Gas Condensation Phenomena in Inertial Confinement Fusion Reaction Chambers

Robert R. Peterson

October 1985

UWFDM-654

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

Gas Condensation Phenomena in Inertial Confinement Fusion Reaction Chambers

Robert R. Peterson

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

http://fti.neep.wisc.edu

October 1985

UWFDM-654

GAS CONDENSATION PHENOMENA IN INERTIAL CONFINEMENT FUSION REACTION

CHAMBERS

Robert R. Peterson

University of Wisconsin-Madison
Fusion Technology Institute, 1500 Johnson Dr.
Madison, WI 53706-1687

INTRODUCTION

The vaporization and recondensation of material in the reaction chamber of an Inertial Confinement Fusion (ICF) facility can have far reaching consequences on the facility design. If one is designing a plant that produces commercial electrical power, the condensation of vaporized material should be considered because it may put an upper limit on the rate at which targets may be exploded and may have a strong effect on the economic viability of the plant. Both in power plants and in near term devices where target explosions may be very infrequent one must consider the effects of condensation on things such as optical components, whose performance or survival may be compromised by the deposition of a layer of material. There may be beneficial aspects of the recondensation as well, such as redeposition of vaporized material back onto the first wall of the reaction chamber. The complexities of these issues may be avoided by designing facilities that have low target yields and large chamber radii and thus have no vaporization of wall material, but this increases the costs and lowers target gain. For these and other reasons, understanding the vaporization and condensation of material in reaction chambers is a critical part of technology research for ICF.

This paper will begin with a summary of the conditions of the reaction chamber gas at the time of target ignition for the three main options for ICF drivers; short wavelength lasers, light ions, and heavy ions. A discussion of the important physics effects in the vaporization and condensation of reaction chamber material is then presented. Finally the results of a simulation with a computer code that models these effects are presented. A summary is then made and conclusions as to what future work is needed are put forth.

VAPOR DENSITY AT DRIVER BEAM INJECTION

The limitation of the reaction chamber repetition rate by vaporization and recombination may be a very important consideration for ICF power plants. This limit comes about because the density of the gas in the chamber at the time of the next shot is determined by the mode of propagation for the driver beam. Lasers require a density of between 10^{-3}

and 1 torr (the pressure the gas would have at 0°C), light ion beams 1 to more than 100 torr, and heavy ion beams 10^{-4} to 10 torr depending on the mode of propagation. There is considerable uncertainty in these limits.

The breakdown of gases with intense laser beams has been extensively studied theoretically and experimentally.[1,2] Calculations of the breakdown threshold laser intensities within the multiphoton absorption and cascade models do not always agree with experimental results, which are themselves somewhat inconsistent. It has been found that the breakdown threshold depends greatly on the laser pulse width and frequency, the focusing optics,[3] and the gas involved, including the density, species and impurities. An additional complication is that if the breakdown is limited to a small part of the beam path, much of the laser energy may still reach the target, especially if the breakdown occurs very near to the target as it is likely to do.[4] This all means that it is very difficult to state generally the density limits on the reaction chamber gas, because it is strongly dependent on the design of the facility.

The gas density limits in the case of light ion beam fusion depend on the mode of beam propagation. Propagation in laser guided plasma channels is currently the favored scheme.[5-8] For correct channel formation the gas mass density in the target chamber should be about 2×10^{-5} gm/cm^3. The species of the gas ranges from hydrogen to xenon, but is always a noncondensable gas. The number density ranges from 2 torr for xenon to 350 torr for hydrogen. The effects of condensable vapor mixed in with background gas may be significant to the formation of the channel and the behavior of the fireball in the gas that results from the target explosion,[9] but numerical limits on the condensable density are not known to this author. In the past, I have used the condition on the condensable vapor density that it cannot change the total mass density by more that 10%. As an alternative to propagation in channels, schemes using co-moving electron beams[10] to charge and current neutralize the ion beam have also been considered. These methods typically require cavity gas densities on the order of 10^{-4} torr.

Heavy Ion Fusion has several beam propagation schemes, with required target chamber gas densities ranging from 10^{-4} torr to several 10's of torr.[11] The lowest target chamber gas densities are required by ballistic focusing of heavy ion beams. As one increases the cavity gas density, there is increased ion loss due to scattering. As the density continues to increase, the background gas provides some charge and current neutralization. However, at low gas densities there exist two-stream instabilities in the background plasma-ion beam system that prevent effective ion beam propagation. Once the density reaches a level of about 0.1 torr,[12] the collision frequency in the plasma damps out the plasma instabilities to the point that the ion beam may propagate in a charge and current neutralized mode. At higher densities, plasma channels could possibly be used in much the same way as in Light Ion Fusion. Other means of beam propagation include propagation in a self-pinched mode, which is possible at a somewhat lower density.

From the discussion above, one can see that the vapor density required at the time of beam propagation can vary over about six orders of magnitude depending on the mode of propagation. Any material that is

vaporized by the target explosion must condense at a sufficient rate that the density reaches the required level before the next shot. The calculation of that rate of condensation and the amount of vaporization is the topic of the remainder of this paper.

PHYSICS OF VAPORIZATION AND CONDENSATION

The vaporization and recondensation of material in the target chamber of an ICF reactor are often broken down into two distinct phases.[13-15] The vaporization can be of two types; rapid adiabatic vaporization that is due to essentially instantaneous absorption of target generated x-rays and slow vaporization due to energy that is radiated from the target chamber gas over a longer enough time that vaporization is limited by heat transfer into the material. In a reactor with a low cavity gas density, which I will call case 1, the x-rays from the target deposit mostly in the first surface that they meet in the target chamber, whereas in reactor schemes with higher gas densities, hereafter referred to as case 2, this energy is mainly absorbed in the gas. In case 1 both superheated vapor and vapor at the local boiling temperature of the vaporizing material come off of the surface in a very complicated way, that will be discussed further later. This vapor will then meet with the energetic target debris ions and will be further heated. Over the next 100 ms or so the vapor will radiate to the first surface, causing additional vaporization, hydrodynamically move throughout the target chamber, and condense back onto the first surface. In this case, the presence of noncondensable gases may or may not affect the rate of condensation. In case 2, the x-ray and debris energy from the target create a fireball in the target chamber gas that radiates its energy to first surface over a time on the order of 1 ms. The radiant energy of the first surface is spread out over a long enough time that heat conduction into the material can drastically reduce the amount of vaporization. The vaporized material then mixes in with the noncondensable target chamber gases, where it is moved about the target chamber by the hydrodynamic motion of the fireball and is eventually condensed back out of the noncondensable gases. The rate of condensation can be greatly reduced by the presence of the noncondensable gases.

In both of the scenarios described above, similar physical phenomena must be considered. In many cases, heat transfer through the first surface material is the major process that determines the condensation rate.[16] Slow heat transfer through the material can keep the temperature near the surface up, which causes a high vapor pressure that slows the net condensation rate. In a liquid metal first surface, one must be aware that convective heat transfer can decrease the surface temperature and increase the condensation rate.[17] Hydromotion in the target chamber gas can also play a role by affecting the radiative heat transfer and the local vapor density adjacent to the first surface. The physics of the sticking of vapor atoms onto the condensing surface is very complicated,[18] being affected by the molecular state of the vapor, the energy of the condensing atoms, and the state of the condensing surface. The molecular state of the vapor is determined in case 1 during the time shortly after the rapid vaporization, when the vapor is very hot and dense. In fact, there are other important processes occurring at this time: there may be rapid recondensation because the vaporized mass is still very close to the first surface, there may be additional vaporization because the vapor has been heated by the debris ions so that the heat flux to the surface is very high, or both. In case 1, the physics of vaporization itself is rather complex and great differences in the

3

vaporized mass can be predicted by equally reasonable vaporization models.

A computer code has been under development at the University of Wisconsin that attempts to model many of these physics issues. With the use of this code, much can be learned about the relative effects of the aforementioned issues. However, it is clear that, both to study each item separately and to benchmark the computer code, experiments are needed.

COMPUTER SIMULATION OF VAPORIZATION AND CONDENSATION

The vaporization and condensation of lithium in an ICF target chamber has been simulated with the CONRAD computer code. The initial conditions for this simulation are listed in Table 1. These parameters are consistent with the Los Alamos National Laboratory FIRST STEP design,[14,15] which was chosen for the sake of an example. The x-ray spectrum used for a 30 MJ target explosion[20] is shown in Fig. 1 and the deposition power profile it creates over a 10^{-13} second pulse in liquid lithium is given in Fig. 2. The long tail is due to the hard component of the x-rays. CONRAD is a one-dimensional Lagrangian hydrodynamics multigroup radiation transport computer code. CONRAD models heat transfer and hydrodynamics in the gas or vapor in the target chamber and heat transfer, vaporization and condensation in the first surface surrounding the gas. Multigroup x-ray deposition in the gas and surface material is calculated as though it were instantaneous and the energy from target debris ions is included in the lowest x-ray energy group. The Lagrangian zones are dynamically rezoned as mass is transferred between the surface material and the vapor. Data tables of equations-of-state and opacities are read by CONRAD and are provided by the MIXERG computer code.[19]

In the past, CONRAD has been used to study the importance of radiative heat transfer from the vapor to the first surface on the net condensation rate.[13] It was found that energy radiated from the vapor, over a time long compared to the heat pulse directly from the target and short compared to the thermal diffusion time in the surface material, can cause significant additional vaporization that slows the overall reduction of the vapor density. CONRAD simulations have also shown that the tempera-

Table 1. Initial Conditions for Computer Simulation

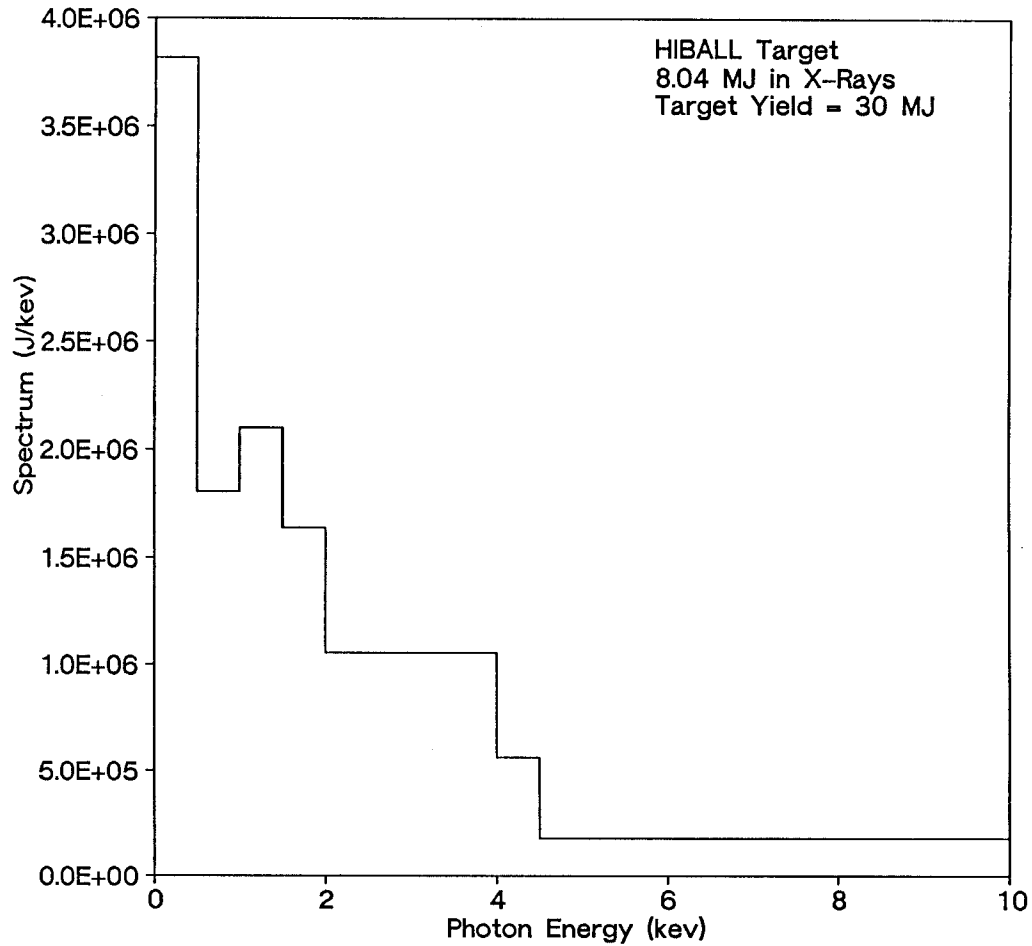| First Surface	Liquid Lithium
Nominal Target Yield	25 MJ
First Surface Position	2 meters from target
Target X-Ray Spectrum	"HIBALL"
Time Dependence of X-Ray Pulse	Instantaneous
Desired Repetition Rate	10 Hz
Driver Beam	KrF Laser (wavelength = 0.25 μm)

TARGET X-RAY SPECTRUM

Fig. 1.   Target X-ray Spectrum for HIBALL Type Target.   Target debris energy is added to lowest energy group.

ture and mass of the condensing particle, by affecting the mobility of the particles and thus their diffusion speeds, can have a marked effect on the condensation rate. Recently, the effects of vaporization modeling and vapor density dependent boiling temperatures have been studied.

Three vaporization models are included in CONRAD, the user's choice of model being an input parameter. The models can be understood with the help of Fig. 3. Here the energy density after deposition of x-rays in the surface material is plotted against distance from the surface nearest the target, as is the energy density needed to raise the material to the boiling temperature and that needed to vaporize the material. One should notice that there is one region, region I, where there is more than enough energy present to vaporize the material, a region II where there is more than the sensible heat required to raise the material to the boiling point but not enough to vaporize it, and a region where the material is below the boiling point. Three different models have been used
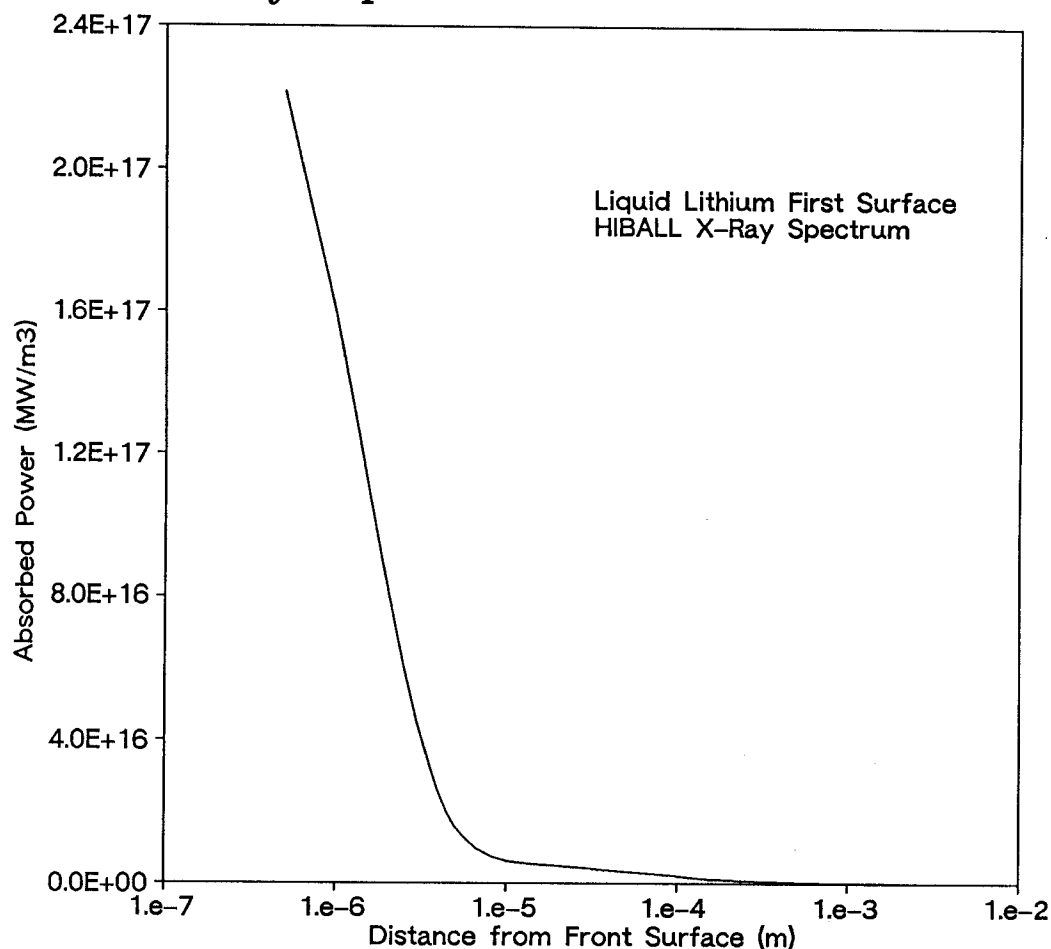
5

X-Ray Deposition Profile

Fig. 2. Deposition Power in Lithium for Spectrum in Fig. 1. Distance from target is 2 meters.

to study this situation; model A, which is not shown in Fig. 3, assumes that all of the energy from regions I and II is free to spread around to vaporize the maximum amount of material, model B only allows region I to vaporize, and model C uses all of the energy in region I to vaporize material in region I and the energy in region II to vaporize as much material as possible in region II. A series of calculations of the amounts of vaporized mass has been carried out with CONRAD for target yields ranging from 3.0 MJ to 450 MJ, the results of which are presented in Fig. 4. One can see that the vaporized mass can vary by a factor of several between the results of models B and C. This difference is due in part to the long tail on the deposition profile seen in Fig. 2. Calculations were not done for model A, which is considered to be the least physical of the three.

An effect that may seriously limit the condensation rate is that the equilibrium boiling temperature of the condensing material is a function of the local vapor density. Using the Clausius-Claperyon, one can deduce

6

Vaporization Models

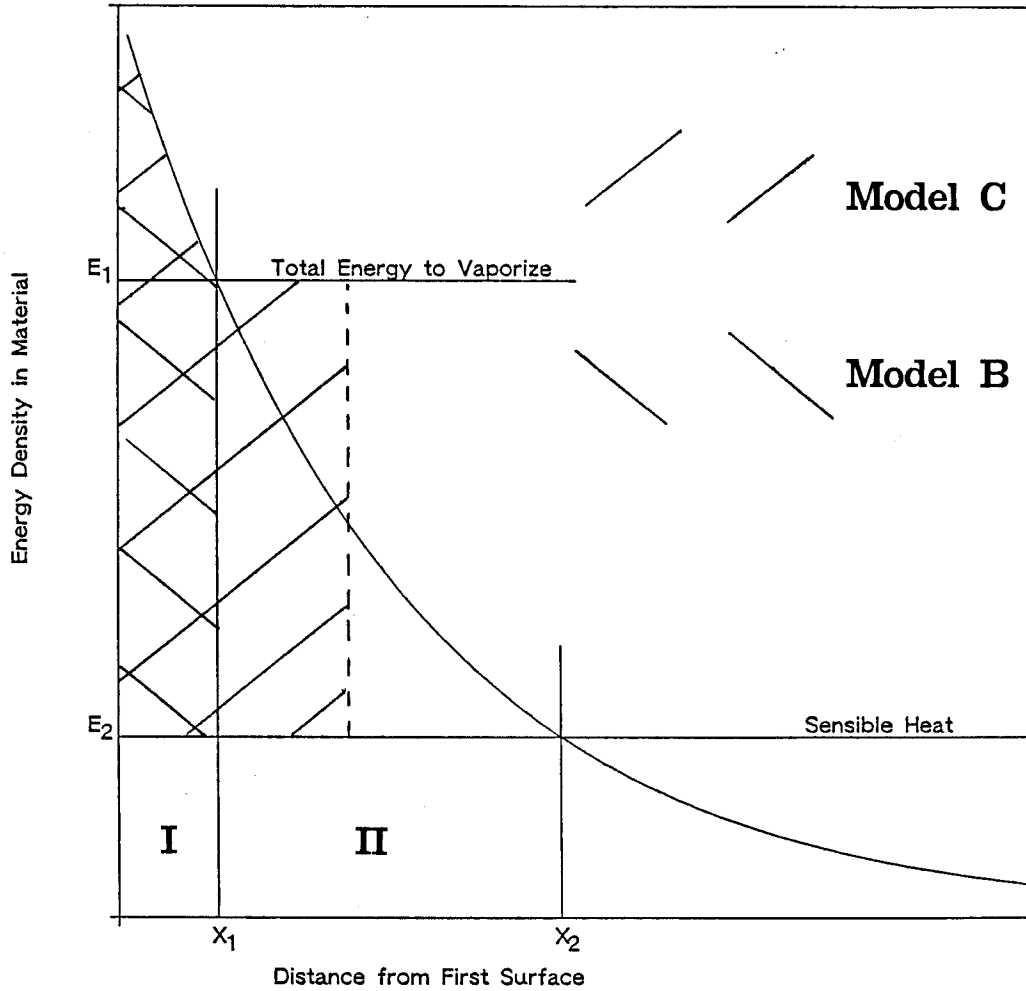
Fig. 3. Vaporization Models.

that the boiling temperature at some pressure P is related to the boiling temperature at 1 atmosphere by

$$T_{boiling} = \frac{1}{[\frac{1}{T_{boiling}(P = 1 \text{ atm})} - \frac{R}{\Delta H_v} \ln (\frac{P}{1 \text{ atm}})]} \tag{1}$$

where P is the local partial pressure of the vapor in atmospheres, R is the gas constant and ΔH_v is the latent heat of vaporization. In Fig. 5, the boiling temperature of lithium is plotted against the vapor pressure. The unit of vapor pressure is J/cm^3, which is equivalent to MPa. To test the importance of this to the condensation rate, CONRAD has been used to simulate the condensation of 200 gm of lithium vapor, that is initially near the vaporizing surface and at an initial temperature of 0.5 eV, onto the lithium walls of a 2 meter radius target chamber. This is the con-

ABLATED MASS

.164 cm thick Lithium
Back Temp. = 773 K
Boiling Temp. = 902 K
Init Density = 10^{14} cm^{-3}

Ablated Mass (gm) vs Yield/ Area (MJ/m**2)
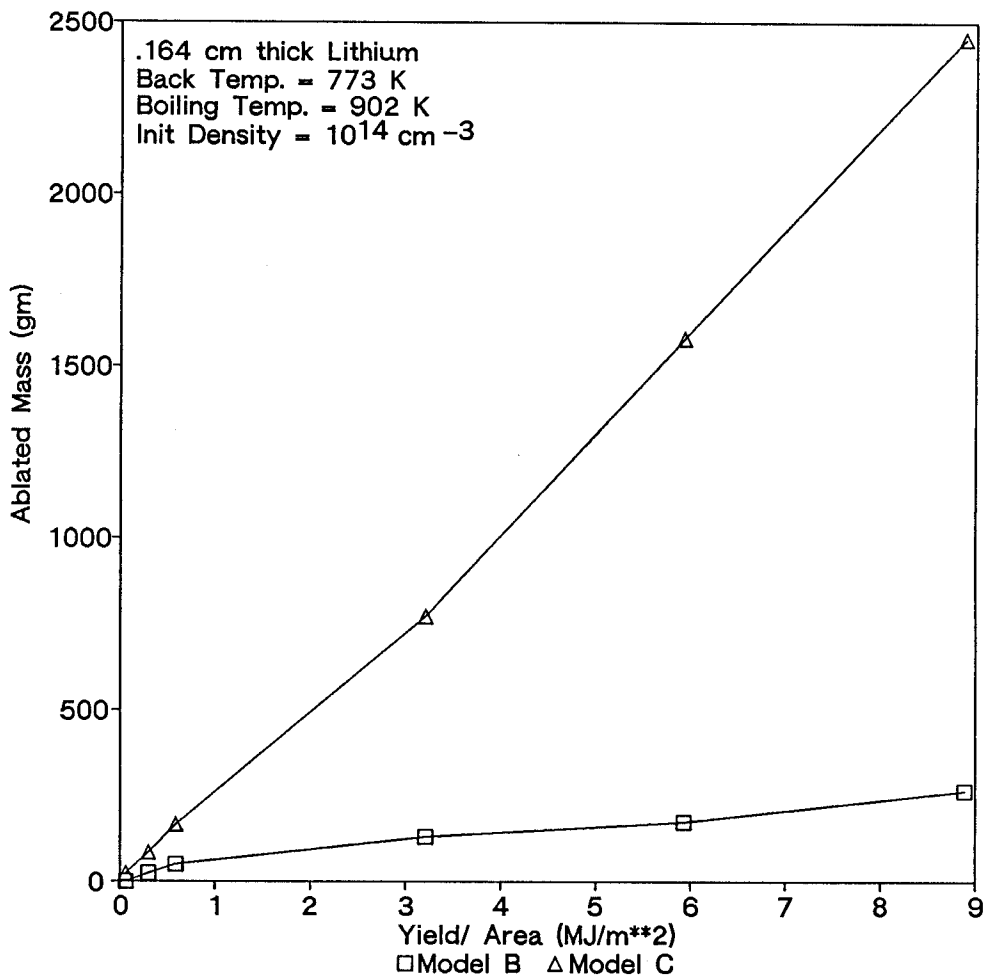
□Model B △Model C

Fig. 4. Vaporized Masses for a Two Meter Radius Spherical Target Chamber With a Liquid Lithium First Surface versus Target Yield per Unit Target Chamber Surface. Calculations have been made within model B and C.

dition of the vapor shortly after a 30 MJ shot. The results of simulations for the case where the boiling temperature is calculated in this manner is compared in Fig. 6 with a calculation where the boiling temperature is held constant. Here the average density in the target chamber is plotted against time. One sees that, as long as the average density is more than a few torr, the two calculations agree. Once an average density of about 1 torr is reached, the case where the boiling temperature is calculated no longer sees any net condensation, while the other calculation continues to condense. This is due to a reduction in the boiling temperature below the temperature of a significant part of the wall, leading to vaporization of that part of the wall. This additional vaporization, of course, increases the density of the vapor in the chamber, and increases the boiling temperature. This feedback between the boiling temperature and the vapor density causes the oscillations that are seen. Eventually, the temperature of the wall will decrease enough that net condensation will continue. In fairness to liquid lithium first
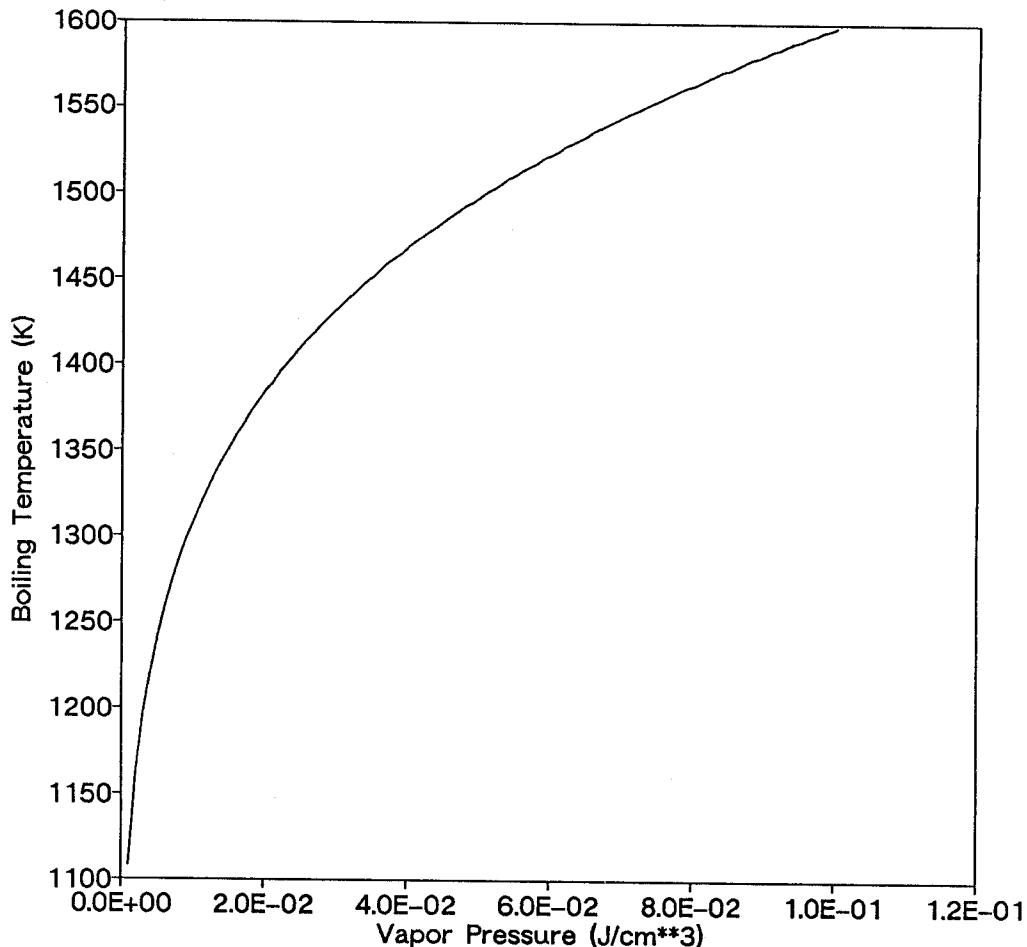
BOILING TEMPERATURE FOR LITHIUM

Fig. 5. Lithium Boiling Temperature versus Local Vapor Pressure.

wall protection schemes, it should be mentioned that convective heat transfer in the liquid, which is not taken into account here, could decrease the temperature in the wall more rapidly and speed the condensation process.

SUMMARY AND CONCLUSIONS

Vaporization and condensation phenomena in ICF target chambers can be critically important in determining the repetition rate of the facility. These phenomena are most important to designs that require very low target chamber gas densities at the time of driver beam propagation, such as heavy ion fusion in a ballistic beam focusing mode. The density required varies by six orders of magnitude, depending on the propagation mode.

There are several physics issues that are important to understanding vaporization and condensation phenomena. Heat transfer through the
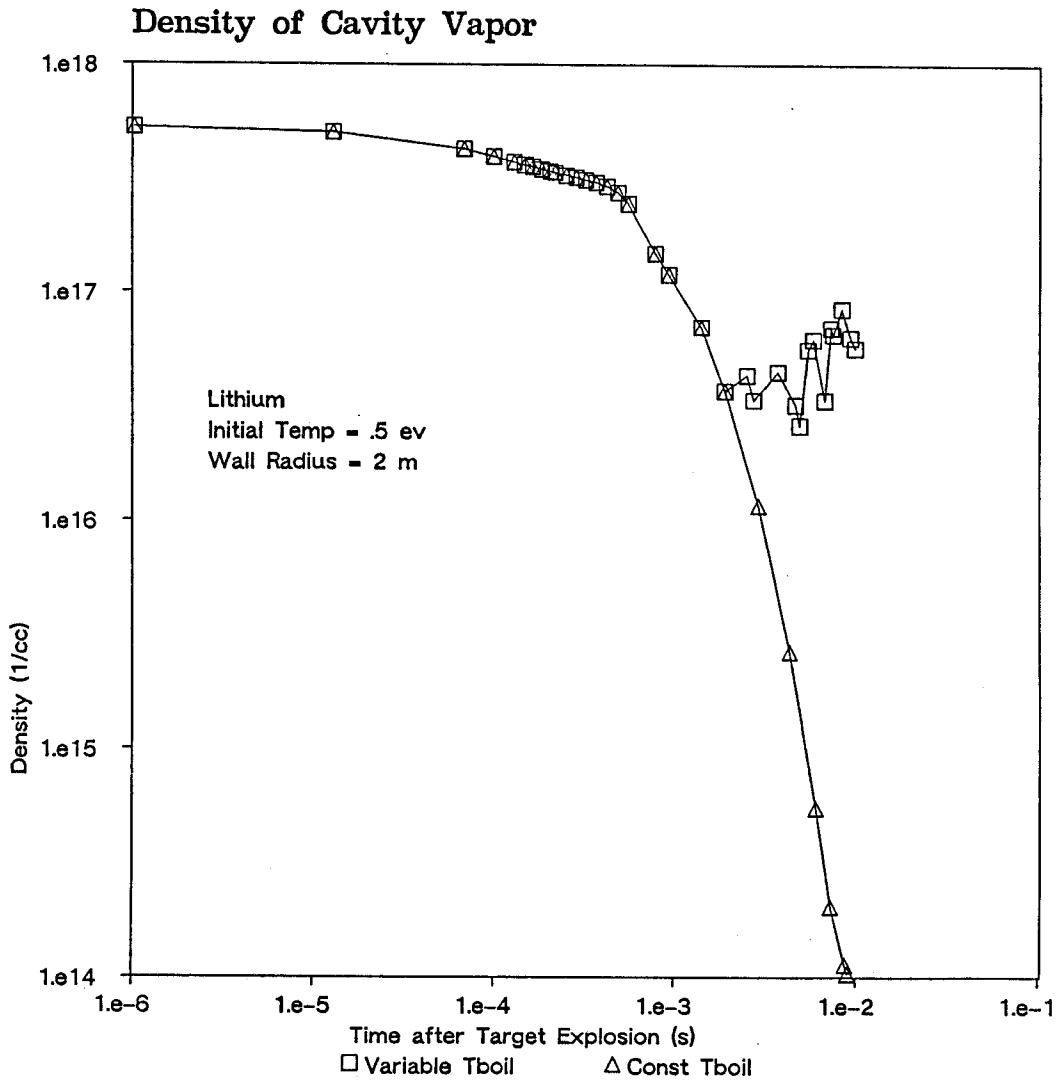
9

Density of Cavity Vapor

Fig. 6. Average Vapor Density in a Two Meter Radius Spherical Target Chamber With a Liquid Lithium First Surface With a 25 MJ Target Explosion versus Time After Explosion. Calculations have been done with variable and constant boiling temperatures.

vaporizing or condensing surface is clearly important when the thermal diffusion time is comparable to or shorter than the time over which heat is deposited. The conditions of the vapor, that is its temperature and density, can have a large effect on the condensation of the gas. The physics of sticking, which may be greatly influenced by the chemistry of the vapor phase, can also dominate the condensation rate.

A computer code is under development that simulates these phenomena in ICF reactor target chambers. Presently, the CONRAD code models vaporization, hydromotion and ionization in the vapor, radiative heat transfer from the vapor back onto the surface, and condensation. The detailed physics of sticking and vapor chemistry are not presently included in the code. To date, CONRAD has been used to show the importance of radiative heat transfer, of correct modeling of the vaporization process, of using the proper target x-ray spectrum, of calculating the heat transfer in the

surface, and of using the proper boiling temperature in the surface material.

Experimentation is needed to benchmark computer codes and study specific physics issues. Many of the physics issues rely on models that need experimental verification. For example, there are presently at least three candidate models for vaporization, where each gives a different result. Experiments are needed to better understand the details of this complicated process. Even if all of the individual physics issues are understood, experiments that involve all of the issues together are needed to test the validity of the computer codes such as CONRAD.

ACKNOWLEDGMENT

REFERENCES

1. E. Panarella, Theory of Laser-Induced Gas Ionization, Foundations of Physics 4 No. 2;227-259 (1974).
2. J.F. Ready, "Effects of High Power Laser Radiation," Academic Press, New York (1971).
3. Ya.B. Zel'dovich and Yu.P. Raizer, "Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena," Academic Press, New York (1967).
4. R.E. Palmer, J.P. Anthes, M.A. Palmer, Effect of Background on the Propagation of a High-Intensity Laser Beam to a Target, Technical Digest of the Topical Meeting on Inertial Confinement Fusion, February 26-28, 1980, San Diego, CA.
5. P.A. Miller, et al., Propagation of Pinched Electron Beams for Pellet Fusion, Phys. Rev. Lett. 39;92 (1977).
6. G. Cooperstein, et al., NRL Light Ion Beam Research for Inertial Confinement Fusion, Naval Research Laboratory Memorandum Report 4387 (November 1980).
7. J.R. Freeman, L. Baker, and D.L. Cook, Plasma Channels for Intense-Light-Ion-Beam Reactors, Nucl. Fusion 22;383 (1982).
8. J.N. Olsen and R.J. Leeper, Ion Beam Transport in Laser Initiated Discharge Channels, J. Appl. Phys. 53;3397 (1982).
9. R.R. Peterson, G.A. Moses, and G.W. Cooper, Cavity Gas Analysis for Light Ion Fusion Reactors, Nucl. Tech./Fusion 1;377 (1981).
10. Z.G.T. Guiragossian, Description of a Novel Light Ion Accelerator System for ICF, Bull. Am. Phys. Soc. 24;1033 (1979).
11. C.L. Olson, Ion Beam Propagation and Focusing, J. Fusion Energy 1;309 (1981).
12. P. Stroud, Streaming Modes in HIF Beam Final Transport, Los Alamos Report LA-UR-85-2809 (1985).
13. B. Badger, et al., HIBALL - A Conceptual Heavy Ion Beam Driven Fusion Reactor Study, Kernforschungszentrum Karlsruhe Report KFK-3202 and University of Wisconsin Fusion Technology Institute Report UWFDM-450 (1981).
14. R.R. Peterson and T.J. Bartel, ICF Reactor Target Chamber Issues for the Los Alamos National Laboratory FIRST STEP Reactor Concept, University of Wisconsin Fusion Technology Institute Report UWFDM-580, (1984).

15. R.R. Peterson, Liquid Metal Vaporization and Recondensation and the Repetition Rate of a Liquid Lithium First Surface Inertial Confinement Fusion Reactor, The 1984 IEEE International Conference on Plasma Science, May 1984.
16. M. Martinez-Sanchez, MIT, private communication.
17. J. Pendergrass, Los Alamos National Laboratory, private communication.
18. A. Ladd, Lawrence Livermore National Laboratory, private communication.
19. R.R. Peterson and G.A. Moses, MIXERG - An Equation of State and Opacity Computer Code, Computer Physics Communications 28;405 (1983).
20. G.A. Moses, R.R. Peterson, M.E. Sawan, and W.F. Vogelsang, High Gain Target Spectra and Energy Partitioning for Ion Beam Fusion Reactor Design Studies, University of Wisconsin Fusion Technology Institute Report UWFDM-396 (November, 1980).