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ENERGY DEPOSITION AND FIRST WALL RESPONSE IN THE SIRIUS-T TARGET CHAMBER

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Abstract

The response of the first wall of the SIRIUS-T inertial confinement fusion (ICF) target chamber to high-gain target explosions has been investigated numerically. Calculations were performed for 100 MJ target explosions in target chambers filled with a 1 torr Xe background gas and lined with a graphite tile first wall. We used x-ray and debris ion spectra consistent with single-shell direct-drive targets. A 1-D radiation-hydrodynamics code was used to study the target energy deposition in the cavity gas and graphite tiles, the growth of and radiative emission from the microfireball, expansion of the shock front, and vaporization of and thermal conduction through the first wall. Our results indicate that the inner radius of the target chamber must be at least 3.7 meters to prevent premature degradation of the tiles due to vaporization.

Introduction

A conceptual design for the SIRIUS-T symmetric-illumination ICF tritium production facility has recently been reported [1]. In the SIRIUS-T design, a 1 - 2 MJ KrF laser illuminates single-shell direct-drive targets with 92 beams at a rate of 10 Hz. The target chamber is spherical and lined with 1 cm-thick graphite tiles. Target yields of 100 MJ are envisioned, requiring gains of 50 - 100. Roughly one-fourth of the total target yield is released in the form of x-rays and energetic debris ions. The target chamber is filled with a buffer gas of 1 torr xenon to protect the graphite first wall from the x-rays and debris. A schematic illustration of the SIRIUS-T target chamber is shown in Fig. 1.

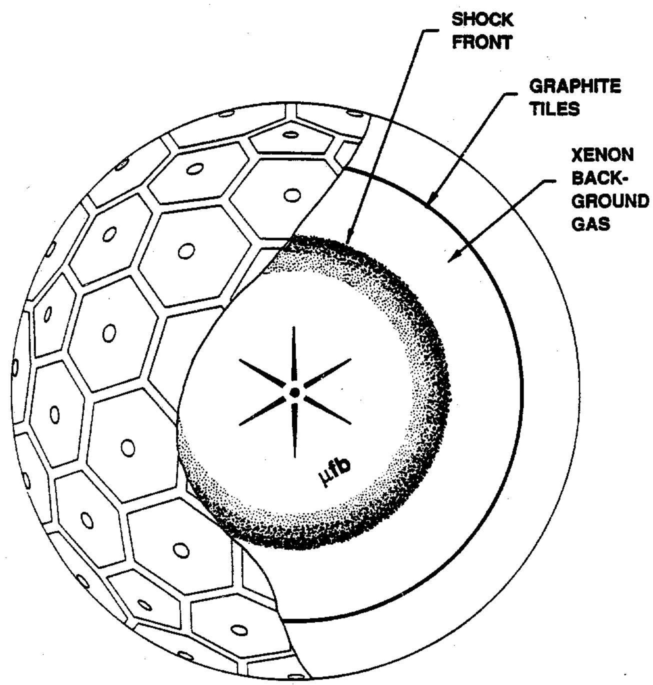

Fig. 1. Schematic illustration of the SIRIUS-T target chamber.

The size of the target chamber is influenced by several competing factors. The vaporization rate of the first wall must be sufficiently low that the graphite tiles can survive for a period of at least several years. This requirement defines the minimum inner radius of the target chamber in our study. It is expected that damage to the first wall structure by neutrons and gammas will require replacement of this structure every several years. The principal motivations for keeping the chamber as small as possible are economic considerations and the desire to maximize the tritium breeding ratio.

In this paper, we report the results of numerical calculations that simulate the time-dependent radiation-hydrodynamic environment of the SIRIUS-T target chamber. The purpose of the calculations was to determine the free paths and usually deposit the bulk of target energy deposition in the chamber, the heat flux and blast wave pressures at the first wall, and the vaporization rate of the graphite tiles. Below, we briefly review the models used in our calculations and present detailed results from simulations for SIRIUS-T.

Numerical Simulations

We have used the CONRAD target chamber physics code to simulate the radiation-hydrodynamic environment for SIRIUS-T. Details of the numerical and physics models used in this code have been presented elsewhere [2,3,4]. Only a brief review of the major features of the code will be presented here.

CONRAD is a one-dimensional Lagrangian radiation-hydrodynamics code that simulates the major physical processes that will occur within the target chambers of high-gain ICF facilities. The code simulates time-dependent energy deposition by the target debris ions and x-rays, the expansion of the microfireball and blast wave, radiative emission from the microfireball, and the vaporization of and thermal conduction through the first wall material. The x-rays and debris ions emanate from a point source at the center of the chamber. (Neutrons have much longer mean free paths and usually deposit the bulk of their energy beyond the first wall.) Spherical symmetry is assumed. X-ray energy is deposited in the background gas and first wall using an exponential attenuation model which includes bleaching (electron stripping) effects [5]. Analytical fits are used for the x-ray cross-sections [6]. Debris ion energy deposition is calculated using a time-, charge-, energy-dependent stopping power model [3]. Collisional ionization, collisional, radiative, and dielectronic recombination, and charge-exchange reaction rates are evaluated to determine the time-dependence of the debris ions as they travel through the background gas/plasma.

CONRAD transports radiation using a multigroup flux-limited diffusion model. Twenty photon energy groups were used in the calculations discussed below. Equation of state and opacity data are computed with the IONMIX code [7]. In this code, steady-state ionization and excitation populations are calculated by balancing collisional ionization and excitation rates with collisional and radiative recombination and deexcitation rates. Hydrogenic ion approximations are used to compute bound-bound, bound-free, and free-free contributions to the opacities. Vaporization in CONRAD is modeled using a combination of energy balance and kinetic theory models [4].

The chamber and target parameters used in our calculations are summarized in Table 1. The target was composed of a thin plastic shell surrounding the DT fuel. The partitioning of the target energy is characteristic of single-shell direct-drive targets, with a relatively high x-ray/debris yield ratio compared with targets with high-Z outer shells. The target x-ray spectrum was determined from target-burn calculations [8] and is shown in Fig. 2. The debris ion characteristics are listed in Table 2. Each ion species was divided into 10 groups that were emitted from the target over a period of 5 ns. (For computational reasons the D and T species were grouped together.) The ions leave the target fully ionized and pick up electrons as they travel through the Xe background plasma. The Xe density corresponds to a pressure of 1 torr at 0°C. The graphite tiles are actively cooled in the SIRIUS-T design and have a temperature of 500°C prior to each shot.

Table 1. Chamber and Target Parameters

Total Target Yield	100.0 MJ
X-ray Yield	6.0 MJ
Debris Ion Yield	20.9 MJ
First Wall Material	Graphite
Background Gas Species	Xenon
Background Gas Density	3.5×10^{16} cm^{-3}

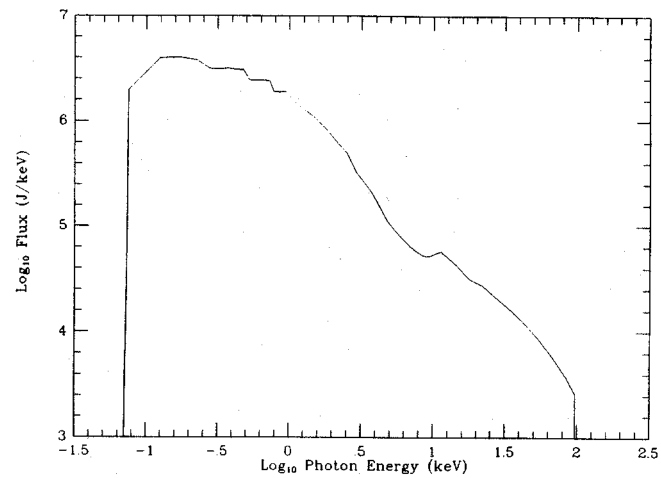

Fig. 2. Target x-ray spectrum.

Table 2. Debris Ion Properties

Ion	Initial Energy (keV)	Number of Ions	Total Energy (MJ)
H	138	1.05×10^{20}	2.3
D	94	9.70×10^{19}	1.5
T	140	9.70×10^{19}	2.2
He	188	3.73×10^{19}	1.1
C	1650	5.23×10^{19}	13.8

Results from our calculations are shown in Figs. 3 through 6. The radius of the target chamber cavity was varied between 2 and 4 meters to determine the minimum radius for which the 1 cm-thick graphite tiles could survive for a period of at least several years. We have chosen the maximum allowed vaporization rate to be 1 mm per full power year (FPY). Material at the graphite tile surfaces can vaporize as energy from the microfireball reaches the first wall and heats the inner surface. No material is vaporized as a result of direct energy deposition by the target x-rays because the Xe gas significantly attenuates the x-rays. Most of the x-rays that do penetrate the Xe have high energies (> 1 keV), and hence have rather long mean free paths in graphite as well. For these reasons, the temperature increase in the graphite tiles due to photoabsorption of the target x-rays is small.

The mass of graphite vaporized per shot is plotted in Fig. 3 as a function of the first wall radius. The dashed line corresponds to a vaporization rate of 1 mm/FPY based on a shot rate of 10 Hz and a facility availability of 75%. Our results indicate that the inner radius of the target chamber must be at least 3.7 meters for the graphite

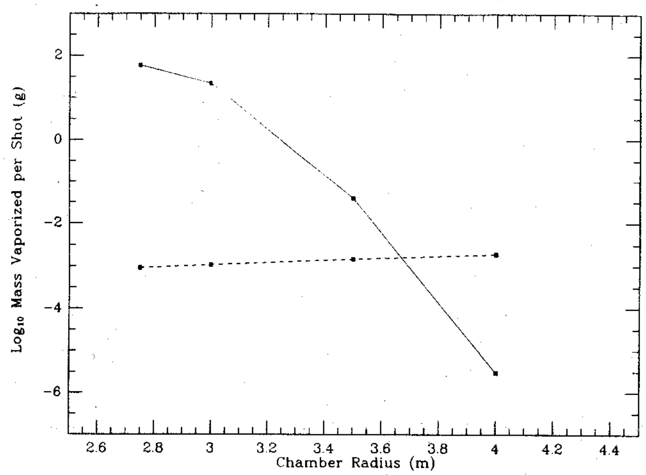

Fig. 3. Mass of graphite tiles vaporized per shot as a function of first wall radius.

tiles to survive for the desired length of time. We have therefore chosen an inner radius of 4 meters as our base case. The results described in the remainder of this paper are from calculations with a 4 m radius unless otherwise indicated.

The temperatures within the Xe gas are shown in Fig. 4 at several simulation times. At these times, two regions with large temperature gradients are evident at each

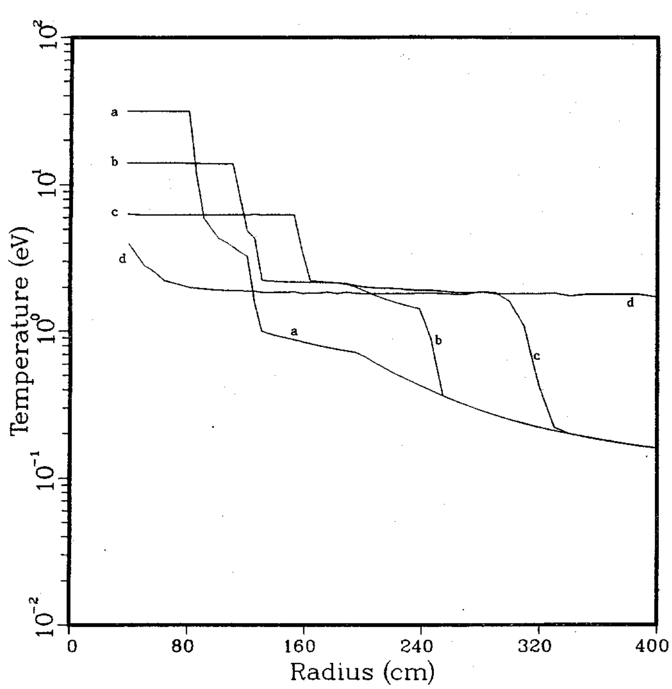

Fig. 4. Temperature profiles in the Xe gas at simulation times of (a) 0.28, (b) 0.78, (c) 4.5, and (d) 13 seconds.

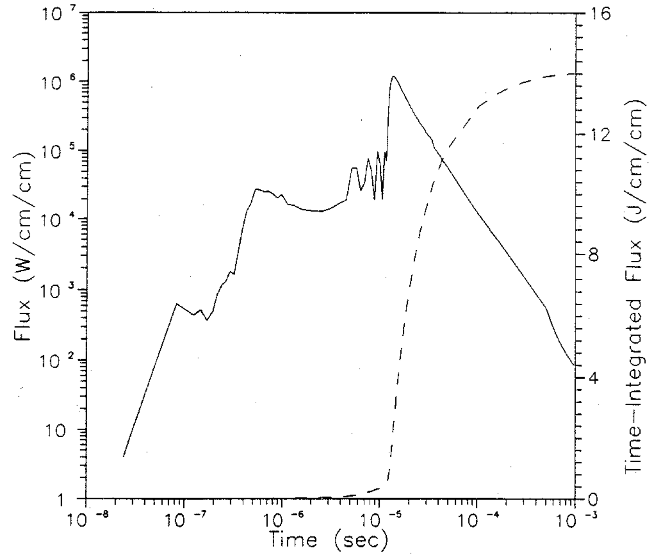

Fig. 5. Radiation flux and time-integrated flux at the first wall.

time. The innermost region corresponds to the outer boundary of the expanding microfireball. The outer region corresponds to the location of the carbon debris ions. By about 1- 2 μs, essentially all of the target debris has been stopped in the background gas. A strong shock forms near the outer boundary of the microfireball. However, by the time the shock reaches the first wall, the pressures are quite small ($P_{max} \sim 0.02$ MPa = 0.2 bar).

Little radiative energy is absorbed by the graphite tiles before the microfireball has expanded to fill the chamber. This is because radiation emitted by the microfireball is reabsorbed in the relatively cool Xe gas surrounding it. The radiation flux and time-integrated flux at the first wall are shown in Fig. 5. By $\sim 10^{-5}$ s, the microfireball fills the chamber so that the temperatures throughout the chamber cavity are above 1 eV. At this time the radiative flux at the first wall rises dramatically. By 10^{-4} s, most of the energy deposited by the target within the cavity has been radiated to the graphite tiles.

The temperature at the inner surface of the graphite tiles is plotted in Fig. 6 for the 4 meter (solid curve) and 3 meter (dashed curve) radius chambers. For the 4 m case, the temperature rises to a maximum of about 2200°K. The temperature quickly drops as energy is transported through the tiles and away from the surface by thermal conduction. Little mass is vaporized in this case (see Fig. 3). For the 3 meter case, the temperature at the inner surface rises to above 4000°K, resulting in a much larger amount of mass vaporized. The lower temperatures in the 4 meter case are largely a result of the greater first wall surface area that ultimately absorbs the energy from the target.

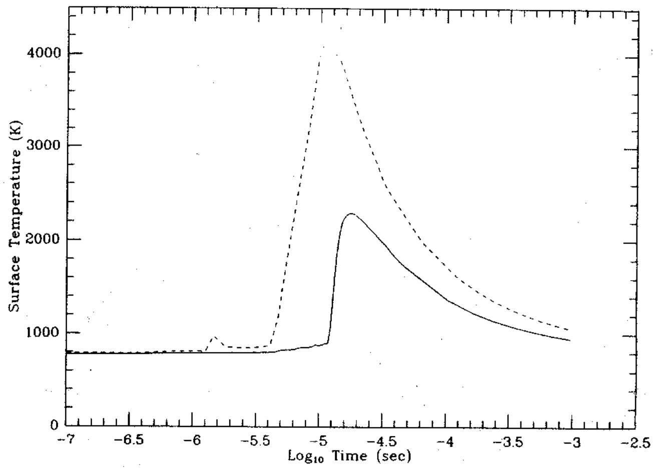

Fig. 6. Temperature at the graphite tile surfaces as a function of time.

Summary

We have performed radiation-hydrodynamic simulations for the SIRIUS-T target chamber. Our results indicate that the inner radius of the target chamber must be at least 3.7 meters for the graphite tiles to survive a period of several years or more. For a 4 meter inner radius chamber, 79% of the target x-ray energy and all of the debris ion energy is stopped in the Xe background gas before being reradiated to the first wall. We find that temperatures near the graphite tile surfaces remain below about 2200°K, resulting in very little vaporization. We also find the blast wave produced by the expanding microfireball provides a very small impulse at the first wall.

Acknowledgements

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