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LOW DENSITY CAVITY GAS FIREBALL DYNAMICS IN THE LIGHT ION BEAM TARGET DEVELOPMENT FACILITY

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First wall survivability is a critical problem in the design of Inertial Confinement Fusion reactor cavities. Previous studies have shown that in a Light Ion Beam Fusion Reactor scenario, a bare, actively cooled ferritic steel first wall protected by a 50 Torr argon and sodium cavity gas will not experience excessively large stresses and could survive for the lifetime of the reactor. A Target Development Facility to be completed in the late 1980's would have higher target yields and less gas protection than the LIFR.

Recent calculations of wall stresses show that in a TDF, thermal stresses are much larger than mechanical stresses and that the maximum total stress is considerably larger than the yield stress for the ferritic steel. It is proposed that a graphite fabric liner be inserted on the inside edge of the cavity wall to reduce the total stresses in the wall to below the yield stress.

Introduction

First wall survivability has been an important concern in Inertial Confinement Fusion (ICF) reactor designs.[1-4] Designs of Light Ion Beam Fusion Reactors (LIFR)[5] can be different from other fusion reactor designs in that the reactor cavities are most probably filled with a gas at a pressure of between 5 and 50 Torr (when measured at 0°C). In such designs, this gas serves as a medium for the formation of plasma discharge channels which form renewable electrical connections for guiding the ion beams from the pulsed power drivers to the fusion target. This gas, if its atomic number is larger than 10, stops the soft component ($h\nu \leq 1$ keV) of the target generated X-rays and all of the ion debris. Only the hard X-rays directly reach the first wall but they should not cause serious damage because their deposition lengths are long. The fraction of the non-neutronic target energy absorbed by the gas will, however, heat the gas and generate a fireball. This fireball can propagate to the first wall, depositing a shock overpressure and a radiant heat flux. Critical problems in the analysis of LIFR designs are the determination of this overpressure and heat flux and the calculation of the resulting mechanical and thermal stresses in the first wall structures.

Specifically, in a study conducted by Sandia Labs and the University of Wisconsin, the survivability of a bare, actively cooled, ferritic steel first wall in a LIFR has been considered.[6] The gas, xenon or argon with an alkali metal vapor impurity, is chosen to permit laser guided formation of beam plasma channels and adequate protection of the reactor first wall. First wall stresses have been found to be acceptably low for 100 MJ target explosions in a 50 Torr argon gas in a 4 meter radius right circular cylindrical cavity.

The Target Development Facility (TDF), having many features in common with a LIFR, has been proposed to follow PBFA II and would begin operations in the late 1980's. Being a machine to be used in experiments, the number of explosions expected in its lifetime is much lower than in the LIFR (~ 10^4 compared with 10^9). The radius of the cavity has been lowered to 3 meters in view of the reduced number of explosions. Also, the expected target yield has been increased to 200 MJ and the argon gas densities of most interest have been changed to 10 and 20 Torr. Additionally, xenon has been included as a possible cavity gas.

The heat fluxes, overpressures and the resulting stresses on the first wall of such a TDF are calculated with methods given in the following section. The results of these calculations for the TDF wall are presented for 10, 20 and 50 Torr of argon with a 0.2% sodium impurity and for 5 to 50 Torr of xenon with a 0.5% cesium impurity. The stresses on the walls are larger than in the LIFR and a change in the design of the TDF is proposed as a solution to the problem.

Analysis of Fireball and Stresses

To calculate the dynamics of the fireball and the overpressure and heat flux on the first wall of the TDF, it is necessary to first determine the opacity and the Equation of State (EOS) of the cavity gas. This is done with the MIXER computer code.[7] The atomic physics of a monatomic gas is modeled by assuming either that the average ionization state follows the Saha formalism and that the six most populous ionization states have densities spread about the average in a Gaussian or that the ionization follows the Coronal model where the densities of ionization states obey Boltzmann statistics. The choice of model is made on the basis of which recombination mechanisms are important at the given gas temperature and density. The first 20 atomic energy levels are included where their populations are assumed to obey Boltzmann's law. Once the EOS of the gas has been calculated, the Rosseland and Planck opacities are calculated considering photo-ionization, inverse Bremsstrahlung, atomic line absorption and Thompson scattering as photon stopping mechanisms.[8]

This analysis shows that, as long as one considers photons with energies greater than the first ionization potential, photo-ionization is the dominant mechanism of photon stopping. When the photon energy drops below this energy, the absorption coefficient drops by several orders of magnitude so that the gas is relatively transparent to low energy photons. An inert gas like argon with a high value for the first ionization energy will be transparent to much higher energy photons than an alkali metal vapor like sodium. Thus, the addition of a small amount of sodium will not significantly change the opacity of the gas to higher energy photons but will greatly increase the opacity to low energy photons. Thus, when the photons are of low energy, increasing amounts of alkali metal vapor rapidly increase the photon stopping ability of gas.

Once the optical properties of the gas are known, the physics of the fireball propagation may be studied.[9] The argon or xenon will absorb target generated X-rays and ion debris in a small volume, creating a hot fireball at the center of the cavity which is surrounded by cold gas. Initially, the radiation mean free paths are long in the fireball but short in the cold gas so that a wave of heat moves into the cold gas by successive warming of layers of gas near the fireball. Initially, this heating wave, whose speed decreases with decreasing fireball temperature, propagates more rapidly than the sound speed. As the fireball expands and cools, the speed of the heating wave drops to the speed of sound and a shock wave is formed which breaks away from the fireball. The fireball continues expanding and cooling until the mean free paths for fireball radiation in the cold gas are longer than the distance to the first wall, at which time the fireball begins radiating its energy to the wall. This continues until the fireball cools to the point where the emission of photons by the gas sharply decreases and the flow of radiant energy ceases. The effect of decreasing the mean free paths to low energy photons in the cold gas is to slow the propagation of the radiation to the wall. Thus, by adjusting the opacity through the variations in the alkali metal concentration, one may control the total amount of heat radiated to the wall per explosion and the rate at which this heat reaches the wall.

A hydrodynamic radiative transfer computer code, FIRE, has been used to simulate this behavior in fireballs.[10] FIRE is a one-dimensional hydrodynamics code that calculates the dynamics of two fluids; the plasma at its own temperature and the radiation at its own temperature. The transport of the radiation fluid is flux limited and upstream averaged. The equation of state of the plasma and mean free paths of radiation in the gas are read from tables of data provided by the atomic physics code MIXER.

Once the heat fluxes and overpressures have been found, the thermal and mechanical stresses are calculated. A simple temperature diffusion computer code is used to find the temperature profiles in the first wall at various times. These temperature profiles are put into the transient stress code TSTRESS[11] to calculate the thermal stresses in the wall. The mechanical stresses, due to the shock overpressure induced flexures in the first wall structures, are then calculated analytically and combined with the thermal stresses.[12]

Results

Using the FIRE radiation hydrodynamics code, the heat flux and overpressure on a first wall 3 meters from a 200 MJ exploding pellet are calculated. Cavity gases of argon with 0.2% by volume of sodium and of xenon with 0.5% by volume of cesium are considered. The calculations are started by assuming that 60 MJ of the 200 MJ target yield is in soft X-rays and ions which are stopped in a small sphere of gas surrounding the target. A typical heat flux and overpressure are shown in Fig. 1, which is the case of a 20 Torr argon cavity gas. Previously reported calculations have shown how the heat flux and overpressure are dependent on the fractions of alkali metal vapor[6], but here we will vary the gas density only.

A temperature diffusion code and the transient stress code TSTRESS have been used to calculate thermal stresses in the wall. With the analytically calculated flexural mechanical stress, the thermal stress and the total stress are plotted in Fig. 2 for a 20 Torr argon and sodium cavity gas. In this figure, positive stresses are compressive. Here, the wall is a system of HT-9 panels 47 centimeters wide, 2 meters high and 5 centimeters thick, which are rigidly supported by a frame at the edges of the panels. Also shown in Fig. 2 is the yield stress for HT-9.[13] Notice that, because of the large thermal stress, the total stress is larger than the yield stress. This means the material may deform before reaching this stress.

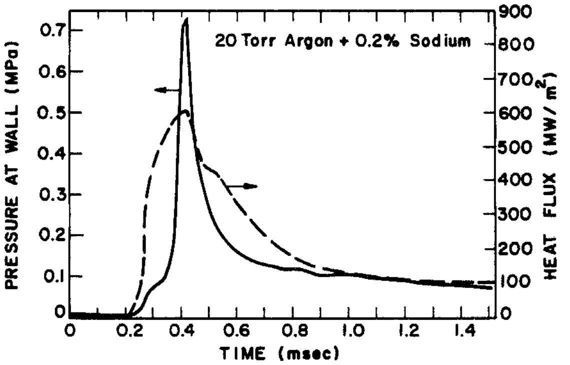

Figure 1 Heat flux and overpressure at first wall versus time. The wall is 3 meters from the target.

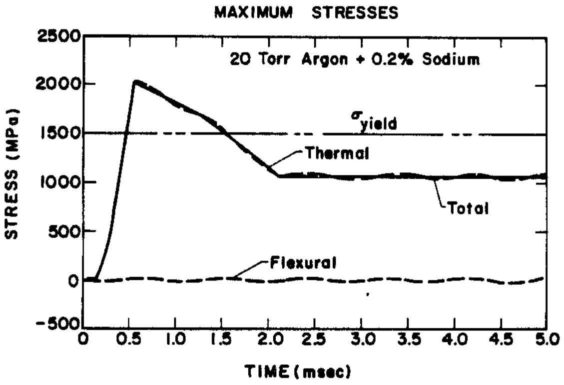

Figure 2 Maximum stresses in 5 cm thick HT-9 wall panel versus time. The wall panel is 2 meters high and 47 cm wide.

Calculations like those described above have been carried out for both argon with sodium and xenon with cesium cavity gases for gas pressures between 5 and 50 Torr (when measured at 0°C). The results of these calculations are tabulated in Table 1. The maximum shock overpressure on the first wall is plotted against gas pressure in Fig. 3. There is little difference between argon and xenon. Also on Fig. 3, these values are compared with the overpressure predicted by strong shock theory.[8] The overpressures are much below the strong shock values because a large fraction of the fireball energy is radiated out of the blast wave to the first wall. The overpressure decreases with decreasing gas density because the amount of radiated energy is higher at low gas densities. Figure 4 shows the energy radiated to the wall per unit area per target explosion plotted against gas density. The values are normalized to the total initial fireball energy divided by the wall surface area, 53 J/cm^2, which is what would occur if there was no cavity gas. Naturally, the amount of radiated energy decreases as

Table 1. Results of Computer Calculations

Wall Radius = 3 m
Initial Energy of Fireball = 60 MJ
Wall Material = HT-9

Panel Thickness = 5 cm
Panel Height = 2 m
Panel Span = 47 cm

Type of Gas	Argon			Xenon			
Gas Pressure (Torr)	10	20	50	5	10	20	50
Max. Overpressure at First Wall (MPa)	0.25	0.79	1.16	0.089	0.18	0.69	1.33
Max. Heat Flux at First Wall (kW/cm^2)	135	53	30	422	177	92	19
Energy Density Radiated to First Wall (J/cm^2)	28.93	24.62	21.18	41.04	34.28	25.75	18.9
Max. Temperature Rise at First Wall (°C)	1321	716	407	2430	1498	640	232
Max. Total Stress at First Wall (MPa)	3236	2050	1207	6262	4368	1919	691

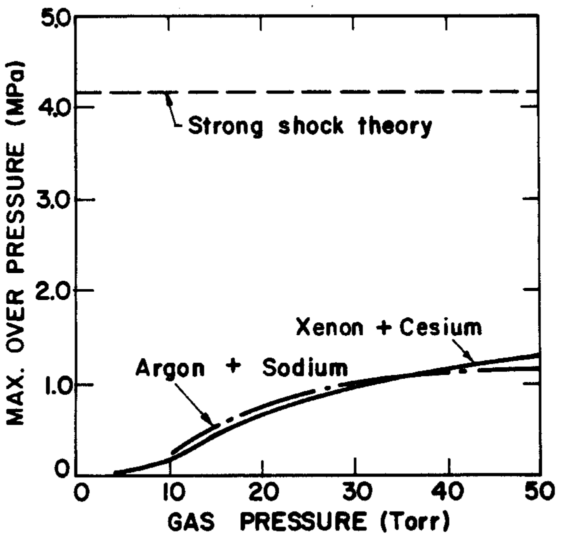

Figure 3 Maximum overpressure versus gas density compared with strong shock over pressure.

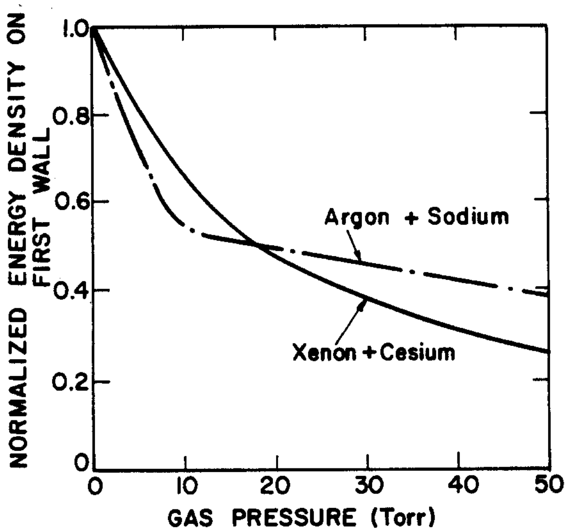

Figure 4 Energy density on first wall versus gas density. The energy density is normalized to 53 J/cm^2, the non-neutronic target yield divided by the first wall surface area.

more gas is put in between the target and the first wall. Figure 5 shows the maximum stress plotted against gas density and the yield stress for HT-9. Notice that only when the gas density is higher than 30 Torr for xenon or 35 Torr for argon does the stress remain below the yield stress.

Conclusions

We have found, because of the reduction in gas protection, that the heat fluxes on the first wall of the proposed TDF are large enough to cause large thermal stresses in a bare HT-9 first wall. These stresses are often larger than the yield stress of HT-9 and make the determination of the lifetime of the first wall difficult. On the one hand, since the maximum stresses are compressive, it might be argued that the stresses actually impede crack growth and lengthen the lifetime. On the other hand, with the stresses being larger than the yield stress, the material under compression may deform to reduce those stresses but leave the wall under tension when the heat flux is removed. This could lead to accelerated crack growth and a reduced wall lifetime.

We propose avoiding this uncertainty in the wall lifetime by changing the design of the first wall. We could suggest that the cavity gas density be increased but the beam channels may not be possible if the gas is

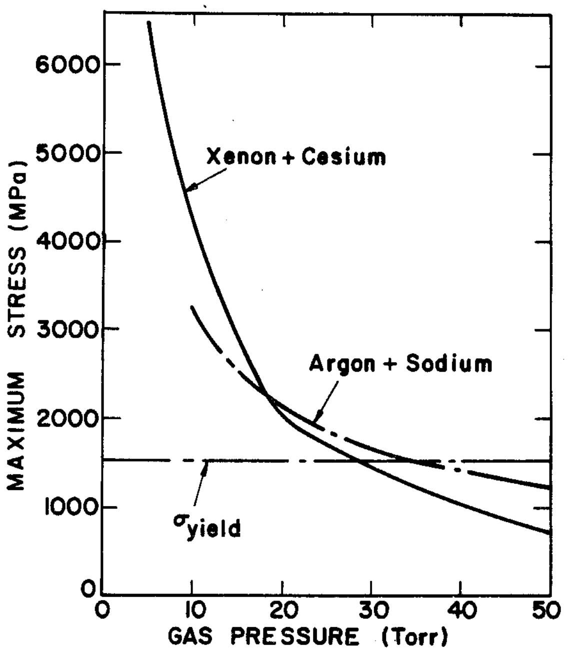

Figure 5 Maximum first wall stress versus gas density compared with yield stress.

dense enough to protect the wall. Since the shock overpressure is not large, we feel that a graphite liner supported by the HT-9 wall could survive the mechanical effects and would protect the HT-9 from the large thermal stresses. The liner would absorb the radiant heat flux and radiate the energy to the steel wall over a long period of time, generating only small thermal stresses in the HT-9. The liner would be constructed of a graphite fabric that would rest against and transmit the mechanical impulse of the shock to the steel wall. We feel that, since the mechanical stresses are so much lower than the thermal stresses, and since this design does not depend upon complicated calculations of the behavior of the first wall material, this is a better choice for the first wall construction of the TDF than the bare steel wall.

Acknowledgement

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