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On the Ejecta from JASPER Targets

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Introduction

Light-gas guns are a well-established technology used for hypervelocity impact research in both military and civilian applications. Such guns use compressed gases that accelerate a projectile to impact upon targets at speeds in excess of 1000 m/sec. Depending on the research issue of interest, the projectile may embed in a large target or drive through smaller targets. The macroscopic behavior in such cases is different, but either result is typically accompanied by the generation of ejecta, solid particulates launched from the area surrounding impact.

Light-gas gun experiments at the Joint Actinide Shock Physics Experimental Research (JASPER) facility at the Nevada National Security Site are unique in that the target is a radiological material of interest. The regulatory requirements of 10 CFR 830, *Nuclear Safety*, mandate some at least qualitative estimate of the airborne release potential from target impact. Two primary physical phenomena occur in a JASPER target impact: (1) ejecta formation, and (2) fusion of the deformable projectile with the bulk of the target. The latter phenomenon is not conceptually complex from a physics perspective; projectile and target drive into the end plates of the Primary Target Chamber (PTC) where they come to rest. This phenomenon has not been of significant historical interest from an airborne release perspective.

Ejecta formation has been of historical interest for airborne release evaluation even though radiological ejecta cannot occur in most JASPER targets. This paper documents the physics of ejecta to support its evaluation in a Document Safety Analysis (DSA).

Theory

Ejecta is a product of tensile stresses in the target that are induced by a rarefication wave, which is a physical response to the compression shock generated by impact. Given hypervelocity impact, the potential for ejecta formation is a function of projectile and target geometry.

For JASPER, the primary geometric characteristics of the projectile (i.e., diameter and composition) may be considered effectively constant. There are many different potential target configurations. For simplicity, this paper focuses on the bounding target configuration for ejecta formation, one continuous disc with a diameter larger than that of the projectile. Ejecta formation occurs in the annular region of that disc outside the face of the projectile. A two-stage light-gas gun[1] such as the gun at JASPER launches a metal plate impactor fixed in a plastic sabot to provide planar impact onto the target. This is depicted schematically in Figure 1 below.

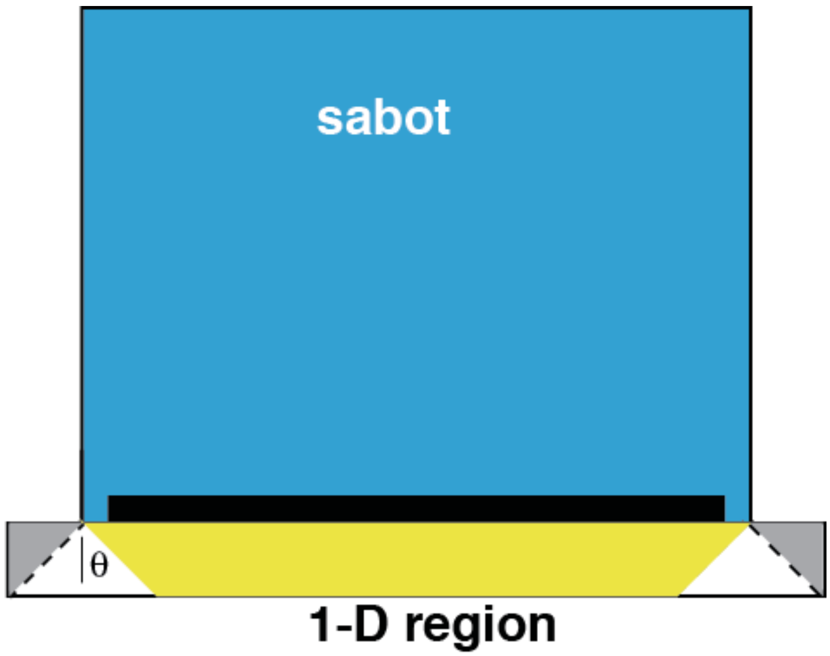

Figure 1. This figure depicts a projectile (filled in color) with an impactor plate (solid black) at the moment of impact on a target. The impactor is moving downward in the figure. Also shown is the boundary of the edge rarefaction (dashed lines), and the maximum ejecta volume (gray triangles). The 1-D region (shown yellow) is the region of the target in which the pressure is constant across the entire width of the colored region. The symbol θ refers to the rarefaction angle described in the text.

At the moment of impact, the target material within the face of the projectile is subject to intense pressure. Outside this impact zone, the pressure on the surface for an impact in vacuum is essentially zero. As the shock passes more deeply into the target (downward in Fig. 1), the region of constant pressure (the 1-D region in yellow) grows smaller. This is because of a rarefaction wave that moves inward at the speed of sound, since there is zero pressure above it or at larger radii. At the same time, a pressure wave moves outward in the target outside of the impact area also at the speed of sound, so it is symmetric with the rarefaction wave. In Figure 1, this is depicted by the white isosceles triangle bounded by the 1-D region and the grey triangles. In this region, the pressure varies smoothly from zero at the dashed lines to the full shock pressure inside the 1-D region.

A. H. Jones, W. M. Isbell, and C. J. Maiden, *J. Appl. Phys.* **37**, 3493 (1966)

In order to estimate ejecta in a DSA, it is necessary to understand and bound the pressure unloading angle θ. A complete derivation[2] is beyond the scope of this small report, but it is fairly easy to understand. The rarefaction unloading angle θ is given by $\theta = \arctan(c / u_s)$ where c is the sound velocity in the metal, and u_s is the shock velocity. As shocks become stronger, the unloading angle decreases because the shock moves much faster than the sound velocity, which is the velocity at which the sideways unloading occurs. For all materials, as a shock gets weaker, its velocity smoothly and linearly approaches the sound velocity. The weakest shocks thus give the largest unloading angle. In the limiting case for weak shocks, u_s approaches c and the rarefaction angle smoothly approaches 45 degrees[3]. This formula also defines the angle that bounds the undisturbed, *i.e.* zero pressure, volume of the target, denoted by the dashed black lines. This is the bounding case for ejecta formation.

The dashed black line defines the outer border of the rarefaction zone; outside of this line (at larger radii), the pressure remains zero. This zone of zero pressure is depicted in grey shading. The pressure below the gray shaded volume (below the dashed line) is greater than zero. If that pressure is greater than the strength of the material, some of the material in the gray shaded area can form ejecta. This is not an issue of thermal or compression stress. It is solely a function of the target metal's structural strength relative to the internal stresses imposed. Any material ejected in this manner has never been subjected to shock heating or compression. It is a "cloud" of solid particles generated by physical fracturing, which accounts for the coherence and uniformity of the ejected material observed in measurements, and why the ejecta look qualitatively the same regardless of target response.

This model is bounding for two reasons. First, the angle θ that defined the boundary of the sideways unloading rarefaction has a maximum value of 45 degrees in the limit of a weak shock. For any real experiment, the angle will be less, and the available volume to form ejecta will be less. Second, not all of the material in the grey shaded volume will become ejecta. The structural stress placed on material in the annular region of the target not within the face of the projectile is a maximum at the target surface. It reduces as one follows the dashed black line through the material, ending when the back face of the target is reached. That is, the structural strength of the metal will not be exceeded all along the dashed black line. Neglecting material strength makes this bounding model extremely conservative.

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[2] *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*, Ya. B. Zel'dovich and Yu. P. Raizer, Academic Press, New York, 1967, p. 746 *et. seq.*

[3] The impact velocity that produces a shock depends on the elastic properties of the material under impact. The point here is that once the shock velocity decreases to equal the sound velocity, there is no shock wave, and the material behavior is completely elastic and reversible.

After impact, the volume in the 1-D region and associated zones that detach with it, fuse with the projectile remains (i.e., sabot material, impactor) and continue to move at high velocity. This agglomeration encounters additional materials in driving through the target assembly (TA), which induces further fusion/mixing with debris. This end product has been sometimes referred to as a "tarry mass." It is driven into the end plates of the Primary Target Chamber (PTC) and deposited there.

Referring back to Fig. 1, we can calculate the maximum volume of the ejected material for the bounding model. If we define the outer radius of the projectile as R, and the target has thickness Δx, then the maximum volume of the ejecta is the volume of the solid of revolution whose cross section is the gray triangle. This implies the assumption that the front surface of the target is neither tamped nor covered (an atypical configuration). To find this volume, we take the volume of the right circular cylinder that has the same outer radius as the grey triangle:

$$V_{cyl} = \pi \Delta x (R + \Delta x)^2$$

This is a general result. It derives from the maximum 45 degree angle, which dictates the target and projectile radii differential equal target thickness.
In reality, the projectile radius is fixed by the launch tube radius, and the experimental apparatus cannot allow for a target radius that increases in direct proportion with target thickness (i.e., target becomes ever larger on both the x and y axes). A working model will set an upper limit on either target radius or target thickness. In the case of JASPER, the DSA has established as a Technical Safety Requirement a maximum target radius. If the maximum target radius is set at r_2, the thickness can be expressed as $\Delta x = (r_2 - R)$, yielding $V_{cyl} = \pi r_2^2 (r_2 - R)$.

To obtain the volume of the shaded grey area, subtract the volume V_0 of the entire 1-D and rarefaction regions, which is the volume of the frustrum of the cone, with base radius r_2, top radius R, with height $\Delta x = r_2 - R$:

$$V_0 = \frac{\pi}{3}(r_2 - R)[r_2^2 + R\, r_2 + R^2]$$

and the maximum ejecta volume is given by

$$V_{max} = V_0 - V_{cyl} = \pi r_2^2 (r_2 - R) - \frac{\pi}{3}(r_2 - R)(r_2^2 + R\, r_2 + R^2)$$

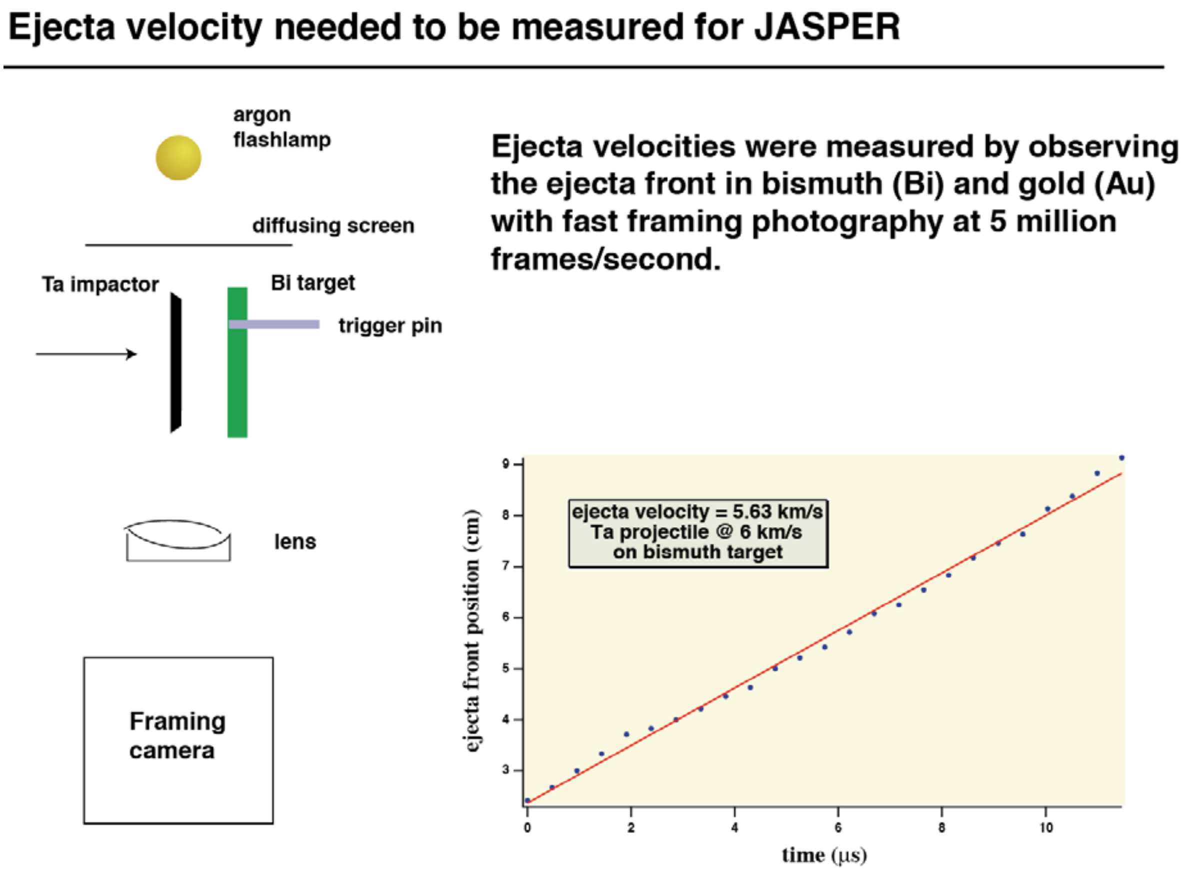
which further reduces to the bounding equation

$$V_{max} = \pi r_2^2 (r_2 - R) - \frac{\pi}{3}(r_2^3 - R^3)$$

If target thickness is less than the radii differential, the volume of the shaded grey area in Figure 1 is less by definition. If target thickness is greater than the radii differential, that increased mass is below the dashed black line and does not contribute to ejecta formation.

Data

To verify the basic ejecta behavior, the JASPER project utilized a framing camera to film actual impacts. This information was also needed to verify ejecta velocity as input to the PTC design. The method used is shown schematically in Fig. 2:



The approach was to make framed images of the ejecta in a plane orthogonal to the target surface. A diffusing screen was illuminated by an Argon flash lamp for about a 100 microsecond interval. Before the framing images of the impact were made, a screen with a 1 cm square grid was placed in the focal plane of the optical system shown above (aligned to the target center) and photographed with identical optics and dimensions. This provided a scale for comparison. The frame rate on film was approximately 5 million frames/sec; the actual frame rate during the experiment was measured in real time

Measurements of the leading edge of the ejecta were made at multiple points over an ejecta travel distance of about 7 cm. The analyzed data are shown in Figures 3 and 4.

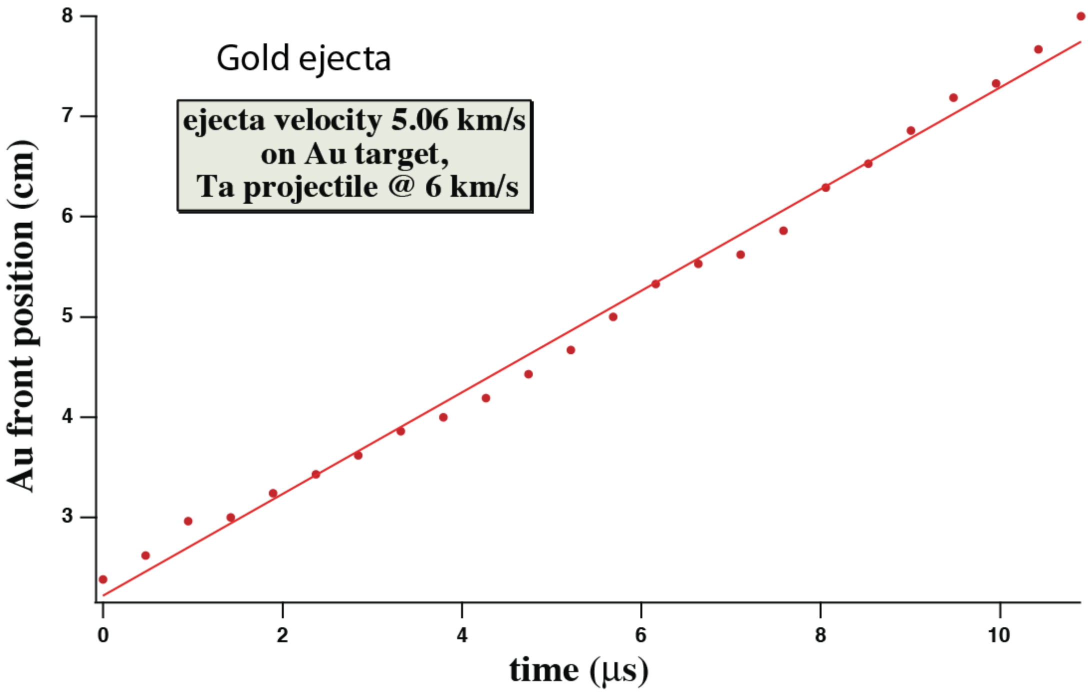


Figure 3. Data from a gold ejecta experiment using a Ta projectile at 6 km/s. The measured gold ejecta velocity was 5.06 km/s.

Bismuth

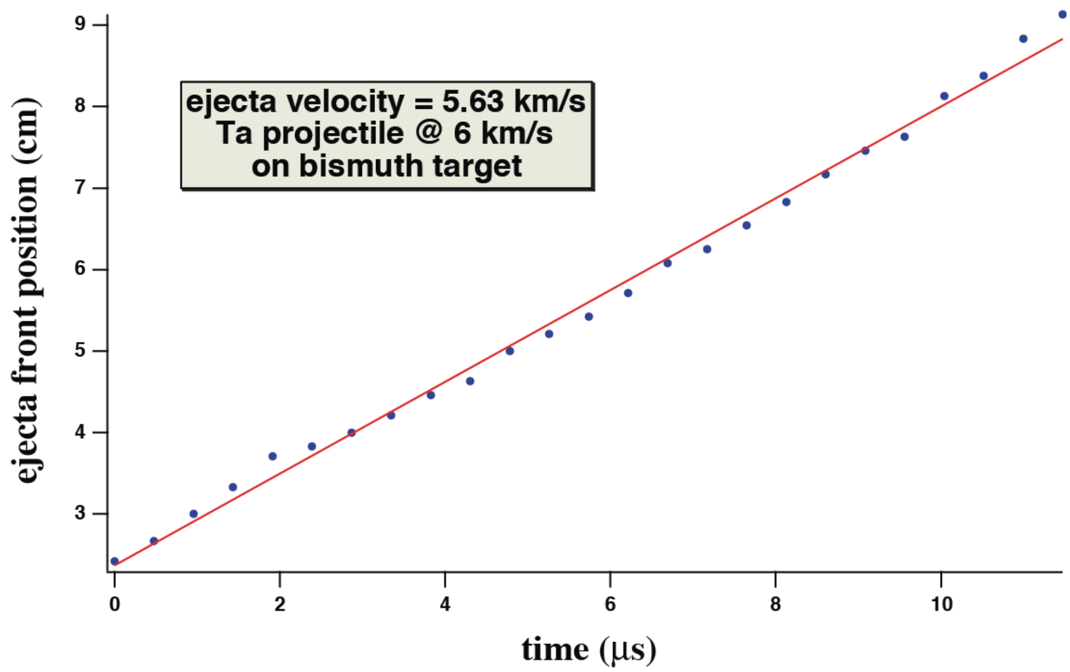
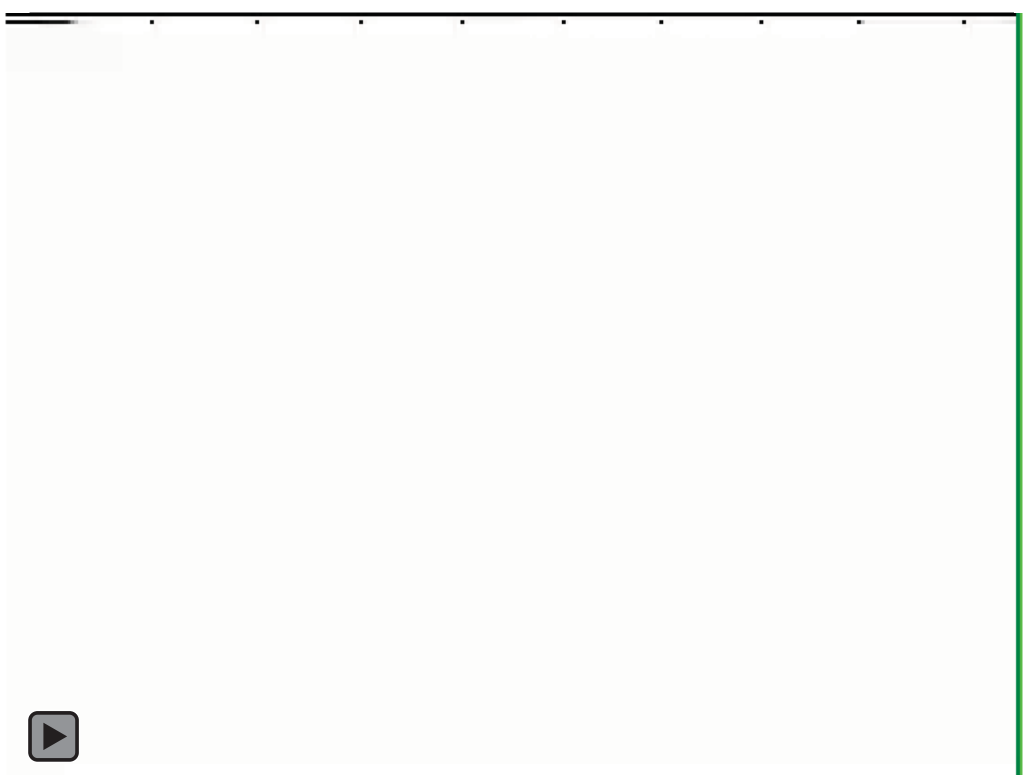


Figure 4. Summary of framing camera data from a Bi ejecta experiment. For a Ta projectile at 6 km/s, the Bi ejecta velocity was 5.63 km/s



Bi ejecta movie (Please click on the image to play)

From these data, we see that the Bi ejecta moved at a little more than 90% of the projectile velocity, and for gold (Au), the ejecta moved at 84% of the impact velocity. This result was consistent with expectations based on gas gun physics. Ejecta are generated nearly simultaneously with the projectile impact and the time to subsequent impact upon the available surfaces of the PTC is practically instantaneous. The ejecta velocities are consistent with one would expect for solid ejecta particles.

From Fig 2, it is easy to understand the spatial distribution of the ejecta. The physical fact of the projectile limits the ejecta to a conical shape with no ejecta present within the outer radius of the projectile. The ejecta are a chunk-like cloud of solid particles moving through a low pressure gas (some of the residual gas from the projectile launch). The data from several framing records show an ejecta cloud moving away from the target surface in directions that smoothly vary from nearly surface-normal at the outer radius of the projectile to a full ninety-degree angle at the ejecta cloud's outer initial radius.

The solid ejecta particles behave as individual projectiles. They have a momentum imparted by the mechanics of impact and travel at velocities rendering gas transport mechanics irrelevant. An aerosol is defined as a gaseous suspension of fine solid or liquid particles. Clearly, a gaseous suspension is not physically possible in the life cycle of the ejecta.

Conclusions

The simple geometric formula used to estimate bounding ejecta quantities for JASPER target impacts confirms to the physics of ejecta phenomena. It is a valid and conservative ejecta estimation technique for use in DSAs.

Ejecta are solid particulates generated at high speeds. It is physically correct to evaluate their behavior as consistent with individual particles experiencing effectively instantaneous impact with available surfaces. It is not physically correct to evaluate their behavior in terms of aerosol physics. Ejecta is not generated as a gaseous suspension of fine solid particles.