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ABSTRACT

Two-dimensional radiation hydrodynamic simulations of a light ion fusion target generated microfireball in a stratified gas atmosphere have been performed. The target location in a two region cavity was varied with the intent to reduce the overpressure on the diodes at the walls of a target chamber with a single cavity gas. Helium and nitrogen at 15 torr were used as the cavity gases; target explosions of 200 and 800 MJ were investigated. It was found that placing the target in a helium region surrounded by nitrogen could reduce the overpressure by a factor of 2 when compared with a single gas cavity of nitrogen. The surface heat flux was also reduced from a pure helium gas cavity.

1.0 INTRODUCTION

The design of a cavity vessel for a light ion beam inertial confinement fusion (ICF) reactor must consider effects from intense pressure loading on the cavity wall.[1] This is because most of the target x-ray and ionic debris energy is absorbed in the cavity gas which is converted to the mechanical and radiant energy of a blast wave. This blast wave exhibits mechanical shock and thermal radiation wave behavior. The vessel must be able to withstand the high peak overpressure and temperature which are experienced from a single event. The present investigation[2] explores the possibility of reducing the pressure impulse by using multiple layered cavity gases with different abilities to stop both thermal photons and x-rays. Strong shock theory[3,4] states that the overpressure is proportional to the energy behind the shock. It is hoped that the expanding radiation field can be directed such that the resulting nonspherical fireball expansion would decrease the mechanical impulse on the diodes or on diagnostic equipment placed below the target. This approach would help avoid excessive structural material in the instrumentation module that affects the measured x-ray and neutron spectra.

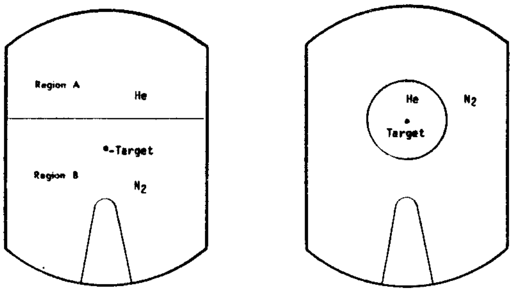


Figure 1. Stratified gas cavity.

Figure 1 illustrates the geometry under consideration: the proposed Target Development Facility (TDF). The cavity has a radius of 3 meters. The diagnostics package is depicted by the module beneath the target. The target chamber was taken as a right circular cylinder for the simulations. This study first considered the cavity gases segregated into the two regions as illustrated; the top region contained an optically transparent gas, helium, and the bottom region contained a gas with a much higher opacity, nitrogen. Two scenarios were investigated: the target location was either in the helium or in the nitrogen region. The target in Fig. 1a is shown for example in the lower or nitrogen gas region. The study also considered a geometry where the target was enclosed in a spherical region of helium surrounded by nitrogen. This configuration is shown in Fig. 1b.

The hypothesis for the target in the nitrogen region (scenario 1a) is that once the radiation front of the expanding fireball has reached the gas interface, "venting" of the radiation upward into the helium gas would result in a nonspherical hydrodynamic pressure expansion in the nitrogen gas region and thus reduce the pressure loading in the radial (diodes) and downward axial (instrumentation) directions.[5] These effects are not unlike an explosion of a depth charge near the surface of the water; the opacity differences take the role of the density ratio.

A different effect was important for the case of the target in the helium region. Since helium is nearly optically transparent, only a portion of the initial x-ray energy will be absorbed in it. The x-ray absorption will be much higher in the nitrogen; therefore, the nitrogen temperature at the gas interface will be substantially increased. The resulting fireball will now be free to expand back into the helium as well as into the nitrogen. This scenario is predicated on the assumption that plasma channels can be formed in the helium region for the ion beam to propagate through. We do not intend to investigate this, but merely assume it.

A 2-D Eulerian radiation fluid dynamics code[2] using diffusion theory was used to model the first scenario; the target in the nitrogen. A 1-D Lagrangian radiation fluid dynamics computer code[6] was used to simulate the cases where the target was located in the helium. This code has multiple material capability.

2.0 TARGET IN NITROGEN REGION

The present analysis used helium as the transparent gas in region A and nitrogen as the target cavity gas in region B as shown in Fig. 1a. The calculations were done in a cylindrical geometry using 5 cm square computational meshes. Typically the axial distance below the target was 250 cm and the He region 200 cm. This was done to prevent boundary contamination from phenomena such as artificial shock reflections from affecting the regions of interest. The radius was taken as 250 cm.

The initial cavity gas number density was taken as that which would have a pressure at 0°C of 15 torr; both gas regions were at the same initial pressure. The shot energy was either 200 MJ (the standard TDF base case) or 800 MJ (for high yield targets). The 2-D code does not model x-ray attenuation; therefore, MF-FIRE[6] was used to obtain the initial gas temperature profile.

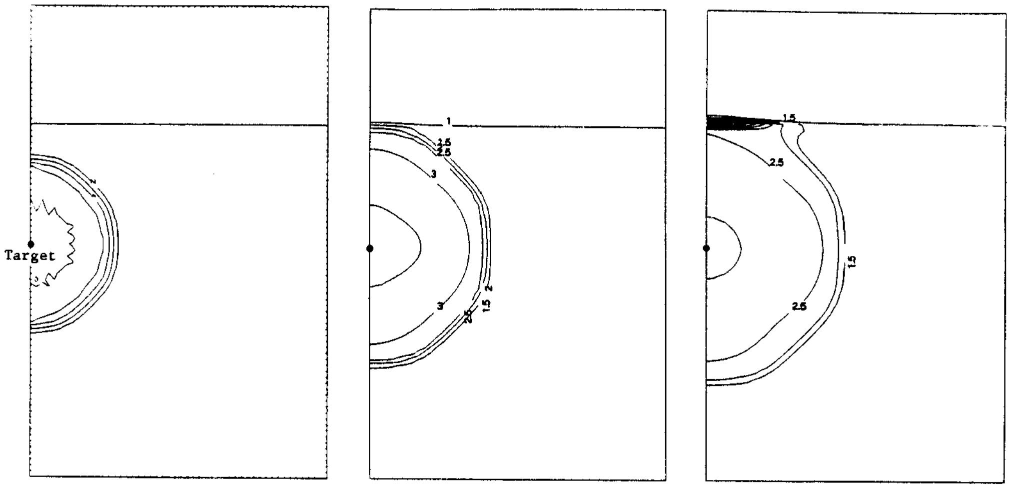
2.1 200 MJ Target Yield

The distance between the target and the helium interface was varied from 100 to 10 cm. They were chosen to be within the region where the shock wave is "launched"; that is, where the fireball hydrodynamic speed is greater than the thermal diffusion speed. For the present test conditions, this value was found to be approximately 130 cm[7].

The first calculation positioned the interface 100 cm above the target. This allowed sufficient time for the fireball to develop before it encountered the helium region. Figure 2 shows the development of the fireball from contours of gas temperature. One can note that the fireball has just begun to interact with the helium at 17 microseconds. Prior to this time, it has essentially undergone a spherical expansion in the nitrogen. At about 32 microseconds, the gas temperature contours have become nonspherical due to the change in gas properties at the interface; the helium was optically transparent to the radiation while the nitrogen was not. Thus, a radiation enhanced thermal wave propagated into the nitrogen. But since the radiation free-streamed in the helium, only a thermal conduction wave propagated in this region. The nitrogen thermal wave was enhanced due to the tight coupling of the radiation and gas fields; its propagation speed is dominated by the energy exchange between these fields. The propagation speed of a thermal conduction wave is due solely to its thermal conductivity; therefore, on the time scales under consideration, the thermal wave does not propagate as far into the helium as into the nitrogen region. Figure 3 illustrates the spatial distribution of the radiation temperature after the fireball has reached the interface. Here we can see that the radiation field had "burst" into the helium gas and the fireball vented energy "upward" into the cavity.

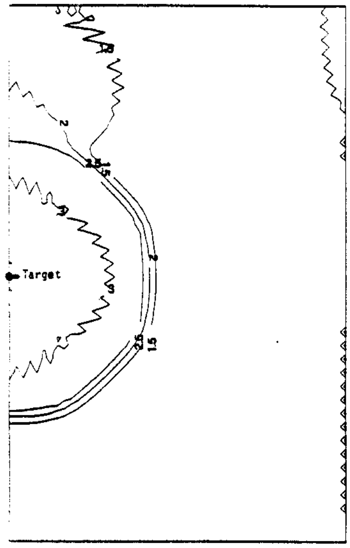
A comparison of pressure and velocity profiles between this vented 100 cm case and a single region nitrogen case showed only minor differences. This is due to the relatively low radiation interface temperature, 2.5 eV, when the fireball reached the helium. Since the radiation energy density is proportional to the fourth power of temperature, the actual energy flux being "vented" out of the fireball is comparatively small; the overpressure reduction would be negligible.

A comparison between the 40 cm vented case and a one-dimensional simulation of a 200 MJ explosion in pure nitrogen showed that the location of the fireball edge, using the point of the maximum velocity, was the same for both calculations. Although the vented fireball contained less energy the respective peak velocities were similar. This is because the peak velocity is essentially determined from the pressure gradient at the edge of the fireball, which was also similar for both calculations. The peak pressure of the vented case was, of course, lower than the non-vented case. It is speculated that the pressure gradient, or equivalently the temperature gradient in the diffusion dominated region, is determined by the



Plasma Temperature t = 2.e-06 s Plasma Temperature t=1.7e-05 Plasma Temperature 3.17 e-5 s

Figure 2. Gas temperature contours (in eV) for the 200 MJ 100 cm case.



Radiation Temperature 2.16e-5 s

Figure 3. Radiation temperature contours (in eV) for 200 MJ 100 cm case.

temperature dependence of the cavity gas opacity at the thermal front. If true, one would expect the gradients to be similar irrespective of the venting process, as the present calculations show.

2.2 800 MJ Target Yield

Although a target yield of 200 MJ was the design base value for the TDF cavity, high gain targets will be periodically tested. For this reason, a stratified cavity gas simulation was performed with a target yield of 800 MJ; a single separation distance of 20 cm was used.

The increased energy deposition of the 800 MJ target over the 200 MJ simulation resulted in a very different hydrodynamic behavior at the fireball core. This is because the 800 MJ target fully ionized the nitrogen gas; the opacity became so small that the gas and radiation were weakly coupled. The radiation temperature remained relatively low. The very high gas temperature resulted in a large pressure gradient which led to rapid hydromotion of the gas out of the core. When the core gas temperature was reduced to a point where the nitrogen opacity became significant, little mass remained in the core. At this point in time, the gas temperature quickly dropped. Therefore the hydromotion in the core reversed and the core compressed as mass moved back into it. However this effect is not important to the overall propagation of the fireball since only a small amount of mass is involved. The majority of the fireball's mass was located at its perimeter.

A comparison between the vented case and a simulation with pure nitrogen showed results similar to the 200 MJ simulations (see Section 4).

3.0 TARGET IN HELIUM REGION

A series of one-dimensional calculations was performed where the target was located in the helium region and the instrument package located in the nitrogen. The initial cavity density was taken as that which would have a pressure at 0°C of 15 torr, the same as the earlier calculations. Two target yields were simulated: 400 and 800 MJ. As before, the distance from the target to the gas interface was varied to determine spatial effects. The distance from the target to the "wall" was kept a constant for all cases: 300 cm.

MF-FIRE[6] was used to simulate this series of calculations. This code has the x-ray deposition model and multi-material capability which were required. This code is only one-dimensional; a spherical coordinate system was chosen for the present investigation. In essence the geometry simulated was one of concentric spheres: the inner one was composed of helium and the outer spherical shell was nitrogen. A spherical system was used as opposed to a cartesian system to account for the $1/r^2$ nature of the x-ray deposition.

Recall that Fig. 1 shows two cavity configurations for the case where the target is in the helium. From the above discussion, the MF-FIRE simulations model the geometry in Fig. 1b. However, these results can still be used to predict the initial pressure and heat flux loads on the instrument package for the cavity in Fig. 1a, but with the target now in the helium region. Since the one-dimensional simulation does not simulate the radiation losses or fluid motion to the upper region, only the initial wall responses can be used. The long term pressure impulse and surface heat flux history must be obtained from a full two-dimensional simulation.

3.1 400 MJ Target Yield

Two calculations in the helium region were performed with a target yield of 400 MJ; the target-to-interface distance was 25 and 50 cm.

Figure 4 shows the initial gas temperatures for the 50 cm simulation. The much higher x-ray stopping power of the nitrogen gas caused the gas temperature rise at the interface. The pressure distribution would be very similar to the temperature distribution. Thus, a sharp pressure gradient was created at the gas interface region. The fireball had become essentially a plane pressure source at the interface and could expand in either direction: into the helium or the nitrogen. One would expect the stagnation pressure on the wall to be reduced by a factor of 2.

Figure 5 shows the stagnation pressure on the wall, located 300 cm from the explosion, for the 400 MJ simulations. The results from simulations with either pure nitrogen or helium are also presented. The peak pressure for the pure nitrogen case is approximately 3 MPa while the peak pressures for either target in helium case is only 1.5 MPa; the maximum pressure point for a pure helium simulation is illustrated for com-

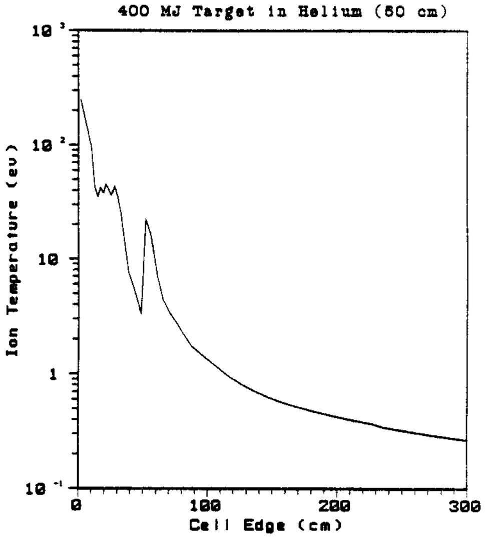


Figure 4. Initial gas temperature for 400 MJ target.

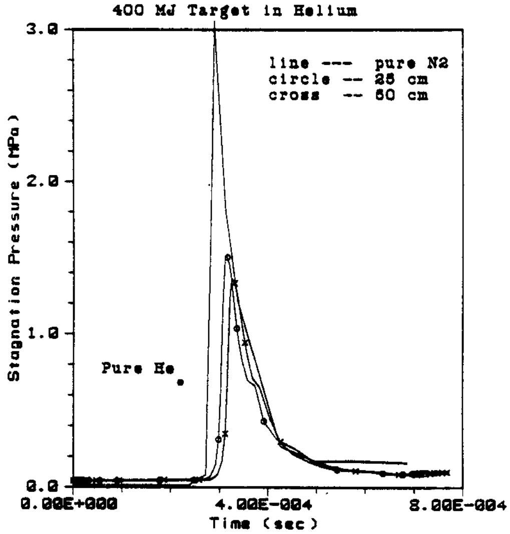


Figure 5. Stagnation pressure for 400 MJ target in helium.

parison. Essentially the use of two gases with different opacities and x-ray stopping powers changes the fireball expansion from having kinetic energy in one direction to having it in two; the maximum pressures are reduced by 50% simply by momentum and energy conservation arguments.

The limiting case of target-to-interface distance, the pure helium simulation, had a maximum pressure of approximately 20% of the pure nitrogen case. This helium peak pressure would correspond to a target yield of 200 MJ in a pure nitrogen cavity.

A drawback to using the helium gas, either in conjunction with nitrogen with the geometry of Fig. 1a or as a single cavity gas, is the resulting increase in surface heat flux. This is simply due to the reduced opacity and x-ray stopping power of the helium. Table 1 shows the maximum surface heat fluxes for the 400 MJ and 800 MJ simulations. One can note the drastic reduction in surface heat loading by using an absorbing gas as opposed to a transparent gas, the helium. Since energy must be conserved, the ratio of pressure loading to surface heat flux can be varied, depending on the particular system limitations. The TDF cavity under consideration is a simulation facility which will explode targets only about 10 times a day; a commercial reactor is expected to have an operation cycle on the order of a fraction of a second. Therefore, the heat flux question is much more important for the reactor, because of wall ablation, than it is for TDF.

3.2 800 MJ Target Yield

A simulation with a single separation distance, 25 cm, was performed for the high yield target case. As was the result for the 400 MJ targets, the peak pressure has been reduced by 50% by the use of a gas interface region. The maximum surface heat fluxes are given in Table 1. The heat flux follows the same inverse trend with the peak pressure as the 400 MJ simulations.

4.0 ANALYSIS

4.1 Target in Nitrogen Region

Figure 6 clearly shows the effects of the venting for the 200 MJ simulations. Here the energy in a pseudo-uniform fireball whose radial profile is taken as the vented case is scaled by the pure nitrogen case where no venting occurs. One can see that the 100 cm separation distance resulted in only a minimal effect while the 10 cm case achieved a reduction of approximately 20%. Since the radial position of the fireball, determined from the locations of the peak velocity, is similar for both the vented and nonvented cases, it is easy to determine the overpressure reduction one would expect. Strong shock theory[3,4] states that the peak stagnation pressure is proportional to the total blast energy and inversely proportional to the radius cubed. Thus for the same radius, the impulse ratio between the vented and nonvented cases simply reduces to the ratio of the fireball energies; therefore, Fig. 6 gives the pressure reduction directly.

Table 1. Maximum Surface Stagnation Pressure and Heat Flux

Case	Stagnation Pressure (MPa)	Heat Flux (MW/cm^2)
200 MJ pure nitrogen	0.62	
400 MJ pure nitrogen	3.06	0.03
400 MJ 25 cm	1.51	0.18
400 MJ 50 cm	1.36	0.13
400 MJ pure helium	0.68	5.75
800 MJ pure nitrogen	6.32	0.10
800 MJ 25 cm	3.19	0.72

The differences between the energy ratios for the 10 and 40 cm cases were simply due to the increased vent area for the 10 cm case. The 100 cm interface was too far from the target and thus its vented energy density was too low to significantly affect the fireball evolution.

4.2 Target in Helium Region

A significant reduction in the peak wall pressure was calculated for the case where the target was in the helium region. This was due to the conversion of the point spherical pressure expansion to that of a surface source; conservation of momentum and energy lead to a 50% reduction in wall pressure loading. A cavity with a single gas, helium, had an even further stagnation pressure reduction when compared with the case of a pure nitrogen cavity. The penalty for this pressure reduction is the increased surface heat flux as shown in Table 1. The use of nitrogen in either a stratified gas mode or as a single cavity gas drastically reduced the wall heat loading. This is just a statement about the conservation of energy.

The reduction in surface heat flux from 25 to the 50 cm case for 400 MJ target explosions is an interesting result. Recall that a 1-D simulation in spherical coordinates was used for these simulations. Thus the actual geometry is a sphere of helium in a larger sphere of nitrogen. The reason for the reduction in surface heat flux when the helium sphere was increased from 25 to 50 cm was that due to the low opacity of the helium, the ion temperature reached an

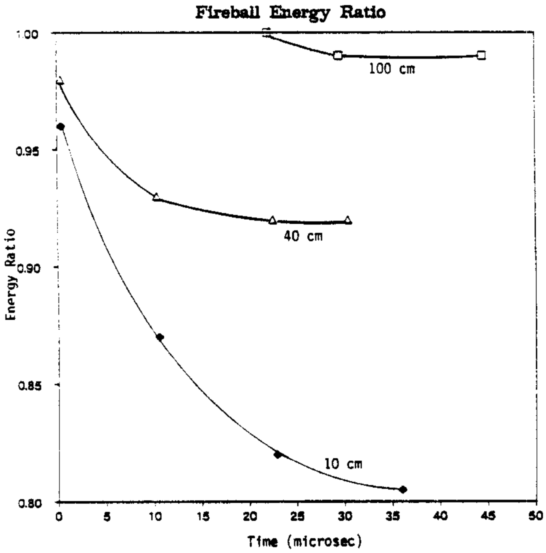


Figure 6. Fireball energy ratio.

almost uniform value shortly after x-ray deposition. The equilibrium value for the 50 cm case will be much lower than for the 25 cm case because roughly the same energy is spread over 8 times the volume. The lower temperature of the 50 cm case simply means a lower source term for the surface heat flux; the initial maximum temperature in the nitrogen region is also much lower for the 50 cm than for the 25 cm case. The net result from both of these effects is a reduced heat flux loading on the wall.

5.0 CONCLUSIONS

"Venting" the radiation energy from a target explosion in nitrogen to a helium region, shown in Fig. 1a, to reduce the surface pressure loading had only a minor effect for the 200 MJ target yields; the 800 MJ targets had little effect. The fireball inertia prevents this loss mechanism to be of significant benefit. The pressure shock is formed at very early times, before any appreciable energy loss can occur.

The geometries with the target in the helium region lead to a 50% peak pressure reduction on the instrumentation package due to the conversion of a spherical expansion to a surface source. However, the surface heat flux for this case was higher than for the pure nitrogen cavity. Table 1 summarizes these results for several calculations.

Exploding the target in the helium region of Fig. 1a will reduce the pressure on the instrumentation package; unfortunately, the diodes will experience a very high heat flux. The use of a central cell of helium, for example a gas bag as shown in Fig. 1b, might be a compromise between pressure reduction and wall heat flux loading for a test facility.

ACKNOWLEDGEMENTS

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