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OF THE LIGHT ION FUSION TARGET DEVELOPMENT FACILITY

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ABSTRACT

Molecular nitrogen is a possible choice for the target chamber gas in the light ion beam driven target development facility. The response of a nitrogen target chamber gas to fusion target explosions is considered. Targets with yields of 200 MJ, 400 MJ and 800 MJ are considered for a target chamber 3 m in radius and 6 m high which is filled with nitrogen gas at a density of 7.07×10^{17} molecules/cm^3. The soft x-rays and ions from the explosion of these targets are stopped in short distances in this gas and create a hot spherical fireball in the center of the target chamber. Heat fluxes and shock pressures on the target chamber first walls due to these fireballs are presented and nitrogen is shown to be an acceptable cavity gas from the point of view of first wall loading.

I. OVERVIEW OF FIREBALL PHENOMENA

The energy released during the burn of a fusion target in the TDF target chamber is distributed between neutrons, x-rays ("hard" and "soft") and target debris. The target chamber gas is not dense enough to stop any significant amount of neutrons or "hard" x-rays (those x-rays with energies above 1 keV).[1] The stopping distances for these are also long in the first wall so that the thermal stresses generated in the first wall due to "hard" x-rays and neutrons are not important. Approximately 30% of the fusion yield is in "soft" x-rays and target debris, which are stopped in a few tens of centimeters by the target chamber gas. The flow of this energy to the first wall is mainly through hydrodynamic shock motion and low energy thermal radiation, both of which can generate large stresses in the first wall. This flow may be thought of as a fireball blast wave and is the topic of this paper.

The physics of fireballs in gases has been extensively studied.[2,3] The soft x-rays and target debris are stopped in the target chamber gas in a short distance, heating the gas in a small spherical "fireball" to a temperature as high as 100 eV. Initially the photons in this gas are of high enough energy that they are strongly absorbed by photo-ionization in the cold gas surrounding this fireball. Thus, the fireball burns its way into the relatively cold target chamber gas by successively heating layers of cold gas. This thermal shock front can be initially supersonic, but since its speed must increase monotonically with the radiant power density at the edge of the fireball, its speed decreases as the fireball cools due to expansion. Eventually, the speed of the thermal shock front drops to the speed of sound. At this time a shock wave is generated. As the speed of the thermal front slows further, the shock wave breaks away from the fireball. This shock proceeds through the cold gas until it reaches the wall of the target chamber and is reflected, imparting a mechanical impulse onto the wall. Though it is cooled by the decompression caused by the shock wave, the fireball continues to heat its way into the cold gas. Finally, many of the blackbody photons leaving the fireball will have energies below the lowest ionization potential of the cold gas atoms and, depending on the gas species, the mean free path of the photons in the gas will become long. Then the fireball will radiate energy to the wall of the target chamber, possibly causing thermal damage. Ultimately, the fireball will have such a low temperature that it no longer emits significant amounts of radiation and flow of the remaining heat to the wall will be mainly through convection.

II. CHOICE OF TARGET CHAMBER GAS

The choice of target chamber gas can greatly affect the behavior of the fireball. The gas species can have an effect through its density, heat capacity, opacity and ability to stop target debris ions. The choice of gas species must be consistent with laser guided plasma channel beam propagation and compatible with the first wall materials. Plasma channel formation puts constraints on the gas density for hydro-

dynamic considerations, requiring that the mass density of the gas is (1-10) x 10^{-5} g/cm^3.[4] The gas species must be chosen so that laser guided channel initiation is possible at an acceptable laser power.[5-7] It is thought that gases meeting this criterion might be either a noble gas with an alkali metal vapor impurity of about 10^{15} atoms/cm^3[5] or one of the molecular gases, NH$_3$[6,7] and N$_2$. The alkali metal atoms can be excited by a laser tuned to an atomic transition frequency so that the atoms will be excited and then give up that excitation energy to a free electron, leading to the runaway of the electrons. The molecules would be excited by an infrared laser tuned to a vibrational transition frequency of the molecule. The molecules would then quickly relax, heating the gas in the channel and leading to preionization and rarefaction of the channel. With these constraints, we limit ourselves to noble gases with an alkali metal impurity and molecular gases.

The heat capacity, opacity and the ability to stop ions have a strong influence on the fireball propagation and the first wall survivability. Though they do have some effect on the beam propagation, we assume that these quantities may be treated as free parameters which can be adjusted for the optimum first wall lifetime. For example, the Planck mean free path of 1.8 x 10^{18} atoms cm^3 of argon is shown in Fig. 1 versus temperature for several impurity concentrations of sodium. The opacity of the gas to the important low energy photons is seen to change by orders of magnitude through small changes in the sodium concentration. Thus, through adjustment of the sodium concentration, the damage to the first wall by the fireball can be controlled.[5,8]

In the balance of this report only N$_2$ will be discussed as a target chamber gas. Fireball propagation in NH$_3$ may not be much different than in N$_2$ and we are concerned about re-establishing the NH$_3$ after the fireball has dissociated the molecules. We will not discuss in detail the noble gases with alkali metal vapor impurities because they have been dealt with at length already.[5,9,10] In the next two sections, we will describe the equation-of-state and opacity of N$_2$ and fireball phenomena in N$_2$. The results of all of the fireball calculations are also summarized.

III. EQUATION-OF-STATE AND OPACITIES

A series of computer codes has been developed over the last few years to provide equations-of-state and opacities for target chamber gases.[11] The latest version, MIXERG,
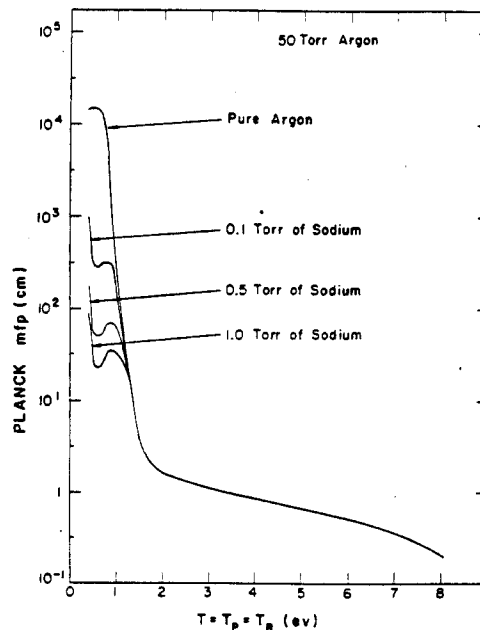

Fig. 1. Planck mean free path versus temperature for various concentrations of sodium in 1.8 x 10^{18} cm^{-3} argon gas. Here the radiation temperature is equal to the gas temperature.

provides ionization states, internal energy densities, heat capacities and opacities for mixtures of up to 5 gases. The ionization is calculated in either the Saha or the Coronal model, depending on which is appropriate. The ionization state, internal energy and heat capacity for a molecular gas may be calculated with MIXERG but, at the time of this report, the energy involved in the dissociation of the molecules is neglected. The opacities calculated by MIXERG are both single frequency group and multi-frequency group and both Planck and Rosseland averaged.[2] The absorption model used is semi-classical[2] and considers photo-ionization, inverse Bremsstrahlung, atomic transition line absorption, Thomson scattering and absorption by plasma waves as absorption mechanisms. For molecular gases, absorption by vibrational and rotational transitions is not included in the published version of MIXERG,[11] but they are included in an ad hoc manner for the results presented in this section. For N$_2$,

we have used a simple mode for the absorption of photons due to molecular and vibrational states when the gas temperature is less than 1 eV. This model assumes that this absorption only occurs between 1 and 7 eV. This yields absorption spectra for N_2 like that shown in Fig. 2 for a gas density of 1.3×10^{14} N_2 molecules/cm^3 and a gas temperature of 0.4 eV. Improvements are planned for MIXERG which would deal with these important molecular processes more carefully.

With MIXERG, equation-of-state and opacity data have been calculated for diatomic nitrogen. We have found that above 50 eV, the nitrogen atoms are almost completely stripped of electrons. The single group Rosseland and Planck opacities have also been calculated for diatomic nitrogen. The opacities for a particu-
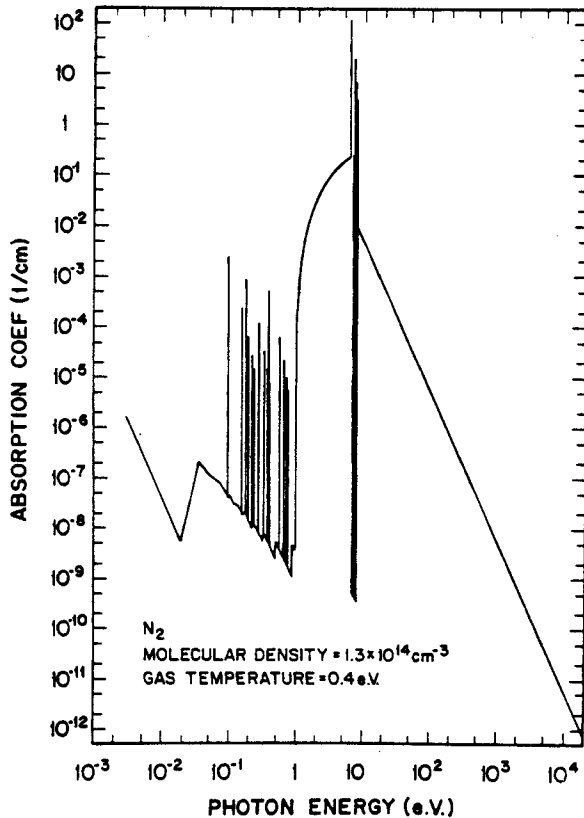
lar density are shown in Fig. 3. Notice that the opacity of the gas to high energy photons (when the radiation temperature is high) drops dramatically when the gas temperature rises above about 50 eV. The same effect is noticed in the Rosseland opacity. This is consistent with the almost complete stripping of atoms above 50 eV. Also notice the increase in the Planck opacity of the gas to low energy photons at low temperature. This occurs because of the "ad hoc" molecular states between 1 and 7 eV. Above 1 eV the gas is assumed to be dissociated so that this effect disappears and the opacity drops drastically.

IV. FIREBALL BEHAVIOR IN TARGET CHAMBER GAS

We have developed a 1-D Lagrangian hydrodynamics radiation transport code to model the behavior of fireballs in target chamber gases.[12] This code, FIRE, uses equation-of-state and opacity data provided by MIXERG as described in the preceding section. This code treats both the gas and the radiation as fluids, each with their own temperatures. When the radiation fluid and the gas fluid are not at the same temperature, energy flows from the hotter fluid

Fig. 2. Absorption coefficient of N_2 versus photon energy. Molecular density equals 1.3×10^{14} molecules/cm^3. Gas temperature equals 0.4 eV.
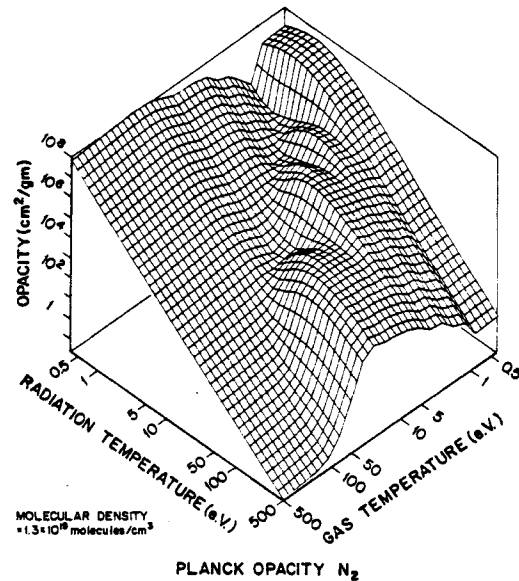

Fig. 3. Planck mean opacity of nitrogen versus gas temperature and radiative temperature. The atomic nitrogen density is 2.7×10^{19} atoms/cm^3.

to the cooler. The coefficients controlling the rate of this energy exchange are chosen on physical grounds so that the energy exchange represents absorption or emission of radiation by the gas. These coefficients naturally make use of the opacities provided by MIXERG.

We have used FIRE with the data from MIXERG to simulate the behavior of fusion target generated fireballs in the Target Development Facility target chamber filled with 20 torr (@ 0°C) N_2 gas. Targets with yields of 200 MJ, 400 MJ and 800 MJ are used where the initial energies in the fireballs are 60 MJ, 120 MJ and 240 MJ, respectively. The target chamber parameters and results of the FIRE calculations are summarized in Table I. The target chamber is actually a right circular cylinder 3 meters in radius and 6 meters high but for our one-dimensional spherical fireball calculation we have put the first wall at 3 meters. The overpressures and heat fluxes at points on the wall more than 3 meters from the fireball center will be lower than those shown in Table I.

More detail of the fireball behavior is given in Figs. 4 through 6. The hydrodynamic motion of the gas during the 200 MJ target yield shot is shown in Fig. 4. The positions of the Lagrangian zone boundaries are plotted against time, showing the propagation of the shock front to the wall and reflection off of the wall. Plots for the 400 MJ and 800 MJ cases are not qualitatively different. The earlier time of arrival of the shock for the higher yield shots may occur because initially the fireball burns into the cold gas more rapidly. In Figs. 5 and 6 the heat flux at the wall surface and the pressure at the wall are shown versus time for 200 MJ and 800 MJ target yields, respectively. The plot for a 400 MJ target yield would show results in between these two with a maximum

overpressure of 3 MPa. In all three cases, there is no significant radiation transfer to the wall until the shock wave reaches the wall. This means that during the propagation of the shock wave to the wall, the mean free path of the radiation in N_2 never gets large compared to the size of the cavity. This is the case because of the high absorption of 1 to 7 eV photons by cold N_2 shown in Fig. 2. The secondary peak in the heat flux and overpressure shown in Fig. 6 is due to a reflection of the shock wave off of the wall, back to the center, off of itself at the center and back to the wall. This effect is not physical because there is not the
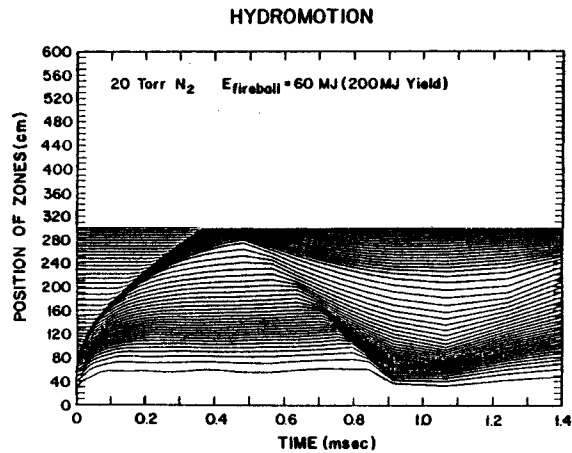
HYDROMOTION

Fig. 4. Hydrodynamic motion of Lagrangian zone boundaries plotted against time. Target yield is 200 MJ in 20 torr (@ 0°C) of N_2.

TABLE I. Fireball Propagation in TDF Target Chamber

Target Yield (MJ)	Initial Fireball Energy (MJ)	Chamber Radius (m)	Chamber Gas	Gas Density (atoms/cm³)	Max. Wall Pressure (MPa)	Energy Radiated to Wall (MJ)
200	60	3	N_2	1.4×10^{18}	1.38 @ 0.39 msec	2.3 @ 1.5 msec
400	120	3	N_2	1.4×10^{18}	3.06 @ 0.29 msec	7.4 @ 1.5 msec
800	240	3	N_2	1.4×10^{18}	6.32 @ 0.21 msec	28.8 @ 1.5 msec

PRESSURE AND HEAT FLUX AT FIRST WALL

Fig. 5. Heat flux and overpressure at a 3 meter radius first wall of a cavity filled with 20 torr (@ 0°C) of N_2. Target yield is 200 MJ.
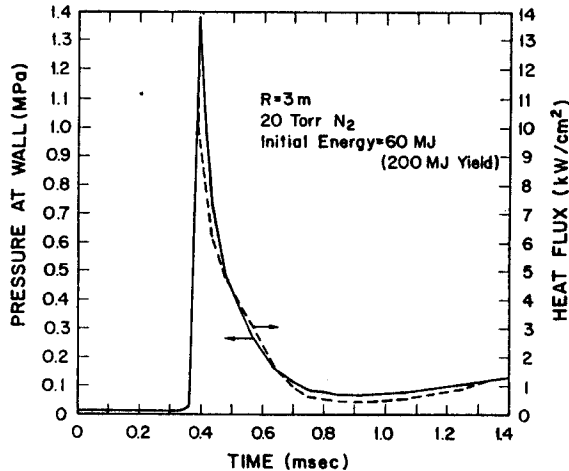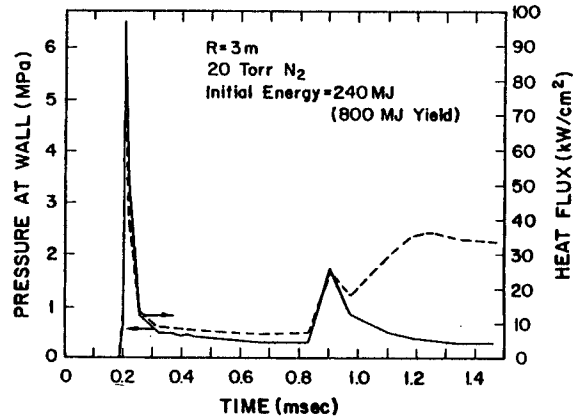
PRESSURE AND HEAT FLUX AT FIRST WALL

Fig. 6. Heat flux and overpressure at a 3 meter radius first wall of a cavity filled with 20 torr (@ 0°C) of N_2. Target yield is 800 MJ.

symmetry needed to produce these multiple reflections.

V. FIREBALL PROPAGATION IN PLASMA CHANNELS

In Section IV we considered the propagation of fireballs through the background target chamber gas. However, this gas is not really uniform as we have modeled it, but is penetrated by 60 preformed beam plasma channels of lower density than the surrounding gas. Because of their lower density these channels may serve as paths of least resistance for the fireball energy.[13,14]

The problem of heat transfer from the fireball down the plasma channels to the diode can be imagined by following the movement of low energy photons. At the intersection of the plasma channel with the fireball, the photons leaving the fireball which would normally be absorbed by the cold target chamber gas will now propagate a longer distance in the channel before being absorbed. This leads to a more rapid propagation of fireball energy down the plasma channel than through the background gas. Because the opacity of the gas in the fireball is low photons throughout the volume of the fireball will begin to flow down the plasma channels. If all of this energy were to reach the end of the channels, there could be sub-

stantial damage to whatever structure was there. However, the temperature difference between the fireball in the channel and the cold gas surrounding the channel becomes large and the surface area of the sides of the channel is three orders of magnitude larger than the cross-sectional area so that the radial heat transfer may be substantial.

We have not as yet completed calculations of this for N_2. However, we have completed one-dimensional FIRE code simulations of a 60 MJ fireball leaking into 60 channels in a 20 torr (at 0°C) background gas of argon with a 0.2% sodium impurity. We have treated the radial heat transfer with a phenomenological loss term, which has been determined by a series of one-dimensional simulations of the radial heat transfer at different temperatures inside the channel. The result of this simulation is that the areal energy density radiated to the first surface down the channel is 42.4 J/cm^2 while it is 29 J/cm^2 on the rest of the first surface. Thus, these very preliminary calculations indicate that for argon with 0.2% sodium the propagation down the channel does not put an unmanageable heat flux on the first surface.

The situation may be very different for N_2 and because two-dimensional effects may be very important. As we have already seen, the opacity of N_2 may be very large and the shock over-

pressure may be much more dangerous to the first wall than the heat flux. There is nothing in these preliminary calculations which would indicate that a pure shock wave would dissipate while travelling down the channel. It is clear that the problem of fireballs in preformed channels is a two or three-dimensional problem.

Work is currently underway on a two-dimensional particle-in-cell computer code to model this problem. This code will include realistic equations-of-state and opacities as well as radiative heat transfer. Further investigation of fireball propagation in channels must wait for the implementation of this code.

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