Nova Upgrade Design Support
Threats from Radiation Effects in the
Proposed Nova Upgrade

**R. E. Tokheim
L. Seaman
D. R. Curran**

Poulter Laboratory

September 1992

**Lawrence
Livermore
National
Laboratory**

This is an informal report intended primarily for internal or limited external distribution. The opinions and conclusions stated are those of the author and may or may not be those of the Laboratory.

Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

SRI International

Final Report • September 1992

NOVA UPGRADE DESIGN SUPPORT

Threats from Radiation Effects in the Proposed Nova Upgrade

R. E. Tokheim, Senior Physicist and Project Leader
L. Seaman, Senior Research Engineer
D. R. Curran, Scientific Director
Poulter Laboratory

SRI Project No. 2802
Subcontract No. B160484

Prepared for:

University of California
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94550

Attn: D. Kumpf, L-479
J. Krueger, L-650
M. Tobin, L-481

NOVA UPGRADE DESIGN SUPPORT

Threats from Radiation Effects in the Proposed Nova Upgrade

**R. E. Tokheim, Senior Physicist and Project Leader
L. Seaman, Senior Research Engineer
D. R. Curran, Scientific Director
Poulter Laboratory**

**SRI Project No. 2802
Subcontract No. B160484**

Prepared for:

**University of California
Lawrence Livermore National Laboratory
P.O. Box 808
Livermore, CA 94550**

**Attn: D. Kumpf, L-479
J. Krueger, L-650
M. Tobin, L-481**

Approved:

**J. D. Colton
Laboratory Director
Poulter Laboratory**

**David M. Golden
Vice President
Physical Sciences Division**

.

ABSTRACT

The program described in this report deals with the proposed Nova Upgrade facility, in which Lawrence Livermore National Laboratory (LLNL) expects to generate typically 20 MJ of total fusion energy. The Nova Upgrade is considered the next practical step after Nova before work begins on development of the Laboratory Microfusion Facility by which LLNL expects to generate 100-1000 MJ of total fusion energy.

SRI International's contributions have been to work with LLNL to understand the radiation-induced vaporization, melting, fracture, and fragmentation resulting from the effects of X-rays, neutrons, and debris irradiation on the target chamber wall, the steel feeder tubes of the cryogenic target holder assembly, and the optics debris shields. We have assessed the major collateral effects of direct and indirect damage from radiation and shrapnel debris on the optics debris shields and have suggested alternative materials and designs to alleviate the effects of radiation and debris. We also analyzed a technique LLNL has developed for producing hot X-rays in a shielded environment that uses a lithium hydride shell to scatter hot X-rays from the source to an experimental target area while using a cone to prevent direct cold-source radiation and neutrons from reaching the experimental target. There do not appear to be any "show stoppers" to prevent recommending continued development of the Nova Upgrade for inertial confinement fusion (ICF) experiments and nuclear effects testing.

CONTENTS

Section	Page
ABSTRACT	iii
LIST OF ILLUSTRATIONS.....	ix
LIST OF TABLES.....	xv
ACKNOWLEDGMENTS.....	xvii
1 INTRODUCTION	1-1
1.1 Description of Nova Upgrade.....	1-1
1.2 Background	1-7
1.3 Specific Source Description.....	1-7
1.4 Objectives.....	1-8
1.5 Approach	1-10
1.6 Sequence of Report.....	1-10
2 CHAMBER FIRST WALL.....	2-1
2.1 Introduction	2-1
2.2 Aluminum as First Wall	2-1
2.2.1 Properties of Aluminum.....	2-1
2.2.2 X-Ray Effects	2-1
2.3 Alumina at First Wall	2-3
2.3.1 Introduction	2-3
2.3.2 X-Ray Effects	2-10
2.4 Other Protective Coatings	2-10
2.4.1 Introduction	2-10
2.4.2 X-Ray Effects	2-15
2.5 Primary Wall Candidates.....	2-21
2.5.1 Introduction	2-21
2.5.2 X-Ray Effects	2-21
2.6 Recommendations.....	2-27

CONTENTS

(Continued)

Section	Page
3 STAINLESS STEEL COOLANT TUBING	3-1
3.1 Introduction	3-1
3.2 Properties of Tubing.....	3-2
3.2.1 Shock Wave Properties.....	3-2
3.2.2 Strength and Fracture Properties	3-4
3.2.3 Fragmentation Properties	3-4
3.3 Helium Properties.....	3-4
3.4 Neutron Energy Deposition.....	3-6
3.4.1 Introduction	3-6
3.4.2 Material State in Tubes.....	3-9
3.4.3 Particle Velocities of Tube.....	3-9
3.4.4 Spall Fracture of Tubes.....	3-9
3.4.5 Splitting in Tubes Under Neutron Loading.....	3-13
3.4.6 Droplet Formation in Liquid Range	3-14
3.5 X-Ray Effects on Stainless Steel Tubes.....	3-19
3.6 Effects of Hohlraum Debris on Tubes.....	3-23
3.7 Combined Effects on Tube Velocities.....	3-30
3.8 Recommendations	3-30
4 OPTICS DEBRIS SHIELDS.....	4-1
4.1 Introduction	4-1
4.2 Properties of Debris Shield Material.....	4-1
4.3 X-Ray Effects	4-1
4.4 Effects of Stainless Steel Fragments	4-3
4.5 Effects of Hohlraum Debris.....	4-6
4.6 Recommendations	4-9
5 APPLICATION OF NOVA UPGRADE AS AN X-RAY SOURCE.....	5-1
5.1 Introduction	5-1
5.2 Choice of Membrane Shield.....	5-1
5.3 Response of Membrane Shield to LiH Cone.....	5-4
5.4 LiH Shell Vaporization and Pressurization Effects	5-4
5.4.1 Properties of Lithium Hydride, Lithium, and Hydrogen.....	5-5
5.4.2 Pressure in the Shell	5-5
5.4.3 Loading on the Membrane Shielding the Targets.....	5-7
5.4.4 Summary	5-8
5.5 Recommendations	5-10

CONTENTS

(Concluded)

Section	Page
6 OVERALL CONCLUSIONS AND RECOMMENDATIONS	6-1
REFERENCES	7-1
APPENDICES:	
A CONSTITUTIVE RELATIONS USED IN SRI PUFF.....	A-1
B SRI PUFF AND FSCATT RESULTS	B-1
C MIE-GRÜNEISEN AND PUFF EXPANSION EQUATIONS OF STATE	C-1
D SPLITTING THE CRYOGENIC TUBES.....	D-1
E MEMBRANE MOTION UNDER IMPACT OR PRESSURE LOADING	E-1

ILLUSTRATIONS

Figure	Page
1-1 Beam layout in target area for Nova Upgrade	1-2
1-2 Elevation view of target chamber area for Nova Upgrade.....	1-3
1-3 The hohlraum indirect-drive capsule physics is essentially driver-independent.....	1-4
1-4 Target cryogenic support assembly.....	1-5
1-5 Nova Upgrade design concept for final optics	1-6
2-1 Aluminum vapor ablation thickness for given X-ray fluence at different blackbody temperatures	2-4
2-2 Aluminum melt ablation thickness for given X-ray fluence at different blackbody temperatures	2-4
2-3 Aluminum maximum vapor velocity for given X-ray fluence at different blackbody temperatures	2-5
2-4 Aluminum average vapor velocity for given X-ray fluence at different blackbody temperatures	2-5
2-5 Aluminum average melt velocity for given X-ray fluence at different blackbody temperatures	2-6
2-6 Aluminum vapor momentum for given X-ray fluence at different blackbody temperatures	2-6
2-7 Aluminum melt momentum for given X-ray fluence at different blackbody temperatures	2-7
2-8 Aluminum velocity profile for X-ray fluence of 7.2 J/cm ² for BBT = 0.175	2-8
2-9 Aluminum velocity profile for X-ray fluence of 7.2 J/cm ² for BBT = 0.350	2-8
2-10 Aluminum velocity profile for X-ray fluence of 7.2 J/cm ² for BBT = 0.700	2-8

ILLUSTRATIONS

(Continued)

Figure	Page
2-11 Aluminum peak tensile strength and time of occurrence for 7.0 MJ X-ray output (3.48 J/cm^2)	2-9
2-12 Aluminum peak tensile strength and time of occurrence for 14.5 MJ X-ray output (7.21 J/cm^2)	2-9
2-13 Aluminum peak tensile strength and time of occurrence for 20.1 MJ X-ray output (10 J/cm^2)	2-9
2-14 Al_2O_3 vapor ablation thickness for given X-ray fluence at different blackbody temperatures	2-11
2-15 Al_2O_3 melt ablation thickness for given X-ray fluence at different blackbody temperatures	2-11
2-16 Al_2O_3 total removal thickness (including spall) of given X-ray fluence at different blackbody temperatures.....	2-12
2-17 Al_2O_3 maximum vapor velocity for given X-ray fluence at different blackbody temperatures	2-12
2-18 Al_2O_3 average vapor velocity for given X-ray fluence at different blackbody temperatures.....	2-13
2-19 Al_2O_3 average melt velocity for given X-ray fluence at different blackbody temperatures.....	2-13
2-20 Al_2O_3 vapor momentum for given X-ray fluence at different blackbody temperatures.....	2-14
2-21 Vaporized thickness of candidate materials for first wall coating with 14.5 MJ X-ray output	2-17
2-22 Melted thickness of candidate materials for first wall coating with 14.5 MJ X-ray output	2-17
2-23 Porous Be 5% W vapor ablation thickness for given X-ray fluence at different blackbody temperatures.....	2-19
2-24 Porous Be 5% W melt ablation thickness for given X-ray fluence at different blackbody temperatures.....	2-19

ILLUSTRATIONS

(Continued)

Figure	Page
2-25 Porous Be 5% W spall removal thickness for given X-ray fluence at different blackbody temperatures.....	2-20
2-26 Porous Be 5% W average melt velocity for given X-ray fluence at different blackbody temperatures.....	2-20
2-27 Vaporized thickness of 3 candidate materials for first wall coating with 14.5 MJ X-ray output (7.2 J/cm ²).....	2-22
2-28 Melt thickness of 3 candidate materials for first wall coating with 14.5 MJ X-ray output (7.2 J/cm ²).....	2-22
2-29 Vaporized thickness of 3 candidate materials for first wall coating with 7.0 MJ X-ray output (3.5 J/cm ²)	2-23
2-30 Melt thickness of 3 candidate materials for first wall coating with 7.0 MJ X-ray output (3.5 J/cm ²)	2-23
2-31 X-ray energy deposition in P-S B 5% Hf first wall.....	2-24
2-32 X-ray energy deposition in beryllium first wall.....	2-24
2-33 Average vapor velocity of candidate materials for first wall coating with 14.5 MJ X-ray output (7.2 J/cm ²).....	2-25
2-34 Average melt velocity of candidate materials for first wall coating with 14.5 MJ X-ray output (7.2 J/cm ²).....	2-25
2-35 Average vapor velocity of candidate materials for first wall coating with 7.0 MJ X-ray output (3.5 J/cm ²)	2-26
2-36 Average melt velocity of candidate materials for first wall coating with 7.0 MJ X-ray output (3.5 J/cm ²)	2-26
2-37 Peak tensile stress in solid beryllium - 3.5 J/cm ² (0.837 cal/cm ²)	2-28
2-38 Stress history in solid beryllium first wall showing typical tensile pulse for 7.05 MJ X-ray yield: 3.5 J/cm ² (0.837 cal/cm ²).....	2-28
3-1 Neutron energy deposited in cryogenic tube (helium and stainless steel) versus radius from end of tube.....	3-8

ILLUSTRATIONS

(Continued)

Figure	Page
3-2 Neutron energy deposited in cryogenic tube versus radius from pellet.....	3-9
3-3 Neutron energy in stainless steel for neutron yields of 4, 16, and 36 MJ	3-10
3-4 Velocity, energy, distance, and mass table for 5, 20, and 45 MJ.....	3-10
3-5 Fragment sizes for 4, 16, and 36 MJ of neutron energy.....	3-15
3-6 Fragment sizes of stainless steel.....	3-16
3-7 Velocities of droplets from stainless steel tubes.....	3-17
3-8 Geometry of hohlraum and tubes for X-ray absorption.....	3-18
3-9 Tube velocities from impact of hohlraum debris.....	3-29
3-10 Particle velocities in stainless steel tubes	3-31
4-1 Energy deposition in debris shield at 55 degrees.....	4-2
4-2 Peak tensile strength and time of occurrence at 55-degree debris shield for 0.350-keV source and 0.47 J/cm ² fluence.....	4-5
4-3 Peak tensile strength and time of occurrence at 55-degree debris shield for 0.350-keV source and 1.30 J/cm ² fluence.....	4-5
4-4 Fractional surface damage for hohlraum debris atomic impacts.....	4-8
5-1 Conversion configuration for obtaining debris-free hot X-rays at target experiments.....	5-2
5-2 Geometry of LiH configuration for producing hot X-rays	5-3
5-3 Pressure history at the membrane caused by flow of the Li and H ₂ gases: closed-end case	5-9
5-4 Pressure history at the membrane caused by flow of the Li and H ₂ gases: flow-by case	5-9

ILLUSTRATIONS

(Concluded)

Figure		Page
D-1	Mottprob fracture probabilities.....	D-3
E-1	Membrane deflection as a function of impulse.....	E-5
E-2	Peak membrane stress as a function of specific impulse	E-5

TABLES

Table		Page
1-1	Nominal source outputs as a function of fusion yield	1-9
2-1	Mie-Grüneisen and PUFF expansion properties of 5083 Al	2-2
2-2	Strength parameters for 5083 Al	2-2
2-3	Fracture parameters used for 5083 Al.....	2-2
2-4	Thermophysical properties of candidate materials for first wall coating.....	2-16
2-5	Front-surface X-ray energy deposition in aluminum wall layer behind candidate material	2-18
3-1	Energies for stainless steel 316.....	3-3
3-2	Comparison of XAR30 and MIL-S-12560B steels	3-5
3-3	Fracture parameters for 316 stainless steel	3-5
3-4	Mie-Grüneisen and PUFF expansion properties of helium.....	3-7
3-5	Energies and states at locations in tubes	3-11
3-6	SRI PUFF simulation cases with energies and pressures.....	3-11
3-7	Particle velocity as function of energy and state.....	3-12
3-8	Diameters of liquid droplets	3-20
3-9	Droplet and fragment sizes for 36-MJ neutron source.....	3-20
3-10	X-ray results for 5-MJ source.....	3-24
3-11	X-ray results for 20-MJ source	3-24
3-12	X-ray results for 45-MJ source.....	3-25
3-13	Velocity of tubes caused by debris impact: 0.5 MJ in debris	3-27
3-14	Velocity of tubes caused by debris impact: 2.0 MJ in debris	3-27

TABLES
(Concluded)

Table		Page
3-15	Velocity of tubes caused by debris impact: 4.5 MJ in debris	3-28
4-1	Threshold fluences for no "melt" in fused silica	4-4
4-2	Results from lead hohlraum debris at debris shield.....	4-7

ACKNOWLEDGMENTS

The work presented in this report was performed for the Target Area design team at Lawrence Livermore National Laboratory. We are especially indebted to Mike Tobin, Target Area Leader, and Ray Smith for continuous support and stimulating discussions and guidance throughout the program. We are also significantly indebted to John Woodworth, Max Tabak, Don Campbell, and many others on the ICF program.

We also wish to thank Bonita Lew at SRI for considerable help in computational support.

Section 1

INTRODUCTION

1.1 DESCRIPTION OF NOVA UPGRADE

Lawrence Livermore National Laboratory (LLNL) currently has a facility called Nova, which has been used to investigate high-energy and high-pressure physics for weapon and inertial confinement fusion studies. The 4.6-m-diameter Nova target chamber steers the focus of ten laser beams, each of which has been amplified from a low-power 1.05- μm neodymium-glass laser to give a total target laser energy on the order of 120 kJ. A six-story building houses the target frame for the Nova. LLNL already has a preliminary design for upgrading the Nova in the current Nova building with *existing* technology that will raise the total target laser energy to 2 MJ at the 0.35- μm wavelength (triple-frequency laser output). The Nova Upgrade design calls for 192-288 laser beams focusing on the target to achieve this goal. Figure 1-1 shows the beam layout in the target area, and Figure 1-2 shows a cross-sectional view of the evacuated target chamber. LLNL believes that their design will provide a fusion yield of 20-30 MJ. Under these conditions, X-rays, neutrons, gamma rays, and debris originating from the tritium-deuterium source pellet and hohlraum (used for coupling the laser-induced X-ray energy efficiently to the pellet capsule, as shown in Figure 1-3) will irradiate the target chamber and pose hazards to the debris shields in the optics ports.

The objects closest to the prescribed radiation source are those in the target cryogenic support assembly shown in Figure 1-4. The major source of fragments is expected to be the stainless steel supply tubes that carry the flow of liquid helium to maintain the required cryogenic temperature of the hohlraum capsule. A separate pair of feeder and return supply tubes supports each side of the hohlraum. The liquid helium is under about 100 atm pressure.

Direct X-irradiation of the first wall of the chamber and debris shields is another major concern. At the first wall, X-ray absorption may cause vaporization that even at low fluence levels and with such a large chamber area, will blow off material that will fill the chamber and may enter the optic ports (see Figure 1-5). Also, X-rays from the source will directly enter the optic ports and irradiate the debris shields. A further threat is direct debris radiation from the hohlraum-capsule itself.

CAM-314581-66

Figure 1-1. Beam layout in target area for Nova Upgrade (courtesy of LLNL).

CAM-314581-67

Figure 1-2. Elevation view of target chamber area for Nova Upgrade (courtesy of LLNL).

CAM-314581-68

Figure 1-3. The hohlraum indirect-drive capsule physics is essentially driver-independent (courtesy LLNL).

CAM-314581-69

Figure 1-4. Target cryogenic support assembly (courtesy of LLNL).

CAM-314581-70

Figure 1-5. Nova Upgrade design concept for final optics (courtesy of LLNL).

In some planned uses of the Nova Upgrade facility, experiments will be performed at several points in the chamber. These experiments and their associated fixtures will face hazards similar to those experienced by the first wall and optics. If these objects are close to the hohlraum source, the hazards could be significantly worse, not only for the experiments and their fixtures but also for the safe operation of the Nova Upgrade itself. If these hazards can be overcome, assuming the desired variety of loading conditions are achieved, then useful inertial confinement fusion (ICF) experiments and nuclear effects tests can be conducted in this facility.

1.2 BACKGROUND

SRI International has worked on two previous programs with LLNL for assessing shrapnel debris generation in LLNL-proposed inertial confinement fusion facilities (Tokheim et al., 1988; and Seaman et al., 1989). The first two programs dealt with the "ultimate" facility, called the Laboratory Microfusion Facility (LMF), by which LLNL expects to generate 100-1000 MJ of total fusion energy. We assessed the possible damage from high-velocity fragments, droplets, and vapor generated in the microfusion chamber from neutrons and X-radiation. We accounted for the X-ray absorption and viscosity effects of a low-pressure argon atmosphere. We considered the pellet to be independently supported and to have a range of source characteristics, including a blackbody temperature range from about 0.1 to 0.4 keV. We primarily addressed the response of an aluminum-coated lead bang-time diagnostic device extended on long support tubes to within 5 to 60 cm of the pellet. We also analyzed the response of a spherical shell of lithium hydride filtering material and a lithium hydride cone, surrounding the radiation source, and estimated the velocities of cone fragments and expanding vapor from the shell that would be generated by irradiation of these materials. Our major concerns were that the fragments generated by irradiation of materials of the bang-time diagnostic device in the chamber would move at such high velocities that they might penetrate the chamber wall, arrive at optical ports before the protective doors could be closed, or penetrate the doors. We computed that high-velocity droplets would be the most serious threat to the optics and would pass through the doors before they could close.

1.3 SPECIFIC SOURCE DESCRIPTION

LLNL supplied guidelines for the work on Nova Upgrade that simply assumed the source characteristics and provided a basis for bounding the computed radiation effects (Tobin, 1991). The source outputs for neutrons, X-rays, and debris were assumed in terms of the fusion yield, Y , as follows, in megajoules (MJ):

Neutrons	$n\%Y$
X-rays	$1 + x\%Y$
Debris	$1 + (1 - n\% - x\%)Y$
Total	$2 + Y$

The "1" at the front of the second column is based on the assumption of 50% conversion of 2 MJ of laser energy to X-rays and the remainder to hohlraum debris. We were to assume an $n\% = 80\%$ for the neutrons and an $x\%$ of 5% to 20% for the X-rays, leaving a contribution of 0% to 1.5% of yield to debris. For our initial X-ray computations, we took the worst-case X-ray output of 14.5 MJ, corresponding to $x\% = 30\%$ for a 45-MJ fusion yield agreed to by LLNL. Later we preferred the nominal X-ray output shown in Table 1-1.

A nominal fusion yield was suggested to be 20 MJ. In most cases, the ranges of energies used in our computations for each type of radiation should be large enough to estimate radiation effects even above the maximum specified 45-MJ fusion yield and for arbitrary partitions of individual radiation energies.

The duration of the neutron radiation is assumed to be less than 1 ns. Assumed durations of interest for the X-rays are 0.5, 1.0, 2.0, and 3.0 ns with a Gaussian time distribution to determine any change in material response due to temporal changes. We used 1.0 ns for most of our computations. We were asked to examine a range in blackbody temperatures (BBTs) of the X-ray source of 0.175 to 0.700 keV.

We assume isotropic radiation of energy from the target as a point source. Consequently, the fluence F at any location within the target chamber is given as a function of the total X-ray source energy S_x and the radial distance R by

$$F = \frac{S_x}{4\pi R^2}$$

Thus, at the 4-m first wall for 4.0-, 7.0-, and 14.5-MJ X-ray sources, we have fluences of $F = 2.0, 3.5,$ and 7.2 J/cm^2 (or $0.48, 0.83,$ and 1.72 cal/cm^2), respectively.

1.4 OBJECTIVES

The purpose of our work has been to assist LLNL in the Nova Upgrade design for the target area, primarily in predicting debris generation and its effects and aiding in the design of Nova experiments to support the computational work. Our objectives included assessing the

Table 1-1

**NOMINAL SOURCE OUTPUTS AS A
FUNCTION OF FUSION YIELD**

Yield (MJ)	Neutrons (MJ)	X-Rays (MJ)	Debris (MJ)	Total (MJ)
0	0	1.0	1.0	2.0
0.1	0.08	1.01	1.01	2.1
5.0	4.0	1.5	1.5	7.0
20.0	16.0	3.0	3.0	22.0
45.0	36.0	5.5	5.5	47.0

hazards of radiation-induced vaporization, melting, fracture, and fragmentation resulting from X-rays, neutrons, and debris irradiation effects on the target chamber wall, the steel feeder tubes of the cryogenic target holder assembly, and the optics debris shields. Part of our effort in the design of Nova experiments was redirected toward the end of the program to include the evaluation of a Nova Upgrade experimental configuration (the lithium hydride shell and cone) for possible nuclear weapon effects testing.

1.5 APPROACH

To meet the objectives, we performed calculations of X-ray and neutron deposition, stress wave propagation computations, and other computational analyses. Assumed source energy partition ranges and neutron energy deposition profiles were obtained from LLNL.

One-dimensional stress wave propagation simulations with planar, cylindrical, and spherical geometries were believed adequate by SRI for the computations. Fracture processes were treated in these simulations, but fragment and droplet sizes were determined by separate analytical treatments. Much of our effort was guided by work on our previous two programs with LLNL.

Early in the program, SRI recommended that LLNL perform LASNEX computations for the target to provide better information about debris emanating from the hohlraum. We suspect that hohlraum debris could be a major player in the radiation effects study. The LASNEX results were, indeed, interesting and could be used to more accurately assess the nature and the effects of the debris on final optics debris shields in a later study.

1.6 SEQUENCE OF REPORT

Section 2 addresses the effects of X-ray absorption by the first wall, with the alternative options of different material coatings. In Section 3, we examine the radiation effects of neutrons, X-rays, and debris on the stainless steel coolant tubing that carries the liquid helium that keeps the hohlraum capsule cold. In Section 4, we study the effects of radiation and debris on the optics debris shields. Finally, in Section 5, we investigate the feasibility of a scheme for using the Nova Upgrade as a hot X-ray source. A recommendations subsection is included at the end of each major section. Many of these recommendations were made in concert with LLNL personnel in project review discussions. Overall conclusions and recommendations are discussed at the end of the report.

Section 2

CHAMBER FIRST WALL

2.1 INTRODUCTION

The absorption depth of X-ray energy at the first wall is very short and considerable vaporization and melting are expected at the largest fusion yield. Because the surface area of the target chamber is so large, so that a short depth of material removed is still a considerable mass, these effects must be investigated to estimate their potential influence on the debris shields.

2.2 ALUMINUM AS FIRST WALL

2.2.1 Properties of Aluminum

We constructed a dynamic model for the 5083 aluminum first wall material based on experience with previous aluminum models (Dein et al., 1984). Features included energy-dependent compression, expansion, and solid behavior including ductile failure, melting, and vaporization. Tables 2-1 and 2-2 give the equation-of-state and mechanical parameters, and Table 2-3 gives the ductile fracture parameters we use for aluminum in our DFRACT (Seaman et al., 1976) high-rate microfracture model. The SRI PUFF input listing is given in Appendix A.

2.2.2 X-Ray Effects

We computed X-ray fluences at the 4-m radius first wall from an assumed isotropic point source, as described in Section 1.3, with X-ray energies ranging from 1 to 20 MJ. Energy absorption in the first wall was determined by the energy deposition FSCATT code (Fisher and Wiehe, 1970) with Biggs and Lighthill (1971) cross sections. Cold cross sections are satisfactory for use at the fluence levels of interest. We computed absorption for each blackbody source temperature of 0.175, 0.350, and 0.700 keV and assumed the short but representative pulse duration of 1 ns. Next we made one-dimensional stress-wave computations with SRI PUFF to obtain ablation,* velocity, and momentum information.

* Can be obtained from FSCATT alone.

Table 2-1
MIE-GRÜNEISEN AND PUFF EXPANSION PROPERTIES OF 5083 Al

Symbol	Value	Description
ρ_{0s}	2.66 g/cm ³	Reference density
C	76.0 GPa	Initial bulk modulus
D	150 GPa	2nd term in series expansion for bulk modulus
S	0.0 GPa	3rd term in series expansion for bulk modulus
E_s	3.0 kJ/g	Vaporization energy
Γ	2.04	Grüneisen ratio
H	0.25	Grüneisen ratio of expanded states
n	0.50	Exponent of variation of the Grüneisen ratio

Table 2-2
STRENGTH PARAMETERS FOR 5083 Al

Parameter	Value	Units	Description
G	30	GPa	Shear modulus
Y_0	200	MPa	Yield strength
Yadd	100	MPa	Work hardening
E_m	0.586	kJ/g	Incipient melt energy

Table 2-3
FRACTURE PARAMETERS USED FOR 5083 Al

Parameters	Value ^a	Units	Description
$T_1 = 3/(4\eta)$	-1.0E5	1/MPa/s	Growth constant
T_2	-400	MPa	Threshold pressure for growth
$T_3 = R_n$	1.0E-3	cm	Nucleation radius parameter
$T_4 = \dot{N}_0$	3.0E9	No./cm ³ /s	Nucleation rate coefficient
$T_5 = \sigma_{n0}$	-300	MPa	Nucleation threshold
$T_6 = \sigma_1$	-40.	MPa	Pressure sensitivity for nucleation

^a Sign convention for pressure is positive in compression.

Vapor and melt[†] thicknesses, velocities, momenta, and velocity profiles were determined for the range of X-ray fluences corresponding to the expected source yield and are shown in Figures 2-1 through 2-10. The table of results on which these plots are based is included in Appendix B. Over the computed fluence range of 0.5 to 10 J/cm², vapor ablation thicknesses are typically in the range of 0.1 to 3 μ m. Melt ablation is mostly in the 1- to 8- μ m range. The vapor ablation shown is generally several times greater than that given by Orth (1991), because our dynamic model is based on the incipient vaporization energy (enthalpy) instead of the sublimation or cohesive energy.

Vapor and melt layers appear to be too thin and not expanding fast enough for small droplet formation, at least until much further expansion away from the wall occurs. Most average vapor velocities of a few kilometers per second are high enough to spray most of the aluminum vapor toward the antipode from each spot of the chamber wall. Molten velocities of 10 to 200 m/s are sufficiently low to be affected by gravity and, in general, will impact the opposite chamber wall significantly below the antipode from each originating spot. Consequently, mostly molten aluminum would likely directly enter beam ports with the current design. These results could be altered by source anisotropy, nonnormal wall design, and refractory coating on the wall. The latter would significantly reduce wall ablation.

Another removal mechanism that needs to be addressed is front-surface spall which can happen when stress generated by deposition at the front surface of the wall is relieved sufficiently to exceed the dynamic material tensile strength. At the fluences of interest, vaporization is not sufficiently high to suppress tension. From our computations we found that peak front-surface tensile stresses slightly exceed our model's ductile void nucleation threshold, as shown by Figures 2-11 through 2-13. However, we estimate that their very short duration is not long enough for appreciable void growth (leading to front-surface spall) at the 14.5-MJ and lower X-ray output levels. Therefore, front-surface spall is unlikely to be an issue for the Nova Upgrade first wall.

2.3 ALUMINA AT FIRST WALL

2.3.1 Introduction

Because aluminum produced so much vapor and melt ablation, we recommended that LLNL consider using a refractory material as a coating over the 5083 aluminum first wall or as a plate protecting the walls. The much greater vaporization and melt energies will greatly reduce the

[†] Melt thickness as opposed to melt depth, which is measured from the initial front surface; i.e., melt thickness excludes vapor removal.

CAM-2802-1

Figure 2-1. Aluminum vapor ablation thickness of given X-ray fluence at different blackbody temperatures.

CAM-2802-2

Figure 2-2. Aluminum melt ablation thickness of given X-ray fluence at different blackbody temperatures.

CAM-2802-3

Figure 2-3. Aluminum maximum vapor velocity for given X-ray fluence at different blackbody temperatures.

CAM-2802-4

Figure 2-4. Aluminum average vapor velocity for given X-ray fluence at different blackbody temperatures.

CAM-2802-5

Figure 2-5. Aluminum average melt velocity for given X-ray fluence at different blackbody temperatures.

CAM-2802-6

Figure 2-6. Aluminum vapor momentum for given X-ray fluence at different blackbody temperatures.

Figure 2-7. Aluminum melt momentum for given X-ray fluence at different blackbody temperatures.

Figure 2-8. Aluminum velocity profile for X-ray fluence of 7.2 J/cm^2 for $\text{BBT} = 0.175$.

Figure 2-9. Aluminum velocity profile for X-ray fluence of 7.2 J/cm^2 for $\text{BBT} = 0.350$.

Figure 2-10. Aluminum velocity profile for X-ray fluence of 7.2 J/cm^2 for $\text{BBT} = 0.700$.

CAM-2802-11

Figure 2-11. Aluminum peak tensile strength and time of occurrence for 7.0 MJ X-ray output (3.48 J/cm²).

CAM-2802-12

Figure 2-12. Aluminum peak tensile strength and time of occurrence for 14.5 MJ X-ray output (7.21 J/cm²).

CAM-2802-13

Figure 2-13. Aluminum peak tensile strength and time of occurrence for 20.1 MJ X-ray output (10 J/cm²).

ablation. We began by considering a 1-mm-thick solid (nearly fully dense) alumina layer over 1 cm of aluminum but immediately found considerable spall on the front-surface and near the alumina/aluminum interface. We then pursued computations for porous, flame-sprayed alumina (2.78 g/cm^3 , 30% porosity), also 1 mm thick, which would attenuate front-surface stress, minimize spall, and provide a much better impedance match to the aluminum wall. The SRI PUFF model used for alumina is given in Appendix A.

2.3.2 X-Ray Effects

Vapor and melt thicknesses, velocities, and momenta were computed for alumina over the range of X-ray fluences corresponding to the expected source yields, and the results are shown in Figures 2-14 through 2-20. The magnitudes of each of these effects are much lower than those for aluminum; the total removal (vapor, melt, and spall) is about a factor of 3 lower, for example. Vapor velocities and momenta are mostly more than a factor of 2 lower. Melt velocities and momenta are about 1 order of magnitude or so lower. Vapor and melt layers still appear to be too thin and not expanding fast enough (at least, initially) for small droplet formation; they will eventually be broken up by overlap convergence. Most average vapor velocities of a few kilometers per second are high enough to spray most of the alumina vapor toward the antipode from each spot of the chamber wall. Molten velocities of 10 m/s are sufficiently low to be affected by gravity and, in general, will impact the opposite chamber wall significantly below the antipode from each originating spot. Consequently, molten alumina and some alumina vapor would likely directly enter beam ports with the current design, but with much less effect than that from aluminum because of the reduced mass.

2.4 OTHER PROTECTIVE COATINGS

2.4.1 Introduction

Refractory coatings are available with even higher melt and vaporization energies than those of alumina (such as beryllium and boride, as well as many beryllides and borides), and they would result in correspondingly lower total wall ablation, given minimum spall characteristics and a good impedance match to the wall. Although beryllium and the beryllides are toxic, LLNL may be prepared to deal with this problem because beryllium may be in the chamber as protection for the target positioning system. Although carbon and carbides have some of the highest vaporization energies, they were excluded in this study because of their well known harmful effects on the

CAM-2802-14

Figure 2-14. Al_2O_3 vapor ablation thickness for given X-ray fluence at different blackbody temperatures.

CAM-2802-15

Figure 2-15. Al_2O_3 melt ablation thickness for given X-ray fluence at different blackbody temperatures.

CAM-2802-16

Figure 2-16. Al_2O_3 total removal thickness (including spall) for given X-ray fluence at different blackbody temperatures.

CAM-2802-17

Figure 2-17. Al_2O_3 maximum vapor velocity for given X-ray fluence at different blackbody temperatures.

Figure 2-18. Al₂O₃ average vapor velocity for given X-ray fluence at different blackbody temperatures.

Figure 2-19. Al₂O₃ average melt velocity for given X-ray fluence at different blackbody temperatures.

CAM-2802-20

Figure 2-20. Al₂O₃ vapor momentum for given X-ray fluence at different blackbody temperatures.

optics. In our computations for each of the candidate materials, we assumed a 1-mm-thick porous coating over a 1-cm-thick 5083 aluminum first wall. (This is an arbitrary minimum aluminum thickness.)

2.4.2 X-Ray Effects

We selected flame-sprayed alumina, porous aluminum nitride, porous magnesium oxide, plasma-sprayed beryllium, plasma-sprayed boron, plasma-sprayed beryllium loaded with 5% (by weight) tungsten, and plasma-sprayed boron loaded with 5% (by weight) hafnium (this last material was added later as a primary wall candidate) for further study. Table 2-4 shows thermophysical and other properties of each of these materials. The first three materials have similar thermophysical properties, although the third has about 30% higher critical energies. The results of FSCATT and critical energy ablation calculations are shown in Figures 2-21 and 2-22 and in the table of results in Appendix B. Removal levels are typically less than a few micrometers. Plasma-sprayed beryllium (see also Appendix B for SRI PUFF results) and boron have significantly higher effective vaporization energies, so vapor generation is largely eliminated for fluences of interest (several joules per square centimeter). Moreover, boron has the highest melt energy and consequently the least melt thickness.

An important caution in considering a material with a low atomic number is to ensure that there is no debonding as a result of significant energy deposition in the aluminum wall behind the coating. For example, Table 2-5 shows that the energy deposition is unacceptable for beryllium and boron coatings at a BBT of 0.700 keV, because it produces Grüneisen stresses ($= \Gamma p_e$) in excess of 100 MPa, which may be sufficient to cause debonding at the coating/aluminum interface. To prevent this phenomenon, plasma-sprayed beryllium and boron should be lightly loaded with a material of a high atomic number (such as that in the example of plasma-sprayed beryllium loaded with 5% by weight of tungsten), even at the expense of some degradation in thermophysical properties to prevent this phenomenon. Plasma-sprayed interface bond strength are typically about 10 MPa and can be increased by "roughing" the surface or introducing a bond. Both additional tungsten loading and coating thickness will reduce interface stresses further if required.

To demonstrate the effects of loading beryllium with tungsten, we made FSCATT and SRI PUFF computations on Be 5% W. Vapor and melt ablation as a function of fluence are shown in Figures 2-23 and 2-24, and front-surface spall removal thickness is shown in Figure 2-25. Vapor ablation is less than about 0.1 μm . The spall removal thickness is slightly more than the melt ablation thickness. The average melt velocity shown in Figure 2-26 is most significant at the lowest BBT (0.175 keV).

Table 2-4

**THERMOPHYSICAL PROPERTIES OF CANDIDATE MATERIALS
FOR FIRST WALL COATING**

Material	Porous Density (g/cm³)	Solid Density (g/cm³)	Incipient Melt Energy (cal/g)	Complete Melt Energy (cal/g)	Incipient Vap. Energy (cal/g)	Sublimation Energy (cal/g)
Flame-sprayed alumina	2.78	3.98	628	873	1466	
Porous aluminum nitride	2.60	3.27	693	1020	1520	
Porous magnesium oxide	3.00	3.77	882	1340	1940	
✓ Plasma-sprayed boron	2.00	2.50	<u>1120</u>	1610	<u>2920</u>	
Plasma-sprayed beryllium	1.58	1.83	879	1190	2180	8640
Plasma-sprayed Be 5% W	1.66	1.94	842	1139	2080	8265
Plasma-sprayed B 5% Hf (5.6% HFB2-loaded B)	2.2	2.61	1080	1550	2800

CAM-2802-21

Figure 2-21. Vaporized thickness of candidate materials for first wall coating with 14.5 MJ X-ray output.

CAM-2802-22

Figure 2-22. Melted thickness of candidate materials for first wall coating with 14.5 MJ X-ray output.

Table 2-5**FRONT-SURFACE X-RAY ENERGY DEPOSITION IN ALUMINUM
WALL LAYER BEHIND CANDIDATE MATERIAL**

Source: BBT = 0.175, 0.350, and 0.700 keV
14.5-MJ X-Ray Yield
(7.20 J/cm² or 1.72 cal/cm²)

Material	Energy Deposition (cal/g) BBT (keV)		
	0.175	0.350	0.700
1 mm flame-spr Al ₂ O ₃	0.0	0.0	7.6E-4
1 mm porous AlN	0.0	0.0	6.3E-4
1 mm porous MgO	0.0	0.0	9.0E-4
1 mm p-s Be	1.4	4.4	54.0
1 mm p-s B	1.4	0.3	8.1
1 mm p-s 5% W-loaded Be	0.0	3.0E-3	0.62
1 mm p-s 5% Hf-loaded B ^a	0.0	3.8E-4	0.19
1 cm solid Be	1.0	0.074	0.34

^a p-s 5.6% HfB₂-loaded B.

Figure 2-23. Porous Be 5% W vapor ablation thickness for given X-ray fluence at different blackbody temperatures.

Figure 2-24. Porous Be 5% W melt ablation thickness for given X-ray fluence at different blackbody temperatures.

CAM-2802-25

Figure 2-25. Porous Be 5% W spall removal thickness for given X-ray fluence at different blackbody temperatures.

CAM-2802-26

Figure 2-26. Porous Be 5% W average melt velocity for given X-ray fluence at different blackbody temperatures.

2.5 PRIMARY WALL CANDIDATES

2.5.1 Introduction

Three primary candidates for the first wall were selected for further study: (1) 1-mm-thick plasma-sprayed Be 5% W over 1-cm-thick 5083 aluminum, (2) 1-mm-thick plasma-sprayed B 5% Hf (through HfB₂) over 1-cm-thick 5083 aluminum, and (3) 1-cm-thick solid Be. We assumed 15% porosity for each plasma-sprayed material. What makes the three candidate materials especially useful is their very high melt and vaporization energies. Another reason for including the solid Be candidate is to provide an option in case the walls must be cleaned of tritium; porous or plasma-sprayed material may not be practical, both because it will readily absorb the tritium and because the wall cannot be easily scrubbed. (We are presuming that the plasma-spraying technology can be adapted to the chamber and is not too expensive to implement.) The computational models we used for the SRI PUFF computations required for vapor and melt velocity information are included in Appendix A.

2.5.2 X-Ray Effects

As we discussed above, the high atomic number loading in the first two candidate materials reduces the energy deposition into the aluminum substrate presumably enough to preclude debonding. This result is evident from the fairly low energy deposition shown in Table 2-5 (at 0.7 keV) for the two loaded primary wall candidates compared with those of the unloaded materials (Be and B). An achievable bond strength (which may require some "roughening" of the surface) of several tens of megapascals should avoid debonding. The third material (solid Be) has a very low atomic number but provides a good alternative because it is thick enough at the cold blackbody temperatures of interest to have low X-ray transmission. If the beryllium is at a stand off from the aluminum wall, then the primary concern is that the beryllium only be thick enough to prevent front surface spall arising from deposition in the aluminum.

Figures 2-27 through 2-32 show ablation effects of the three candidate materials at X-ray outputs of 14.5 and 7.0 MJ, corresponding to fluences of 7.2 and 3.5 J/cm² at the wall. Removal is typically tenths of a micrometer for vapor ablation and micrometers for melt ablation. Maximum removal occurs at the lowest BBT (0.175 keV). Of the 3 candidates, plasma-sprayed B 5% Hf has the most vapor ablation (0.3 μ m) but the least melt ablation (about 1 μ m or less) because it has the lowest vaporization energy and the highest melt energy.

CAM-2802-27

Figure 2-27. Vaporized thickness of 3 candidate materials for first wall coating with 14.5 MJ X-ray output ($7.2\text{J}/\text{cm}^2$).

CAM-2802-28

Figure 2-28. Melt thickness of 3 candidate materials for first wall coating with 14.5 MJ X-ray output ($7.2\text{J}/\text{cm}^2$).

CAM-2802-29

Figure 2-29. Vaporized thickness of 3 candidate materials for first wall coating with 7.0 MJ X-ray output (3.5 J/cm^2).

CAM-2802-30

Figure 2-30. Melt thickness of 3 candidate materials for first wall coating with 7.0 MJ X-ray output (3.5 J/cm^2).

CAM-2802-31

Figure 2-31. X-ray energy deposition in P-S B 5% Hf first wall.
7.05 MJ X-ray yield: 3.5 J/cm^2 (0.837 cal/cm^2).

CAM-2802-32

Figure 2-32. X-ray energy deposition in beryllium first wall.
7.05 MJ X-ray yield: 3.5 J/cm^2 (0.837 cal/cm^2).

CAM-2802-33

Figure 2-33. Average vapor velocity of candidate materials for first wall coating with 14.5 MJ X-ray output (7.2 J/cm^2).

CAM-2802-34

Figure 2-34. Average melt velocity of candidate materials for first wall coating with 14.5 MJ X-ray output (7.2 J/cm^2).

CAM-2802-35

Figure 2-35. Average vapor velocity of candidate materials for first wall coating with 7.0 MJ X-ray output (3.5 J/cm^2).

CAM-2802-36

Figure 2-36. Average melt velocity of candidate materials for first wall coating with 7.0 MJ X-ray output (3.5 J/cm^2).

The average vapor and melt velocities are shown in Figures 2-33 through 2-36 for the 14.5-MJ and 7.0-MJ X-ray output levels. The highest average vapor velocities are a few kilometers per second or less. The highest average melt velocities are several thousand meters per second. However, the average melt velocity of the plasma-sprayed B 5% Hf is less than only 100 m/s, because of the very high melt energy.

Figures 2-37 and 2-38 show results from a solid Be SRI PUFF "no-damage" run for 7 MJ (3.5 J/cm^2). Figure 2-37 shows the minimum stress (i.e., maximum tensile stress) versus depth in Be. Peak tensile stresses in the solid Be can exceed the threshold fracture stress of several hundred megapascals here, but the duration is unlikely to grow cracks from nucleation. Even at a depth of 0.25 cm into the solid Be for the worst case BBT = 0.350 keV, the tensile pulse width is only 20 ns (it would be shorter at shallower depths), as shown in Figure 2-38.

The plasma-sprayed B 5% Hf appears to have the best overall properties for suppressing vapor and especially melt. The solid Be wall is also a good performer. The plasma-sprayed Be 5% W may be acceptable, but shows front-surface spall, which we did not see in our estimated model for plasma-sprayed B 5% Hf.

2.6 RECOMMENDATIONS

Further computations should be made to determine the effects of the expected time-dependent X-ray source spectrum on material removal instead of just the simple blackbody assumption we have made. The effects of heat conduction on material removal should also be investigated. Moreover, we should calculate the expansion of vapor and melt layers produced at the wall to better determine their effects at the antipode locations in the target chamber.

We support LLNL's planned experiment in Nova to determine the extent and anisotropy of hohlraum radiation and debris in a "dud" fusion shot.

Further experimental (gas gun, Nova X-ray) and computational equation-of-state work is needed to more accurately sort out the advantages and disadvantages of each of the above primary materials over another. There is some uncertainty in the vapor behavior of plasma-sprayed Be 5% W and B 5% Hf models. Also, the porous compaction and thermal softening curves for B 5% Hf are largely unknown. A rapidly degrading thermal softening behavior with increasing temperature would reduce the tensile strength and could make front-surface spall more of a liability than we have assumed.

CAM-2802-37

Figure 2-37. Peak tensile stress in solid beryllium for 7.05 MJ X-ray yield: 3.5 J/cm^2 (0.837 cal/cm^2).

CAM-2802-38

Figure 2-38. Stress history in solid beryllium first wall showing typical tensile pulse for 7.05 MJ X-ray yield: 3.5 J/cm^2 (0.837 cal/cm^2).

The effects of multiple-shot degradation of properties should be further investigated by use of our fracture models. However, we also recommend that Nova or lower-level fluence X-ray experiments be performed to investigate this phenomenon before proceeding too much further to consider using plasma-sprayed material in a Nova Upgrade design. We need to find out whether the surface material strength is seriously degraded by multiple-shot exposure. However, we expect the vapor and melt erosion of each shot to eliminate some of the "stored-up" fracture from a previous shot.

Section 3

STAINLESS STEEL COOLANT TUBING

3.1 INTRODUCTION

The hohlraum is suspended on four very fine stainless steel tubes that conduct helium as a coolant to maintain the temperature of the hohlraum. During a fusion experiment, these tubes are radiated by neutrons and X-rays from the source and are struck by the hohlraum debris expanding from the test center. During the first nanosecond, the neutron energy is deposited into the tubes and the helium in the tubes within 5 cm of the target, heating them and causing them to expand rapidly. Because the tubes are small and the deposition is quite uniform, the tubes simply expand radially. A few to several nanoseconds later, depending on the target design, X-ray radiation is deposited in the near-surface of the tubes. This radiation vaporizes a thin layer of the surface: the expansion of this vapor causes an impulse that pushes the tubes away from the hohlraum. After some tens or hundreds of nanoseconds, the expanding hohlraum debris impinges on the tubes, further pushing on the tubes.

Under neutron heating, the stainless steel tubes are transformed into vapor, liquid, or heated solid material, depending on the local intensity of the radiation. The rapid expansion of the solid portions of the tubes causes some parts of the tubes to spall and split into small fragments. Similarly, the liquid portions are broken into droplets. All these fragments are propelled radially at significant velocities (300 to 3000 m/s for fragments of the solid to liquid types, and depending on the deposited energy). The later X-radiation vaporizes a small portion of additional material and modifies the direction and velocity of the fragments. The impact of the debris on the expanding tubes also tends to alter the direction and velocity of the tube fragments.

In the following sections, we describe these processes and the computations we have performed to estimate the response of the tubes. For ease in simulating the overall behavior, we have separated the computations into a series of steps. Then we have assembled the results of each step to describe the overall behavior.

The tubes have inner diameters of 0.0125 cm and outer diameters of 0.02 cm. They extend about 20 cm from the hohlraum to the target inserter. These tubes are filled with cold helium.

3.2 PROPERTIES OF TUBING

The properties of the stainless steel tubing are required for representing the response of the tubes during the deposition of the X-rays and neutrons and the impact of the hohlraum debris. The temperature of the stainless steel is 16 to 18 K initially, and the steel is heated in a few nanoseconds to elevated temperatures. Below we give our best estimates of the appropriate properties for the stainless steel under these circumstances. First we indicate the thermal properties of the steel, based on the properties of the component metals. Then we give the Hugoniot (shock wave information) and estimates of the fracture properties.

The thermal properties of the 316 SS stainless steel used in the calculations are based on the following proportions of elements (Smith, 1991):

Mn 2.0, Mo 2.5, Cr 17.0, Ni 12.0, Fe 66.5%

With these components we constructed Table 3-1 to determine the internal energies of major interest. We assumed that the iron, chromium and nickel determine the general behavior of the mixture of metals, so their melting and vaporization temperatures govern. Nickel melts first at 1728 K, so that temperature determines the onset of melting. Chromium melts last at 2130 K, so that temperature defines the end of melting. Similarly, chromium boils first at 2952 K and nickel boils last at 3157 K. Then we determined the enthalpies of each of the elements at these temperatures. The enthalpy for stainless steel is taken as a weighted average of these values. Clearly, these energies do not account for eutectic behavior but are only rough estimates of the appropriate behavior.

3.2.1 Shock Wave Properties

The shock wave properties include the Hugoniot pressure-volume curve (bulk modulus) and the Grüneisen ratio. The bulk modulus was taken as 165 GPa from a combination of acoustic, Hugoniot, and other data. The Grüneisen ratio Γ is from specific heats and volumetric thermal expansion data. The range of Γ is from 2.2 down to 1.4 over the temperature range for which we have data, with 1.5 over much of the midrange, so 1.5 is the value used here. The parameters we used for stainless steel 316 are given in Appendix A, and the Mie-Grüneisen and PUFF expansion equations of state we used are described in Appendix C.

Table 3-1
ENERGIES FOR STAINLESS STEEL 316

	<u>Iron</u>	<u>Chrom.</u>	<u>Nickel</u>	<u>Molybd.</u>	<u>Mangan.</u>	<u>SS 316</u>	<u>Note</u>
Fract. in 316	66.5%	17.0%	12.0%	2.5%	2.0%	100%	
Atomic wt.	55.847	51.996	58.71	95.94	54.938	56.520	
H @ 1728K	1070 J/g	996 J/g	888 J/g	475 J/g	1396 J/g	1027 J/g	Begin melt
H @ 2130K	1642 J/g	1781 J/g	1446 J/g	626 J/g	1733 J/g	1619 J/g	End melt
H @ 2952K	2320 J/g	2403 J/g	1991 J/g	1382 J/g	6257 J/g	2350 J/g	Begin vapor
H @ 3157K	8740 J/g	9055 J/g	8558 J/g	1462 J/g	6340 J/g	8542 J/g	End vapor
Sublim. en.	7399 J/g	7605 J/g	7293 J/g	6852 J/g	5134 J/g	7362 J/g	
Melt temp.	1809K	2130K	1728K	2896K	1519K	—	
Boil temp.	3133K	2952K	3157K	4952K	2334.5K	—	

3.2.2 Strength and Fracture Properties

Strength properties were also provided by Smith (1991). The yield strength was given as 30 ksi (207 MPa) and the ultimate strength as 80 ksi (552 MPa) with a 60% elongation; all these values are at room temperature. At temperatures near absolute zero, the strength is probably three times as high and the material is more brittle. As the material is heated to melting, its strength reduces to zero and the elongation increases, but for dynamic loading we know that the strength tends to degrade more slowly with increasing temperature. Therefore, these room-temperature properties were assumed valid from the initial conditions of about 20 K up to melting.

From these properties, we then constructed the parameters for the BFRACT (Seaman et al., 1985) microfracture model for high-rate brittle fracture. The threshold stress for microfracture was taken as the static strength, 552 MPa. We set the nucleation and growth rates to be like those of fairly ductile steels we have characterized before (armor steels XAR30 [Seaman et al., 1975] and MIL-S-12560B [Shockey et al., 1973]), as shown in Table 3-2. Table 3-3 describes the microfracture properties T_1 through T_6 and lists the estimated properties of the stainless steel.

3.2.3 Fragmentation Properties

A fragmentation procedure developed by Mott (1947) was used to determine how the stainless steel tubes are split under the radiation loading. This computation required the following properties:

Density of 8.00 g/cm³
Tensile strength of 552 MPa
Mean tensile strain to failure of 60%
Gamma = 40

Gamma is a critical parameter of Mott's procedure; it represents the standard deviation of the tensile strain around the mean value. The value of 40 gives a root mean square (rms) failure strain of $1.28/40 = 3.2\%$, according to Mott's analysis (see Equation D-7 in Appendix D).

3.3 HELIUM PROPERTIES

The properties of helium are needed from 4.5 K up to temperatures associated with the vaporization of steel. These properties are needed to model the deposition of the neutron energy into the helium in the stainless steel tubes and the subsequent expansion of the helium, which contributes to the expansion of the tubes.

Table 3-2

COMPARISON OF XAR30 AND MIL-S-12560B STEELS

Property	XAR30		MIL-S-12560B		Units
	Static	Impact ^a	Static	Impact ^a	
Yield	1.4		1.03		GPa
Tensile Strength	1.7		1.12		GPa
Elongation	13.0		20.0		%
T_1		-550.0		-900.0	1/MPa/s
T_2		-10.0		-200.0	MPa
$T_3 = R_n$		4.0E-3		3.0E-3	cm
$T_4 = \dot{N}_0$		4.0E14		2.5E14	No./m ³ /s
$T_5 = \sigma_{n0}$		-2500.0		-1120.0	MPa
$T_6 = \sigma_1$		-178.6		-100.0	MPa

^a Sign convention for stress is positive in compression.

Table 3-3

FRACTURE PARAMETERS FOR 316 STAINLESS STEEL

Parameters	Value ^a	Units	Description
T_1	-400.0	1/MPa/s	Growth coefficient
T_2	-100.0	MPa	Threshold stress for growth
$T_3 = R_n$	0.004	cm	Initial crack size paramete
$T_4 = \dot{N}_0$	5.0E14	No./m ³ /s	Nucleation rate coefficient
$T_5 = \sigma_{n0}$	-2500.0	MPa	Nucleation threshold stress
$T_6 = \sigma_1$	-200.0	MPa	Stress sensitivity for nucleation
$T_7 = R_{max}$	0.1	cm	Maximum flaw size in nucleation size distribution

^a Sign convention for stress is positive in compression.

A code called FITGAS was constructed to fit thermodynamic data for helium to an analytical equation of state for use in the wave propagation calculations. The data on helium were obtained from Sychev et al. (1987). For the analytical form, we chose the Mie-Grüneisen and PUFF expansion equations of state, which we use regularly in our radiation and wave-propagation computations. These equations are described in Appendix C. We made a least-squares fit of the data to the analytical forms of these equations. The resulting values are given in Table 3-4 (also see Appendix A). The analytical form appeared to be a good representation of the data values in the range of interest here.

The starting conditions for the helium were given by Tobin (February 1992) as

$$P = 100 \text{ atm}$$

$$\rho = 0.207 \text{ g/cm}^3$$

$$T = 4.5 \text{ K}$$

The internal energy in helium needed to provide a pressure of 10 MPa and a density of 0.207 g/cm^3 is $3.825\text{E}7 \text{ erg/g}$ (according to the equation of state fitted above). These values were used as starting conditions. Generally this energy value is negligible for neutron radiation values and so was disregarded.

3.4 NEUTRON ENERGY DEPOSITION

3.4.1 Introduction

The neutron energy deposited into the cryogenic tubes provided the major response for these elements. Therefore, we start with the neutron aspect of the problem. First we examine the amounts of energy deposited and the states (vapor, liquid, solid) achieved. Then we determine the particle velocities with which each portion of the tube expands radially because of this neutron loading. Finally, we examine the spall fracture and splitting of the hot solid portions and droplet formation in the liquid portions of the tubes.

The neutron energy deposited into the stainless steel tubes and the helium inside the tubes were provided in two figures from Tobin (January 1992). These figures, which are reproduced as Figures 3-1 and 3-2, provide the energy in J/g per MJ of neutron source from two computations: One computation emphasized the region near the hohlraum, and the other gave an energy deposition to 20 cm along the tube. The neutron energy is assumed to be deposited within 1 ns.

Table 3-4
MIE-GRÜNEISEN AND PUFF EXPANSION PROPERTIES OF HELIUM

Symbol	Value	Description
ρ_0	0.1719 g/cm ³	Reference density
C	34.68 MPa	Initial bulk modulus
D	49.7 MPa	2nd term in series expansion for bulk modulus
S	147.4 MPa	3rd term in series expansion for bulk modulus
E_s	4.59 J/g	Sublimation energy
Γ	1.753	Grüneisen ratio
H	0.697	Grüneisen ratio of expanded states
n	2.055	Exponent of variation of the Grüneisen ratio

CM-2802-39

Figure 3-1. Neutron energy deposited in cryogenic tube (helium and stainless steel) versus radius from end of tube.

CM-2802-40

Figure 3-2. Neutron energy deposited in cryogenic tube versus radius from pellet.

The X-rays arrive later (assumed to be a few nanoseconds) and the hohlraum debris still later; thus, the initial conditions are set by the neutron deposition.

3.4.2 Material State in Tubes

These data on deposited neutron energy as a function of distance along the tubes were used to construct graphs of energy intensity as a function of distance for three specific source energies of interest, as shown in Figure 3-3 and listed in Table 3-5. The three curves correspond to total source energies of 5, 20, and 45 MJ. Here we have assumed that 80% of these total energies was in neutron radiation. The listed energy values are the total source energies in neutrons. Regions on the graph are marked with the states of the material to aid in assessing the material behavior. For example, in the highest-energy case, 1.3 cm of the front of the tube reaches the vapor or liquid-vapor range. The graph also shows the regions of expected fracture damage (split and spall) for material that is hot but remains solid. These fracture processes are discussed later.

3.4.3 Particle Velocities of Tube

Under neutron radiation, the tube at each radial distance from the hohlraum experiences an essentially uniform energy intensity. This energy varies gradually with location along the tube, as indicated in Figure 3-3. Hence, we can assume that the tube expands uniformly like a ring at any position along its length, although the amount of expansion varies with position. Therefore, the particle velocities of the tube were determined by a series of cylindrically symmetrical simulations at various positions along the tube. We selected those positions corresponding to energies at the transitions from solid to solid-liquid, solid-liquid to liquid, and so forth, as shown in Table 3-6. The results depended only on the radiant energy and were therefore independent of the position along the tube and the yield of the pellet. The computations were made with our one-dimensional wave propagation code SRI PUFF in its cylindrically symmetrical mode. The resulting average velocities of the inner and outer surfaces of the tubes are shown in Figure 3-4 with the indicated material state noted. This information is also listed in Table 3-7. A very similar behavior was noted for aluminum tubes under neutron radiation in Appendix B of a previous report (Seaman et al., 1989). There we discovered that the velocity-energy relation can be approximated analytically.

3.4.4 Spall Fracture of Tubes

Fracture in the tubes can be separated into three types: (1) spall separation along the midplane of the tube, (2) splitting of the outer surface of the tube into strips, and (3) bending and breaking of the strips. The three types occur in numerical order in time. The first two types occur

Figure 3-3. Neutron energy in stainless steel tubes for neutron yields of 4, 16, and 36 MJ.

Figure 3-4. Particle velocity in stainless steel tubes as a function of deposited neutron energy.

Table 3-5

ENERGIES AND STATES AT LOCATIONS IN TUBES

Energy and State	4 MJ^a	16 MJ^a	36 MJ^a
100 J/g	3.2 cm	6.3 cm	9.3 cm
200	1.8	4.6	6.8
✓ 400 Fracture into strips	1.2	3.2	5.0
600	0.8	2.2	4.0
✓ 700 Spall threshold	0.65	2.0	3.6
800	0.6	1.8	3.3
1040 Begin melt	0.5	1.6	2.8
1650 End melt	0.2	1.15	2.0
2306 Begin liquid-vapor	—	0.85	1.5
8783 End liquid-vapor	—	—	0.5

^a Total neutron energy in the source yield.

Table 3-6

SRI PUFF SIMULATION CASES WITH ENERGIES AND PRESSURES

Material State	Stainless Steel		Helium	
	Energy^a	Pressure^b	Energy^a	Pressure^b
Begin fracture	4.0E9	4.8E10	7.2E10	2.178E10
Begin melt	10.4E9	1.248E11	18.72E10	5.65E10
End melt	16.5E9	1.98E11	29.7E10	8.96E10
Begin sublimation	2.306E10	2.77E11	4.15E11	1.251E11
End sublimation	8.78E10	1.054E12	1.58E12	4.76E11
High range	1.E12	1.2E13	1.8E13	5.424E12

^a Energies in erg/g.

^b Pressures in dyn/cm².

Table 3-7
PARTICLE VELOCITY AS FUNCTION OF ENERGY AND STATE

State of Material	Energy (J/g)	Velocity (m/s)
Solid	100	80
Solid	200	207
Threshold of splitting fracture	400	327
Solid, splitting	600	423
Threshold for spalling	700	486
Solid, splitting and spalling	800	511
Boundary: solid and solid-liquid	1,027	586
Boundary: solid-liquid and liquid	1,650	849
Boundary: liquid and liquid-vapor	2,306	1,058
Boundary: liquid-vapor and vapor	8,783	2,703
Vapor	100,000	13,500

primarily in response to the motions induced by the neutron radiation. The third type may occur because of neutrons, X-rays, and debris. We treat the first two types in detail here and only presume that the third type occurs but provide no detailed examination.

Spall occurs because of the rapid expansion of the tubes under the neutron radiation. This radiation is deposited within a time period on the order of 1 ns; hence, the tube cannot expand during this deposition. The helium in the tubes is also heated by this radiation. This sudden heating causes high pressures in the tubes and the helium, which reaches about half the pressure of the tubes. The high pressures in the tubes are quickly relieved by rarefaction waves that travel into the tubes from the outer free surface and from the interface between the helium and the tubes. When these rarefaction waves meet at the midplane of the tubes, they produce a state of tensile stress, which, if high enough, causes microfractures to form; if this stress persists long enough, the fractures coalesce into a complete separation: a spall. Thus, each tube separates into two concentric tubes. The spall fractures occur during a period from 20 to 60 ns.

The spall fracture process was simulated with the SRI BFRACT model for brittle microfracture by use of the parameters indicated earlier in Table 3-3. From the one-dimensional cylindrically symmetrical PUFF computations, we determined that a deposited energy of 700 J/g was enough to cause full spall. Lesser energies down to about 400 J/g cause partial fracture but not complete separation. The 700-J/g threshold was shown earlier in Figures 3-3 and 3-4. A more detailed description of the fragments formed is given below.

3.4.5 Splitting in Tubes Under Neutron Loading

According to our simulations, the circumferential tensile stress generated in the tubes by the neutron heating is enough to cause fracture with energies greater than 400 J/g. This fracture will lead to axial splitting of the tubes into strips. This splitting will extend from the location in the tube at which the energy just reaches 400 J/g to the region in which the tube reaches incipient melting, about 1027 J/g. In the region from 400 to 700 J/g, the splitting will extend from the outer to the inner surface of the tube. From 700 to 1027 J/g (the range of spall fracture), the inner and outer portions of the tube will split separately.

When a tube splits, it also generally divides into segments lengthwise. We have estimated for the current program that the length of the segments are not longer than ten times the minimum dimension in the thickness or circumferential direction. This additional fracture process may be caused by nonsymmetrical loadings from the X-rays and debris or simply by the irregularity of the fracture in the splitting direction.

The splitting of the tubes was computed by use of the procedure developed by Mott (1947) for analyzing the disintegration of shell cases. Curran (1988) recently verified this theory experimentally and theoretically. The basis of the theory is outlined briefly in Appendix D. This procedure was written into a small code called MOTT for computing the splitting fractures. Then a second code (MOTT2) was constructed to provide for the breaking of the strips lengthwise and to assemble size distributions of the fragments. We used Curran's data to determine the Mott parameter γ at about 40 for the stainless steel.

The results of the splitting computations using the Mott theory are shown in Figures 3-5 through 3-8. Figure 3-5 shows all the fragments per tube as a function of the fragment mass for the three neutron yields of interest. According to Table 3-7, these fragments should be moving at velocities between 327 and 586 m/s. In Figure 3-6(a) through (c), these variations in velocity are treated in more detail for each source yield. Here we have clearly constructed fragment size distributions only for specific energy or velocity levels (327, 467, and 586 m/s). The velocity 467 m/s is the boundary between splitting alone and the combination of spalling and splitting; hence, there are two size distributions at this velocity, one for splitting and one for the combination.

3.4.6 Droplet Formation in Liquid Range

As the tube material with enough energy to reach melting expands, we expect it to stretch and then form droplets. These droplets will then continue toward the walls with approximately their initial particle velocity, as shown in Table 3-3, that is, between 586 and 2703 m/s. The droplet computations are taken from an analysis by Trucano et al. (1990). We do not believe this theory is sufficiently verified, but the droplet sizes should be accurate within a factor of 3.

Grady's formula for the droplet diameter is

$$D = \left(\frac{48\gamma}{\rho(d\varepsilon/dt)^2} \right)^{1/3}$$

Here γ , the surface tension, is about 1800 dyn/cm for iron, chromium, and nickel at temperatures near melting. The strain ε is given by

$$\varepsilon = \sqrt{\frac{2}{3}} \sqrt{\varepsilon_r^2 + \varepsilon_\theta^2} = \sqrt{\frac{4}{3}} |\varepsilon_r| \quad \text{because } \varepsilon_r = -\varepsilon_\theta$$

CAM-2802-31

Figure 3-5. Fragment sizes for 4, 16, and 36 MJ of neutron energy.
(Fragment velocities range from 327 to 586 m/s.)

(a) 4 MJ of neutron energy

(b) 16 MJ of neutron energy

(c) 36 MJ of neutron energy

CAM-2802-44

Figure 3-6. Fragment sizes of stainless steel tubes.
(Fragment velocities of 327, 467, and 586 m/s.)

Figure 3-7. Velocity of droplets from stainless steel tubes.

(a) Relative location at point A

(b) Direction of radiation absorption at point A

CM-2802-46

Figure 3-8. Geometry of hohlraum and tubes for X-ray absorption.

The circumferential strain rate is

$$\frac{d\epsilon_{\theta}}{dt} = \frac{V}{r} \text{ and therefore, } \frac{d\epsilon}{dt} = \sqrt{\frac{4}{3}} \frac{V}{r}$$

where V is the radial velocity and r is the current radius. Hence, the droplet diameter in centimeters (radius in centimeters and velocity in centimeters per second) is

$$D = 26.3 \left(\frac{r_0}{V} \right)^{2/3}$$

Here we have also let the tube radius r at the time of fracture be $1.5 r_0$ to allow for expansion before fragmentation. The original mean radius r_0 of the stainless steel tubes is 0.01625 cm. The computed diameters are listed in Table 3-8 with the associated particle velocities. The numbers of droplets (not listed here) is simply the mass of material divided by the mass per particle.

The information on the droplet sizes and numbers was combined with the fragment size information from Section 3.4.5 to construct Table 3-9 and Figure 3-7. Here a mean diameter for the fragments has been constructed as the radius of a sphere with the same mass as that of the computed fragment. The horizontal lines show the range of droplet or fragment diameters, and the Xs in the midranges show the mean diameter. Figure 3-7 shows only the velocity as a function of particle diameter and hence is valid for all neutron source magnitudes. The numbers (actually numbers of fragments or droplets per tube) are listed in Table 3-9 for each range between the energies at phase boundaries. Table 3-9 is specific for the case of the 36-MJ neutron source because it also shows the number of particles, which depends on the amount of tube material brought to each phase.

So we have indications of the fragment and droplet size distributions for the stainless steel tubes over the entire range from solid to vapor.

3.5 X-RAY EFFECTS ON STAINLESS STEEL TUBES

The X-rays are deposited into the tube materials somewhat later than the neutrons. Here we assumed that the X-rays begin to arrive a few nanoseconds after the initiation of neutron radiation and persist for 10 ns. We also assumed that the X-ray source is a blackbody with a temperature of 350 eV.

Table 3-8
DIAMETERS OF LIQUID DROPLETS

Energy (J/g)	Velocity (m/s)	Diameter (μm)	Material State
1027	586	11.0	Boundary: solid & solid-liquid
1650	849	8.83	Boundary: solid-liquid & liquid
2306	1058	7.54	Boundary: liquid & liquid-vapor
8783	2703	4.04	Boundary: liquid-vapor & vapor

Table 3-9
DROPLET AND FRAGMENT SIZES FOR 36-MJ NEUTRON SOURCE

Energy (J/g)	Velocity (m/s)	Diameter (μm)	Numbers per Tube	Material State
400	327	46.7		Begin splitting
			{400	Splitting
700	467	32.7		Begin spalling
			{770	Spall and split
1027	586	26.1 (Sol.) 11.0 (Liq.)		Solid to solid-liquid
			{1.1 x 10 ⁶	Solid-liquid
1620	849	8.8		Solid-liquid to liquid
			{1.2 x 10 ⁶	Liquid
2306	1058	7.5		Liquid to liquid-vapor
			{7.8 x 10 ⁶	Liquid-vapor
8783	2703	4.0		Liquid-vapor to vapor

The geometry of the hohlraum and tubes is shown schematically in Figure 3-8. From this sketch we see that the X-rays coming from the source strike the tubes at point A at an angle defined by ϕ to the normal direction (radially outward from the tubes). These X-rays strike only the surface facing the hohlraum and generally penetrate less than 1 μm . This material is then vaporized and blows off radially outward from the tubes, sending a compressive wave back into the tube walls. This compressive wave tends to impart a particle velocity on the wall in the direction away from the hohlraum. The tubes have already begun to expand radially from the neutron-deposited energy. The X-rays then add a velocity component that opposes the direction of the velocities caused by the neutrons, but the X-rays act only on the side facing the hohlraum. Computations must be made in each case to appropriately add the X-ray and neutron contributions (the hohlraum debris adds another contribution that is considered later) to determine the motions of the tubes in detail. The X-rays strike while the tubes are still expanding under the influence of the neutron heating and before spall has occurred. The interaction of the motions induced by the neutrons and the X-rays will reduce the tendency to spall on the side facing the hohlraum, but otherwise the fracture processes are unaffected by the X-rays. We have not taken this minor interaction effect into account.

In the following discussion we briefly outline the steps taken to compute the X-ray energy deposited into the tubes and the resulting particle velocity. The fluence F at any location along the tubes is given by the natural relation between the total X-ray source energy S_x and the radial distance R (in Figure 3-8a) to the location:

$$F = \frac{S_x}{4\pi R^2} = \frac{S_x}{4\pi[c^2 + (r_h + h)^2]}$$

where c is half the length of the hohlraum cylinder, r_h is its radius, and h is the distance from the hohlraum along the tube to the location of interest.

When X-rays are deposited into a sloping surface, they are absorbed in the same way they would be if the surface were normal to the direction of the X-rays (this approximation is especially good for X-rays from a low-temperature source). Although the X-rays penetrate to the usual distance x (illustrated as point B in Figure 3-8[b]), the actual depth X_{act} into the tube wall is reduced by the cosine of the angle to the normal, as shown in Figure 3-8(b).

$$X_{\text{act}} = x \cos \phi$$

We performed deposition computations with the FSCATT code (Fisher and Wiehe, 1970) with radiation absorption data fitted by Biggs and Lighthill (1971). This calculation was

performed for a fluence of 1 cal/cm² and the results were scaled to the particular fluences and deposition angles required.

The next step was to use the deposition profile to determine the actual depth at which the energy was deposited, estimate the momentum caused by the blowoff of the vapor, and compute the velocity that would be imposed on the rest of the tube by this momentum. Deposition computations were made for selected points along the tubes for each of the three source energies: 5, 20, and 45 MJ. The selected points were generally at boundaries between material phases. These computations were made with SRI PUFF using the FSCATT-generated deposition profile. Here the fluences and the actual depths (scaled by the cosine of ϕ) were used. From these PUFF simulations we determined the momentum and the resulting velocities of the tube.

The momentum was computed with the McCloskey-Thompson formula. The momentum I_j is the cumulative momentum imparted to the rest of the material by vapor blowoff (and liquid splashoff), summing from the free surface to the depth x_j :

$$I_j = 1.2 \left\{ 2 \int_0^j z \left[E - E_m \left(1 + \ln \frac{E}{E_m} \right) \right] dz \right\}^{1/2}$$

where E is the deposited energy at the depth x (erg/g),

E_m is the melt energy (erg/g),

x is the depth coordinate (cm),

z is the cumulative mass at the depth x given by ρx (g/cm²), and

I_j is the impulse at depth x_j (dyn-sec/cm²).

The foregoing analysis of the momentum was performed for a planar situation, but we have a cylindrical geometry. In our case, the energy intensity must vary around the tube, with a maximum in front and zero at the sides. To represent this variation approximately, we can multiply by $\cos \theta$, where θ is the angle from the point nearest the hohlraum. The velocities of the vapor are directed radially outward from the tube, and we want the component only in the direction toward the hohlraum; hence, we must apply another $\cos \theta$ factor,

$$V_{xray} = I_{max} \frac{\int_{-\pi/2}^{\pi/2} \cos \theta \cos \theta d\theta}{m} = \frac{I_{max}}{2m}$$

where $I_{\max}$ is the total momentum at a location along the tube and m is the mass per unit area of the side of the tube. The results of these simulations and the subsequent evaluation of the velocity V_{xray} are given in Tables 3-10 through 3-12. Because of the geometry of the problem, there is no simple relationship between the neutron energy and X-ray quantities such as the impulse or velocity.

3.6 EFFECTS OF HOHLRAUM DEBRIS ON TUBES

The material of the hohlraum is vaporized during the fusion event and flows past the tubes, imparting some momentum to these tubes. The hohlraum is assumed to consist of a metal cylindrical shell with end caps and to have the density of lead. Here we consider the effect of the expanding hohlraum debris on the response of the cryogenic tubes.

The hohlraum debris is assumed to expand very rapidly (on the order of 100 km/s), so the first material arrives at the tubes around 60 ns after the event, long after X-ray deposition is completed (10 to 15 ns) and after spall and splitting have occurred. The X-ray deposition onto the tubes produces a thin layer ($<1 \mu\text{m}$) of vapor that expands at velocities comparable to those of the hohlraum material; hence, this vaporized tube material is not near the tubes at the time the hohlraum material flows by, so there is no interaction between these vapors that can affect the tubes. But the hohlraum debris does strike the residual solid material of the tubes, which is still in essentially the same original location.

We visualize the expanding hohlraum as a high wind blowing past the tubes. To define its effect on the tubes, we must know the histories of the pressure, the particle velocity, and the density of the hohlraum wind at specific locations on the tubes. For this purpose we performed spherically symmetrical computations of the expansion of a spherical shell under prescribed heating and determined the flow parameters at radial positions corresponding to selected locations along the tubes. To determine the motion of the tubes, we computed two impulses: that provided by the pressure in the hohlraum wind and that from the dynamic pressure ($1/2\rho V^2$). Then we divided these impulses by the tube masses to obtain the velocities imparted by the hohlraum wind on the tubes.

For our computations the hohlraum was taken as a spherical lead shell. The energy (10% of the source energy) was inserted uniformly into the material of the shell, raising its state well into the vapor range. Spherically symmetrical wave propagation computations were made with SRI PUFF to follow the expansion of these gases. During the computations, the pressures densities, and particle velocities were recorded at the Eulerian locations of specific points on the stainless steel tubes. Generally these points were chosen as phase boundaries.

Table 3-10
X-RAY RESULTS FOR 5-MJ SOURCE
(0.5 MJ IN X-RAYS)

Region	Neutron Fluence (J/g)	Dist.^a (cm)	X-Ray Fluen. (J/cm²)	X-Ray Impuls. (ktap)	X-Ray Vel. (m/s)	Dist. 90% E (μm)
Solid	100	3.2	3,180	0.7994	26.1	0.144
	200	1.8	8,540			
Begin fr. strip	400	1.2	15,900	4.144	135.4	0.34
	600	0.8	27,200			
Begin spall	700	0.65	34,500	9.072	296.5	0.495
	800	0.6	37,500	9.877	322.8	0.52
Begin melt	1040	0.5	44,700	11.78	385.0	0.57
End melt	1650	0.2	79,600	21.08	688.9	0.76
Begin liq-vapor	2306	—	—			

Table 3-11
X-RAY RESULTS FOR 20-MJ SOURCE
(2.0 MJ IN X-RAYS)

Region	Neutron Fluence (J/g)	Dist.^a (cm)	X-Ray Fluen. (J/cm²)	X-Ray Impuls. (ktap)	X-Ray Vel. (m/s)	Dist. 90% E (μm)
Solid	100	6.3	3,633	0.4608	15.06	0.073
	200	4.6	6,560			
Begin fr. strip	400	3.2	12,700	1.654	54.05	0.14
	600	2.2	24,500			
Begin spall	700	2.0	28,700	3.771	123.2	0.22
	800	1.8	34,200	4.492	146.8	0.24
Begin melt	1040	1.6	41,200	5.433	177.5	0.265
End melt	1650	1.15	67,700	8.956	292.7	0.345
Begin liq-vapor	2306	0.85	101,000	13.44	439.2	0.435
End liq-vapor	8783	—	—			

^a Dist. is the distance along the tube from the hohlraum.

Table 3-12
X-RAY RESULTS FOR 45-MJ SOURCE
(4.5 MJ IN X-RAYS)

Region	Neutron Fluence (J/g)	Dist.^a (cm)	X-Ray Fluen. (J/cm²)	X-Ray Impuls. (ktap)	X-Ray Vel. (m/s)	Dist. 90% E (μm)
Solid	100	9.3	3,875	0.3312	10.83	0.046
	200	6.8	7,070			
Begin fr. strip	400	5.0	12,600	1.098	35.88	0.09
	600	4.0	19,100			
Begin spall	700	3.6	23,200	2.027	66.24	0.125
	800	3.3	27,100	2.376	77.65	0.144
Begin melt	1040	2.8	36,300	3.19	104.25	0.162
End melt	1650	2.0	64,600	5.703	186.34	0.221
Begin liq-vapor	2306	1.5	103,000	9.082	296.8	0.28
End liq-vapor	8783	0.5	402,000	35.84	1171.1	0.57

^a Dist. is the distance along the tube from the hohlraum.

For each selected point on the stainless steel tubes, impulses were computed from the pressure and the dynamic pressure. From the pressure history (termed the "static pressure" in shock tube literature), the impulse is simply

$$I_p = \int P dt$$

The impulse from the dynamic pressure is

$$I_d = \frac{1}{2} \int \rho (V \cos \phi)^2 dt$$

where ϕ is the angle from the normal to the tubes to the direction of flow. To determine the velocity imparted to the stainless steel tubes, we equated the sum of the impulses to the momentum change of the tubes. The total momentum change of the tubes is mV_t , where

$$mV_t = mV_p + mV_d = C_D(I_p + I_d)$$

and V_t , V_p , and V_d are the total velocity change and the velocity changes caused by the pressure term and the dynamic pressure term. C_D is the drag coefficient. Here m is the mass per unit area of the tubes:

$$m = \frac{\text{mass of tube per cm along tube}}{2R} = 0.153 \text{ g/cm}^2$$

The drag coefficient C_D for a cylinder in a high Reynold's number flow can vary between 1.2 (Re from 8000 to 80,000) and 0.3 (Re above 400,000), according to Gray (1972). For a flow velocity of 100 km/s (typical for the expanding debris), a tube diameter of 0.04 cm, and a kinematic viscosity of 1 cm²/s (a rough estimate for this velocity range), $Re = 4 \times 10^5$. Hence, we are at a boundary between the lower and higher ranges of C_D values. We chose to use a conservative value of C_D equal to 1.0.

The values of the resulting tube velocity changes for debris emanating from the hohlraum for 5-, 20-, and 45-MJ sources are listed in Tables 3-13 through 3-15. These results are also summarized in Figure 3-9. There is a significant effect on the particle velocities of the tubes only in the first few centimeters.

Table 3-13**VELOCITY OF TUBES CAUSED BY DEBRIS IMPACT: 0.5 MJ IN DEBRIS**

Distance (cm)	Velocity of Tubes (m/s)			Material State
	Pressure	Dyn. Press.	Total	
0.0	1212	6733	7945	Liquid
0.2	592	3211	3803	Sol-liq & liquid
0.5	202.6	1160	1362	Solid & sol-liq.
0.6	146.4	769.8	916.3	Solid, spall
0.65	125.6	655.3	780.9	Begin spalling
1.2	30.1	145.8	175.9	Begin stripping
3.2	1.22	5.83	7.05	Solid

Table 3-14**VELOCITY OF TUBES CAUSED BY DEBRIS IMPACT: 2.0 MJ IN DEBRIS**

Distance (cm)	Velocity of Tubes (m/s)			Material State
	Pressure	Dyn. Press.	Total	
0.0	2438	13270	15710	Liquid-vapor
0.85	142.3	727.9	870.2	Liq & liq-vap
1.15	67.8	332.8	400.6	Sol-liq & liquid
1.6	26.9	124.7	151.6	Solid & sol-liq.
1.8	18.9	87.1	106.0	Solid, spall
2.0	13.6	62.2	75.8	Begin spalling
2.2	10.0	45.5	55.5	Stripping
3.2	2.5	11.8	14.3	Begin stripping
4.6	0.21	2.69	2.90	Solid
6.3	0.0	0.18	0.18	Solid

Table 3-15
VELOCITY OF TUBES CAUSED BY DEBRIS IMPACT: 4.5 MJ IN DEBRIS

Distance (cm)	Velocity of Tubes (m/s)		Total	Material State
	Pressure	Dyn. Press.		
0.0	6450	27650	34100	Vapor
0.5	1159	4652	5811	Vap. & liq-vap
1.5	92.0	324.4	416.4	Liq & liq-vap
2.0	37.4	130.8	168.2	Sol-liq & liquid
2.8	10.5	39.1	49.6	Solid & sol-liq.
3.3	4.55	20.78	25.33	Solid, spall
3.6	2.51	14.34	16.85	Begin spalling
5.0	0.0	0.29	0.29	Begin stripping
9.3	0.0	0.0	0.0	Solid

Figure 3-9. Tube velocities from impact of hohlraum debris.

3.7 COMBINED EFFECTS ON TUBE VELOCITIES

The velocity changes caused by the combination of the neutron and X-ray radiation and the impact of the expanding hohlraum debris are shown in Figure 3-10(a) through (c) for the three sources we have studied. The velocities from the neutron radiation radiate outward from the centers of the tubes, whereas the X-rays and the debris cause velocity away from the hohlraum. In some cases these sets of velocity changes oppose one another. Generally the velocity from the expanding debris dominates only for the first centimeter of the tubes. Thereafter, the neutron effect is most important. The X-ray effect is always small in comparison to the debris or neutron effects.

The foregoing velocities should be used in connection with the droplet and fragment motions considered earlier in Tables 3-8 and 3-9 and Figure 3-7. For example, Figure 3-7 shows velocities caused only by the neutron deposition and therefore independent of the source energy. We can combine these velocities with the velocity results in Figures 3-9 and 3-10 and the range information in Figure 3-3 to determine the velocities of fragments and droplets for specific sources.

3.8 RECOMMENDATIONS

We recommend that Nova X-ray experiments be performed with the stainless steel tubing to verify one aspect of radiation loading response. A hohlraum debris experiment with Nova would also be helpful to test the predicted response of the stainless steel tubing.

Figure 3-10. Particle velocities in stainless steel tubes.

Section 4

OPTICS DEBRIS SHIELDS

4.1 INTRODUCTION

The optics debris shields (see Figure 1-5), made of fused silica, protect the laser optics from unwanted radiation and debris from the hohlraum-capsule source. We examine the effects of X-rays, of fragments from the cryogenic stainless steel tubes supporting the hohlraum, and of hohlraum debris. We assume that the blowoff and melt threat from the chamber first wall have been eliminated by the refractory coating.

4.2 PROPERTIES OF DEBRIS SHIELD MATERIAL

Fused silica is an amorphous form of silica (SiO_2) with a density of 2.2 g/cm^3 . It is a supercooled liquid at room temperature and a glass with low transmission loss at the Nova Upgrade laser frequencies.

We modeled this material for stress wave computations using the Mie-Grüneisen and PUFF Expansion equation of state described in Appendix C. We used the parameters given by Rice (1980), as shown in Appendix A. The Grüneisen ratio of 0.035 is about a factor of 50 lower than those for most solids, so the stress generated by energy deposition is very low.

Rice gives a vaporization energy of 870 cal/g and an effective "melt" energy of 454 cal/g . Sinz (1971) concluded that the boundary between surviving and removed material was associated with an energy of $1.0\text{E}9 \text{ J/m}^3$. For a density of 2.2 g/cm^3 , this value gives a removal energy of 109 cal/g .

4.3 X-RAY EFFECTS

We investigated the effects of an 8.3-MJ X-ray yield, corresponding to 2.19 J/cm^2 (or 0.52 cal/cm^2) at the debris shield distance of 5.5 m. Figure 4-1 shows the results of FSCATT calculations of energy versus depth for the three source blackbody temperatures of interest. Because the debris shields are tilted at the Brewster angle of 55 degrees, the effective blackbody temperature is lower than the incident temperature (by roughly the cosine of the angle), although

CAM-2802-51

Figure 4-1. Energy deposition in debris shield at 55 degrees.
(8.3 MJ X-ray yield: 0.52 cal/cm².)

the front-surface dose is the same. In Figure 4-1, we see a threshold fluence, nearly independent of blackbody temperature, for which there is a removal depth of about 1 μm at the effective "melt" energy.

If we examine threshold fluences for which no "melt" occurs in fused silica, we find in Figure 4-1 the results shown in Table 4-1. Therefore, very low fluences are required to avoid surface melting. This finding appears contradictory to the experimental results obtained by LLNL, similar to the second case in Table 4-1, in which a fluence of 1.3 J/cm² showed no signs of surface cracking. We conclude that surface melting must have occurred, but refreezing of the melted layer was not evident because both refrozen and sublayer material were amorphous. Under such conditions, we can show from Figure 4-1 that vapor would be only 0.1 μm at the blackbody temperature of 0.175 keV.

We further examined the possible removal of material from front-surface spall by using SRI PUFF. The results shown in Figures 4-2 and 4-3 gave a maximum tensile stress of 2.5 MPa at 0.47 J/cm² and 6.6 MPa at 1.3 J/cm², both much lower than the room-temperature dynamic threshold spall level of 280 MPa. Hence, even with significant thermal softening, front-surface spall seems unlikely to occur.

Further work should include modeling the Nova fused-silica experiments by accurately characterizing the source, by using an improved fused-silica equation-of-state model (Sinz, 1971), and by performing micrographic examination of surface and cross sections of the Nova test samples.

4.4 EFFECTS OF STAINLESS STEEL FRAGMENTS

The results of our analysis of fragment sizes and numbers and the fragment velocities are given in Table 3-9. Velocities range from 300 m/s to 2.7 km/s. Effective particle numbers and diameters range from 400 50- μm -diameter particles to 10⁷ 4- μm -diameter particles. The total cross-sectional area of these particles is less than 2.5 cm². If the radiation were isotropic for the hemisphere containing the steel tubes, then—assuming the fragments are coming from a source with a radius of only a few centimeters—we find at the first wall an areal reduction factor on the order of 10⁻⁶. Consequently, the effective area of each debris shield that might be affected by such fragments is negligible.

Table 4-1
THRESHOLD FLUENCES FOR NO "MELT" IN FUSED SILICA

BBT Source (keV)	Front-Surface Deposition (cal/g)	Fluence (J/cm²)	Fluence (cal/cm²)
0.175	5.48E3	0.180	0.043
0.350	2.18E3	0.47	0.112
0.700	7.42E2	1.34	0.320

CAM-2802-52

Figure 4-2. Peak tensile strength and time of occurrence at 55-degree debris shield for 0.350-keV source and 0.47 J/cm² fluence.

CAM-2802-53

Figure 4-3. Peak tensile strength and time of occurrence at 55-degree debris shield for 0.350-keV source and 1.30 J/cm² fluence.

4.5 EFFECTS OF HOHLRAUM DEBRIS

The hohlraum debris is assumed to come from a lead spherical shell. At the debris shield, located 5.5 m from the target chamber center and tilted at a 55-degree angle from the normal, the thickness T of impacting mass is assumed to be ~ 0.25 A. Assuming an ionized atomic diameter for Pb of 3.50 A, the fractional impacted area of the debris shield becomes

$$0.238/3.5 \approx 7\%$$

The effective area will be increased by the yield of fused-silica molecules produced by the impact with the debris shield. We obtain some estimate of this effect by following the approach of Johnson (1992). The yield is related to the incident ion energy per mass. Taking the normal velocity at the debris shield gives an energy e of

$$e = \frac{1}{2} [v \cos(55)]^2$$

We can use this value to determine the required

$$\text{incident ion energy} = 1.04\text{E-}12 \times e(\text{erg/g}) \quad \text{eV/mass-unit-molecule}$$

These normalized energies and corresponding yields are shown in Table 4-2 below. Only the lowest debris energy gives the lower yield of 6. According to Johnson (1992), yields of 9 or lower involve momentum transfer to target atoms as opposed to electronic excitations.

From our estimated fractional impact area, we see that the maximum (monolayer) crater area* could be $9 \times 7\% = 63\%$, according to the referenced results, and that it occurs at the two higher total energy cases. The minimum crater area would occur for maximum penetration of incident atoms, giving 7%. What occurs is probably something in between these extremes. Actually, the smaller area is more likely; our computations of velocity with SRI PUFF are too high, because they disregard the ionization energy.

Consider the plot shown in Figure 4-4. The end points on the axes suggested by the above estimations are shown with a quadratic interpolation, indicating the anticipation of increasing resistance to greater penetration. We would expect that, in general, several layers of fused-silica molecular layers would be reached. The actual curves will depend on an accurate description of brittle failure in fused silica.

* The molecular diameter of fused silica is also assumed to be about 3.5 A.

Table 4-2

RESULTS FROM LEAD HOHLRAUM DEBRIS AT DEBRIS SHIELD

Total Energy (MJ)	Debris Energy (MJ)	Average Velocity at Wall (km/s)	Inc. Ener./ Mass^a at Shield (eV/u)	Impact Yield (molecule/ion)
45	4.5	365	228	9
20	2.0	168	48.4	9
5	0.5	83	11.8	6

^a 55-degree angle from normal to debris shield.

CAM-2802-54

Figure 4-4. Fractional surface damage for hohlraum debris atomic impacts.

The above simplified analysis suggests that hohlraum debris will cause significant surface damage to the fused-silica buffer. We do not know what effect such damage might have on the laser transmission properties.

4.6 RECOMMENDATIONS

Because hohlraum debris must consist of ionized cations, we recommend investigating how such atoms could be deflected in a suitable electric or magnetic field, thereby minimizing impact to the debris shield. For example, the optics tube could, with insulators along an axis plane, serve as a "cathode ray" deflector. Also, walls could be serrated to stop impacting particles more effectively. We recommend that an experiment be performed on Nova to investigate the effects of hohlraum debris on the fused-silica debris shield.

We also recommend that stress transmission or particle-velocity experiments be performed on Nova, similar to the fused-silica experiments already performed (BBT ~ 0.2), to obtain data for equation-of-state modeling in the regime of interest.

Section 5

APPLICATION OF NOVA UPGRADE AS AN X-RAY SOURCE

5.1 INTRODUCTION

LLNL has developed a concept for producing hot X-rays in a shielded environment that uses a lithium hydride (LiH) shell to scatter hot X-rays from the source to an experimental target area, while using a truncated spherical cone to prevent direct cold-source radiation and neutrons from reaching the target. The concept is illustrated in Figure 5-1, with actual layout dimensions for the LiH shell shown in Figure 5-2. The cone support shown in Figure 5-1 is only representative and was added after we analyzed the impact response of the cone on the membrane shield. The desired hot X-rays pass through a membrane shield, which protects the experimental target from indirect (random) debris and shrapnel produced in the vicinity of the LiH shell and cone. The membrane shield also protects the experimental target area from gas pressure generated primarily by the LiH shell. Neither impact loading nor gas pressure effects must cause the membrane to exceed its peak tensile stress.

The key question to answer in this effort is whether the debris shield that is thin enough to transmit most of the desired X-radiation is also thick enough to survive the pressure and the impact of debris. In our computations, we assumed roughly a 20 MJ fusion yield (plus 2-MJ laser energy) with 14-MJ in neutrons, 4 MJ in X-rays, and 4 MJ in hohlraum debris. Under these conditions, the radiation (assumed to be uniform) directed toward the membrane was assumed to be a blackbody of 8 keV temperature with a fluence of 0.3 cal/cm^2 .

5.2 CHOICE OF MEMBRANE SHIELD

For the above spectrum, we calculated 87% transmission of fluence for a 1-mm-thick Kapton or Kevlar/epoxy target. The front-surface dose on the shield was 0.78 cal/g , and the approximate transmitted spectrum was shifted by absorption in the membrane to that of a blackbody with a temperature of about 9 keV. Stress generation in such a target is negligible (less than 2 MPa for 0.3 cal/cm^2), even for fluence one order of magnitude greater. LLNL may want to put a Be layer behind the plastic to reinforce the sheet and further protect against any loose LiH or other pieces of shrapnel. Transmission would probably still be about the same. There appear to be many design possibilities.

CM-314581-71A

Figure 5-1. Conversion configuration for obtaining debris-free hot X-rays at target experiments.

CM-2802-55

Figure 5-2. Cross-section geometry of LiH configuration for producing hot X-rays (courtesy of LLNL).

5.3 RESPONSE OF MEMBRANE SHIELD TO LiH CONE

We next considered the impulsive loading on the membrane shield of a loosely supported LiH cone (that is, no rigid support). We estimated from our current work that the debris loading on the cone is probably negligible. For the X-ray loading, we estimated from our previous work (Seaman et al., 1989), that with its somewhat lower blackbody temperature of 0.11 keV, the velocity contribution to the cone motion would be 18 cm/s. For the neutrons, we estimated from past work a velocity contribution of somewhat less than 1.0 m/s. The net result is that the neutron energy source is the primary contributor to cone motion.

Assuming a cone velocity of 5.0 m/s for the cone of 74 kg impacting the 1-mm-thick Kapton membrane, we find the membrane motion for this point loading from the analysis shown in Appendix E. The maximum deflection is 12 cm, and the maximum tensile stress in the membrane is 19 MPa, somewhat less than the effective material tensile strength of about 50 MPa. Therefore, the 1-mm Kapton membrane should be adequate to contain the momentum of the cone. However, although the Kapton membrane can contain the cone motion, a rigid cone support should be simple enough to provide. Then only scattered pieces of LiH cone material might impact the membrane.

5.4 LiH SHELL VAPORIZATION AND PRESSURIZATION EFFECTS

Another possible threat to the membrane is high-equilibrium pressure from entrapped gas that could build up within the ellipsoidal LiH shell, resulting from hohlraum- and LiH-vaporized material. We discussed with LLNL various ways to reduce the pressure buildup, such as drilling holes in the LiH shell or replacing the shell with rings having significant spacing between them. LLNL has performed experiments with Nova in which, even with holes, a spherical shell sustains a pressure with a time constant of many tens of microseconds (Smith, 1992).

Under the planned conditions of a 20-MJ experiment, most heating of the lithium hydride will be caused by X-radiation, so other effects were disregarded. Under radiation, some portions of the surfaces of the shell and cone are vaporized (the material is actually dissociated into Li and H₂ gases) and this vapor expands to fill the shell. Then the gases expand through various ports in the shell and impinge on the membrane shielding the experimental targets to the right in the test chamber. Here we want to determine the probable pressure in these expanded gases and the effect of this pressure on the shielding membrane.

In the following paragraphs we begin with the properties of the lithium hydride and the two gases formed by its dissociation. These properties contain the greatest uncertainties for the computations. Then we deposit the X-ray energy into the lithium hydride shell and estimate the

amount of material vaporized. The pressure in the expanded gases is determined and used in a one-dimensional wave propagation computation to follow the flow of the gases toward and past the membrane. Finally the gas pressure is applied to the membrane to determine its motion.

5.4.1 Properties of Lithium Hydride, Lithium, and Hydrogen

The lithium hydride, which forms the shell and the cone, appears as a slightly porous sandlike material. Its solid density is 0.689 g/cm^3 . At 298 K, lithium hydride has an enthalpy of -2.725 kcal/g (Barin and Knacke, 1973). During the radiation deposition, some of the lithium hydride on the surface of the shell and cone is rapidly heated and vaporized. The lithium hydride melts at 961.8 K under standard conditions. At 1223 K (with an enthalpy of -0.633 kcal/g), it dissociates into Li gas and H_2 gas. Thus the enthalpy needed to heat the lithium hydride from 298 to 1223 K is 2.088 kcal/g . The enthalpies of Li and H_2 gas at 1223 K are

Li	6.196 kcal/g
H_2	3.279 kcal/g

The combined gas (by mass weighting) then has an enthalpy of 5.826 kcal/g . The dissociation therefore requires energy of $5.826 - (-0.633) = 6.459 \text{ kcal/g}$. Bringing the material from the initial state of 298 K to complete sublimation requires $6.459 + 2.088 = 8.547 \text{ kcal/g}$.

At the temperatures and pressures considered, hydrogen is nearly a perfect gas. The reference; density under standard conditions is the molecular weight divided by the molar volume, 22.4 L; hence, $\rho_0 = 2.016 / 22.4\text{E}3 = 9.00\text{E} - 5 \text{ g/cm}^3$. The adiabatic exponent for hydrogen varies from 1.41 to 1.32 as the temperature rises from 15° to 2000°C (*Handbook of Chemistry and Physics*, 1970). We chose $\gamma = 1.32$ for our computations. As noted above, H_2 has an enthalpy of 3.279 kcal/g at 1223 K, the dissociation temperature.

The lithium gas is somewhat less well known than the hydrogen. The reference density is $6.941/22.4\text{E}3 = 3.10\text{E} - 4 \text{ g/cm}^3$. The enthalpy at dissociation is 6.196 kcal/g . We could locate no indication of a γ value for lithium.

5.4.2 Pressure in the Shell

The shell is irradiated by neutrons, X-rays, and debris from the hohlraum. Only the X-irradiation appears to have a significant effect on the lithium hydride shell and cone. We used a blackbody temperature of 350 keV and a source of 4 MJ (the remaining energy is in neutrons and debris). At the shortest distance between the shell and the source (115 cm) the fluence is $\text{source/area} = 24.07 \text{ J/cm}^2 = 5.75 \text{ cal/cm}^2$. According to Orth's (February 1992) computations,

this deposition should cause vaporization to a depth of 6 to 7 μm . According to our FSCATT depositions, the material at this depth experiences about 1000 cal/g. Therefore, we adjusted our threshold for vaporization (dissociation) downward to 1000 cal/g. (With our value of 2088 cal/g, only 1.4 μm of the surface would be vaporized.)

Next we want to determine the average energy deposited in the vaporized portion of the lithium hydride. According to our computations, about 16% of the total energy, or 0.64 MJ, is deposited within the first 6 to 7 μm into the lithium hydride. The total area of the ellipsoid is

$$x = 300$$

$$A = 2\pi \int_0^x y \sqrt{dx^2 + dy^2} = 2.15\text{E}5 \text{ cm}^2$$

So the total mass of gas is $6.5\text{E}-4 * 2.15\text{E}5 * 0.689\text{g/cm}^3 = 139.75 \text{ cm}^3 * 0.689 = 96.288 \text{ g}$. The energy density is $0.64\text{E}6/96.288 = 6650 \text{ J/g} = 1588 \text{ cal/g}$. As noted above, 6459 cal/g are required for complete dissociation. But here we have only 588 cal/g above the threshold of 1000 cal/g. Therefore, only a fraction F will be dissociated:

$$F = \frac{1588 - 1000}{6459} = 0.091$$

Hence, the actual mass of the vaporized material is only

$$m = 0.091 * 96.288 \text{ g} = 8.77 \text{ g} = 1.102 \text{ mol of LiH}$$

This material will remain at the dissociation temperature of 1223 K until all the material is dissociated. Hence, we know the temperature in the gas before it begins to expand.

Next, we determine the pressure in the lithium and hydrogen gases in the condensed state before expansion. We use the standard relation:

$$P = \frac{nRT}{V} = \frac{(1.102 + 1.102/2) * 8.314\text{E}7 * 1223}{8.77 \text{ g} / 0.689 \text{ g/cm}^3} = 1.32\text{E}10 \text{ dyn/cm}^2$$

Because there is only one-half mole of H_2 for each mole of Li gas, the partial pressures of the hydrogen and lithium gases are, respectively, $4.40\text{E}9$ and $8.80\text{E}9 \text{ dyn/cm}^2$.

By using two expressions for the equations of state for the gases, we can get an estimate for the Grüneisen ratio. The equations are

$$P = \rho \Gamma E = \frac{nRT}{V}$$

For hydrogen the Grüneisen ratio is

$$\Gamma_h = \frac{n_h RT}{EV\rho_h} = 0.367$$

This value is reasonable, in comparison with the tabular value of 0.32. Similarly, we can obtain an estimate of the Grüneisen ratio of the lithium gas. Here, we add a threshold energy to the expression:

$$\Gamma_L = \frac{n_L RT}{(E - E_v)V\rho_L}$$

Then we combine this expression with the preceding one for Γ_h to obtain

$$\frac{\Gamma_L}{\Gamma_h} = \frac{n_L E_h M_h}{n_h (E - E_v) M_L} = \frac{0.26}{0.32}$$

Hence, we now have an estimate of the Grüneisen ratio for the lithium gas.

Our next step is to allow an adiabatic expansion of the two gases and to determine the partial pressures in the expanded state. The density in the expanded state is simply $8.77 \text{ g} / 1.127\text{E}7 \text{ cm}^3 = 7.77\text{E} - 7 \text{ g/cm}^3$. For the expansion we use the standard polytropic expression:

$$P_h = P_{ho} \left(\frac{\rho_h}{\rho_{ho}} \right)^\gamma = 4.40\text{E}9 \left(\frac{7.77\text{E} - 7}{0.689} \right)^{1.32} = 62.0 \text{ dyn/cm}^2 = 6.2 \text{ Pa}$$

and

$$P_L = 8.80\text{E}9 \left(\frac{7.77\text{E} - 7}{0.689} \right)^{1.26} = 282.0 \text{ dyn/cm}^2 = 28.2 \text{ Pa}$$

The total pressure is

$$P = P_h + P_L = 344 \text{ dyn/cm}^2 = 34.4 \text{ Pa}$$

To provide for the later wave propagation computations, we generated an equivalent polytropic gas that would provide the same pressures and densities for this expansion. The Grüneisen ratio is 0.275. The internal energy is $6.97\text{E}10 \text{ erg/g}$ at the initial state and $1.61\text{E}9 \text{ erg/g}$ at the expanded state.

5.4.3 Loading on the Membrane Shielding the Targets

The loading on the membrane shielding the targets was determined by a wave propagation computation (with SRI PUFF) simulating the motion of the gases through the shell. The shell was

treated as a tube of varying cross section, including the port of 20-cm diameter at the left end, the volume taken by the cone, and the presence of the membrane. The computation is essentially one-dimensional, although it accounts for the varying cross-sectional area. The mixture of gases was initialized uniformly throughout the 300-cm length of the shell.

Two computations were performed with the PUFF code. In the first, the tube was closed at the location of the membrane in an attempt to obtain the dynamic pressure on the membrane. In the second, the constriction of the membrane was present but the gases were allowed to flow past. These two computations are expected to bracket the actual pressure history on the membrane.

The results of the closed-end computation include the velocity of the expanding gas before it reaches the membrane (peak velocity of 470 m/s, arriving at 1.6 ms) and the pressure history at the membrane (Figure 5-3). There is a 10-ms pressure spike to 130 Pa; then the pressure oscillates between 25 and 30 Pa. The effect of this combination of impulse and steady pressure on the membrane was obtained through the analysis described in Appendix E. For a 1-mm-thick Kevlar membrane, the peak displacement was 3.9 cm and the membrane stress was 2 MPa. The peak displacement occurred at 0.07 s.

The corresponding pressure for the open end configuration is shown in Figure 5-4; the pressure rises only to 11 Pa, then decays rapidly to less than 1 Pa by 100 ms. The total impulse is about $3.5 \text{ dyn-s/cm}^2 = 0.35 \text{ Pa-s}$. For the 1-mm-thick Kevlar membrane, the peak displacement was only 1.8 cm and the membrane stress was 0.4 MPa. The peak values occur at 0.08 s.

The expected response of the membrane to the expanding Li and H₂ gases is expected to lie between these cases for an open and closed end on the LiH shell. We may expect the actual pressure history on the center of the membrane to show a spike of 130 Pa, as shown in Figure 5-3, followed by a rapid decay to 1 Pa, as shown in Figure 5-4. In this case, the total loading is essentially the impulse of 1.0 Pa-s. When this impulse was applied, we obtained a peak displacement of 3 cm and a stress of 1.1 MPa. These values suggest that a suitable membrane for shielding the target can be readily provided.

5.4.4 Summary

We considered a LiH shell for scattering hot X-rays from the source to an experimental target area, while using a truncated spherical cone to prevent direct cold-source radiation and neutrons from reaching the target. Computations were made to examine the gases generated in the target chamber by radiation into the surrounding lithium hydride shell. A thin layer of the inner surface of the shell is dissociated into Li and H₂ gases and expands to fill the shell. Then these gases flow out of the shell and impinge on the membrane shielding the target samples.

CAM-2802-49

Figure 5-3. Pressure history at the membrane caused by flow of the Li and H₂ gases: closed end case.

CAM-2802-50

Figure 5-4. Pressure history at the membrane caused by flow of the Li and H₂ gases: flow-by case.

We assumed a 20-MJ fusion yield with 14 MJ of neutrons, 4 MJ of X-rays, and 4 MJ of debris. The pressure in the shell under this loading is only 34 Pa. As these gases expand, they provide an impulse of about 1.0 Pa-s on the membrane and cause a maximum deflection of 3 cm and a stress of 1.1 MPa. For a loosely supported LiH cone, we found that a 1-mm-thick Kapton or Kevlar/epoxy membrane shield moves only 7 mm, would provide high transmission of X-rays, and would mechanically contain the cone without rupturing. Hence, the membrane appears easily able to protect the target samples.

5.5 RECOMMENDATIONS

We recommend supporting the cone by a rigid support to eliminate direct impact of the cone fragments. With the current configuration and energy levels, the gas pressure from the LiH shell configuration we have considered is a negligible threat because the shell material vaporizes so little. This finding suggests that greater hot X-ray fluences could be obtained for potential experiments (behind the membrane shield) by moving the shell closer to the hohlraum-pellet source, and this idea should be further optimized.

Section 6

OVERALL CONCLUSIONS AND RECOMMENDATIONS

We have provided a description of the major direct and indirect effects of neutrons, X-rays, and hohlraum debris on the optics debris shields. We have suggested possible solutions to potential "show stoppers." We examined the preliminary feasibility of a design using the Nova Upgrade as an X-ray source. We have recommended experiments on the Nova for design verification. Because there appear to be no "show stoppers" on the basis of this program's assessment of radiation effects on the target chamber, we recommend continuing assessment of the Nova Upgrade design for nuclear effects and ICF testing.

REFERENCES

- I. Barin and O. Knacke, "Thermochemical Properties of Inorganic Substances," Springer-Verlag, Berlin, 1973.
- F. Biggs and R. Lighthill, "Analytical Approximations for X-Ray Cross Sections II," SC-RR-71-0507, Sandia National Laboratories, Albuquerque, NM, December 1971.
- D. R. Curran, "A Reexamination of the Mott Theory of Fragmentation," Symposium on Shock Wave Compression of Condensed Matter, Washington State University, Pullman, WA, September 1988.
- J. Dein, R. E. Tokheim, D. R. Curran, and H. Chau, R. Weingart, and R. Lee, "Aluminum Damage Simulation in High-Velocity Impact," *Shock Waves in Condensed Matter—1983*, Proceedings of the American Physical Society Topical Conference, Santa Fe, NM, 1983.
- R. H. Fisher and J. W. Wiehe, *A User's Guide to the FSCATT Code*, Final Report DASA 2618 by Systems, Science and Software, for Defense Atomic Support Agency, November 1970.
- D. E. Gray, *American Institute of Physics Handbook*, 3rd edition, McGraw-Hill, pp. 2-267, 1972.
- R. E. Johnson, "Electronic Sputtering: From Atomic Physics to Continuum Mechanics," *Phys. Today*, March 1992.
- N. F. Mott, "Fragmentation of Shell Cases," *Proc. R. Soc. London A*, 189, pp. 300-308, 1947.
- C. Orth, "Vaporized Aluminum Ablation Using Profile Code," personal communication through M. Tobin, September 1991.
- C. Orth, personal communication, February 1992.
- M. H. Rice, "PUFF 74 EOS Compilation," Final Report SSS-R-80-4296 by Systems, Science, and Software for Air Force Weapons Laboratory, February 1980.
- L. Seaman and D. A. Shockey, *Models for Ductile and Brittle Fracture for Two-Dimensional Wave Propagation Calculations*, Final Report by SRI for Army Materials and Mechanics Research Center, Watertown, MA, AMMRC CTR 75-2, February 1975.
- L. Seaman, D. R. Curran, and D. A. Shockey, "Computational Models for Ductile and Brittle Fracture," *J. Appl. Phys.*, **47** (11) (November 1976).
- L. Seaman, D. R. Curran, and W. J. Murri, "A Continuum Model for Dynamic Tensile Microfracture and Fragmentation," *J. Appl. Mech.*, **52**, 593-600, September 1985.
- L. Seaman, R. Platz, R. E. Tokheim, and D. R. Curran, *Continuing Assessment of Debris Generation from a Megajoule Inertial Confinement Fusion Experimental Facility*, Final Report by SRI International for Lawrence Livermore National Laboratory under Purchase Order No. B063696, May 1989.

- D. A. Shockey, L. Seaman, D. R. Curran, P. S. DeCarli, M. Austin, and J. P. Wilhelm, *A Computational Model for Fragmentation of Armor Under Ballistic Impact*, Final Report by SRI International for U. S. Army Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland 21005, December 1973.
- K. Sinz, *X-Ray Induced Damage in Fused Silica*, Lawrence Livermore National Laboratory Internal Report, July 1991.
- R. Smith, personal communication, May 1992.
- R. Smith, personal communication, December 1991.
- V. V. Sychev, A. A. Vasserman, A. D. Kozlov, G. A. Spiridonov, and V. A. Tsymarny, *Thermodynamic Properties of Helium*, T. B. Selover, Jr., Eds., Hemisphere Publishing Corporation, Washington, New York, and London, 1987.
- M. Tobin, personal communication, October 1991.
- M. Tobin, personal communication, January 1992.
- M. Tobin, personal communication, February 1992.
- R. E. Tokheim, L. Seaman, D. A. Shockey, and D. R. Curran, *Assessment of Debris Generation from a Megajoule Inertial Confinement Fusion Experimental Facility*, Final Report by SRI International for Lawrence Livermore National Laboratory, September 26, 1988, LLNL Subcontract No. B059169, SRI Project 6661.
- T. G. Trucano, D. E. Grady, and J. M. McGlaun, "Fragmentation Statistics from Eulerian Hydrocode Calculations," *Int. J. Impact Eng.* **10**, Nos. 1-4, Proceedings of the 1989 Symposium on Hypervelocity Impact, San Antonio, Texas, December 12-14, 1989, Pergamon Press, 1990.
- R. C. Weast, editor, *Handbook of Chemistry and Physics*, The Chemical Rubber Co., Cleveland, Ohio, 1970.

Appendix A

CONSTITUTIVE RELATIONS USED IN SRI PUFF

Appendix A

CONSTITUTIVE RELATIONS USED IN SRI PUFF

The properties for many materials were used during the computations on this project. Below we list the material properties used in the form in which they appear in the SRI PUFF code.

The required data are in cgs units and include the bulk and shear moduli and initial density of the solid material; the pressure-volume loading curve for the porous material; a deviator stress process, including the yield strength, for both porous and solid materials; Grüneisen ratios for solid and gas; an initial density for the porous material; melt and vaporization energies; and the thermal strength reduction function.

A sample of the data for a flame-sprayed material is considered below in detail. The first line provides the name, the initial density of the solid material (RHOS), and a series of indicators (CFP and DPY).

ALUMINA-FLS(2.78) RHOS = 3.969E+00 CFP = 003 DPY = 005

This material has an initial porous density of 2.78 g/cm³ and a solid density of 3.969 g/cm³. The Hugoniot parameters below are those for solid alumina. In the order given here, they are C, D, E, Γ , H, S, and n. C, D, and S are the bulk modulus series describing the Hugoniot of the material (listed here in dynes per square centimeter). E is the vaporization energy (incipient for this material) in ergs per gram. Γ is the Grüneisen ratio, and H is the effective Grüneisen ratio for the gaseous material; n is the exponent that determines the variation of the Grüneisen ratio from the solid value to the gaseous value in the PUFF expansion equation of state.

EQST = 2.655E+12 4.200E+12 3.653E+10 1.320E+00 8.000E-02 2.090E+12 1.670E+00

The initial density RHO of the porous material is read on the next line.

RHO = 2.780E+00

The fourth line for a porous material contains special input for the PEST* model; this line describes the pressure-volume curves used for compaction, tension, and reloading for quasi-static and rate-dependent processes. KCS, TS, and RS refer to the quasi-static properties for compression, tension, and reloading, respectively, and KCD, TD, and RD refer to dynamic loading.

KCS, TS, RS 1 1 0 KCD, TD, RD 1 1 0 ..

The data reading by the POREQST subroutine begins with the moduli AK and MUP (initial bulk and shear moduli), describing the initial loading of the porous material. Y0 is the initial yield strength of the porous material. This value, rather than the YIELD value read later, is the initial strength of the porous material. The last quantity, RHOP1, is the porous density at which the initial porous moduli are specified by the MacKenzie* formulation of moduli variation.

AK = 1.000E+12 MUP = 4.000E+11 Y0 = 1.000E+07 RHOP1 = 2.910E+00

The number of density regions into which the pressure-volume curve is separated is called NREG. Five regions are permitted.

NREG = 4

The densities corresponding to the boundaries of each density interval are listed in order. The first RHOP value need not coincide with RHO. Only four regions are given.

RHOP = 2.780E+00 2.890E+00 3.333E+00 3.917E+00

The artificial viscosities are listed for each interval. The normal values for COSQ and C1 are 4. and 0.05, respectively, but larger values are often required for porous materials. The coefficients should be selected to provide an essentially straight Rayleigh line (plot of mechanical stress R versus specific volume V) and a minor amount of oscillation. Generally larger values are used in the central density regions where the distance between the compaction curve and the Rayleigh line is greatest. The coefficients are prescribed at the density values and interpolated for intermediate densities. This alumina model was exercised in a region of high energy, and the use of larger viscosity values was not critical.

COSQ = 4.000E+00 4.000E+00 4.000E+00 4.000E+00 4.000E+00
C1 = 5.000E-02 5.000E-02 5.000E-02 5.000E-02 5.000E-02

* L. Seaman, R. E. Tokheim, and D. R. Curran, *Computational Representation of Constitutive Relations for Porous Material*, SRI International Final Report DNA 3412F for Defense Nuclear Agency, Washington, D.C., May 1974.

The initial yield point on the pressure-volume curve is designated as 0 P2.

0 P2 = 1.000E+08

The following sets of P2 (pressure) values pertain to the end points of each of the four regions. The last P2 is the consolidation pressure, at which point the porous compaction surface reaches the solid surface. The DELP values are the central offsets from a straight line in the pressure-volume plane in each interval. DELP should not exceed $(P2 - P1)/4$ in any interval, or the curve in that interval will have a portion with a negative slope. Negative values of DELP mean that the intervening curve drops below the straight line between the end points. The YADDP indicate increments in yield strength that are cumulative with density to give the total yield strength.

1 P2 = 1.000E+10 DELP = -1.200E+09 YADDP = 1.000E+09
2 P2 = 6.100E+10 DELP = -2.400E+09 YADDP = 1.000E+09
3 P2 = 1.400E+11 DELP = -1.500E+10 YADDP = 3.000E+09
4 P2 = 3.350E+11 DELP = -2.200E+10 YADDP = 1.000E+10

The constant solid strength model used has the solid strength given by TER5 and the relative void volume for failure given by TER7.

TER5 = -5.000E+08 TER7 = 5.000E-01

The following listing contains SRI PUFF data for both porous and solid materials.

The MELT array provides a thermal strength reduction effect for all materials. The first number in the array is the melt energy in ergs per gram. The other numbers specify a series of parabolas describing a curve that starts at 1.0 for the initial conditions and gradually reduces to zero at the melt energy.

MELT = 2.630E+10 1.350E+10 2.000E-02 9.000E-01-2.000E-01

In some cases a specific heat is also used:

SPH = 2.960E-01

The yield data for the solid include a yield strength and the shear modulus.

YIELD = 6.600E+10 1.600E+12

The tensile strength array includes a strength for the solid, an initial strength for the porous material (unless preempted by the porous strength model), and a bond strength to the next material in the problem.

TENS = -3.000E+09-1.000E+10-1.000E+11

The artificial viscosity parameters for the solid material are provided by the three numbers COSQ, C1, and C2 (for quadratic coefficient, linear coefficient, and linear coefficient for expanded states).

VISC = 4.000E+00 5.000E-02 5.000E-02

Parameters for materials we used in our computations for this program are given as follows:

5083 ALUMINUM WITH DUCTILE FRACTURE

AL5083 RHOS = 2.660E+00 CFP = 010 DPY = 004
EQSTC= 7.600E+11 1.500E+12 3.000E+10 2.040E+00 2.500E-01 0.000E+00
DFR1_1145-1.000E-02-4.000E+09 1.000E-04 3.000E+09-3.000E+09-4.000E+08
MELT = 5.860E+09
YIELD = 2.000E+09 3.000E+11 1.000E+09
VISC = 3.240E+00 2.500E-01
TENS = -1.000E+11-1.000E+11-1.000E+11

FLAME-SPRAYED, POROUS ALUMINA

ALUMINA-FLS (2.78) RHOS = 3.969E+00 CFP = 003 DPY = 005
EQST = 2.655E+12 4.200E+12 3.653E+10 1.320E+00 8.000E-02 2.090E+12 1.670E+00
RHO = 2.780E+00
KCS,TS,RS 1 1 0 KCD,TD,RD 1 1 0
AK = 1.000E+12 MUP = 4.000E+11 Y0 = 1.000E+07 RHOP1 = 2.910E+00
NREG = 4
RHOP = 2.780E+00 2.890E+00 3.333E+00 3.917E+00
COSQ = 4.000E+00 4.000E+00 4.000E+00 4.000E+00 4.000E+00
C1 = 5.000E-02 5.000E-02 5.000E-02 5.000E-02 5.000E-02
0 P2 = 1.000E+08
1 P2 = 1.000E+10 DELP = -1.200E+09 YADDP = 1.000E+09
2 P2 = 6.100E+10 DELP = -2.400E+09 YADDP = 1.000E+09
3 P2 = 1.400E+11 DELP = -1.500E+10 YADDP = 3.000E+09
4 P2 = 3.350E+11 DELP = -2.200E+10 YADDP = 1.000E+10
TER5 = -5.000E+08 TER7 = 5.000E-01
MELT = 2.630E+10 1.350E+10 2.000E-02 9.000E-01-2.000E-01
SPH = 2.960E-01
YIELD = 6.600E+10 1.600E+12
TENS = -3.000E+09-1.000E+10-1.000E+11
VISC = 4.000E+00 5.000E-02 5.000E-02

PLASMA-SPRAYED, POROUS BERYLLIUM

BERYLLIUM_PS (1.58) RHOS = 1.850E+00 CFP = 003 DPY = 003
 EQSTS200 1.114E+12 3.784E+12 3.550E+11 1.450E+00 2.500E-01
 RHO = 1.580E+00
 KCS,TS,RS 1 1 0 KCD,TD,RD 4 1 0
 AK = 1.550E+11 MUP = 0.000 Y0 = 0.000 RHOP1 = 1.580E+00
 NREG = 3
 RHOP = 1.580E+00 1.667E+00 1.754E+00
 COSQ = 4.000E+00 4.000E+00 4.000E+00 4.000E+00 4.000E+00
 C1 = 1.000E-01 1.000E-01 1.000E-01 1.000E-01 1.000E-01
 0 P2 = 1.000E+08
 1 P2 = 5.600E+09 DELP = -8.000E+08 YADDP = 2.000E+08
 2 P2 = 1.750E+10 DELP = -1.400E+09 YADDP = 4.000E+08
 3 P2 = 8.000E+10 DELP = -2.000E+09 YADDP = 2.000E+09
 TER5 = -1.000E+08 TER7 = 5.000E-01
 SPH = 1.500E-08
 MELT = 2.780E+10 1.400E+10 1.500E-01 2.500E-01-6.000E-02
 YIELD = 2.700E+09 1.453E+12
 TENS = -1.000E+11-1.000E+11-5.000E+08

BERYLLIUM WITH 5% TUNGSTEN BY WEIGHT (POROUS)

BE 5% W (1.655) RHOS = 1.938E+00 CFP = 003 DPY = 003
 EQSTS200 1.114E+12 3.784E+12 3.460E+11 1.450E+00 2.500E-01
 RHO = 1.655E+00
 KCS,TS,RS 1 1 0 KCD,TD,RD 4 1 0
 AK = 1.550E+11 MUP = 0.000 Y0 = 0.000 RHOP1 = 1.655E+00
 NREG = 3
 RHOP = 1.655E+00 1.746E+00 1.833E+00
 COSQ = 4.000E+00 4.000E+00 4.000E+00 4.000E+00 4.000E+00
 C1 = 1.000E-01 1.000E-01 1.000E-01 1.000E-01 1.000E-01
 0 P2 = 1.000E+08
 1 P2 = 5.600E+09 DELP = -8.000E+08 YADDP = 2.000E+08
 2 P2 = 1.750E+10 DELP = -1.400E+09 YADDP = 4.000E+08
 3 P2 = 8.000E+10 DELP = -2.000E+09 YADDP = 2.000E+09
 TER5 = -1.000E+08 TER7 = 5.000E-01
 TPH = 1.500E-08
 MELT = 3.520E+10 0.38 1.500E-01 2.500E-01-6.000E-02
 YIELD = 2.700E+09 1.453E+12
 TENS = -1.000E+11-1.000E+11-5.000E+08

PLASMA-SPRAYED BORON WITH HAFNIUM BORIDE

P.S. HFB2-BN (2.20) RHOS = 2.610E+00 CFP = 003 DPY = 003
 EQST 1.800E+12 1.060E+12 1.170E+11 0.590E+00 1.000E-01 0. 2.0
 RHO = 2.200E+00
 KCS,TS,RS 1 1 0 KCD,TD,RD 1 1 0
 AK = 1.000E+12 MUP = 8.000E+10 Y0 = 1.000E+08 RHOP1 = 2.200E+00
 NREG = 2
 RHOP = 2.200E+00 2.2055E+0
 COSQ = 4.000E+00 4.000E+00 4.000E+00 4.000E+00 4.000E+00
 C1 = 5.000E-02 5.000E-02 5.000E-02 5.000E-02 5.000E-02
 0 P2 = 0.000E+00
 1 P2 = 2.000E+09
 2 P2 = 8.000E+10 DELP = -1.000E+10

```

TER5 = -1.000E+08 TER7 = 2.500E-01
MELT = 4.500E+10 0.50 0. 5.000E-01
YIELD = 5.000E+10 1.600E+12
TENS = -1.000E+11-1.000E+11-3.000E+08

```

BERYLLIUM S200 (SOLID)

The first model contains the stress-dependent deviator model; the second model does not. The latter was used because the first model failed under high energy-deposition loading conditions.

```

BERYLLIUM S 200 RHOS = 1.850E+00 CFP = 000 DPY = 602
EQSTS200 1.114E+12 3.784E+12 3.550E+11 1.450E+00 2.500E-01
STRS200 7.500E+01 1.350E+09 2.200E+09
MELT = 3.680E+10 0.38 1.500E-01 2.500E-01-6.000E-02
YIELD = 2.700E+09 1.453E+12

```

```

BERYL NSTRS2 S 200 RHOS = 1.850E+00 CFP = 000 DPY = 003
EQSTS200 1.114E+12 3.784E+12 3.550E+11 1.450E+00 2.500E-01
MELT = 3.680E+10 0.38 1.500E-01 2.500E-01-6.000E-02
YIELD = 2.700E+09 1.453E+12
TENS = -1.000E+11-1.000E+11-1.000E+11

```

FUSED SILICA

```

FUSED SILICA (RICE) RHOS = 2.200E+00 CFP = 000 DPY = 073
EQST = 7.690E+11-4.214E+12 3.640E+10 1.600E-02 2.500E-01 2.001E+13
MELT = 1.900E+10 1.000E+10 1.250E-01 5.000E-01-1.000E-01
VISC = 4.000E+00 5.000E-02 1.000E-01
TENS = -1.000E+11-1.000E+11-1.000E+11

```

STAINLESS STEEL 316 FOR CRYOGENIC TUBES

```

STAINLESS STEEL RHOS = 8.000 CFP= 020 DPY= 002 NVAR = 3
EQSTC = 1.650E+12 0. 7.428E+10 1.5 0.25 0.
BFR = -4.00E-05 -1.00E+09 4.000E-03 5.000E+08 -5.52E+09 -2.00E+09 0.1
BFR2 = 8. 0. 0.33 1.0 0.2 3.
INIT NUC= 0 GRO= 0 PRINT= 1 RAD= 0 JFRAG= 0 NDS= 0 EXTRA= 0
YIELD = 2.070E+09 1.088E+12 0.
EMELT = 1.040E+10 1.000E+10 0.01 0.96 0.

```

LEAD FOR THE NOMINAL HOHLRAUM MATERIAL

```

LEAD (KOHN) RHOS = 11.355 CFP = 000 DPY = 001
EQST = 5.008E+11 4.986E+11 9.155E+09 2.2 .25 2.019E+12
COSQ = 10. 0.3 0.1

```

HELIUM @ 10 MPA AND 4.5 K INITIALLY

```

HELIUM @ 10 MPA, 4.5 K RHOS = 0.1719 CFP = 000 DPY = 000
EQST = 3.460E+08 4.970E+08 4.598E+07 1.753 0.697 1.474E+09 2.055
Also set RHO = 0.207 g/cm3

```

A COMPOSITE GAS FOR THE MIXTURE OF LI AND H₂

LIH gas		RHOS =	0.689	CFP = 000	DPY = 011		
EQST =	1.	0.	-1.	0.275	0.275	0.	0.
Q =	1.610E+09	VISC =	20.	0.5	0.2		

Also set RHO = 7.770E-07 g/cm³
Energy = 1.61E9 erg/g
Pressure = 34.4 Pa

Appendix B
SRI PUFF AND FSCATT RESULTS

1st Wall Response to Possible X-Ray Outputs from Nova Upgrade						11/13/91						
	BBT=0.175											
	X-Ray Output	Fluence	Fluence	Vapor	Melt	Melt	Max Vapor	Avg Melt	Vap Imp	Melt Imp	Avg Vap	
Code File	(MJ)	(J/cm^2)	(cal/cm^2)	Thkns(μm)	Depth(μm)	Thkns(μm)	Vel(km/s)	Vel(m/s)	(tap)	(tap)	Vel(km/s)	
MPAL5083A7.DAT	1.00	0.497	0.119	0.07	0.8	0.7	3.26	54.00	1.5	1.0	0.8	
MPAL5083A6.DAT	1.50	0.746	0.178	0.20	1.2	1.0	6.3	41.00	4.5	1.1	0.8	
MPAL5083A5.DAT	2.50	1.243	0.297	0.34	1.7	1.36	6.9	36.00	11.8	1.3	1.3	
MPAL5083A4.DAT	4.00	1.988	0.475	0.5	2.2	1.7	13.5	16.60	23.9	0.8	1.8	
MPAL5083A3.DAT	7.00	3.479	0.832	0.9	3.3	2.4	19.1	0.01	47.9	0.1	2.0	
MPAL5083A2.DAT	14.50	7.207	1.722	1.48	4.88	3.4	28.7	0.02	100	0.2	2.5	
MPAL5083A1.DAT	20.10	10.00	2.39	1.81	5.4	3.59	34.2	0.03	134.4	0.3	2.8	
	BBT=0.350											
	X-Ray Output	Fluence	Fluence	Vapor	Melt	Melt	Max Vapor	Avg Melt	Vap Imp	Melt Imp	Avg Vap	
	(MJ)	(J/cm^2)	(cal/cm^2)	Thkns(μm)	Depth(μm)	Thkns(μm)	Vel(km/s)	Vel(m/s)	(tap)	(tap)	Vel(km/s)	
MPAL5083B7.DAT	1.00	0.497	0.119	0	0.7	0.7	0	86	0	1.55	*Error*	
MPAL5083B6.DAT	1.50	0.746	0.178	0	1.3	1.3	0	115	0	3.9	*Error*	
MPAL5083B5.DAT	2.50	1.243	0.297	0.1	2.3	2.2	2.6	125	2.2	7.3	0.8	
MPAL5083B4.DAT	4.00	1.988	0.475	0.4	3.1	2.7	5.46	112	12.2	8.05	1.1	
MPAL5083B3.DAT	7.00	3.479	0.832	0.9	4.7	3.8	9.17	67.3	40.3	6.8	1.7	
MPAL5083B2.DAT	14.50	7.207	1.722	2.03	7.0	5.0	15.1	12.6	110	1.8	2.0	
MPAL5083B1.DAT	20.10	10.00	2.39	2.5	8.6	6.1	18.3	0.29	156	0.2	2.3	
	BBT=0.700											
	X-Ray Output	Fluence	Fluence	Vapor	Melt	Melt	Max Vapor	Avg Melt	Vap Imp	Melt Imp	Avg Vap	
	(MJ)	(J/cm^2)	(cal/cm^2)	Thkns(μm)	Depth(μm)	Thkns(μm)	Vel(km/s)	Vel(m/s)	(tap)	(tap)	Vel(km/s)	
MPAL5083C7.DAT	1.00	0.497	0.119	0	0.15	0.15	0	94	0	0.4	*Error*	
MPAL5083C6.DAT	1.50	0.746	0.178	0	1.1	1.1	0	84	0	2.4	*Error*	
MPAL5083C5.DAT	2.50	1.243	0.297	0	2.2	2.2	0	126	0	7.34	*Error*	
MPAL5083C4.DAT	4.00	1.988	0.475	0	3.4	3.4	0	193	0	16	*Error*	
MPAL5083C3.DAT	7.00	3.479	0.832	0.55	5.1	4.6	4.3	150	19.9	18	1.4	
MPAL5083C2.DAT	14.50	7.207	1.722	1.76	8.69	6.9	8.86	100	88.1	16.8	1.9	
MPAL5083C1.DAT	20.10	10.00	2.39	2.6	10.7	8.1	11.2	70	138	15	2.0	

1st Wall Al2O3 Response to Possible X-Ray Outputs from Nova Upgrade									12/16/91				
	BBT=0.175												
	X-Ray Output	Fluence	Fluence	Vapor	Melt	Melt	Spall	Sp	Max Vapor	Avg Melt	Vap Imp	Melt Imp	Avg Vap
Code File	(MJ)	(J/cm^2)	(cal/cm^2)	Thkns(	Depth	Thkns	Depth	Thkns	Vel(km/s)	Vel(m/s)	(tap)	(tap)	Vel(km/s)
MPAL2O3A7.DAT	1.00	0.497	0.119			0.0		0					0.0
MPAL2O3A6.DAT	1.50	0.746	0.178	0	0.19	0.19	0.19	0	0	0	0	0	0.0
MPAL2O3A5.DAT	2.50	1.243	0.297	0.12	0.52	0.4	0.52	0	2.14	0	1.53	0	0.5
MPAL2O3A4.DAT	4.00	1.988	0.475	0.36	0.85	0.49	0.85	0	5.4	0	5.5	0	0.5
MPAL2O3A3.DAT	7.00	3.479	0.832	0.6	1.30	0.7	1.3	0	9.5	0.01	15.5	0	0.9
MPAL2O3A2.DAT	14.50	7.207	1.722	0.85	1.90	1.05	1.9	0	16.4	0*	39.4	0	1.7
MPAL2O3A1.DAT	20.10	10.00	2.39	1.3	1.90	0.6	1.9	0	20.5	0*	57	0	1.6
	BBT=0.350												
	X-Ray Output	Fluence	Fluence	Vapor	Melt	Melt	Spall	Sp	Max Vapor	Avg Melt	Vap Imp	Melt Imp	Avg Vap
	(MJ)	(J/cm^2)	(cal/cm^2)	Thkns(	Depth	Thkns	Depth	Thkns	Vel(km/s)	Vel(m/s)	(tap)	(tap)	Vel(km/s)
MPAL2O3B7.DAT	1.00	0.497	0.119			0		0					0.0
MPAL2O3B6.DAT	1.50	0.746	0.178	0	0	0	0	0	0	0	0	0	0.0
MPAL2O3B5.DAT	2.50	1.243	0.297	0	0.31	0.31	0.31	0	0	15.9	0	0.1	0.0
MPAL2O3B4.DAT	4.00	1.988	0.475	0.06	0.75	0.69	0.75	0	0.4	2.6	0.36	0.05	0.2
MPAL2O3B3.DAT	7.00	3.479	0.832	0.4	1.3	0.9	1.3	0	3.1	0	5.44	0	0.5
MPAL2O3B2.DAT	14.50	7.207	1.722	1.3	2.2	0.9	2.9	0.7	7.7	0.02	27.4	0.0005	0.8
MPAL2O3B1.DAT	20.10	10.00	2.39	1.7	2.9	1.2	3.8	0.9	10.3	0*	45.7	0	1.0
	BBT=0.700												
	X-Ray Output	Fluence	Fluence	Vapor	Melt	Melt	Spall	Sp	Max Vapor	Avg Melt	Vap Imp	Melt Imp	Avg Vap
	(MJ)	(J/cm^2)	(cal/cm^2)	Thkns(	Depth	Thkns	Depth	Thkns	Vel(km/s)	Vel(m/s)	(tap)	(tap)	Vel(km/s)
MPAL2O3C7.DAT	1.00	0.497	0.119			0.00		0					0.0
MPAL2O3C8.DAT	1.50	0.746	0.178			0.0		0					0.0
MPAL2O3C5.DAT	2.50	1.243	0.297	0	0	0.0	0	0	0	0	0	0	0.0
MPAL2O3C4.DAT	4.00	1.988	0.475	0	0.08	0.09	0.08	0	0	0.14	0	1.7E-4	0.0
MPAL2O3C3.DAT	7.00	3.479	0.832	0	0.74	0.74	1.00	0.26	0	25.8	0	0.53	0.0
MPAL2O3C2.DAT	14.50	7.207	1.722	0.5	2.5	2.0	2.5	0	1.73	0	5.19	0	0.4
MPAL2O3C1.DAT	20.10	10.00	2.39	1	3.3	2.3	3.3	0	3.3	0.01	16.4	0	0.6

Fine-Zone FSCATT Removal Thicknesses on Candidate Materials for First Wall Coating										2/7/92
	Porous	Solid								
	Density	Density			X-Ray Output	Fluence	Fluence	Vapor	Melt	Melt
Material	(g/cm ³)	(g/cm ³)	Code File	BBT	(MJ)	(J/cm ²)	(cal/cm ²)	Thkns(μm)	Depth(μm)	Thkns(μm)
Flame-spr alumina	2.78	3.98	FAL203A2A.DAT	0.175	14.50	7.207	1.722	1.03	1.69	0.66
Flame-spr alumina	2.78	3.98	FAL203B2A.DAT	0.350	14.50	7.207	1.722	1.16	2.47	1.31
Flame-spr alumina	2.78	3.98	FAL203C2A.DAT	0.700	14.50	7.207	1.722	0.59	2.44	1.85
Porous aluminum nitride	2.60	3.27	FALNA1A.DAT	0.175	14.50	7.207	1.722	0.99	1.68	0.69
Porous aluminum nitride	2.60	3.27	FALNB1A.DAT	0.350	14.50	7.207	1.722	1.11	2.52	1.41
Porous aluminum nitride	2.60	3.27	FALNC1A.DAT	0.700	14.50	7.207	1.722	0.53	2.39	1.86
Porous magnesium oxide	3.00	3.77	FMGOA1A.DAT	0.175	14.50	7.207	1.722	0.82	1.37	0.55
Porous magnesium oxide	3.00	3.77	FMGOB1A.DAT	0.350	14.50	7.207	1.722	0.85	1.77	0.92
Porous magnesium oxide	3.00	3.77	FMGOC1A.DAT	0.700	14.50	7.207	1.722	0.22	1.44	1.22
Plasma-spr beryllium	1.58	1.83	FBEA1A.DAT	0.175	14.50	7.207	1.722	0.06	2.54	2.48
Plasma-spr beryllium	1.58	1.83	FBEB1A.DAT	0.350	14.50	7.207	1.722	0	1.27	1.27
Plasma-spr beryllium	1.58	1.83	FBEC1A.DAT	0.700	14.50	7.207	1.722	0	0	0
Plasma-spr boron	2.00	2.50	FBA1A.DAT	0.175	14.50	7.207	1.722	0.65	1.60	0.95
Plasma-spr boron	2.00	2.50	FBB1A.DAT	0.350	14.50	7.207	1.722	0.18	1.14	0.96
Plasma-spr boron	2.00	2.50	FBC1A.DAT	0.700	14.50	7.207	1.722	0	0	0
Plasma-spr Be 5%W	1.66	1.94	FBEW5A1A.DAT	0.175	14.50	7.207	1.722	0.11	2.60	2.49
Plasma-spr Be 5%W	1.66	1.94	FBEW5B1A.DAT	0.350	14.50	7.207	1.722	0	1.79	1.79
Plasma-spr Be 5%W	1.66	1.94	FBEW5C1A.DAT	0.700	14.50	7.207	1.722	0	0	0

1st Wall Porous Be Response to Possible X-Ray Outputs from Nova Upgrade									2/10/92			Sp &	
	BBT=0.175												
	X-Ray Output	Fluence	Fluence	Vapor	Melt	Melt	Spall	Sp	Max Vapo	Avg Melt	Vap Imp	Melt Imp	Avg Vap
Code File	(MJ)	(J/cm^2)	(cal/cm^2)	Thkns(	Depth(	Thkns	Depth(μm	Thkns(μm	Vel(km/s)	Vel(m/s)	(tap)	(tap)	Vel(km/s)
MPBEA7.DAT	1.00	0.497	0.119			0.0							
MPBEA6.DAT	1.50	0.746	0.178			0.00							
MPBEA5.DAT	2.50	1.243	0.297			0							
MPBEA4.DAT	4.00	1.988	0.475			0							
MPBEA3.DAT	7.00	3.479	0.832			0.0							
MPBEA2.DAT	14.50	7.207	1.722	0.07	2.57	2.5	3.86	1.29	13.00	190	4.3	9.4	3.9
MPBEA1.DAT	20.10	10.00	2.39			0							
	BBT=0.350											Sp &	
	X-Ray Output	Fluence	Fluence	Vapor	Melt	Melt	Spall	Sp	Max Vapo	Avg Melt	Vap Imp	Melt Imp	Avg Vap
	(MJ)	(J/cm^2)	(cal/cm^2)	Thkns(	Depth(	Thkns	Depth(μm	Thkns(μm	Vel(km/s)	Vel(m/s)	(tap)	(tap)	Vel(km/s)
MPBEB7.DAT	1.00	0.497	0.119			0.00		0					
MPBEB6.DAT	1.50	0.746	0.178			0.00		0					
MPBEB5.DAT	2.50	1.243	0.297			0.00		0					
MPBEB4.DAT	4.00	1.988	0.475			0.00		0					
MPBEB3.DAT	7.00	3.479	0.832			0.00		0					
MPBEB2.DAT	14.50	7.207	1.722	0	1.35	1.35	2.09	0.74	0	1640	0	44.6	0
MPBEB1.DAT	20.10	10.00	2.39			0.00		0					
	BBT=0.700											Sp &	
	X-Ray Output	Fluence	Fluence	Vapor	Melt	Melt	Spall	Sp	Max Vapo	Avg Melt	Vap Imp	Melt Imp	Avg Vap
	(MJ)	(J/cm^2)	(cal/cm^2)	Thkns(	Depth(	Thkns	Depth(μm	Thkns(μm	Vel(km/s)	Vel(m/s)	(tap)	(tap)	Vel(km/s)
MPBEC7.DAT	1.00	0.497	0.119			0.00							
MPBEC6.DAT	1.50	0.746	0.178			0.0							
MPBEC5.DAT	2.50	1.243	0.297			0.0							
MPBEC4.DAT	4.00	1.988	0.475			0.00							
MPBEC3.DAT	7.00	3.479	0.832			0.00							
MPBEC2.DAT	14.50	7.207	1.722	0	0	0.0	1.31*	1.31*	0	0	0	0.01	
MPBEC1.DAT	20.10	10.00	2.39			0.0							

*Also the interface bond strength of 0.5 kbar was exceeded within about 10 ns, by energy deposition in the aluminum wall layer.

[illegible]

1st Wall Porous B-5% Hf (HfB2 and B mixture) Response to Possible X-Ray Outputs from Nova Upgrade											4/16/92			
	BBT=0.175											Sp &		
	X-Ray Output	Fluence	Fluence	Vapor	Melt	Melt	Spall	Sp	Max Vapo	Avg Melt	Vap Im	Melt Im	Avg Vap	
Code File	(MJ)	(J/cm^2)	(cal/cm^2)	Thkns(	Depth	Thkns	Depth(μm	Thkns(μm	Vel(km/s	Vel(m/s)	(tap)	(tap)	Vel(km/s	
MPBHF5A7.DAT	1.00	0.497	0.119											
MPBHF5A6.DAT	1.50	0.746	0.178			0.00		0	0					
MPBHF5A5.DAT	2.50	1.243	0.297	0.01	0.24	0.23	0.24	0	0					
MPBHF5A4.DAT	4.00	1.988	0.475	0.1	0.44	0.34	0.44	0	1.69	0.02	1.1	0	0.50	
MPBHF5A3.DAT	7.00	3.479	0.832	0.27	0.80	0.53	0.8	0	5.00	0	5.7	0	0.96	
MPBHF5A2.DAT	14.50	7.207	1.722	0.34	1.51	1.17	1.51	0	11.00	0.01	20.4	0	2.73	
MPBHF5A1.DAT	20.10	10.00	2.39											
	BBT=0.350											Sp &		
	X-Ray Output	Fluence	Fluence	Vapor	Melt	Melt	Spall	Sp	Max Vapo	Avg Melt	Vap Im	Melt Im	Avg Vap	
	(MJ)	(J/cm^2)	(cal/cm^2)	Thkns(	Depth	Thkns	Depth(μm	Thkns(μm	Vel(km/s	Vel(m/s)	(tap)	(tap)	Vel(km/s	
MPBHF5B7.DAT	1.00	0.497	0.119			0.00		0						
MPBHF5B6.DAT	1.50	0.746	0.178			0.00		0						
MPBHF5B5.DAT	2.50	1.243	0.297	0	0	0.00	0	0	0	0	0	0	0	0
MPBHF5B4.DAT	4.00	1.988	0.475	0	0.08	0.08	0.08	0	0	0	0	0	0	0
MPBHF5B3.DAT	7.00	3.479	0.832	0	0.36	0.36	0.36	0	0	66	0	0.46	0	0
MPBHF5B2.DAT	14.50	7.207	1.722	0.21	1.27	1.06	1.27	0	2.7	0	2.7	0	0.58	
MPBHF5B1.DAT	20.10	10.00	2.39											
	BBT=0.700											Sp &		
	X-Ray Output	Fluence	Fluence	Vapor	Melt	Melt	Spall	Sp	Max Vapo	Avg Melt	Vap Im	Melt Im	Avg Vap	
	(MJ)	(J/cm^2)	(cal/cm^2)	Thkns(	Depth	Thkns	Depth(μm	Thkns(μm	Vel(km/s	Vel(m/s)	(tap)	(tap)	Vel(km/s	
MPBHF5C7.DAT	1.00	0.497	0.119			0.00								
MPBHF5C6.DAT	1.50	0.746	0.178			0.0								
MPBHF5C5.DAT	2.50	1.243	0.297			0.0								
MPBHF5C4.DAT	4.00	1.988	0.475			0.00	0	0	0	0	0	0	0	0
MPBHF5C3.DAT	7.00	3.479	0.832	0	0	0.00	0	0	0	0	0	0	0	0
MPBHF5C2.DAT	14.50	7.207	1.722	0	0.06	0.06	0.06	0	0	64	0	~.04	0	0
MPBHF5C1.DAT	20.10	10.00	2.39											

[illegible]

Appendix C

MIE-GRÜNEISEN AND PUFF EXPANSION EQUATIONS OF STATE

Appendix C

MIE-GRÜNEISEN AND PUFF EXPANSION EQUATIONS OF STATE

MIE-GRÜNEISEN EQUATION

The Mie-Grüneisen equation is used for all states in which the density is larger than the reference density. This equation was taken in the following form:

$$P = (C\mu + D\mu^2 + S\mu^3) (1 - \Gamma\mu/2) + \rho\Gamma E \quad (C-1)$$

where C, D, and S are coefficients with the units of pressure, E is the internal energy, ρ is the density, and Γ is the Grüneisen ratio. The compression μ is given by

$$\mu = \frac{\rho}{\rho_0} - 1 \quad (C-2)$$

where ρ_0 is the initial density. The Grüneisen ratio varies in the following way:

$$\Gamma = \Gamma_0 + \Gamma_1 \left(\frac{\rho_0}{\rho} - 1 \right) \quad (C-3)$$

This form is used in the GRAY equation of state, with $a = \Gamma_1$. With this form the Grüneisen ratio can vary only from Γ_0 to $\Gamma_0 - \Gamma_1$. For $\Gamma_0 = \Gamma_1$ we obtain the commonly observed result that $\Gamma\rho$ is a constant.

The C-D-S terms in the Mie-Grüneisen equation give the reference compression curve. For this curve we use the Hugoniot relations:

$$P_H = C\mu + D\mu^2 + S\mu^3 \quad (C-4)$$

where P_H is the Hugoniot pressure.

PUFF EXPANSION EQUATION

The current PUFF expansion equation of state has the following form:

$$P = \rho\Gamma_e \left\{ E - E_{se} \left(1 - \exp \left[N_e \left(1 - \frac{\rho_0}{\rho} \right) \frac{\rho_0}{\rho} \right] \right) \right\} \quad (C-5)$$

where

ρ, ρ_0 = current and initial density.

Γ_e = $H + (\Gamma_0 - H)(\rho/\rho_0)^n$, the effective Grüneisen ratio for the expanded states.

H = $\gamma - 1$ for the expansion at low densities and γ is the polytropic gas exponent.

E_{se} = effective sublimation energy.

n = a constant, usually 0.5 for metals, larger for ceramics.

N_e = a parameter defined to force continuity between the PUFF expansion and Mie-Grüneisen equations:

$$N_e = \frac{C}{\Gamma_0 \rho_0 E_{se}} \quad (C-6)$$

E_{se} = effective sublimation energy. This effective quantity is equal to E_s , the input sublimation energy, unless E is greater than E_s . Then we use the McCloskey-Thompson variation,

$$E_{se} = E_s \left[1 + \ln \left(\frac{E}{E_s} \right) \right] \quad \text{for } E > E_s \quad (C-7)$$

E_s = sublimation energy.

Appendix D
SPLITTING OF THE CRYOGENIC TUBES

Appendix D

SPLITTING OF THE CRYOGENIC TUBES

The stainless steel tubes are split because of excessive tensile strain caused by radial expansion under the neutron heating. This splitting is similar to the fracture that occurs in a military round when the contained explosive is detonated. The fracture and fragmentation process can be described by the method developed by Mott,* who described the fragmentation of a ring of material that is initially expanding at a uniform rate. Because of this expansion, the ring undergoes tensile strains that eventually reach levels that cause separation of the ring into fragments. The gradual separation of the ring is accounted for by recognizing the statistical spread in critical strains around the mean value and the random location of the weaker spots around the ring.

In the calculation, the ring is initialized with a specific tensile strain rate. The strain is allowed to increase until it is sufficient to generate one separation. The location of the separation is determined by a random procedure. Upon separation, unloading waves propagate into the remaining intact material from the break, reducing the stress to zero and halting the straining in the unloaded regions. But the rest of the material continues to strain. The calculation then progresses forward in time until there is sufficient strain for another separation, and that one is also randomly located. Unloading waves also proceed from this second break. The foregoing procedure is repeated until the entire ring is unloaded so no further separations can occur.

The resulting pattern is the fragment size distribution for the ring. Because of the random nature of the choice of location for the separations, several calculations should be conducted and the results should be averaged to obtain a representative fragment size distribution.

The foregoing procedure was implemented into a small computer program called MOTT. Some of the prominent features of the procedure and the program are described below.

The unloading wave proceeds slowly away from the break point so that the distance traveled is

$$x^2 = \frac{2Y_r \Delta t_b}{\rho V} \quad (D-1)$$

* N.F. Mott, "Fragmentation of Shell Cases," Proc. R. Soc. London A, 189, pp. 300-308, 1947.

where Y is the yield strength (the entire ring is assumed to be at yield), r is the current ring radius, V is the radial velocity, ρ is the material density, and Δt_b is the time since the break.

The probability of fracture is described by prescribing the probability dp that fracture will occur during a strain increment $d\epsilon$:

$$dp = C \exp(\gamma \epsilon) d\epsilon \quad (D-2)$$

where C and γ are constants. With this assumption, the probability p that the specimen breaks before a strain ϵ is reached is given by

$$\frac{dp}{d\epsilon} = (1 - p) C \exp(\gamma \epsilon) \quad (D-3)$$

and

$$p = 1 - \exp\left[-\frac{C}{\gamma} \exp(\gamma \epsilon)\right] \quad (D-4)$$

The average strain for fracture is given as the integral over the product of the strain and the probability:

$$\epsilon_{avg} = \int_0^1 \epsilon dp = \int_0^\infty \epsilon \frac{dp}{d\epsilon} d\epsilon = \frac{1}{\gamma} \left[\ln\left(\frac{\gamma}{C}\right) + 0.577 \right] \quad (D-5)$$

The factor 0.577 is recognized as Euler's constant. The value of the material constant C is determined by inverting Eq. (D-4):

$$\ln C = \ln \gamma + 0.577 - \gamma \epsilon_{avg} \quad (D-6)$$

To explore and illustrate the nature of the probability function for fracture strain, we computed a range of probabilities for several values of γ . The constant C was evaluated from Eq. (D-5) by using a mean strain of 1. The family of computed curves are given in Figure D-1. All the curves pass through the common point $p = 0.8315$ at a strain of 1. For small values of γ , the function shows a finite probability of fracture for very small strains (and hence is probably an inappropriate form), but for larger γ values (30 and above) the function has approximately the expected shape.

CAM-2802-56

Figure D-1. Mottprob fracture probabilities.
(Curves for gamma = 5, 10, 30, 50, 75, and 100.)

According to Mott, the rms value of the scatter in the fracture strain is

$$\Delta \epsilon_{\text{rms}} = \left[\int_0^{\infty} (\epsilon - \epsilon_m)^2 \frac{dp}{d\epsilon} d\epsilon \right]^{1/2} = \frac{1.28}{\gamma} \quad (\text{D-7})$$

The mean size of the fragments is given by x_0 :

$$x_0 = \sqrt{\frac{2\sigma_F}{\rho\gamma} \frac{(1 + \epsilon_m)r_0}{V}} \quad (\text{D-8})$$

where σ_F is the tensile failure stress, r_0 is the original radius of the tube, ϵ_m is the mean failure strain, and V is the radial velocity of the tube.

Appendix E

MEMBRANE MOTION UNDER IMPACT OR PRESSURE LOADING

Appendix E

MEMBRANE MOTION UNDER IMPACT OR PRESSURE LOADING

IMPACT OF THE CONE ONTO THE MEMBRANE SHIELD

The shield is expected to have a radius of about 1.5 m, but a thickness of less than 1 cm. Therefore, the shield must act essentially as a membrane, and its main resistance will be provided by the radial tensile stresses built up in the membrane. The deflections are expected to be large (tens of centimeters), and the strains may also be large.

Here we use the standard membrane equations to determine the response of the membrane to the impact of the LiH cone. The momentum equation describing the membrane response has the following form:

$$m_c \frac{dV_c}{dt} + m_m \frac{dV_m}{dt} + F(x) = \pi a^2 q \quad (\text{E-1})$$

where m_c and m_m are the masses of the LiH cone and protective membrane, V_c and V_m are the velocities of the cone and membrane, t is time, x is the displacement, $F(x)$ is the resisting force acting in the spring (the membrane), a is a radius of the membrane, and q is pressure on the membrane. We assumed that the cone strikes the membrane as a cluster of chunks all traveling at about the same velocity. To estimate the effect of this impact on the membrane, we used the solution for a membrane loaded by a uniform pressure over its surface. This assumption is a nonconservative, so the stresses and displacements from this solution should be slightly increased to account for the expected concentration of the loading. According to Timoshenko and Woinowsky-Krieger,* a uniform pressure q applied to a membrane causes a deflection x and maximum in-plane stress σ given by

$$x = 0.662 a \sqrt[3]{\frac{qa}{Eh}} \quad (\text{E-2})$$

$$\sigma = 0.328 \sqrt[3]{\frac{Eq^2 a^2}{h^2}} \quad (\text{E-3})$$

where a is the radius of the membrane, h is the its thickness, and E is the Young's modulus.

* S. Timoshenko and S. Woinowsky-Krieger, *Theory of Plates and Shells*, McGraw-Hill Book Company, Inc., New York [1959], p. 403.

To initiate the solution, we assume that the cone debris strikes the membrane with a velocity V_{oc} and sticks. Then the initial velocity of the combination of cone debris and membrane is

$$V_1 = \frac{V_{oc}m_c}{m_c + m_m} \quad (E-4)$$

By transforming Eq. (E-2), we can find the restoring spring force acting in the membrane:

$$F = \pi a^2 q = \frac{\pi E h x^3}{0.662^3 a^2} = R x^3 \quad (E-5)$$

where x is the central deflection of the membrane. This equation defines the spring constant R . Then Eq. (E-1) takes the form

$$(m_c + m_m) \frac{dV}{dt} + R x^3 = \pi a^2 q \quad (E-6)$$

Now the velocity V is common to both masses from the time of impact. This relation can now be used for impacts of objects, for application of an impulse I (initialize the velocity to I/m_m), or for a constant pressure loading.

We used a "centered" scheme to integrate Eq. (E-6) so that the velocity moved from V_n to V_{n+1} during the n^{th} time step. For use in Eq. (E-6), we defined and computed an average displacement at the midpoint of the time step: $x_{n+1/2}$. The displacement was computed from the auxiliary equations:

$$x_{n+1/2} = x_n + \frac{V_n}{2} \Delta t_n \quad (E-7)$$

$$x_{n+1} = x_n + \frac{V_n + V_{n+1}}{2} \Delta t_n \quad (E-8)$$

To integrate this differential equation (E-6), we examined the appropriate time step for stability and accuracy. For this purpose we studied the period of the membrane. Because of the nonlinearity of the force-displacement for a membrane, this period depends on the amount of deflection. At any time the apparent stiffness is

$$k = \frac{dF}{dx} = 3R x^2 \quad (E-9)$$

Then the period is

$$T = 2\pi \sqrt{\frac{M}{k}} = 2\pi \sqrt{\frac{m_c + m_m}{3R_x^2}} \quad (E-10)$$

An appropriate initial time step is $\Delta t = T/(20\pi)$. Therefore, we began with

$$\Delta t_1 = \frac{1}{10x} \sqrt{\frac{m_c + m_m}{3R}} \quad (E-11)$$

Our next step is to estimate an appropriate value for x at the initial time. For this impact and impulsive loads, we proceed as follows. During the initial time step we move the deflection from zero to $V_1\Delta t_1/2$, as shown in Eq. (E-7). Hence,

$$x_{1+1/2} = \frac{V_1\Delta t_1}{2} \quad (E-12)$$

Combining Eqs. (E-11) and (E-12), we find that

$$\Delta t_1 = \sqrt{\frac{1}{5V_1}} \sqrt{\frac{m_c + m_m}{3R}} \quad (E-13)$$

For pressure loading, we can use the static deflection of the membrane under the pressure q from Eq. (E-2). Then $x = \sqrt[3]{\pi a^2 q / R}$, and the appropriate value of Δt_1 , is found from Eq. (E-11).

Now we rewrite Eq. (E-6) in numerical form:

$$V_{n+1} = V_n + \frac{\Delta t}{m_c + m_m} \left(\pi a^2 q - R x_{n+1/2}^3 \right) \quad (E-14)$$

This relation, together with the auxilliary Eqs. (E-7) and (E-8) and the accuracy relation (E-11), was integrated step by step until the peak deflection was reached. With the peak deflection known, we solved for the average apparent force in the spring and the stress in the membrane (using Eqs. E-2 and E-3).

The foregoing relations were implemented into a small computer program called MEMBRANE, and solutions were found for a few cases of interest. The membrane was assumed to have a Young's modulus of 3 GPa and a thickness of 1 mm. For the total cone mass of 74 kg propelled against the protective membrane at a velocity of 1 m/s, the maximum deflection was 5.5

cm and the stress in the membrane was 4 MPa. For a velocity of 5 m/s, the maximum deflection was 12 cm and the peak stress in the membrane was 19 MPa.

IMPULSIVE LOADING OF THE GASES ONTO THE MEMBRANE SHIELD.

Here we assume that gases venting from the LiH ellipsoid are propelled against the protective membrane and gradually dissipate. The pressures were estimated to be many atmospheres and to persist for about 100 μ s. This duration of loading is much shorter than the periods of the membrane (12 ms for 1-mm-thick membrane under nominal loading), so we approximated the gas pressure loading as an impulse, which was applied to the membrane as an initial velocity of the membrane mass. Then the differential equation was solved in the same way as above for the impact of the cone on the membrane.

The results of the membrane motion for the gas pressure impulse are shown in Figures E-1 and E-2. The deflections and stresses depicted here can be used to select an appropriate membrane material and thickness. Some computations were also made for constant pressure loadings and for combinations of pressure and impulse; the results are described in Section 5.

Figure E-1. Membrane deflection as a function of impulse.
(Membrane thicknesses of 0.10, 0.25 and 1.00 mm.)

Figure E-2. Peak membrane stress as a function of specific impulse.
(Membrane thicknesses of 0.10, 0.25 and 1.00 mm.)