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UWFDM-443

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The INPORT concept of first surface protection in ICF reactors is discussed in the context of a heavy ion beam reactor. Porous SiC tubes bathed in liquid $Pb_{83}Li_{17}$ lose a layer of film to X-ray evaporization. The dynamics of this vaporized film's consequent radiation of energy back to the tubes, condensation and revaporization are studied in detail. The presence of this vapor is found to not degrade the overall performance of the reactor.

Introduction

The design of Inertial Confinement Fusion (ICF) reactor first surfaces poses a uniquely difficult engineering problem. In the absence of a sufficiently dense cavity gas (i.e., the gas density is less than 10^{17} atoms/cm^3) these first surfaces must survive the effects of the fusion generated X-rays, ion debris and fast neutrons. Several solutions to these problems have been proposed in a variety of reactor studies.[1-4] In the HIBALL[4,5] heavy ion beam fusion reactor study the first structures encountered by the fusion products are INPORT[5] tubes specifically designed to address these problems. The INPORT tubes, filled with flowing $Pb_{83}Li_{17}$ coolant, protect the first structural wall from excessive neutron damage. The SiC tubes themselves are protected from the short range X-ray and ion debris by a thin layer of PbLi that flows down the outside of the porous tube.

After a target explosion, the X-ray energy is deposited within 10^{-3} cm of the first surface. The temperature of a thin layer of $Pb_{83}Li_{17}$ exceeds its boiling temperature, and is vaporized. This ablated material flows toward the center of the cavity and intercepts the ions generated by the explosion. The energy associated with the ions is absorbed by the $Pb_{83}Li_{17}$ gas and does not initially reach the first surface. The gas heats up to a very high temperature and starts to release its energy by thermal radiation toward the cool first surface. The liquid surface temperature increases upon receiving energy from this thermal radiation and condensation of the vapor. The higher surface temperature increases the vapor pressure and consequently increases the vaporization rate. The gas density is very high after the initial X-ray deposition, and varies by the combined effects of evaporation and condensation.

It is of critical importance to beam transport to determine the time dependent cavity gas density. One important factor determining repetition rate is that the gas density in the cavity be low enough at the time of the next target explosion to allow beam transport. In this paper, we present an analysis of this cavity gas behavior and show that, for a reasonable set of parameters, the INPORT concept remains valid. The sensitivity of the cavity gas density at the time of the next explosion to the target spectrum is also investigated and commented on.

X-ray Energy Deposition and the Resulting Evaporation

Target generated X-rays deposit their energy over a short range in Pb-Li film on the innermost INPORT tubes, and heat this thin layer to high temperatures. The X-ray deposition and the energy densities of the Pb-Li after deposition are computed. This leads to a simple heat balance method of calculating the mass of vaporized Pb-Li.

The energy deposition from X-rays can be described by exponential attenuation inside the material. The photoelectric cross sections are those given by Biggs.[6] Determination of the energy deposited from a given spectrum must also account for transport of any scattered photons. If, however, the primary interaction is the photoelectric effect, the scattering can be ignored and an exponential deposition profile can be assumed. The photoelectric effect comprises 90% of the interactions for photon energies up to 10 keV, 30 keV and 70 keV for carbon, iron and molybdenum, respectively.[7] Since lead is of yet higher Z, the photoelectric effect is dominant to even higher photon energy.

The integrated X-ray spectrum on the surface of the INPORT tubes is shown in Fig. 1. This was obtained from a thermonuclear burn calculation for the proposed HIBALL target.[8] The X-ray spectrum is peaked around 3 keV and extends up to 300 keV with another peak around 100 keV. The 3 keV peak is where most of the X-ray energy is and is due to radiation from the burn heated outer Pb layer of the target while the 100 keV peak is due to direct fusion X-rays and accounts for only a small fraction of the X-ray energy.

Because most photons have energies of 100 keV or less, we have used the Biggs data and the A*THERMAL exponential X-ray deposition code to obtain the energy deposited in the Pb-Li film as a function of depth into the film. The sensitivity of this deposition profile to the X-ray spectrum is displayed in Fig. 2 where three different blackbody spectrums are assumed.

The amount of mass vaporized due to the X-ray energy deposition is computed using a simple model. We

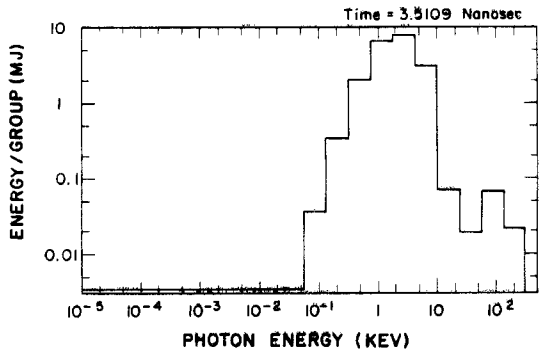

Fig. 1. Time integrated target X-ray spectrum.

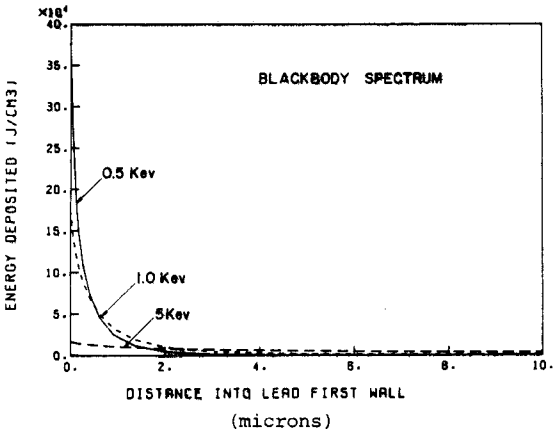

Fig. 2. Energy deposition due to different blackbody X-ray spectra and 33.6 total X-ray energy.

have determined the total energy per unit volume required to vaporize the lead, 8.7×10^3 J/cm^3. From the X-ray energy deposition calculation the depth of the material that will be vaporized can be determined. This adiabatic model becomes more accurate for very short X-ray deposition times, i.e., instantaneous. To account for energy deposition above $C_p(T_b-T_o)$ in the region between the saturated liquid and the region of sensible heat, we have assumed that there is some additional vaporization. This additional vaporization, where δ is the actual thickness of the vaporized layer, is shown schematically in Fig. 3. Following this procedure for the spectrum in Fig. 1 and for 88 MJ of X-ray energy per explosion, we obtain a total thickness of ablated Pb-Li of 4.3 microns. Only those tubes in direct line of sight of the target receive these X-rays which, in the HIBALL design, form a right circular cylinder 5 meters in radius. Thus we obtain a total mass of ablated material of about 13 kg. Because the deposition profile is sensitive to the X-ray spectrum (see Fig. 2) the amount of vaporized material may also be adjusted by changing the target design and thus the target X-ray spectrum. Naturally the amount of vaporized Pb-Li is also dependent on the target yield which may also be varied through changes in the target design.

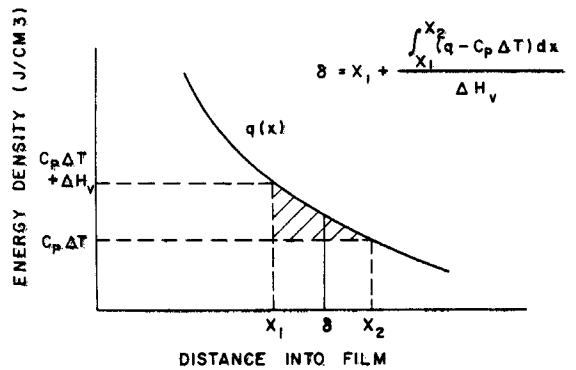

Fig. 3. Conceptual representation of Pb-Li vaporization.

PbLi Gas Dynamics and Radiation

As discussed in the preceding section, target generated X-rays vaporize several kilograms of Pb-Li off of the INPORT tubes. The resulting gas absorbs the target generated ions, reaches a temperature of about 1 eV and becomes partially ionized. As this gas spreads from the tubes into the center of the reactor cavities, it radiates photons which put a heat flux back onto the tubes. Eventually, the gas uniformly fills the cavity and cools enough that the heat flux on the tubes is insignificant. Before this happens, though, there may be some additional vaporization of Pb-Li due to the heat flux. As the gas radiates, it also cools, affecting the rate of recondensation. For these reasons, it is important to consider the behavior of this gas between the time of vaporization and recondensation.

To study this problem, it is necessary to know the equation-of-state and optical data for gaseous Pb-Li. The atomic physics of this gas is studied with the MIXER[9,10] computer code. This code has been developed at the University of Wisconsin to provide data tables of internal energy density, ionization state, heat capacity and radiation opacities of gas mixtures. This is done as functions of gas temperature, gas density and radiation temperature. Ionization is assumed to occur in either the Saha[11] or the Coronal[12] model and radiative processes to follow a semi-classical formalism.[13] In a mixture of gases the electron density is calculated self-consistently and the interaction of radiation is considered with the 20 lowest excited states of the six most common ionization states for each gas species.

We have modeled the behavior of the Pb-Li gas with the 1-D Lagrangian radiation-hydrodynamics computer code, FIRE.[14] This code has explicit hydrodynamics and implicit energy transport where heat is conducted through two fluids - the gas at a local temperature of T_{gas} and the radiation fluid at a temperature of $T_{radiation}$. In these calculations, conduction through the radiation field dominates the thermal transport.

FIRE cannot accurately model the behavior of fluid which is as dense as a liquid. Thus, we must analytically calculate the dynamics from the time when the Pb-Li is at liquid density until the time that the density is low enough for FIRE calculations to be appropriate. We assume that the gas obeys an isothermal blow-off formalism where the temperature of the gas is that due to the deposited target generated X-ray energy minus the energy of vaporization and the energy of ionization. We arbitrarily assume that the energy from target generated ions is uniformly deposited in the gas at 1.5×10^{-4} seconds after vaporization and that FIRE can be used any time after this. Thus, at this time we start the computer calculations with the gas density profile being the Gaussian shape predicted by the blow-off model and the total energy of the gas being the target generated X-ray and ion energy minus the vaporization and ionization energy.

The FIRE calculation simulates the gas dynamics until the time the gas reaches the center of the cavities. Figure 4 shows the positions of the Lagrangian zone boundaries for a typical calculation during this period. Upon reaching the center, the gas begins to convert its bulk kinetic energy into heat, but FIRE, being a one-dimensional code, predicts that the gas will reflect off the center and propagate back towards the tubes. This is not physical because the system

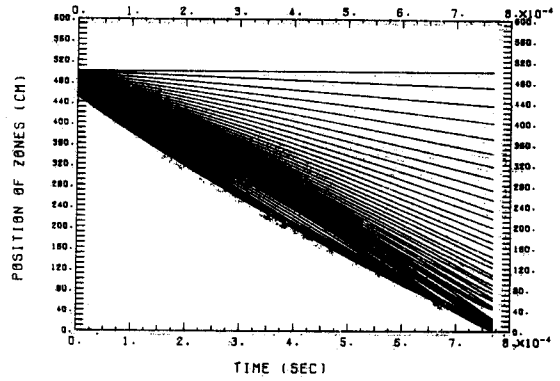

Fig. 4. Hydrodynamic motion of Pb-Li moving from tubes to cavity center.

does not have the symmetry needed for such reflections. For this reason we stop this first simulation calculation at the time when the gas reaches the center, typically about 1 millisecond after vaporization.

To simulate the behavior past this time we assume that the gas has a uniform temperature and density and has no bulk kinetic energy immediately after the gas collapses in the center. We then use FIRE again with this new initial condition and with the gas constrained not to move. By combining both uses of FIRE, we calculate the heat flux on the tubes due to radiation and the average temperature of the gas versus time.

To test the sensitivity of the gas behavior to the total mass of Pb-Li vaporized, we have completed calculations for three different total masses; 6.7 kg, 13.3 kg and 26.6 kg. The heat fluxes on the surface of the innermost tubes is shown for these three cases in Fig. 5. Comparison of the three curves shows that the heat flux can vary by two orders of magnitude when the total mass is changed by a factor of four. At low gas mass the temperature must be high because the internal energy density is high. Also, the radiation passes through less dense gas more easily. Thus, the heat fluxes are higher for low total gas mass. As the mass of the gas is increased, both of these trends are reversed and the gas radiates energy more slowly back to the tubes.

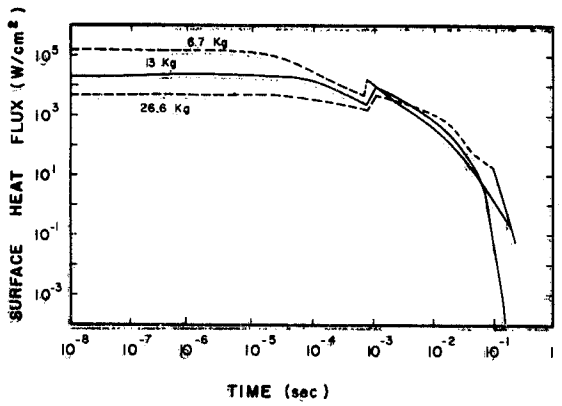

Fig. 5. Total surface heat fluxes for different vapor masses vs. time after vaporization.

Evaporation/Condensation

Once the radiation heat flux and the temperature of the gas is known, the behavior of the gas density in the cavity over time can be investigated. The rate that gas leaves the cavities is governed by the geometry of the cavities and the gas temperature. The rate that gas is added to the cavity through evaporation off of the tubes is determined by the temperature of the Pb-Li film on the tubes. This temperature can be found through a temperature diffusion calculation in this film for the surface heat fluxes calculated in the previous section. Standard temperature diffusion and evaporization rate equations are used and a perfect sticking approximation is used for the condensation rate. The temperature diffusion equation is solved with a finite difference method with the net heat flux due to radiation, condensation and evaporization deposited at the surface of the film and with the surface of the film nearest the center of the tube fixed to the coolant temperature. The film is assumed to initially be at a temperature of 1150 K in the outside 10^{-4} cm and the gas pressure and temperature are 108 Torr and 14500 K, respectively. The calculation is carried out over a few cycles until the temperature profile in the film reaches a quasi-steady-state. With the assumptions that the first surface is spherical with a 5 meter radius (it is, approximately), only Pb is being condensed and evaporated, material properties are temperature independent, the thickness of the tube wall is 1.5 mm, and the coolant has a temperature of 324°C and heat transfer coefficient of 12 W/cm^2-°C, we obtain the results shown in Fig. 6. Here, the condensed evaporated and total masses in the cavity are plotted against time for an initial mass of 13 kg.

Results and Conclusions

In the HIBALL reactor the first surface is protected from the target explosion by a film of liquid

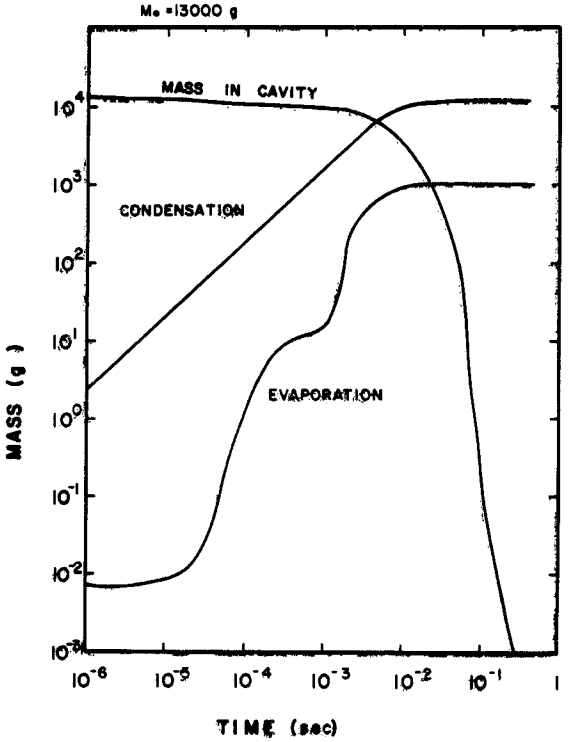

Fig. 6. Total condensation, evaporization and net masses in cavity for 13 kg of initial Pb-Li vapor.

Pb-Li adherring to SiC tubes. This keeps the pulsed energy off of the tubes but until now, it has been unclear that the cavity will be ready for the next shot soon enough to allow a 5 Hz rep rate.

The vacuum pressure at time = 0.2 second should be low enough to allow beam propagation. The particle density at this time is 4×10^{10} cm^{-3}. The calculation of the beam stripping cross section will show that this density is acceptable. It must be noted, however, that the total mass in the cavity is only 7×10^{-3} g. This is obtained by subtracting the condensation mass from the sum of initial mass and evaporation mass, both of which are large and very close. The total condensation mass is 1.5×10^{4} gm. Therefore, the uncertainty of the total mass in the cavity at t = 0.2 second is very large. A change of assumption may lead to a significant variation on the final particle density.

A change of the target design may change the energy associated with the X-rays and/or the spectrum of the X-rays. This will change the initial mass evaporated by the X-ray deposition. To study the effect of different X-ray energies or spectra, a different initial mass is assumed. The larger mass reduces the initial gas temperature and also the radiation heat flux to the first surface. Consequently, the thermal energy deposited on the first surface is spread over a longer period of time and the condensation rate is reduced because of the lower thermal velocity of the vapor atoms. Smaller initial mass, on the other hand, increases the initial gas temperature. The high gas temperature results in a large heat flux to the first surface and, consequently, causes a large evaporation rate. Thus, the effect of evaporation dominates cavity mass transfer. Figure 7 shows the atomic density in the cavity versus time for the three initial masses. There is a sharp minimum at M_0 = 13 kg which is due to the gas temperature being high enough for quick condensation and the heat flux being low enough for insignificant evaporation.

In summary, we have considered the vaporization, gas dynamics and condensation of Pb-Li from the film on the INPORT tubes. The mass of the gas vaporized by the target generated X-rays is 13.3 kg and the gas density in the cavity 0.2 seconds after the target explosion is low enough for ion beam propagation. The gas density at 0.2 seconds has been found to be sensitive to the mass of vaporized Pb-Li and thus, sensitive to changes in the target X-ray spectrum.

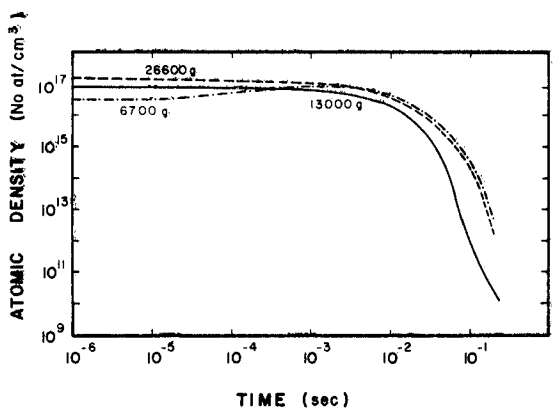

Fig. 7. Atomic densities for different masses of vaporized Pb-Li vs. time after vaporization.

Acknowledgment

Support for this work has been provided by the Kernforschungszentrum Karlsruhe and the Bundesministerium für Forschung und Technologie, Federal Republic of Germany, under research agreement with Fusion Power Associates, Gaithersburg, MD.

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