Investigations into X-Ray Damage to the First Wall of the Inertial Confinement Fusion Laboratory Microfusion Facility

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FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

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Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

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University of Wisconsin-Madison
Madison, WI 53706

INTRODUCTION

The target chamber of an Inertial Confinement Fusion (ICF) power plant or of an ICF Laboratory Microfusion Facility (LMF)[1] must survive repetitive blasts from microexplosions of targets. The LMF would explode perhaps as many as 1500 targets, each with a yield of 1000 MJ, over its 30 year lifetime, and several thousand more at lower yields. A typical ICF power plant design might explode 10^8 targets per year. One challenge of ICF target chamber design is the mitigation of the effects of the target generated x-rays on the first surface. The design criteria for the LMF and for an ICF power plant differ significantly. Because of the large number of explosions, the first surface for a power plant must have essentially no vaporization of the solid wall or erosion of the wall will limit the lifetime. Wall erosion is a minor issue for the LMF, so significant vaporization of the first wall material could occur. One consequence of significant vaporization is the launching of shock waves into the solid wall. These vaporization driven shocks are the subject of this paper.

In an LMF target chamber, tens or hundreds of MJ of x-rays will be released by the burning target over a pulse width of a few ns. If x-ray absorbing structures or gases are placed between the target and the first wall, then the energy of the x-rays can be re-radiated to the wall over a time that is long compared to the thermal response time of the wall and vaporization of the surface of the wall may be avoided. A gas of high enough density and atomic number may prevent the propagation of the driver beam, though there may be solutions to this problem as well. In the absence of something to absorb the target generated x-rays, the x-ray power intensity on the first wall will be high enough to vaporize the first wall surface.

I will begin this paper with a study of the response of LMF first walls to target x-rays. I have used computer simulations to study the effect of the x-ray pulse width on the strength of shock waves in the wall material. I will also show the results of computer simulations of possible experiments to mimic the x-ray damage to potential first wall materials. I will then discuss such experiments done using x-rays from gas pinches generated on the SATURN accelerator at Sandia National Laboratories (SNL) in Albuquerque, New Mexico.

FIRST WALL

The first wall responds to target x-rays through very rapid energy deposition in a thin layer of material. This leads to volumetric vaporization of from a few to a few tens of microns of material and the generation of shock waves moving into the material. The volumetric vaporization has been a topic of study for several years[2] and will not be discussed in this report. I will concentrate on the generation of shocks.

An important aspect of this investigation of x-ray vaporization is computer simulation. I have used two different sets of computer codes in this, which have compensating strengths and weaknesses. I have used these codes to consider x-ray vaporization in ICF target chambers. Part of this has been to study the dependence of the wall response on x-ray pulse width. Finally, I have used computer simulations to help design and understand x-ray vaporization experiments.

Computer Codes

I have used two different sets of computer codes to study the launching of shocks by intense x-ray deposition and the subsequent propagation of these shocks into the material. The first set is the IONMIX code[3] coupled to the CONRAD code.[4] These were developed and are being maintained at the University of Wisconsin. CONRAD is a one-dimensional Lagrangian hydrodynamics code with multigroup radiation diffusion. Equations-of-state and multigroup opacities are provided by the IONMIX code in tables. CONRAD includes time-dependent x-ray and ion sources and models energy deposition, thermal conduction, and phase transition in a solid or liquid wall. CONRAD has the advantage that one can directly calculate the mass of material vaporized, which is important both to target chamber design and to validation of the physical models assumed in the vaporization process. The heats of melting and vaporization can be a significant part of the energy budget and care has been taken to include them in CONRAD. In codes designed for use at higher energy densities, the heats of melting and vaporization are only included through the equation-of-state tables, and one is often not sure of the details. The other set is a radiation hydrodynamics code coupled to CSQ. I have used the radiation hydrodynamics code to simulate the deposition of x-rays in the material. This calculation is then coupled to the CSQ computer code. CSQ is a code written and maintained at SNL, that uses two-dimensional Eularian hydrodynamics and has sophisticated modeling of phase transitions and crush physics that are probably important to shock attenuation in materials.[5] CSQ has rather limited radiation transport modelling, which makes such coupling to another computer code advisable when doing x-ray vaporization simulations.

First Wall Simulations

I have used these computer codes to simulate the responses of LMF first walls to the direct deposition of target x-rays. I have used LMF concepts devised both at SNL, applicable to light ion driven fusion, and Lawrence Livermore National Laboratory (LLNL), more tied to laser driven inertial fusion. The parameters used for the calculations and the results are summarized in Table 1. The SNL concepts often require a short distance between the last elements in the beam generation hardware and the target. The present baseline design invokes ballistic focussing of the ions with lens magnets.[6] The beam divergence places an upper limit on the distance between the lens and the target, which is currently believed to be 150 cm. The first wall of the target chamber is placed at the lens position. LLNL concepts using lasers have the final driver components many meters from the target, so there is greater freedom in positioning the first wall of the target chamber. I have considered wall radii of 4 and 5 m, respectively for calculations #4 and 5. For all calculations I have assumed that the target is releasing 220 MJ of x-rays from a total yield of 1000 MJ in 1 ns. I assume that the x-ray spectrum is as shown in Fig. 1. These are all consistent with the HIBALL target[7] and there will be some variation from this in the LMF due to different target designs.

Table 1. X-Ray Vaporization in LMF First Walls

Calculation #	1	2	3	4	5
Code	CONRAD	CONRAD	CSQ	CSQ	CONRAD
Concept	SNL	SNL	SNL	LLNL	LLNL
X-Ray Fluence (J/cm^2)	780	780	780	70	110
Wall Material	Al	C	Al	Al	Frost
Vaporized Mass (kg)	2.8	1.8	*	*	12.6
Peak Pressure in Vapor (GPa)	150	84	*	50	1.2
Impulse on Wall (Pa-s)	310	257	300[a]	100[b]	90.2

*Not Calculated
[a]5×10^3 cm in back of surface
[b]5×10^2 cm in back of surface

Response versus Pulse Width

I have tested the scaling of pressure with x-ray power with computer simulations. In all the calculations, the x-ray fluence is 780 J/cm^2 and the spectrum is as in Fig. 1. Only the pulse width of the x-rays on the wall is varied. I found that the vaporized mass and the total impulse are not much affected by the pulse width. However, as is shown in Fig. 2, the peak pressure on the wall is very much affected. I have proposed a scaling law,

$$P = P(\Delta t = 1\ \mathrm{ns})/\Delta t^n\ , \qquad (1)$$

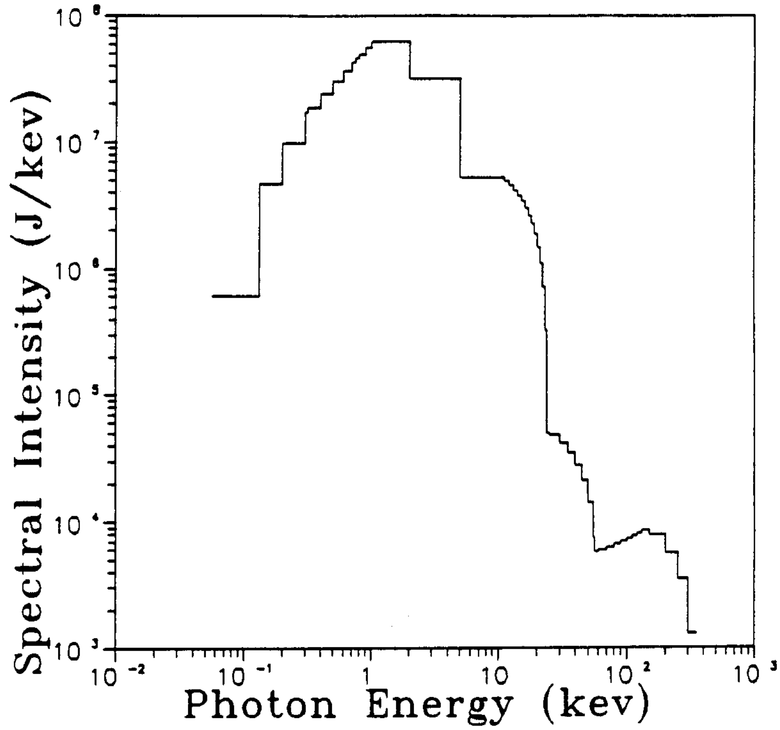

Fig. 1. HIBALL target x-ray spectrum.

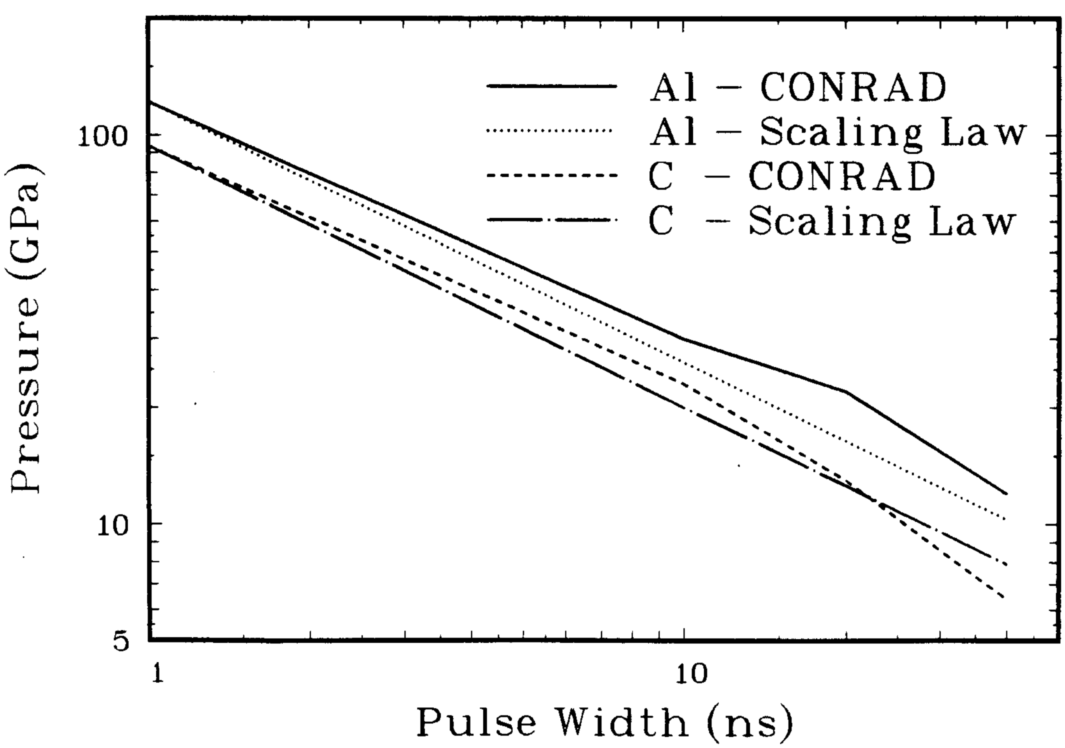

Fig. 2. Pressure on aluminum and graphite walls versus x-ray pulse width. The energy fluence is 780 J/cm^2 and the calculations were done with CONRAD. Scaling laws are also shown.

where P is the peak pressure, Δt is the pulse width, and n is some real number. I have also plotted this scaling law for $n = 2/3$, and one can see that there is a reasonable fit.

I have also looked at the dependence on pulse width of the peak pressure inside the material with CSQ simulations. The results of these simulations are shown in Fig. 3. One can see that as one considers the pressure at greater distances from the surface, the dependence on the pulse width becomes weaker. Therefore, whether the x-ray pulse width is important becomes a question of whether or not one is interested in the material response near to the surface. The issue of pulse widths can be important when considering experiments to simulate the response of LMF first wall materials, which is the topic of the next section.

Simulation of Experiments

I have used CSQ to study how sample first wall materials might behave in experiments that mimic target chamber x-ray conditions. I have done such computer calculations for samples of aluminum, a thin layer of alumina on aluminum, and graphite. Parameters for three experimental environments are shown in Table 2 along with LMF conditions for SNL and LLNL concepts, where in all cases the wall or sample material is aluminum. PROTO-II and SATURN are electron accelerators at SNL that have been used for a number of years to create pulses of x-rays with gas pinches.[8] Specifically, gas puff pinches of neon produce the spectrum shown in Fig. 4.[9] When one compares this spectrum with the HIBALL target spectrum in Fig. 1 it is seen both have peaks at about 1 keV in photon energy. One must also compare the time dependence of the pinch generated x-rays to what the target emits. Here one finds that the HIBALL target emits x-rays over a period of 1 to 2 ns, while a neon gas pinch radiates 1 keV x-rays over 15 to 20 ns and lower energy photons over 100 ns. The pinch is created in the center of a circle of current return posts and the closest that a sample can be placed to the x-ray source is just outside these posts. GAMBLE-II is a machine at NRL that can accelerate protons in a beam to simulate x-ray deposition. One should note that the pulse width of the ion beam on GAMBLE-II is more than 40 ns while the gas pinch x-ray sources have less than half the pulse width. If one is only interested in stresses in the center of the material so that the energy density is important, then experiments on all three machines can be relevant to the LMF. If, however, stresses near the surface are important, the power density (power deposited per unit mass) is the important parameter and only SATURN can do LMF relevant experiments. Even SATURN can only provide a power at one half the LLNL LMF value. The most direct measure is the achievable stress in the material, which I have calculated with CSQ for PROTO-II, SATURN, and SNL and LLNL versions of the LMF. In aluminum, PROTO-II can provide stresses of 1 GPa 0.05 cm in back of the first surface and SATURN can provide 7.5 GPa. I have not yet calculated the stresses that GAMBLE-II could generate in aluminum, though based on the power density one would expect about 1 GPa. I calculated the stresses in a LLNL and SNL LMF aluminum wall to be 7.5 GPa and 14.0 GPa respectively. The calculation of the PROTO-II stresses was rather interesting

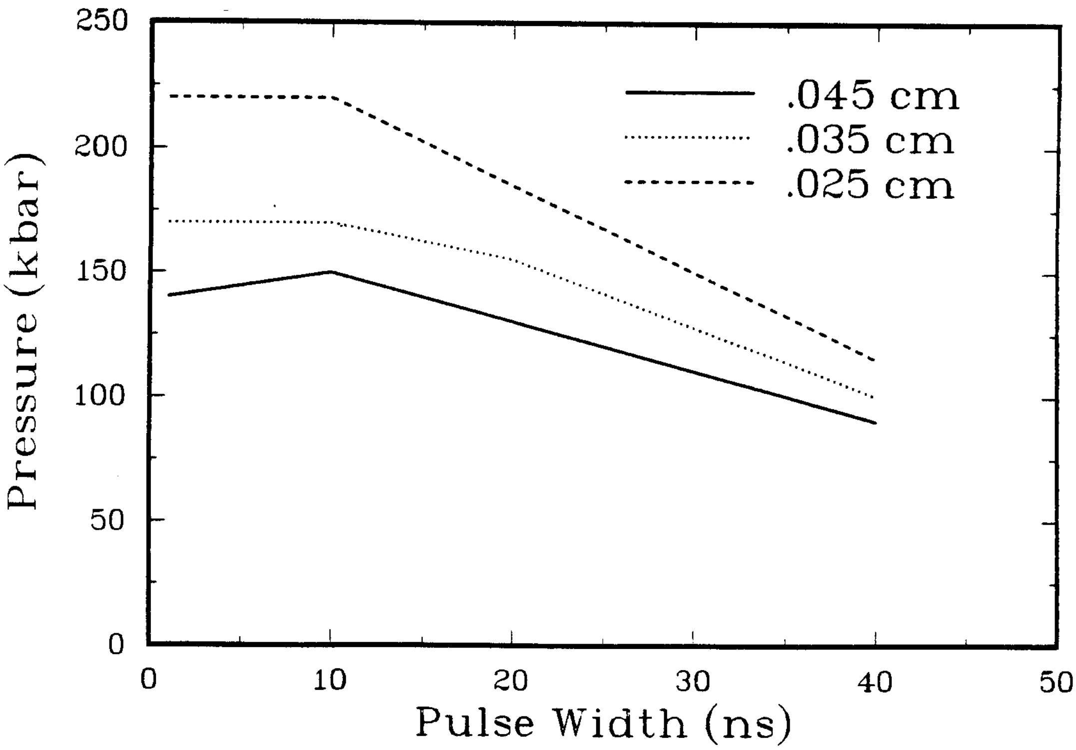

Fig. 3. Stresses at various positions in an aluminum wall versus x-ray pulse width. The energy fluence is 780 J/cm^2 and the calculations were done with CSQ.

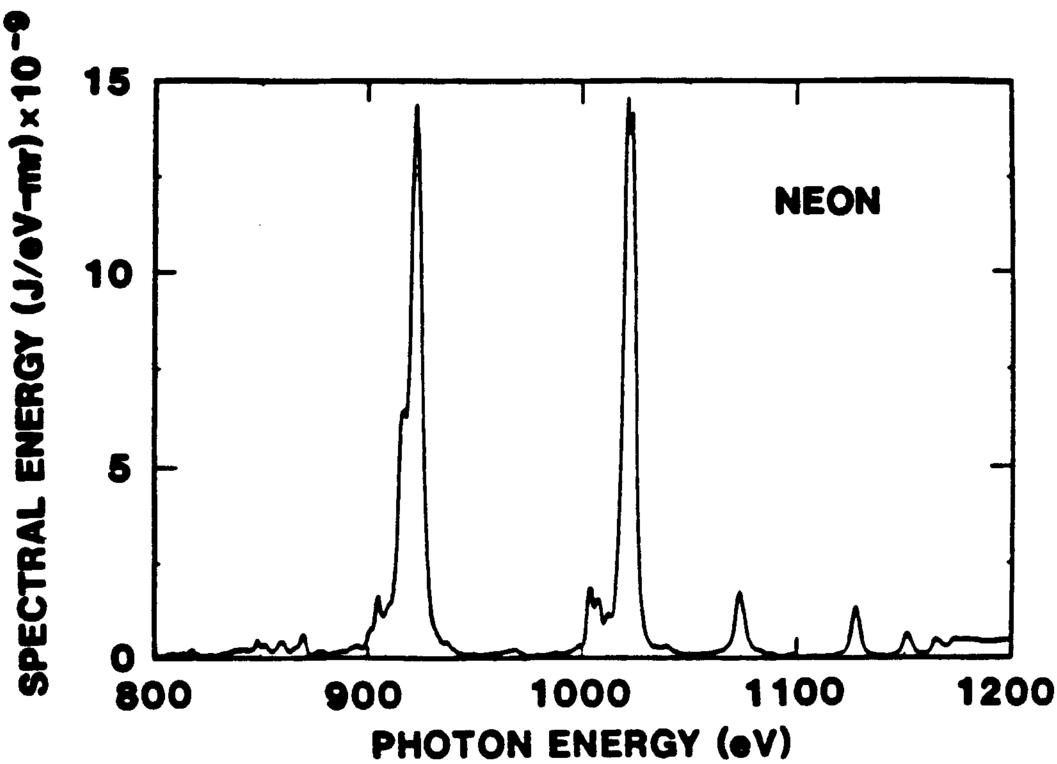

Fig. 4. X-ray spectrum from a neon gas pinch on PROTO-II. Only the component above 900 eV in photon energy is shown. There is another component to the spectrum below a few hundred eV that has about 4 times the energy but more than 5 times the pulse width.

because here the stresses are only a factor of a few larger than the yield stress and the stresses are non-isotropic. The longitudinal stresses at 0.05 cm peaked at 1.0 GPa while the transverse stresses peaked at 0.7 GPa. These simulations show that experiments on SATURN have the potential to much more closely mimic the conditions in the LMF target chamber than do experiments on GAMBLE-II or PROTO-II.

Table 2. X-Ray Driven Stresses in Aluminum

	PROTO-II (gas pinch)	SATURN (gas pinch)	GAMBLE-II (ions)	LMF/LLNL	LMF/SNL
Range in Al (mg/cm^2)	0.83[a]	0.83[a]	3.9[b]	0.83[a]	0.83[a]
X-Ray Energy (MJ)	0.008	0.100	0.017	220	220
Distance (cm)	3.8	3.8	N.A	500	150
Energy Fluence (J/cm^2)	42	550	400	68	780
Energy Density (kJ/g)	51	660	108	82	940
Pulse Width (ns)	20	15	43	1	1
Power Intensity (GW/cm^2)	2.6	37	9.3	68	780
Power Density (GW/g)	2.5	44	2.5	82	940
Calculated Stress (@ 0.05 cm) (GPa)	1	7.5	not calculated	7.5	14

[a]Assuming 1 keV photons
[b]Assuming 1 MeV protons and no range shortening

I have simulated the response of four different materials to x-rays from SATURN with CSQ. The results are summarized in Table 3. In all cases, the samples are assumed to be 3.8 cm from the pinch, which is assumed to generate 100 kJ of x-rays in the lines shown in Fig. 4. There is assumed to be another 400 kJ in x-rays below about 200 eV in photon energy, making a total of 500 kJ in x-rays. I have assumed that the x-rays above 900 eV are emitted in 20 ns in these simulations and that the low energy component is radiated over 100 ns. I have done simulations for aluminum, graphite and aluminum coated with a 100 micron thick layer of alumina.

I have considered the effects of these low energy photons. I have done simulations where these photons are filtered out, perhaps with an aluminum foil, and where they are allowed to irradiated the sample. The ranges of 200 eV x-rays in aluminum and alumina are more than an order of magnitude less than the ranges of 1 keV x-rays and should be mostly absorbed in the blow-off plasma and not contribute to the launching of a shock in the material. Therefore, I only show results for these materials were the low energy photons have not been filtered out; the results with filtering are essentially the same. This is not the case for graphite because the range of 200 eV x-rays is only a little shorter than that for 1 keV x-rays. Both unfiltered and filtered simulations are shown for graphite.

Table 3 Stresses in Various Materials Generated with SATURN X-Rays

	Aluminum unfiltered	Graphite unfiltered	Graphite filtered	Alumina/ Aluminum unfiltered
Range of 1 keV x-rays (mg/cm^2)	0.83	0.50[a]	0.50	0.38
Mass Density (g/cm^3)	2.7	1.7	1.7	3.5
Energy Fluence (J/cm^2)	550[b]	2750	550	550[b]
Energy Density (kJ/g)	660	5500	1100	1440
Power Density (GW/g)	44	367	73	96
Calculated Stress @ 0.05 cm (GPa)	7.5	36.0	10.2	3.5
Calculated Stress @ 0.15 cm (GPa)	4.8	12.5	5.0	1.8
Calculated Stress @ 0.25 cm (GPa)	2.7	8.0	N.A	1.0

[a]The ranges of 1 keV and 300 eV x-rays in carbon are the same The range of 100 eV x-rays is 0.05 mg/cm^2.
[b]Because of the much shorter range of low energy photons, the part of the spectrum below 900 eV is ignored and is not included in the energy fluence.

Except in the case of alumina on aluminum, one can see that the stress increases with energy density and power density. The stress is recorded at three positions in the material, and one sees that the shock is attenuated in all cases. For the case of alumina on aluminum, the calculated stresses are much lower than the energy and power would predict. There is a mismatch in the speed of sound, mass density, and material strength at the alumina/aluminum interface. This leads to poor transmission of the shock across the interface and a great reduction of the shock strength in the aluminum, where the calculated stress is measured.

EXPERIMENTS ON SATURN

During May, 1989 I fielded some x-ray vaporization experiments on SATURN like those described in the previous section. All of the samples were donated by LLNL or SNL. The space on the machine was just what remained on experiments that were already planned. The exception to this was shot 669 which only had my samples on it and was donated by SNL. I did not have any active diagnostics to measure the stress levels. The sample holders were loaned to me by other experimenters at SNL. The samples were held in stainless steel 316 Swaglok fittings that held the samples in place with an annular lip. The backs of the samples were supported with carbon foam that was, in turn, supported with a thin aluminum disk. I am still in the process of analyzing these experiments. The samples after they were irradiated with x-rays are shown in Fig. 5. One can see in Fig. 5 that all samples except 2 and 5 were utterly destroyed. Sample 5, a two-directionally woven graphite in a carbon matrix called K-Karb, was not damaged in the plane of the graphite fibers but these planes became delaminated. Sample 2, aluminum 6061 with a layer of alumina blasted on its surface, survived well except that the alumina was removed. All of the other samples were fine grained graphites or graphites with short fibers. Sample 3, Graphnol, was a fine grained graphite that survived the best of these as it was broken into about 6 pieces. The others were turned into powder. I could not even find any pieces of sample 4.

In August of 1989, I fielded another set of experiments on SATURN. These used argon gas pinches as an x-ray source. The spectra from these pinches differ from those for neon in the photon energy of the dominant lines; neon has lines at about 0.9 and 1.0 keV, while argon emits lines in the 3 to 4 keV

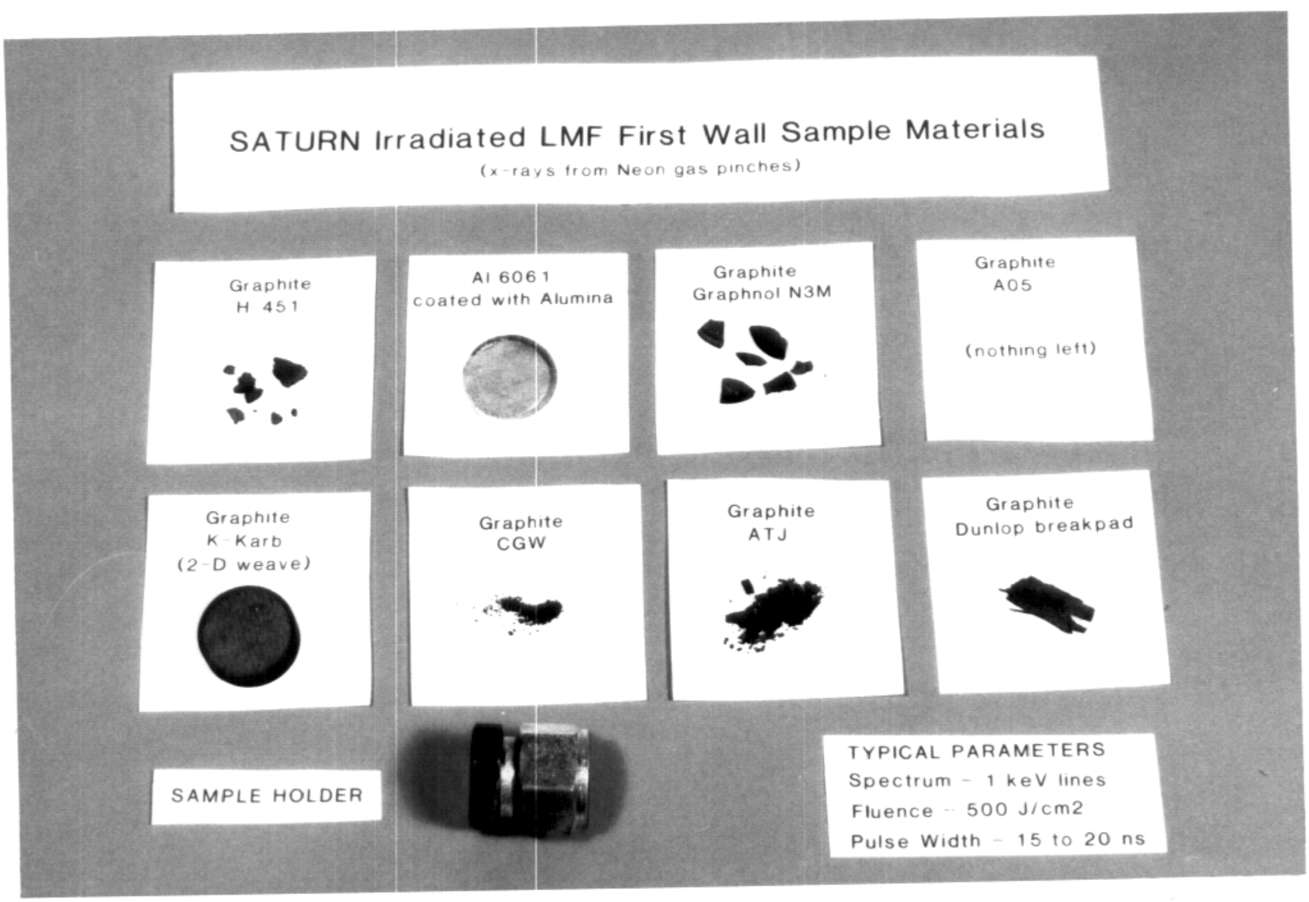

Fig. 5. Photograph of eight samples shot on SATURN during May 1989.

range. Also, argon has about 40 kJ in these lines, while neon can have as much as 100 kJ in its lines. The pulse widths of the x-rays can be as low as 10 ns for argon gas pinches. For these experiments, I used 3 and 4 directionally woven graphites in a solid carbon matrix, bare aluminum 6061 and aluminum 6061 coated with a layer of carbon, a loose carpet material made of graphite, and two samples of 2-directionally woven graphite, where the x-rays were unfiltered and then filtered with a thin aluminum foil. The 3 and 4 directional graphites were an attempt to stop the delamination seen in K-Karb. The aluminum experiments are an extension of the previous experiments with alumina on aluminum in that they use a sacrificial layer to protect the aluminum, while carbon would be much easier to spray onto the wall of an LMF before each shot. The carbon carpet is a relatively new idea for LMF target chamber wall protection,[10] which uses the looseness of a long fibered carpet to prevent the generation of a shock. The filtering of x-rays is an experimental test of the low energy photon effects examined computationally.

The results of these experiments are given in Table 4. One can see that the aluminum survived both with and without the carbon protection. The 4-directional weave was successful in combating delamination, though the 3-directional random weave was not. The graphite carpet was almost totally undamaged by the x-rays. The unfiltered 2-directional weave was destroyed, while the filtered sample survived. I have no quantitative results yet as to the performance of the gas pinches, but preliminary indications are that there were in excess of 350 kJ of x-rays on all shots.

Table 4. Samples of LMF First Wall Materials Irradiated with SATURN X-Rays in August 1989

Sample #	Shot #	Material	Result
1	736	Bare aluminum 6061	survived
2	736	Carbon coated aluminum 6061	survived
3	736	Stapleknit graphite	destroyed delaminated
4	737	4-D woven graphite (FMI)	survived
5	739	3-D random fiber graphite	destroyed
6	737	A05 graphite fine grained	survived
7A	739	2-d woven graphite (unfiltered)	destroyed
7B	739	2-d woven graphite (filtered)	survived
8	737	Graphite carpet	survived

I should reemphasize here that this work is in progress. Several of the numbers quoted in Table 4 are still preliminary; I am still working on the fluences and spectra for these shots. I have done no post-shot analysis of the samples yet. I plan to study those that survived with a scanning electron microscope to see if the shocks caused any changes to the materials. I need to run computer simulations for the exact fluence and pulse width parameters for each sample, once they are well established.

SUMMARY AND CONCLUSIONS

I have used a simple scaling law and computer simulations to show that target x-rays will generate shocks in the first surfaces of unprotected LMF target chamber walls whose strength depends on the x-ray fluence, power intensity, and fluence. I have shown that gas pinches on the SATURN electron accelerator can provide x-rays that are of relevance to some LMF concepts. I have performed preliminary experiments on SATURN that have shown bare aluminum, aluminum coated with a thin layer of alumina or graphite, four-directionally woven graphite, and graphite carpet all survive a single pulse of x-rays. I have begun to study the effects of low energy photons in the experiments done on graphite.

Several issues need to be studied before a first wall material is chosen for the LMF. The experimental results reported in this paper are still preliminary in nature and much more data is needed. Samples need to be analyzed with electron or optical microscopy. The changes in material properties, such as elastic modulus and yield strength, brought about by the shocks need to be measured. Samples need to be repetitively irradiated with x-rays to study how the changes in properties will affect the response to shocks. Additional computer simulations will be needed as more information on properties of the material is obtained. The effect of debris in the SATURN experimental chamber needs to be addressed as does damage to the samples not related to the passage of shocks. Finally the techniques developed in this project should be applied to other materials that may be more relevant to ICF power plant designs.

ACKNOWLEDGEMENT

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