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High Velocity Impact Generated Air Blast**

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**Abstract**

High velocity impactors or re-entry vehicles produce air blast by three very different mechanisms. Because they are supersonic, they will produce a bow shock which is often referred to as a sonic boom. An air column following the body will strike the surface immediately behind the re-entry body, and the stagnated dynamic pressure will contribute to the generation of air blast. The kinetic energy of the impacting body itself will be divided between cratering and ground motion and air blast.

The pressure in the bow shock is a function of the shape of the incoming re-entry body and a function of the velocity. Blunt objects and high velocities form stronger bow shocks. A cylindrical body at 10 kft/sec produces a bow shock of ~150 PSI that extends well behind the incoming vehicle.

The re-entry body forms a long cylindrical cavity in the atmosphere behind the body. This cavity is tens to hundreds of meters long with a diameter of 1 to 3 times the diameter of the solid body. The air in this cylinder has a velocity of approximately that of the incoming body and a density just below ambient atmospheric. This column of air has a dynamic pressure of about 50 bars at 10 kft/sec. The stagnation pressure of this column of air will be on the order of the dynamic pressure. The total energy released is a function of the velocity, length and diameter of the air column.

The greatest amount of energy available for air blast comes from the stagnation of the kinetic energy of the body itself. Small scale experiments indicate that the energy going into cratering goes as the 1.74 power of the impactor velocity. The total kinetic energy goes as the velocity squared. The difference in these energies is the energy available to form air blast. At 10 kft/sec, the excess energy (the energy going into air blast) is over 90% of the total incoming kinetic energy. The impactor energy available for air blast is therefore nearly twice that of the detonation of the same mass of TNT.

This paper gives examples of the potential generation of air blast by each of the three sources mentioned above: bow shock, air column, and sudden conversion of kinetic energy.

Some recently discovered data from a 1973 Sandia sled test supports the high proportion of kinetic energy converted into airblast.

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## 1. Sources of Air Blast

Air blast from impacting bodies may be generated by at least three different phenomena. The first source is the bow shock generated by the supersonic incoming body. The strength of the bow shock and its duration are strong functions of the incoming velocity and the shape of the incoming body. The second source of air blast is the column of air following the body. At the tail of the incoming body, the velocity of the following air is very nearly that of the body. The velocity then decays as a function of distance behind the body, but significant velocities, of the order of that of the incoming body, exist for tens to hundreds of meters behind the body. The density of the air in this column is the order of the ambient air density. The mass of this column may exceed the mass of the re-entering body and contain nearly as much kinetic energy.

The third source of air blast is the result of the stagnation of the kinetic energy of the re-entering body. The stagnated kinetic energy is divided between the energy going into ground shock and cratering with the remaining energy available for airblast. The amount of energy available to air blast is a function of the incoming velocity and of the body geometry. A long rod will penetrate further than a sphere, thus depositing more energy into the ground. As the velocity increases, the fraction of the energy going into air blast also increases, as will be discussed later in this paper.

Let us examine the ranges of velocities of various types of penetrators. Conventional penetrating bombs reach velocities of 700 to 1400 feet per second (200 to 400 m/s), depending on the height from which they are dropped and the trajectory they follow. Boosted penetrators may enhance these velocities to 1100 to 3000 feet per second (400 to 900 m/s). Fragments from cased munitions, shaped charges and explosively formed penetrators may reach velocities as high as 12,000 ft/s (3500 m/s). Re-entry vehicles from intercontinental missiles attain impact velocities between 3,000 and ~15,000 ft/s (1 to 5 km/s), depending on the trajectory, characteristics of the reentry vehicle and the altitude of the ground. Special designs could increase these velocities to perhaps 6 km/s, but that remains speculation.

Figure 1 is a plot of the kinetic energy density of an object as a function of its velocity. A few interesting energy levels are called out. An energy density of  $1.0 \times 10^{10}$  ergs/gm corresponds to the melting point of steel. At a velocity of 2.8 km/s, the kinetic energy density is equal to the detonation energy of TNT and at a velocity of 5 km/s the kinetic energy density is the vaporization energy for aluminum or more than three times the detonation energy of TNT.

The consequences of these high energy densities bring up some interesting thoughts. At just over 4,000 ft/s (1.2 km/s), steel will begin to melt on impact. (This is why the maximum velocity demonstrated for steel penetrator case survival is ~4,000 ft/s) As the impact velocity increases, the steel may rapidly oxidize, thus adding more energy to the system. Aluminum burns on impact at 12,000 ft/s (3.7 km/s). The rapid burning of aluminum releases significant amounts of energy; about  $\frac{3}{4}$  of the energy per gram of a TNT detonation. The timing of this burning is dependent on the availability of oxygen and mixing of air in the

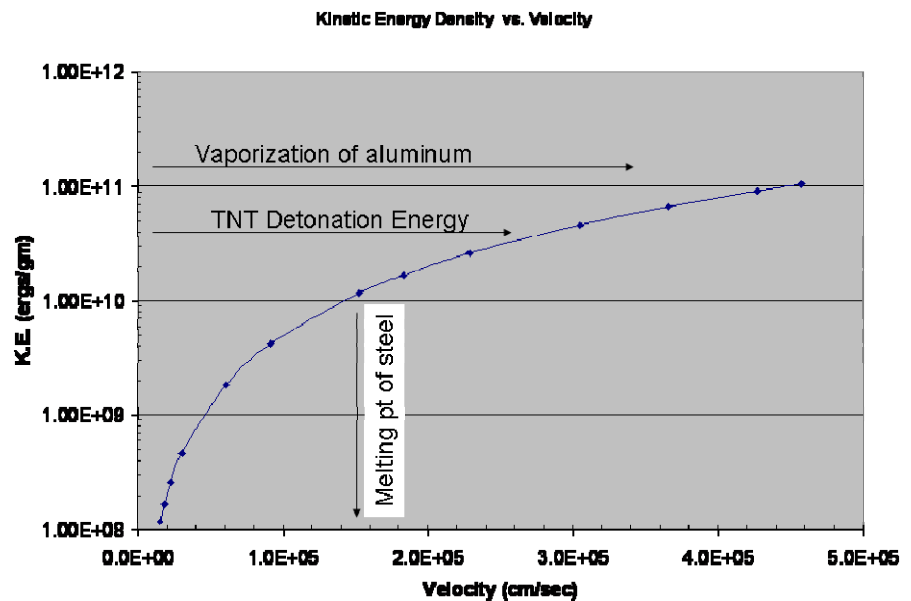


Figure 1. Total kinetic energy density as a function of velocity.

burning fireball of vaporized aluminum. A thin aluminum shell could burn in less than a millisecond. This rapid deposition of energy in the air creates additional sources of air blast and produces little to no penetration.

The next set of figures shows the results of numerical calculations of various shapes of reentry bodies at a velocity of 10,000 ft/s (3 km/s). Figure 2 is the result for a conical shape showing the extent and decay of the bow shock. The peak pressure of over 100 bars occurs at the tip of the cone and is not visible on the scale of this plot. The overpressure in the bow shock at the side of the vehicle is about one bar and extends for more than 10 meters behind the body. The bow shock overpressure falls off as  $\sim 1/R$  because of the cylindrical nature of the source and the shock is traveling horizontally at a Mach number of about 1.35.

The velocity of the air column following the cone is greater than 1 km/s, is close to pressure and density equilibrium with the ambient atmosphere, has a diameter equal to that of the cone and extends for at least several meters behind the cone.

Figure 3 shows the results of the calculation for a spherical reentry body at the same velocity. The peak bow shock pressure can now be seen along the leading surface of the sphere and has a value of just over 100 bars. This is the same as was found in the conical case and should not be surprising because the reentry velocity is the same; therefore the stagnation pressure should be the same. The extent of the high pressure is much greater than found with the cone, and decays more slowly. At the side of the sphere the overpressure exceeds 20 bars (300 PSI). The decay of the pressure still follows the  $1/R$  rule because the source is cylindrical. Thus at 10 meters behind the sphere, the shock extends to a radius of nearly 3 meters with an overpressure of about 2 bars and is expanding at  $\sim$ Mach 1.7. This should be compared to the shock from the cone, which extends to less than 2 meters in radius and is a factor of two weaker at the 10 meter distance.

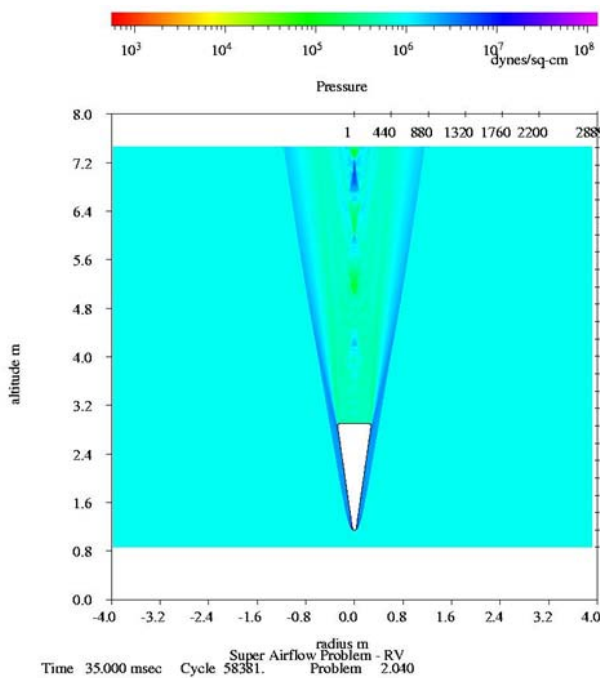


Figure 2. Bow shock for a conical shape at 10 kft/s.

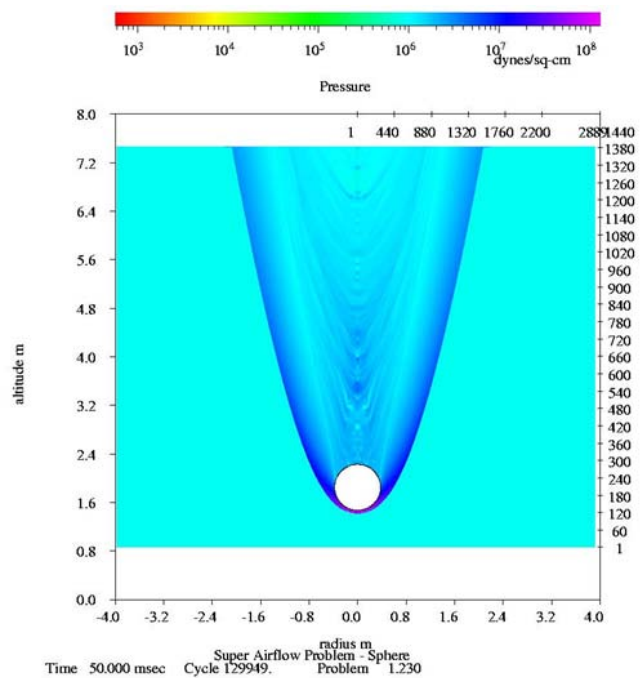


Figure 3. Bow shock for a spherical shape at 10 kft/s.

Figure 4 shows the calculated results for a cylindrical reentry body at 10 kft/s (3km/s). The peak stagnation pressure at the leading edge is the same as the two previous examples and decays similarly to the spherical case shown previously. While the air following the conical reentry body was at or below atmospheric pressure, the air within the wake of the cylindrical body is at or above ambient pressure.

The flow field generated by the reentering cylinder is shown in Figure 5. The diameter of the air column in the wake of the cylinder is more than twice the diameter of the cylinder. The velocity in this region reaches the reentry velocity immediately behind the cylinder and falls to about 40% of that at a distance of 10 meters behind the body. Thus a significant amount of energy has been transferred to the air column traveling with the reentry body.

Figure 6 shows the pressure field for the bow shock around the cylindrical body on an extended scale. We see that the strength of the bow shock remains above a bar at a distance of more than 30 meters behind the reentry body and a radius of over 6 meters. The air in the wake of the cylinder decays to atmospheric pressure within 8 meters of the nose and remains at about atmospheric throughout the interior of the bow shock.

The flow field on the extended scale is shown in Figure 7. This figure clearly shows the column of air following the cylindrical body. There is very little divergence of the column and surprisingly little decay of the velocity with distance behind the body. The velocity of the air column remains nearly half of that of the body at a distance of 40 meters behind the leading edge.

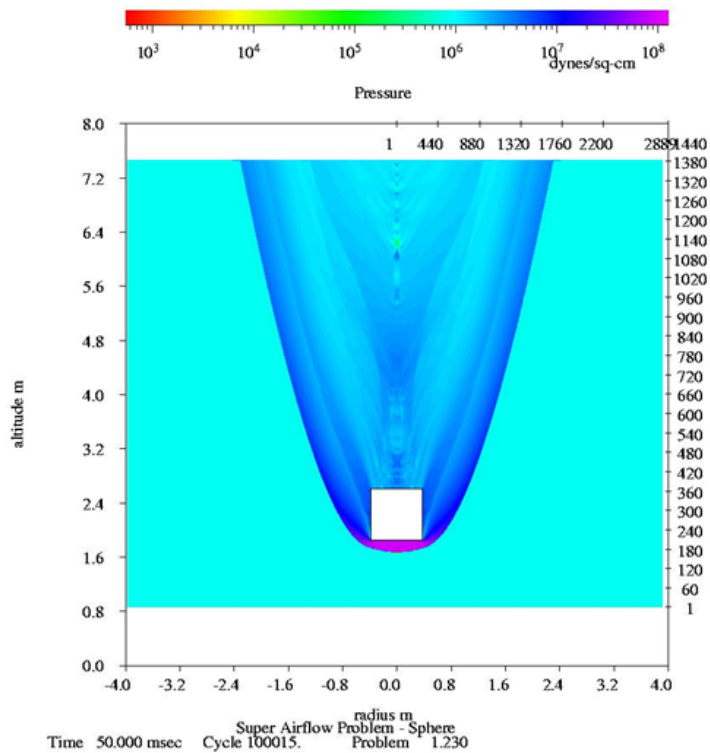


Figure 4. Bow shock for a cylindrical shape at 10 kft/s.

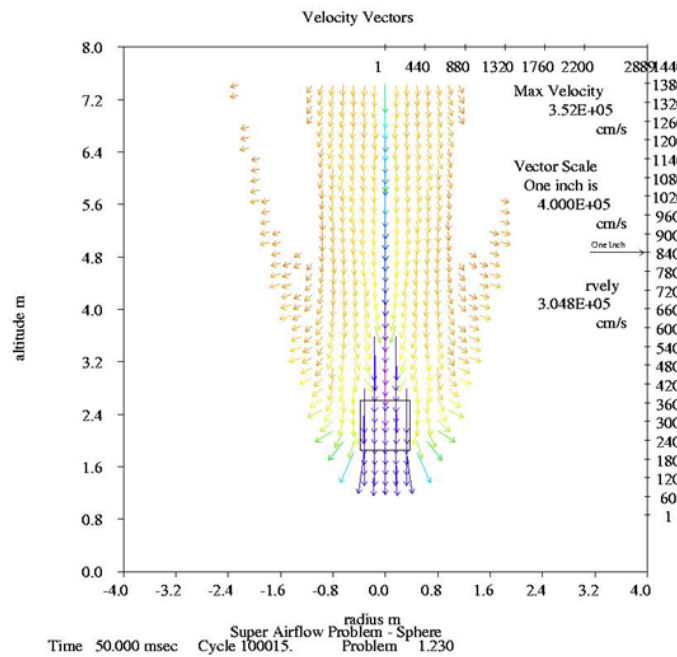


Figure 5. Velocity flow field for the cylindrical reentry body

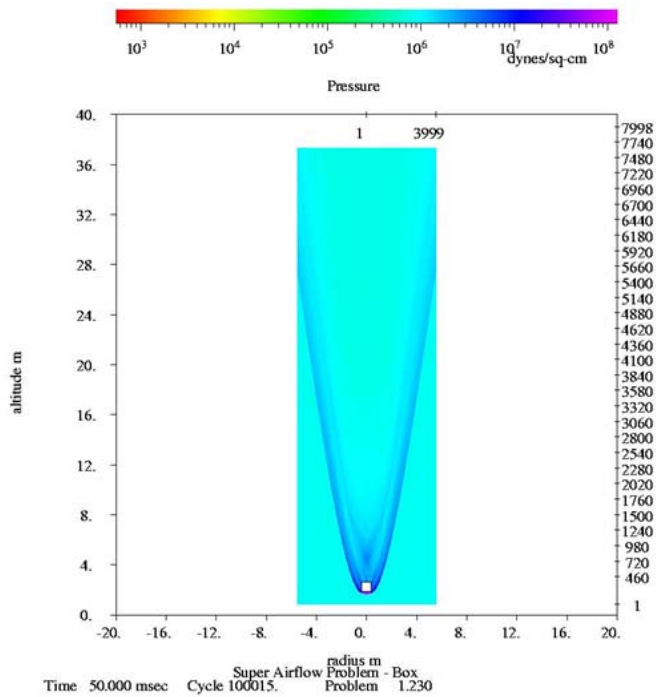


Figure 6. Bow shock for a cylindrical shape at 10 kft/s., extended scale.

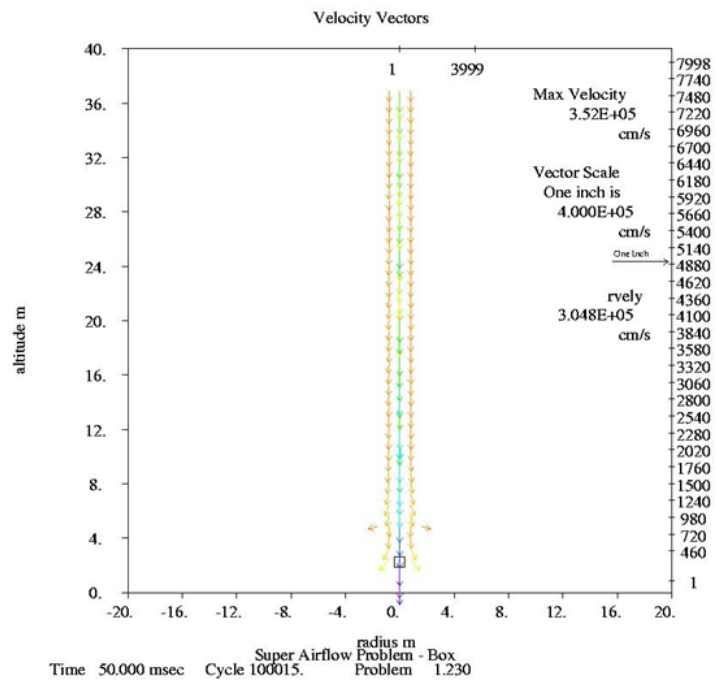


Figure 7. Velocity flow vectors for the cylindrical body, extended scale.

These results are significantly different from the experience of conventional penetrating warheads. Figure 8 is taken from the results of a calculation (using the same CFD code) for a conventional guided bomb at a velocity of 1.4 kft/s (425m/s). This calculation was fully three dimensional and included the nose and tail fins. The angle of the shocks from the various fins and geometry variations can be seen as extending nearly radially from the body. The angle of the bow shocks is a function only of the Mach number of the body and can be readily calculated. The weak shocks in this case are propagating at essentially sound speed, while the body is traveling slightly supersonically. At transonic speeds, the shocks would radiate perpendicular to the path of the moving body. The body would be moving at the same speed as the shock front.

Note that a turbulent wake follows this body and extends for tens to hundreds of meters behind the bomb. The wake expands very slowly with an angle of only 1 or 2 degrees. This calculation included a full turbulence model and this expansion includes the turbulent mixing region induced by the shear velocities behind the body.

The kinetic energy of the air column behind the cylindrical body can be approximated by taking the average velocity to be half of that of the reentry body and the volume to be twice the radius and, for a first cut, a distance behind the body of 40 meters. For the cylindrical body, the radius of the air column is 1 m., at 10,000 feet/sec. The energy is then given by:  $E = \pi * r^2 * h * \rho * V^2 / 2 = \pi * 10^4 * 4.e3 * (1.e - 3) * (9e10) / 2$  or 5.65e15ergs; the equivalent of 300 pounds of TNT in just the air behind the body.



**Figure 8. Calculated wave pattern for a conventional guided bomb at 1.4 kft/s**

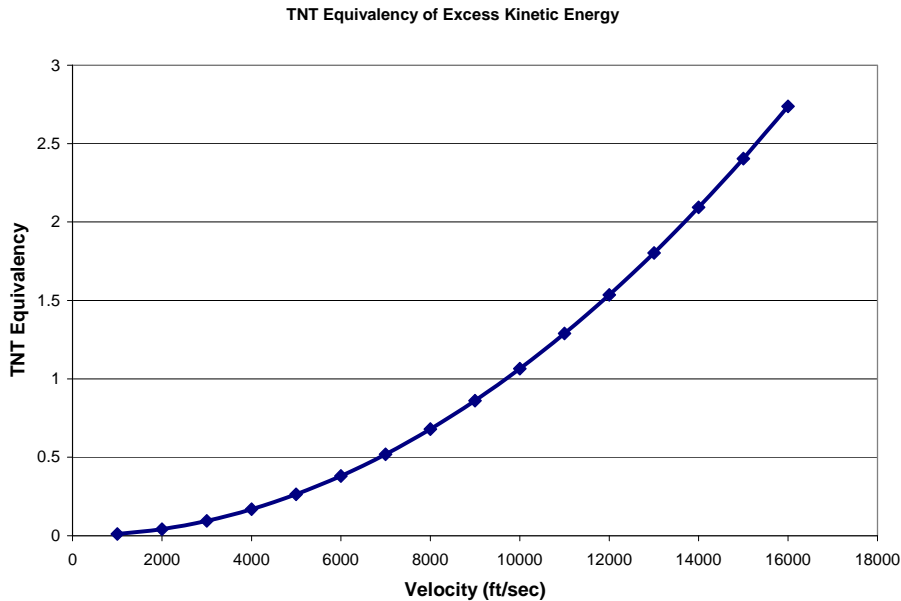
This air kinetic energy will be stagnated in the time it takes for the column to travel 40 meters at a velocity of 3 km/sec or about 13 ms.

## 2. Impact Energy Conversion

When the moving body hits the surface, the kinetic energy is converted to internal energy or heat. The amount of energy converted is dependent not only on the impactor velocity but on the relative densities of the impactor and the surface material density. The efficiency of the energy conversion is proportional to the square root of the density ratio. Without much more detailed information, I have depended on the results of small scale impact and cratering experiments. These experiments show that over a fairly broad range of velocities, the crater volume and therefore the energy in the ground is proportional to the incoming velocity to the 1.74 power. <sup>(1)</sup>

If we assume that the excess energy, that is the kinetic energy that does not go into cratering and ground shock, goes into air blast, we can use the results shown in Figure 9. This plot was generated with the assumption that the proportionality constant for the cratering energy was 0.5. Thus the function plotted is:

$E_e = 0.5(V^2 - V^{1.74})$ , where V is the impactor velocity.



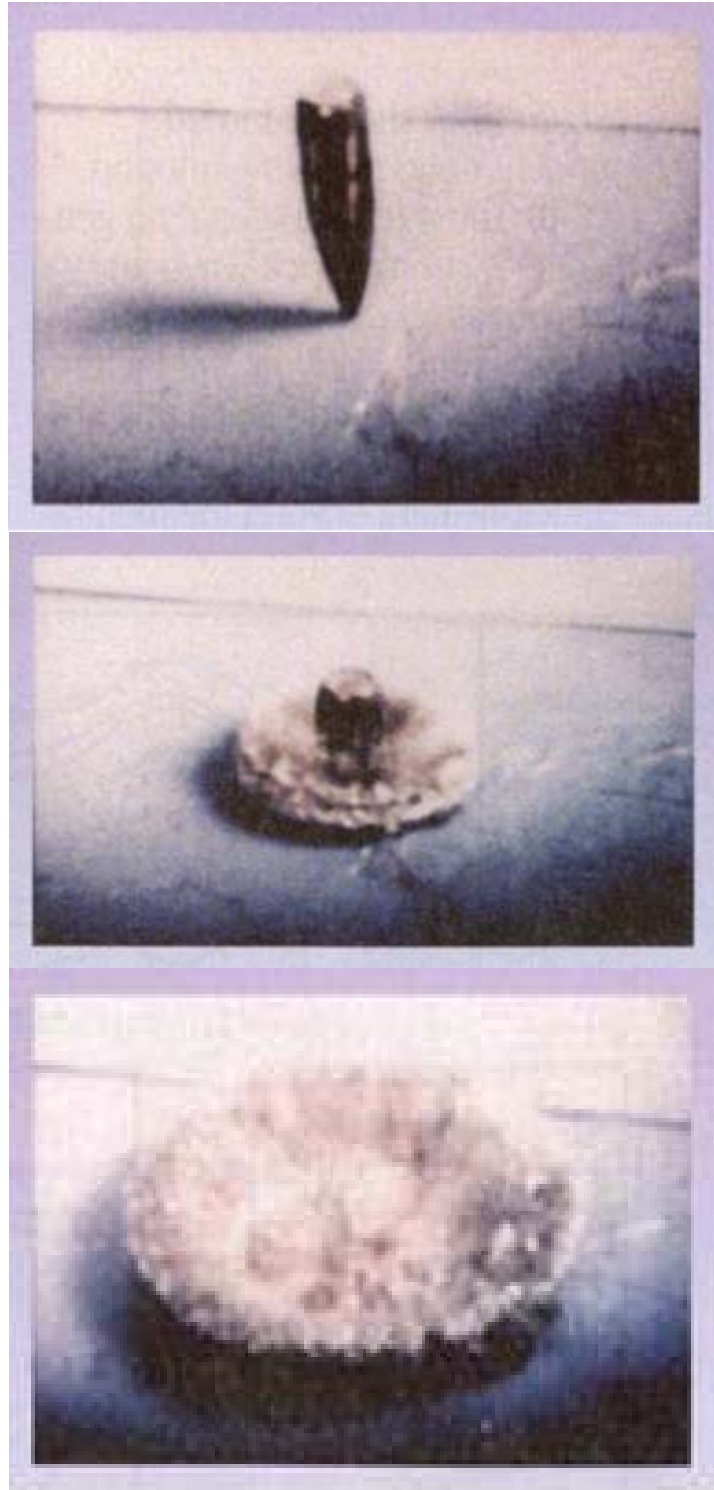
**Figure 9. Excess kinetic energy as a function of impact velocity**

This plot shows that at velocities less than about 2000 feet per second, a negligible amount of energy goes into excess energy and air blast. Even at 4000 feet per second, the excess energy is only about 20% of the detonation energy of TNT. However, at velocities greater than about 7000 feet per second, the excess energy becomes a significant fraction of the equivalent of a TNT detonation of the same mass.

There is good experimental evidence that the simple density ratio “law” may only apply for velocities such that the materials involved in the impact remain in the solid state. Figure 10 is a sequence of three figures showing the near normal impact of a .30 caliber copper jacketed lead bullet striking a steel plate at a velocity of 2790 ft/s. From the simple density relations it would be expected that the bullet would penetrate the steel. The figures make it quite clear that the bullet essentially melts on impact, and behaves as a high density fluid, spreading over the surface of the plate with very little penetration. This is somewhat surprising because the total stagnation energy just accounts for the energy required to melt the impactor. This does account for the fact that little penetration or even damage to the steel plate was observed, essentially all of the incoming kinetic energy was converted to thermal heating of the impactor.

Continuing with the implications of these data, the distance from the impact was plotted point to several overpressure levels as a function of the impact velocity for a 1000 pound impactor. The assumption is that the total kinetic energy is converted into overpressure. At low velocities, this is a significant over estimate; however for velocities above about 3000 feet per second this approximation is valid and is illustrated in Figure 9. Figure 11 shows that the range to 100 PSI, a pressure that is damaging to nearly all structures, can extend to a range of 100 feet at an incoming velocity of ~15000 ft/s.





**Figure 10. Sequence of a .30 caliber copper jacketed lead bullet striking a steel plate at 2790 ft/s (850 m/s). (Photos courtesy of and with the permission of the Heflin steel division of the ESCO Corp.)<sup>(2)</sup>**

At a velocity of 10,000 ft/s, the 2 PSI range extends to more than 500 feet from the impact point. An overpressure of 2 PSI is sufficient to cause structural damage to frame constructed structures and will break most windows.



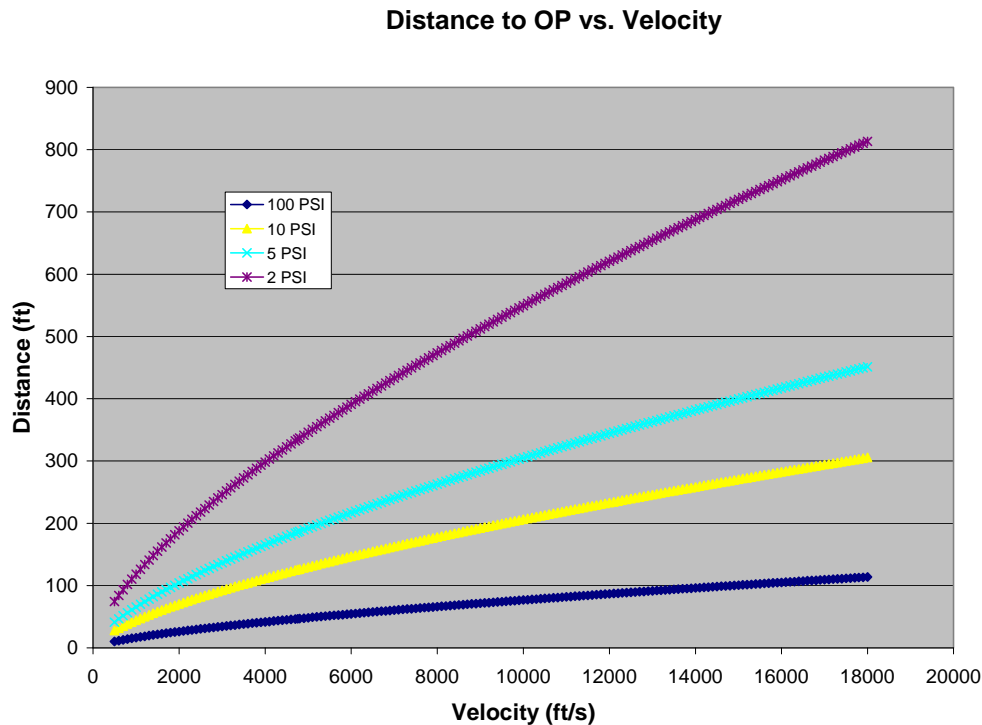


Figure 11. Distance to several pressure levels as a function of impact velocity for 1000 pound impactor.

### 3. Experimental Confirmation

In support of a 1973 Sandia sled test, Jack Reed was making pressure measurements to determine the pressure distribution of the sonic boom. He placed an array of gages on a line parallel to the sled track. In examining the records from the test he found some secondary signals that could not be caused by the passing of the sled. Upon checking the arrival times, he was able to determine that the signal originated at the target at the end of the track. By using the magnitude of the pressure peaks, the impulse and the rate of decay with distance, he was able to determine the effective yield of the air blast. He found that a “good fit” was obtained when he used the TOTAL kinetic energy of the sled; including the sled, motor, fuel and test object. The energy in the blast wave was indistinguishable from the total kinetic energy of the impacting mass.

### 4. Conclusions

Air blast from penetrators is not a significant concern for impact velocities of less than ~2500 feet/second. For velocities greater than this, the airblast must be considered, especially if collateral damage is important. As the impacting velocity increases, a greater proportion of the kinetic energy goes into air blast. At 10,000 ft/sec, the excess kinetic energy will produce an airblast with a TNT equivalent to the mass of the incoming object. For higher velocities, the TNT equivalent is greater than 1 and approaches a value of 2 at ~14,000 ft/sec.

This paper details three sources of the air blast created by high velocity bodies approaching the surface. While the largest source of stagnated energy is that of the impacting body itself, the stagnation of the following air column may be greater than 30% of that generated by the impact of the reentry body.

### 5. Vitae

Charles Needham is a principal physicist and associate at Applied Research Associates, Inc.

### 6. References

- (1) Judd, O’Dean, “Kinetic Penetrators and Impactors” April, 2003.
- (2) Photos courtesy of and with the permission of the Heflin steel division of the ESCO Corp.