Parametric Target Chamber Simulations for the Inertial Fusion Energy Integrated Test Facility

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UWFDM-944

Prepared for the Eleventh Topical Meeting on the Technology of Fusion Energy, June 19–23, 1994, New Orleans LA.

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PARAMETRIC TARGET CHAMBER SIMULATIONS FOR THE INERTIAL FUSION ENERGY INTEGRATED TEST FACILITY

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ABSTRACT

The essential physical phenomena that will occur in Inertial Fusion Energy (IFE) reactors can be studied in a facility where the driver energy and target yield are reduced. The Integrated Test Facility (ITF) will study reactor relevant phenomena affecting drivers, beam transport, targets, and target chambers. The target chambers for reactors and the ITF could be designed using any one of several target chamber concepts. This paper involves the comparison, with computer simulation, of the phenomena occurring in the target chambers of three power reactor concepts (OSIRIS, HYLIFE-II, and CASCADE) with that occurring in ITF target chambers using the same design concept.

I. INTRODUCTION

The essential phenomena of IFE target chambers need to be understood before the first IFE power plants can be designed and built. These phenomena include interaction of target x rays with the target chamber walls and internal structures, vaporization, mass and energy flow in the target chamber, condensation of vaporized material and heat flow out of the chamber. Some understanding of these phenomena can be gained through experiments on existing facilities, such as the Nova laser or the Saturn x-ray source. Facilities that will become available in the next ten years, such as the National Ignition Facility (NIF) solid state laser and the Jupiter pulsed power x-ray source, will have higher, and therefore more IFE relevant, x-ray fluences over larger areas than today's machines. However, these machines will not allow the testing of a whole target chamber prototype under power plant conditions. The Integrated Test Facility[1] would have a target chamber which is a scaled down version of a power plant target chamber. Targets of reduced yield would be ignited in the chamber in bursts of shots that would test the viability of the target chamber concept. The chamber size would be scaled down in radius so approximately the same phenomena would occur in both the power plant and ITF chambers. To minimize cost, the size of the ITF driver would be the smallest needed to reliably produce gain and yield. In our example, we assumed a 1.5 MJ driver with a target gain of 20. This gives a fusion yield of 30 MJ and a total yield of 31.5 MJ when the driver energy is included. Target chambers of various concepts could be tested in this manner. The ITF would have great value in the verification of the computer codes used in the design and analysis of IFE power plant target chambers.

This paper involves the comparison, with computer simulation, of the phenomena occurring in the target chambers of three power reactor concepts (OSIRIS, HYLIFE-II, and CASCADE) with that occurring in ITF target chambers using the same design concept. The target yield in the ITF is reduced from a few hundred MJ in the reactors to 30 MJ and the distances from the targets to the first surface is reduced to keep the yield per unit first surface area constant.

II. ITF TARGET CHAMBER DESIGNS

In each of the three reactor concepts, the vapor pressure of the first wall material is low enough to allow ballistic propagation and focusing of the heavy ion driver beams. The number density of the chamber gas is very low, and the gas will not absorb the target x rays or ions. Therefore, the first surface in all three concepts is partially vaporized by the target x rays. The different chamber concepts have a variety of critical issues which could be studied on an ITF.

The OSIRIS[2] concept uses a film of the molten salt FLIBE to absorb the target x rays. FLIBE is shorthand for the class of molten salts which are a mixture of LiF and BeF_2. The FLIBE coats a graphite fabric, which is continuously soaked by FLIBE flowing through the fabric from back to the surface facing the target. FLIBE has low thermal conductivity, which greatly slows the rate at which the vapor created by the target x rays can recondense back onto the fabric. Therefore, the target chamber is designed to direct the vapor downward into a spray and a pool that have sufficient surface area to recondense the vapor. Critical issues to be studied with the ITF for the OSIRIS concept include the vaporization blowoff velocity and the resulting pressure on the fabric, the bulk motion of the vapor in the chamber, and the recondensation of vapor on the droplets and pool.

The CASCADE[3] concept uses a granular first wall that is held in place by the centrifugal force supplied by the rotation of the first wall. The wall is two equal cones, joined at their bases and with their vertices removed, that rotate about their common axes. Granules flow in through the holes and exit the chamber at the joined bases. The granules are ceramic (graphite or BeO) and absorb the target x rays, leading to the vaporization of some of the material. This vapor expands, absorbs the target debris and eventually recondenses on the granules. The granules are mixing as they flow down the wall, increasing the heat transport and improving the recondensation. The critical issues are the vaporization process and the pressure imposed on the granules that may lead to fracture or spallation, the mixing in the granule bed and recondensation.

HYLIFE-II[4] is a concept that uses jets of FLIBE to protect the first wall. The jets are directed in such a way that most of the volume of the target chamber is filled by FLIBE, where a cavern is left for the target and paths for the beams remain clear. When the target explodes, the x rays and ions vaporize the parts of the jets nearest the target, forming a hot core of vapor, and the neutrons are deposited in the bulk of the jets. Channels are left in the jets by which the high pressure in the core can vent, avoiding a disintegration of the jets. The neutron heating causes the jets to expand, possibly closing the venting channels before the core pressure is sufficiently reduced. This is a critical issue in the HYLIFE-II concept. To test the concept on the ITF, similar vaporization and neutron deposition need to occur.

III. TARGET PARAMETERS

Simulations have been performed for the ITF conditions, with the fractions of non-neutronic energy in x rays and debris ions being varied. In all cases the sum of x-ray and ion energy equals about 30% of the total target yield. We have assumed that all three reactor concepts use the HIBALL[5] heavy ion target. The target debris consists of 176 keV Pb ions. The x-ray spectrum has been calculated and has approximately a 300 eV blackbody shape with a high energy component between 50 and 100 keV. The 300 eV blackbody has a pulse width of 1.5 ns and the hard spectrum has a pulse width of about 100 ps.

The energy in x rays and debris ions is varied, as is shown in Tables I through III. The total target yield for the OSIRIS, HYLIFE-II, and CASCADE power plants (denoted as OSIRIS-0, HYLIFE-II-0, and CASCADE-0) is 430, 350, and 375 MJ respectively. In these power plants it is assumed that 20% of the total target yield is in x rays and 10% is in debris ions. In the ITF versions of these chambers, the fraction of energy in x rays and ions is varied to study the sensitivity of the results to the target energy partition. Cases designated by 1 have 18% in x rays and 9% in ions. In cases designated by 3, the fractions are reversed and in cases with a 2 there are 13.8% in both x rays and ions.

IV. COMPUTER CODES

Simulations have been performed with the CONRAD[6] computer code, which is a one-dimensional Lagrangian radiation-hydrodynamics code with x-ray and ion energy sources. CONRAD has been developed at the University of Wisconsin and used in several fusion plasma applications. Vaporization and condensation phenomena on a surface are modeled in the code. Radiation transport is calculated with a one-dimensional multigroup flux-limited diffusion method. Equations of state and opacities are interpolated from tables that are either supplied by the IONMIX[7] computer code or from the SESAME[8] tables. Realistic time-dependent target x-ray and debris ion spectra are used. Target x-ray deposition is calculated from the cold stopping powers of Biggs and Lighthill,[9] with corrections to account for depletion of atomic energy levels by the x rays. Ion deposition is calculated in CONRAD with a modified Mehlhorn

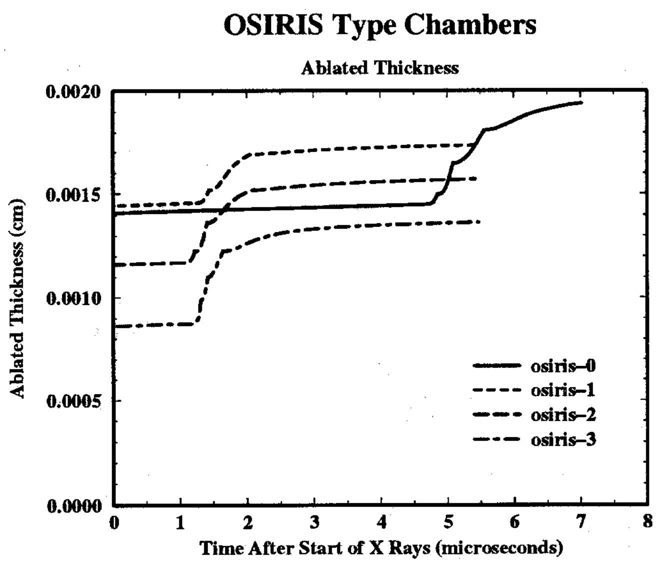

Fig. 1. Ablated thickness in OSIRIS type chambers.

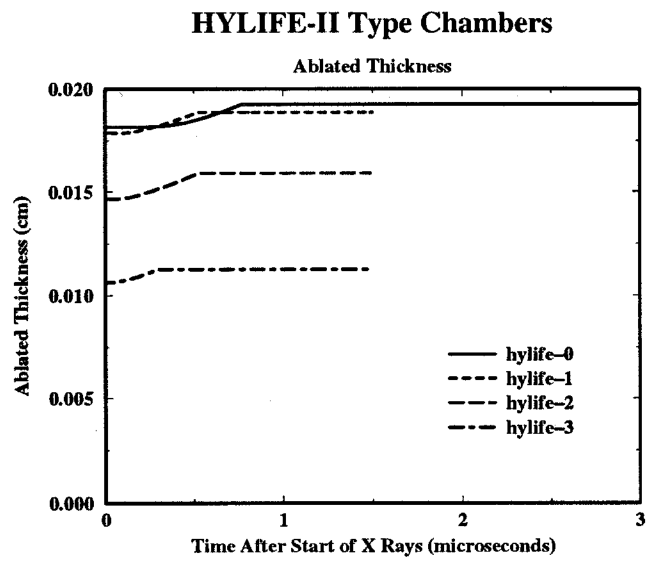

Fig. 2. Ablated thickness in HYLIFE-II type chambers.

model,[10] that is valid to low particle energies. The charge state of the debris ions is calculated in flight.

Simulations are performed in spherical geometry. The chambers are in fact not spherical; OSIRIS is essentially conical, HYLIFE-II is cylindrical, and CASCADE is biconical. In all cases the target emanations are spherical. In the simulations the spherical wall radius is set to the point on the wall nearest the target.

V. RESULTS

The results of the simulations are summarized in Tables I through III. In all three types of chambers, the ablated thickness is highest for the largest fraction of target emanations in x rays. This is so because x rays reach the first surface before the debris ions and generate a vapor layer that absorbs the ions. The debris ion energy heats the vapor to the point that it re-radiates the energy to the first surface, but over a time that is much longer than the original pulse width of the debris ions. This causes additional vaporization in OSIRIS and HYLIFE-II type chambers, because FLIBE has a low enough conductivity that the heat can not be carried away quickly enough to avoid more vaporization. The ablated thickness for OSIRIS type chambers is shown as a function of time in Fig. 1. Here one can see the vaporization due to the x rays and the later and smaller component from the ions. The ion component of the vaporization is about equal in all four cases, but the x-ray component increases with x-ray fluence. The situation is the same for HYLIFE-II, as is shown in Fig. 2. In CASCADE, the conductivity of the graphite is sufficient to avoid additional vaporization, so the vaporization increases with x-ray fluence, as is shown in Fig. 3. The impulsive pressure (the time-integral of the pressure on the surface) is not a strong function of the energy partition between x rays and debris ions for any of the three chamber types. The energy per unit volume in the chamber after the re-radiation has stopped is approximately constant for the OSIRIS and CASCADE versions of the ITF, but increases with the fraction of the target energy in x rays for HYLIFE-II. In all cases the energy per volume, and therefore the steady state pressure, in the ITF is much higher than in a power plant target chamber, because the ITF is designed to have the same energy fluence on the target chamber wall and the surface to volume ratio in the ITF is much higher than that in the power plants.

VI. CONCLUSIONS

The computer simulations show that, for all three target chamber types, initially the parameters and behavior of the x-ray generated vapor are similar in the ITF and the corresponding reactors. In OSIRIS and HYLIFE-II type target chambers, both power plant and ITF, x rays initially vaporize material from the first surface and the vapor is heated to a temperature sufficiently high to lead to more surface vaporization through re-radiation. In CASCADE type chambers, the debris ions play a less important role. The slowly varying pressure in the chamber is proportional to

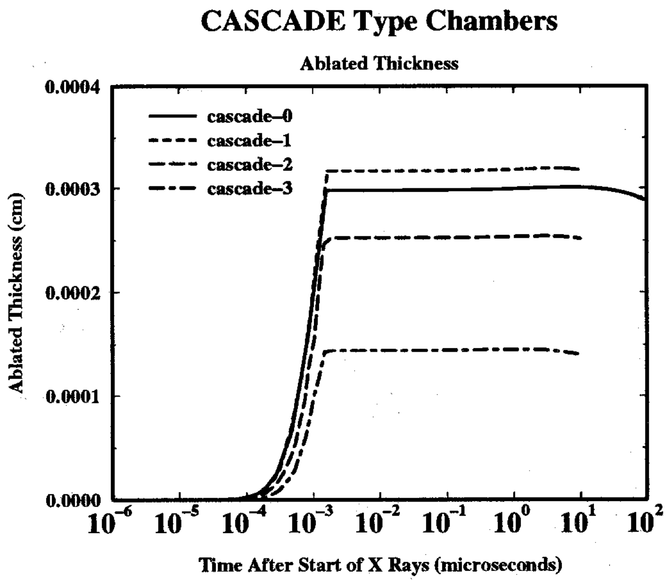

Fig. 3. Ablated thickness in CASCADE type chambers.

energy per volume, so late in time the yield per unit volume becomes important to condensation of x-ray produced vapor and first surface pressure loading in all three chamber concepts.

The ITF will provide an environment where the physics of vaporization, ion deposition, re-radiation and condensation can be studied for power plant relevant parameters. Targets producing relevant x-ray and debris spectra would be exploded. Major uncertainties exist in the opacities of the vapors generated, which could change the predicted performance of a power plant target chamber. The response of the surface materials to the pressure loading will be studied at impulsive pressures that are relevant to power plant target chamber conditions. Some phenomena, such as the recondensation of vaporized material, are dependent on both volumetric and surface effects, so power plant conditions can not be exactly duplicated.

Some experiments should be performed before the ITF is built. The National Ignition Facility (NIF) will produce sufficient x rays to study the x-ray vaporization that occurs in all three concepts. The x-ray spectrum will not be the same as in a power plant, but the basic physics can be studied and computer codes can be verified. The NIF could also be used to test scaled down versions of ITF wall components.

ACKNOWLEDGEMENT

This work is supported by Lawrence Livermore National Laboratory.

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TABLE I

Results of Computer Simulations of Target Chamber Response: OSIRIS

	OSIRIS-0	OSIRIS-1	OSIRIS-2	OSIRIS-3
Total target yield (MJ)	430	31.5	31.5	31.5
X-ray energy (MJ)	86	5.8	4.35	2.9
Debris energy (MJ)	43	2.9	4.35	5.8
First surface radius (cm)	350	90.9	90.9	90.9
X-ray fluence (J/cm^2)	55.9	55.9	41.9	27.9
Debris fluence (J/cm^2)	27.9	27.9	41.9	55.9
Run time (μs)	7.0	5.5	5.5	5.5
Ablated thickness (μ)	19.6	17.5	15.9	13.8
Peak pressure (GPa)	30.3	28.3	24.8	21.5
Impulsive pressure (Pa-s)	122.3	100.5	85.2	83.5
Re-radiation to surface (J/cm^2)	9.53	4.77	7.73	12.9
Cavity E/V (J/cm^3)	0.50	2.00	2.01	2.01

TABLE II

Results of Computer Simulations of Target Chamber Response: HYLIFE-II

	HYLIFE-II-0	HYLIFE-II-1	HYLIFE-II-2	HYLIFE-II-3
Total target yield (MJ)	350	31.5	31.5	31.5
X-ray energy (MJ)	70	5.8	4.35	2.9
Debris energy (MJ)	35	2.9	4.35	5.8
First surface radius (cm)	50	14.4	14.4	14.4
X-ray fluence (J/cm^2)	2228	2226	1669	1113
Debris fluence (J/cm^2)	1114	1113	1669	2226
Run time (μs)	3.0	1.5	1.5	1.5
Ablated thickness (μ)	195	191	161	114
Peak pressure (GPa)	89.0	195	409	741
Impulsive pressure (Pa-s)	1895	1675	1368	1017
Re-radiation to surface (J/cm^2)	1121	1272	1662	2045
Cavity E/V (J/cm^3)	121	386	295	213

TABLE III

Results of Computer Simulations of Target Chamber Response: CASCADE

	CASCADE-0	CASCADE-1	CASCADE-2	CASCADE-3
Total target yield (MJ)	375	31.5	31.5	31.5
X-Ray energy (MJ)	75	5.8	4.35	2.9
Debris energy (MJ)	37.5	2.9	4.35	5.8
First surface radius (cm)	310	86.2	86.2	86.2
X-ray fluence (J/cm^2)	62.1	62.1	46.6	31.1
Debris fluence (J/cm^2)	31.1	31.1	46.6	62.1
Run time (μs)	88.8	10.0	10.0	10.0
Ablated thickness (μ)	2.93	3.12	2.48	1.38
Peak pressure (GPa)	17.1	16.8	13.3	6.85
Impulsive pressure (Pa-s)	32.2	31.4	25.1	30.8
Re-radiation to surface (J/cm^2)	2.38	0.57	0.75	1.05
Cavity E/V (J/cm^3)	0.613	2.50	2.40	2.01