMENT	82.8	
	TOTAL DIRECT COST	2671.8	
91	CONSTRUCTION SERVICES	534.4	
92	HOME OFFICE ENGINEERING AND SERVICES	400.8	
93	FIELD OFFICE ENGINEERING AND SERVICES	267.2	
94	OWNER'S COST	187.0	
95	PROJECT CONTINGENCY	406.1	
	TOTAL OVERNIGHT COST	4467.2	
		CURRENT\$	CONSTANT\$
96	ESCALATION DURING CONSTRUCTION	1441.7	0.0
97	INTEREST DURING CONSTRUCTION	1876.3	417.3
	TOTAL CAPITAL COST	7785.2	4884.6
	COST OF ELECTRICITY		
	CAPITAL	20.51	6.60
	FUEL	0.03	0.01
	O&M	6.77	2.18
	TOTAL	27.30	8.78

CONSTANT \$ RESULTS IN 1988 DOLLARS
CURRENT \$ RESULTS IN 1996 DOLLARS

Table 3. Direct capital cost of HYLIFE's Reactor Plant Equipment (Account 22).

Tracking and alignment systems	30.4
First wall systems	2.4
Tritium extraction systems	25.8
Blanket and shield	60.2
Heat transport system	<u>484.1</u>
Total Reactor Plant Equipment Cost	602.9

Table 4. Direct capital cost of HYLIFE's Heat Transport System.

Recirculating jet array system	147.0
Intermediate heat exchanger	40.2
Primary loop piping	46.3
Primary coolant cleanup plant	14.4
Primary coolant pumps and motors	40.0
Secondary loop piping	24.7
Steam generator	46.7
Secondary coolant pumps and motors	56.0
Secondary coolant cleanup plant	21.7
Steam separator	10.3
Water loop piping	0.1
Steam superheater	<u>36.7</u>
Total Heat Transport System Cost	484.1

Figure 1. HIB target gain curves for an ion range of 0.20 g/cm^2 and a spot size of 0.25 cm . The four cases are:

1. Base-case, two-sided irradiation, single shell
2. Guess at single-sided irradiation
3. Polarized fuel, two-sided irradiation
4. Advanced concepts

HYLIFE reactor
Chamber pulse rate = 1.5 Hz
HIB driver
Single unit plant
Total net power = 1.0 GW_e
Advanced Concepts target

Figure 2. COE versus beam spot size for different ion ranges. A spot size of 0.25 cm and an ion range of 0.20 g/cm² produces the lowest COE for the cases examined.

HYLIFE reactor
 Chamber pulse rate = 1.5 Hz
 HIB driver

Figure 3. The COE versus total net electric power for power plants with a single driver and multiple HYLIFE reactor units of different sizes. The COE decreases with increasing unit size and with increasing total net power.

HYLIFE reactor
HIB driver
Power per unit = 1.0 GW_e

Figure 4. The COE versus HYLIFE chamber pulse rate for single and dual unit power plants. A chamber pulse rate of 1.5 to 2.0 Hz is desirable.

HIB driver
 Single unit plant
 Total net power = 1.0 GW_e

Figure 5. HYLIFE design parameters as a function of the chamber pulse rate. Increasing the pulse rate increases the lithium flow rate and the chamber height.

Thermal efficiency = 37%

Dual unit plant

Total net power = 2.0 GW_e

Figure 6. HIB driver and target factory direct capital cost as a function of the chamber pulse rate. The sum of these two costs decreases sharply between 1 and 3 Hz and has a shallow minimum at 6 - 8 Hz.

Thermal efficiency = 37%
HIB driver
Dual unit plant
Total net power = 2.0 GW_e

Figure 7. Allowable reactor direct capital cost (1st unit) versus chamber pulse rate for a fixed COE. The reactor cost must be less than \$1 B to get a COE less than 5 ¢/kW_eh.

Review of HYLIFE Fluid Dynamics

**Wayne R. Meier
W. J. Schafer Associates, Inc.**

June 23, 1988

People responsible for work in this area

Jim Blink	LLNL
Lew Glenn	LLNL
Mike Hoffman	UC Davis
Jack Hovingh	LLNL
Michael Monsler	WJSA

Resources

- 1) **HYLIFE Report (UCRL-53559) summarizes the concept and contains an extensive annotated bibliography.**
- 2) **Laser Program Annual Reports 1977 - 1981**

- o What has been done to date?
- o What are key uncertainties?
- o What needs to be done to resolve uncertainties?

Figure 2. HYLIFE reaction chamber. The liquid lithium free falls through the nozzle plate into the vacuum chamber, forming 175 jets that protect the wall of the chamber from the damaging effects of the fusion energy pulses at its center. (Ref. 1)

HYLIFE REACTION CHAMBER MIDPLANE CROSS SECTION

RESPONSE OF THE HYLIFE JETS TO A FUSION PULSE

95-01-0381-0620

Figure 8. Hydrodynamic response to fusion-energy deposition in HYLIFE (1800-MJ yield). The peak gas pressure of 0.6 MPa produces a 38-MPa stress in the 40-mm-thick FSW, and later the liquid impact pressure of 0.2 MPa produces a 46-MPa stress in the FSW. (Ref. 1)

Figure 11. Pulsed and steady stresses vs wall thickness and the limiting levels under the ASME code. Wall thicknesses in the 25- to 55-mm range satisfy both ASME criteria: total stress less than yield strength and pulsed stress less than one-half the fatigue strength. This figure is based on an early HYLIFE design with a 2700-MJ yield. The jet array in this early design has a 0.75-m inner radius, is 1.0 m thick, and has a midplane packing fraction of 50%. (Ref. 1)

ASME DESIGN POINT FOR A 1.0 m EFFECTIVE ARRAY
THICKNESS, 5.0 m WALL RADIUS, 1 Hz – 2700 MJ FUSION
PULSES AND 30 YEAR LIFETIME

LMW AND WALL DIMENSIONS THAT MEET BOTH THE FATIGUE AND YIELD ASME DESIGN CRITERIA

5 m Wall Radius, 2700 MJ – 1 Hz Pulses, 50% Packing Fraction, 773° K Li

95-01-1180-4041

DESIGN POINT NORMALIZED ARRAY FLOW RATE FOR CONSTANT INJECTION VELOCITY

Consider three aspects of the fluid dynamics:

- 1) Establishing the desired LM jet array before the fusion pulse**
- 2) Response of the LM jet array to the fusion energy deposition**
- 3) Recondensation and chamber clearing prior to next pulse**

Establishing the LM jet array

Issue: Can a stable configuration of LM jets be established to provide a fairly uniform blanket around the fusion pulse?

Status: Theory and experiments with water at UC Davis (Mike Hoffman and students) concluded that we can establish and maintain the array of jets within the chamber. The LM jets will not break-up before reaching the bottom of the chamber.

Needs: No need for more work in this area at this time.

Response to x-ray and debris energy deposition

Issue: The short range x-rays and debris will vaporize the innermost layer of lithium and cause spall off the back of the exposed jets. What are the implications?

Status: We can calculate the mass and temperature of vaporized lithium with fairly high confidence. The spall off the back of the inner jets is not a significant problem because it merely impacts the next row of jets. The hot vapor expands out through the jets and pressurizes the chamber, but the resulting stresses appear to be acceptable. These processes have been modeled in significant detail by L. Glenn.

Needs: Check with Glenn for his recommendations.

- Issues:** Isochoric heating of jets causes internal pressurization, and the jets to blow apart nearly axi-symmetrically. As adjacent jets impact each other, kinetic energy is converted to thermal energy. The large surface area of LM created in the process is needed to condense the hot LM vapor prior to the next shot. How do the jets explode? What is the drop size distribution? Do liquid drops fly up to the top of the chamber and take a long time to clear beam paths?
- Status:** Theoretical modeling of the jet break-up predicts drop sizes on the order of 1 - 2 mm in radius leading to a couple orders of magnitude increase in surface area available for cooling and recondensation.
- Needs:** Experiments on the break-up of the LM jets. Proposed methods all have drawbacks (see Blink UCRL-53604). New theoretical work may give a different answer but will probably not dimension uncertainty.

Response to combined effects of energy deposition

- Issue:** The hot vapor blows through the exploding jets causing some radial acceleration. Also the inner jets explode more violently, and there is a net outward push which compacts the LM into an annulus moving outward. The annulus of fluid cavitates as it diverges at constant velocity. Does the LM hit the wall as a uniform rain or as a series of relatively large slugs of fluid? What are the implications?
- Status:** Analytical models of the processes, including calculations of stresses in the chamber wall, have been developed and used.
- Needs:** More work on how the fluid tears itself apart as it expands. What are the resulting wall loading for a series of slugs versus a more uniform shower of LM?

Issue: One of the limits on the pulse repetition rate for the HYLIFE chamber may be the time require to recondense the vaporized lithium and/or the time required for the lithium drops caused by the exploding jets to clear out of the beam paths.

Status: Recondensation times have been estimated to range from ≤ 50 ms to about 500 ms (no jet break-up). The recondensation time is dominated by the time required for the hot vapor to cool. It is assumed that since the fluid initially has a downward velocity of 9.5 m/s, and since the neutron heating only adds radial velocity, the net flow of drops will still be primarily downward and thus easily clear below the beam line before the next pulse.

Needs: Experimental verification of the above processes.

Preliminary Neutronics Considerations for HYLIFE-II

**Wayne R. Meier
W. J. Schafer Associates, Inc.**

August 23, 1988

How thick must the Flibe blanket be in a HYLIFE type chamber?

There are two primary considerations:

- 1) Flibe thickness needed for equivalent radiation damage protection
- 2) Flibe thickness needed for adequate tritium breeding

A simple 1-D model was used for these initial calculations

Comparison of spectra of neutrons incident on first wall (no graphite reflector)

Neutron flux incident on chamber wall
Neutrons/(sqcm*MeV) per DT reaction
Wall radius = 5 m

About 80% of the neutron passing through 100 cm of Li
or 50 cm of Flibe have energies below 1 MeV

Displacement damage cross section for iron

31 cm of Flibe or 78 cm of Lithium is needed
to give a wall lifetime of 30 years

Fusion power = 2700 MW

Wall radius = 5.0 m

Capacity factor = 70%

Lifetime = 21 fpy

Dpa limit = 200 dpa

Limiting rate = 9.5 dpa/fpy

Tritium breeding ratio versus Flibe thickness

About 50 cm of Flibe is needed for an
adequate tritium breeding ratio

Zone	T6	T7	TBR
3	0.191	0.066	0.257
4	0.307	0.033	0.340
5	0.264	0.014	0.278
6	<u>0.176</u>	<u>0.005</u>	<u>0.181</u>
TOTAL	0.938	0.118	1.056

- 1) Add Flibe coolant to graphite region
 - reduced neutron leakage (0.092)
 - reduced capture in Fe (0.079) and graphite (0.006)
 - total potential increase in TBR = 0.177

- 2) 2-D calculation should increase TBR
 - longer average line-of-sight through Flibe blanket
 - increase will not exceed the previous 0.177

- 3) Including beam ports would reduce the TBR by 1 to 4 times the solid angle fraction of the ports

Flow rate comparison

Inner radius fixed 0.5 m

Packing fraction fixed 50%

Volume flow rate proportional to flow area

Mass flow rate proportional to density times flow area

	Thickness, m	Flow area, m ²	Density*area, kg/m
Lithium	0.78	12.55	6085
Flibe	0.31	3.16	6374
Flibe	0.50	6.28	12692

Summary of initial findings

- About 50 cm of flibe (equivalent full density thickness) will be needed to get an adequate tritium breeding ratio if all breeding is done in inner blanket
- About 30 cm of Flibe is needed to reduce the dpa rate to the point where a 5-m-radius steel wall will last about 30 years
- It may be possible to get a TBR > 1 with a 30 - 40 cm thick blanket if Flibe is added to the graphite reflector region and reactor is modeled in cylindrical geometry.
- For the same radiation damage protection, the Flibe mass flow rate is about the same as with lithium while the volume flow rate is about a factor of 4 less.

HYFLIER NEUTRONICS UPDATE

Sept. 6, 1988

QUESTION

What is the effect of adding FLiBe coolant to the graphite reflector zone?

MODEL

Same as previously reported with following changes:

Inner blanket: FLiBe, 40 cm effective thickness

Reflector zone: 80 vol% graphite, 20 vol% FLiBe

RESULTS

Tritium breeding ratio:

	T6	T7	T6+T7
Inner blanket	0.125	0.055	
	0.217	0.033	
	0.228	0.018	
	0.191	0.009	
Subtotal	0.761	0.114	0.875
Reflector	0.239	0	
TBR	1.000	0.114	1.114

Dpa rate $\approx$ 5.2 dpa/fpy

(Recall 9.5 dpa/fpy was used as limit for 21 fpy of operation)