Target Chamber Studies for the Inertial Confinement Fusion Technology Test Bed, FIRST STEP: Final Report for the Period 30 April 1985–30 June 1986

Robert R. Peterson

June 1986

UWFDM-697

FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

MADISON WISCONSIN

Target Chamber Studies for the Inertial Confinement Fusion Technology Test Bed, FIRST STEP: Final Report for the Period 30 April 1985–30 June 1986

Robert R. Peterson

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

http://fti.neep.wisc.edu

June 1986

UWFDM-697

DOE/NV/10474-1

TARGET CHAMBER STUDIES FOR THE INERTIAL CONFINEMENT FUSION TECHNOLOGY TEST BED, FIRST STEP

Final Report for the Period April 30, 1985 to June 30, 1986

Robert R. Peterson

Fusion Technology Institute
University of Wisconsin-Madison
Madison, WI 53706-1687

June 1986

UWFDM-697

Work performed under contract DE-AS08-85NV10474
with the U.S. Department of Energy

I. Introduction

The vaporization and condensation of material in the reaction chamber of a heavy ion beam (HIB) driven Inertial Confinement Fusion (ICF) reactor can have important consequences to the facility design.[1] The condensation of material that has been vaporized by energy from the target can limit the rate at which targets can be exploded, which can either require the driver to operate at a lower firing rate than it is capable of providing or the use of several reaction chambers. The repetition rate is limited because, depending on the mode of propagation of heavy ions to the target,[2] there are limits on the density of vapor in the reaction chambers at the time of beam injection. If the mission of the reactor is to produce commercial electric power, limitation of the repetition rate can greatly affect the cost of electricity, while additional reaction chambers can make the overall plant design much more complicated. Therefore, when optimizing the repetition rate of the driver one needs laws by which the condensation and vaporization processes can be modeled.

In addition to condensation of vapor, active pumping of noncondensable gases is required to keep the gas density in the target chamber at the levels required for beam propagation.[1] Noncondensable gases are released by the exploding target. The presence of these gases not only adds atoms to the chamber that can affect beam propagation, but they can also slow the condensation of the vapor and thus lower the allowable repetition rate.[3] Pumping of noncondensable gases will be discussed.

One class of ICF reactor designs uses liquid metal coatings to protect the first walls from the effects of the target explosion. For the study, a design has been chosen that uses liquid lithium as a coating. The relatively

high vapor pressure of lithium at low temperatures (< 500°C) makes lithium potentially susceptible to these repetition rate limiting phenomena and an interesting topic for study. The FIRST STEP[4] design, whose general parameters are listed in Table I, has been chosen as a base case for this study.

II. Computer Modeling of Vaporization and Condensation

The vaporization and condensation of material in ICF reaction chambers has been modeled through computer simulation[5] and scaling laws have been determined. The vaporization and recondensation of material in the target chamber of a heavy ion beam driven ICF reactor can be broken down into two distinct phenomena. Vaporization can occur through the very rapid adiabatic process due to the absorption of target generated x-rays in the first wall material, or through a much slower mechanism caused by radiant and conducted heat from the vapor and gases in the reaction chamber that is absorbed on the surface of the material. Condensation also occurs in two separate phases: an early period when the vapor density is high and condensation is controlled by the speed at which the vapor atoms can reach the surface where condensation takes place, and later, when the vapor density is lower and heat conduction through the material on which the condensation occurs is the phenomenon that governs the condensation rate. The CONRAD computer code simulates these processes[6] by modeling the vapor as a one-dimensional Lagrangian mesh through which heat is transferred via conduction and multigroup radiative heat transfer, by calculating the heat transfer through the wall material with a standard finite difference method,[7] and by considering the energy, momentum, and mass exchanged between the wall material and the vapor. This code has been used parametrically to aid in the development of formulae, or scaling

Table I. FIRST STEP

Target Yield	25 MJ
Target Chamber Repetition Rate	10 Hz
Average Fusion Power	250 MW
Target Chamber Radius	2 m
First Wall Protection Scheme	Liquid Lithium Coating

laws, that show how the vaporization and condensation depend on the radius of the reaction chamber, the yield of the target, the required density of vapor at the time of the next shot, and the properties of the vaporizing and condensing material.

III. Vaporization and Condensation Computer Results and Scaling Laws

Computer simulations of the vaporization and condensation of material in the reaction chamber of a heavy ion beam fusion reactor have been done with the CONRAD computer code. Using basic laws of physics and comparisons between many CONRAD simulations, scaling laws have been devised for the allowable repetition rate.

Parametric calculations have been carried out about the base case with a chamber radius of 2 meters, a target yield of 30 MJ and lithium as a vapor species, where the liquid lithium is initially at 420°C. Liquid lithium has been chosen as the material for vaporization. The target yield was varied to show the dependence of the vaporized mass on the yield per unit area, which is shown in Fig. 1. The linear nature of this curve lets us write the vaporized mass as,

$$M\ (g) = 2.76 \times 10^2\ Y/4\pi R^2 \qquad (1)$$

where Y is the yield in MJ and R is the chamber radius in meters. Starting from the same vapor density profile, the early condensation process is then simulated for several chamber radii, shown in Fig. 2. Parametric variation of the temperature of the vapor shortly after vaporization has been combined with the information in Fig. 2 to provide a scaling law for lithium in the early

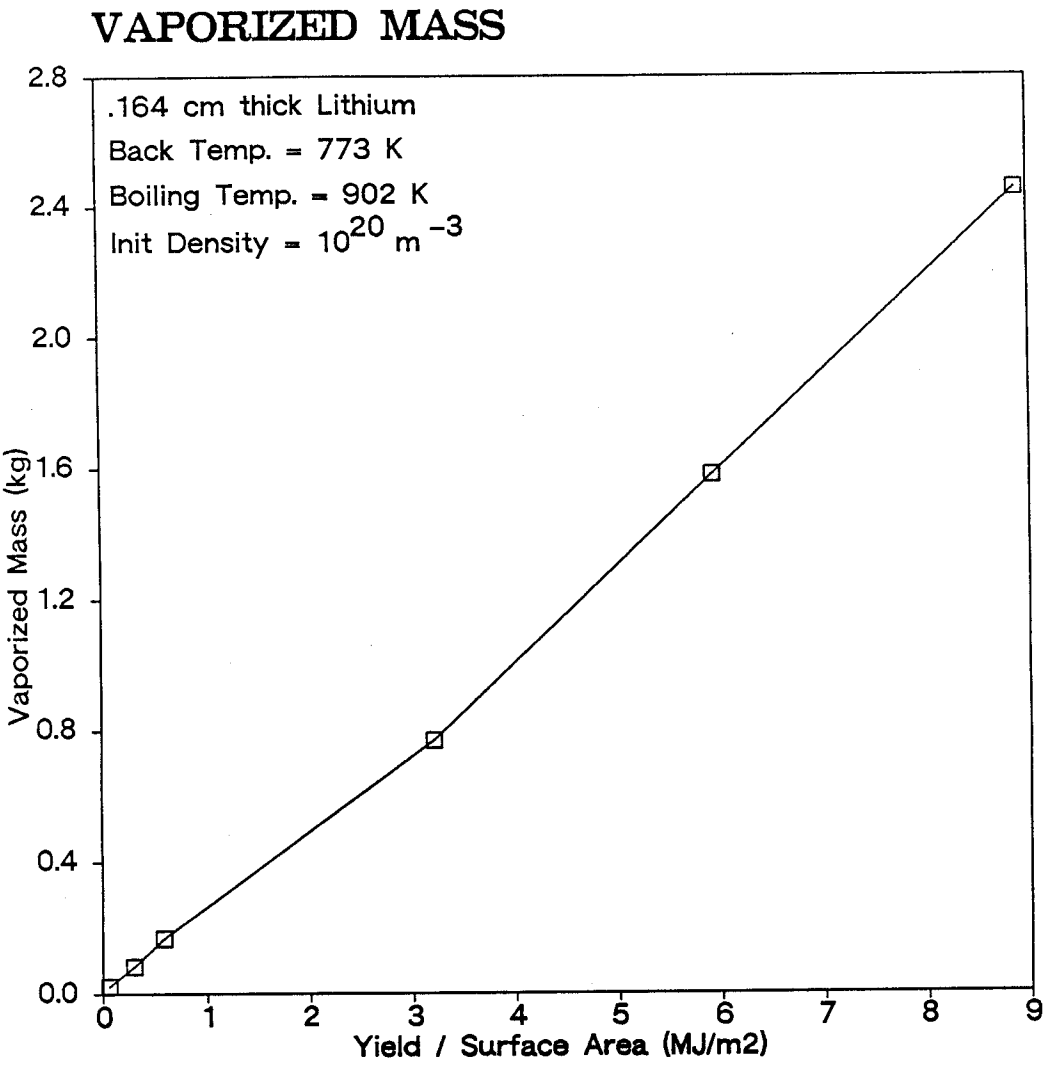

Fig. 1. Vaporized mass as a function of the yield per unit area. The cavity radius is 2 meters, the first wall is lithium and the HIBALL x-ray spectrum is used.

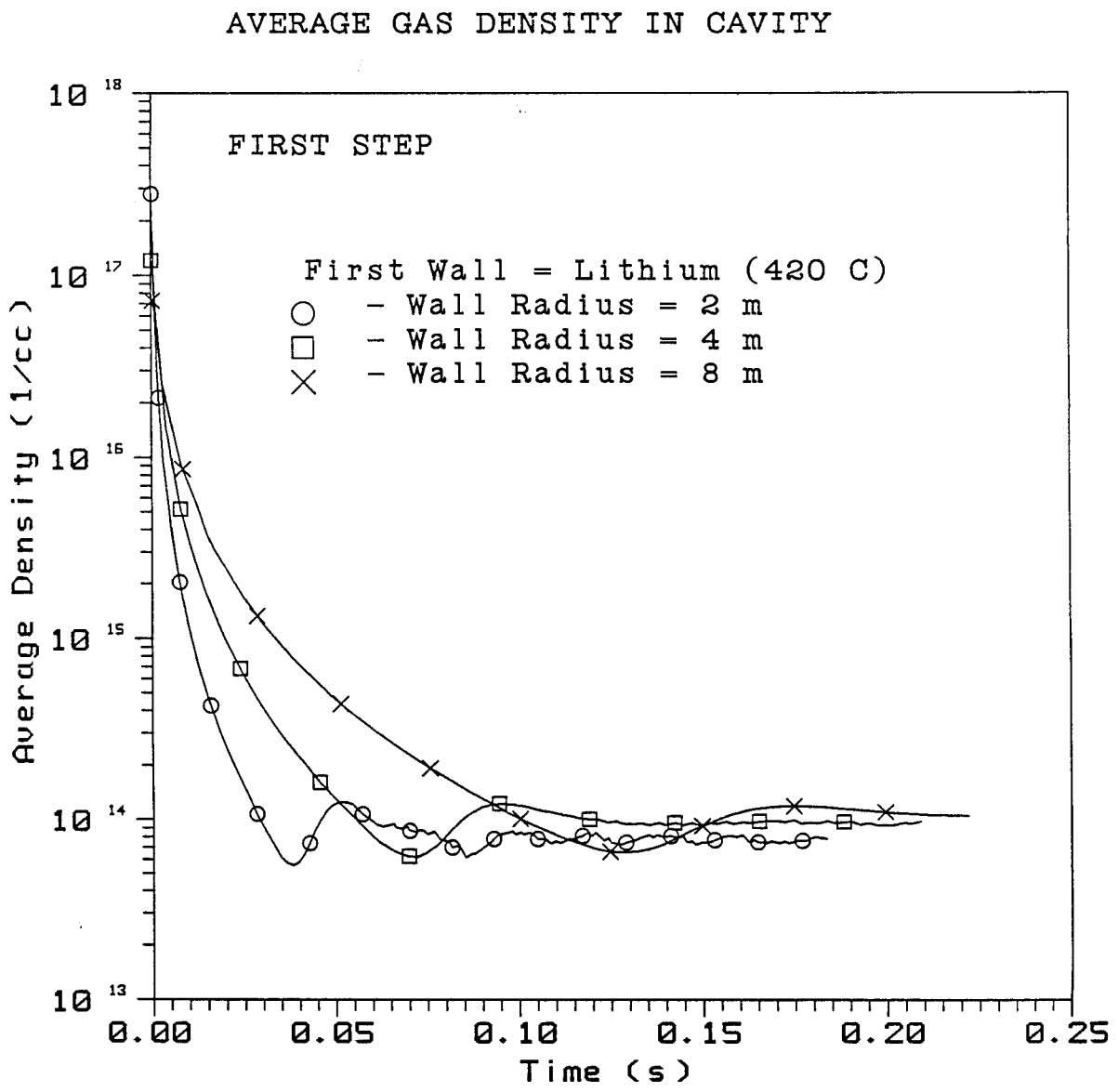

Fig. 2. Average number density in cavity versus time for various target chamber radii. The bulk temperature of the wall is 420°C and there are initially 150 gm of vaporized material.

phase,

$$n(t) = h_o \exp[-t/(0.21 \times 10^{-3} R T^{-0.56})] \quad (2)$$

Here, n(t) is the time-dependent average number density of vapor in the cavity in particles/m^3 and t is the time in seconds. T is the initial vapor temperature in eV, which can be expressed in terms of yield and radius with the use of equation 1. Simple heat transfer relations and the Clausius-Clapeyron equation[8] for vapor pressure as a function of surface temperature give a similar law for the later phase,

$$n(t) = 2.6868 \times 10^{25} \left(\frac{0.025\ eV}{T_v}\right) \exp\left[\frac{N_o K_B}{\Delta H_v}\left(\frac{1}{T_{boiling}(P=1atm)} - \overline{T}_s(t)\right)\right] (m^{-3}) \quad (3)$$

where, $$T_s(t) = T_{bulk} + \frac{1}{\kappa_\ell}\sqrt{\frac{\alpha}{\pi t}}\, Y/4\pi R^2$$

N_o is Avogadro's number, k_B is Boltzmann's constant, and ΔH_v is the heat of vaporization of the material. $T_{boiling}$ is the boiling temperature of the material at 0.1 MPa of pressure, and T_{bulk} is the temperature of the back of the wall. κ_ℓ is the thermal conductivity of the wall material and α is the thermal diffusivity. From Eqs. (1), (2) and (3), the repetition rates for a given required density in the reaction chambers can be calculated for both early and late periods.

IV. Cavity Gas Pumping

Because condensation cannot clear the gas of hydrogen and helium, active pumping must be employed to some degree. Helium and hydrogen enter the cavity as debris from the target explosion. Because there is very little residual cavity gas, the gas ions travel through the cavity as energetic ions that either strike the vapor newly created by the target x-rays, or they hit the liquid metal directly. The hydrogen component in the gas may be adsorbed in the liquid lithium but the helium will remain as gas in the cavity. Cryogenic pumping has been investigated as a means of keeping the helium density in the cavity at acceptable levels. An average helium density of 3.5×10^{12} cm^{-3} (10^{-4} torr) has been chosen as the value required for beam propagation.

The active pumping is opposed by the resistance of the pipe between the pump and the target chamber.[9] A measure of the flow that is allowed in a pipe is the conductance, which can be calculated in the case of molecular flow through the expression,

$$\frac{1}{C} = \left[\frac{6}{16}\frac{\ell}{r} + 1\right] \sqrt{\frac{2\pi m}{8.317 \times 10^7 \, T}} \frac{10^3}{\pi r^2} \left(\frac{s}{\ell}\right) \qquad (4)$$

Here, ℓ is the length of the pipe in cm, r is the pipe radius in cm, T is the gas temperature in K, and m is the molecular weight of the gas in g. Estimating the pipe length to be 400 cm, the pipe radius to be 30 cm and the gas temperature to be 2000 K, one calculates conductances of 2.99×10^4 and 3.83×10^4 liter/s for lithium and helium respectively. From the other helium pumping parameters listed in Table II, the required effective pumping rate may be calculated by the formula,

Table II. Helium Pumping Parameters

Pipe Length	400 cm
Pipe Radius	10 cm
Gas Temperature	2000 K
Gas Volume (V)	3.35×10^4 liters
Required Number Density (n_o)	3.5×10^{12} cm^{-3}
Density Increase Due to Target Debris (n_T)	2.63×10^{11} cm^{-3}
Time Between Shots (t)	0.1 s

$$\frac{1}{S_{eff}} = \frac{\Delta t}{V \ln \left(\frac{n_o + \Delta n_T}{n_o}\right)} \tag{5}$$

which leads to a value of 2.43×10^4 liter/s. Here, n_o is the required average number density, Δn_T is the increase due to the induction of target debris, and Δt is the period of time between shots. The actual pumping rate required is related to the effective pumping and the conductance of the pipe through the relation

$$\frac{1}{S_{pumping}} = \frac{1}{S_{eff}} - \frac{1}{C} \tag{6}$$

The required pumping rate to regulate the helium density is therefore equal to 6.62×10^4 liters/s. If one assumes that 1 cm^2 of cryopanel area provides 5 liters/s of pumping capacity, 1.3×10^4 cm^2 of cryopanel is required. Whether sufficient space is available for these cryopanels depends on the design of the pumps and the beam lines; but in HIBALL[1] there is 2.8×10^4 cm^2 so that, even with a 50% duty factor, there is enough room to do such pumping.

Some of the vaporized lithium will also travel down the beam tube, possibly contaminating the cryopanels or helping to reduce the lithium density in the cavity. The rate that lithium vapor flows down the beam transport tubes is controlled by the same things that constrain the helium pumping. The number of lithium atoms that reach the cryopanels on each shot is expressed in terms of the number of lithium atoms in the cavity at any time t, n_{Li-C}, and the volume of the cavity, V;

$$n_{Li\text{-}pumped} = \int_0^{\Delta t} dt \, \frac{n_{Li-C}(t)}{\left[\left(\frac{1}{S_{pump}} + \frac{1}{C_{Li}}\right) V - t\right]} \tag{7}$$

Since $1/S_{pump} + 1/C_{Li} = 1.66$ s, and $\Delta t = 0.1$ s, $n_{Li\text{-pumped}} < 0.06\ n_{Li}\ (t = 0)$. This means that the effect of the of the active pumping on the overall lithium vapor density as a function of time is not important. Therefore, one can use the density as a function of time from Eqs. (2) and (3) in Eq. (7) to find the mass of lithium that would reach the cryopumps if condensation of the lithium occurred on the inside of the tube. The mass of lithium to reach the pumps in this case is 4.2×10^{-2} g. In fact, much of the lithium that is pulled into the beam transport tube will condense onto the walls of the tube. If the condensation is just proportional to the area of the tube walls divided by the area of the opening on the pump end of the tube, 1.6×10^{-3} g will condense on the cryopanels on each shot. It is conservative to assume that the cryopanels will cease to perform properly once they are covered with 10 monolayers of lithium. This means that they must be heated up to a few hundred degrees C to clean them after 2×10^{-3} g of lithium reaches the pumps. Thus, unless a great deal of additional area for condensation is added, the cryopanels will only function for one shot.

V. Conclusions

Two issues have been examined that are important to HIB cavity design: vaporization and condensation of wall material and active pumping of noncondensable cavity gases. These issues have been studied in the context of a particular target chamber design where the first wall is covered with flowing liquid lithium. A computer code, CONRAD, has been written to simulate the vaporization and condensation. Scaling laws have been devised from basic laws of physics and results of computer simulations for the case of liquid lithium protected cavities. These scaling laws can be used to calculate the allowable

repetition rate for the cavity based on the dimensions and conditions of the cavity and the allowed gas density. Standard gas pumping formulas are used to estimate the pumping power needed clear the cavity of noncondensable gases. The area of cryopanels has been determined for a given design of the tube through which the pumping occurs. The contamination of the cryopanels by lithium vapor has been studied and is found to be a potentially serious problem.

References

1. B. Badger et al., "HIBALL - A Conceptual Heavy Ion Beam Driven Fusion Reactor Study," University of Wisconsin Fusion Technology Institute, Report KfK-3202/UWFDM-450 (1981); and B. Badger et al., "HIBALL-II - An Improved Conceptual Heavy Ion Beam Driven Fusion Reactor Study," Fusion Power Associates Report KfK-3840/FPA-84-4/UWFDM-625 (1984).

2. C.L. Olson, "Ion Beam Propagation and Focusing," J. Fusion Energy 1; 309 (1981).

3. L. Pong and G.A. Moses, "Vapor Condensation in the Presence of a Noncondensable Gas," University of Wisconsin Fusion Technology Institute Report UWFDM-565 (July, 1984).

4. W.W. Saylor, J.H. Pendergrass, D.J. Dudziak, and R.R. Peterson, "Tradeoffs in the FIRST STEP Facility Design," 1984 IEEE International Conference on Plasma Science, May 14-16, St. Louis, Mo., p. 35.

5. R.R. Peterson, "CONRAD - A Combined Hydrodynamics - Vaporization/Condensation Computer Code," University of Wisconsin Fusion Technology Institute Report UWFDM-670 (April, 1985).

6. R.R. Peterson, "Gas Condensation Phenomena in Inertial Confinement Fusion Reaction Chambers," University of Wisconsin Fusion Technology Institute Report UWFDM-654 (October, 1985).

7. R.D. Richtmyer and K.W. Morton, Difference Methods for Initial-Value Problems, (John Wiley & Sons, New York, 1967).

8. H.A. Bent, The Second Law, (Oxford University Press, New York, 1965), page 228.

9. H.A. Steinherz, Handbook of High Vacuum Engineering, (Reinhold Publishing Corporation, New York, 1963).