# AIR CRATERING BY ERODING SHAPED CHARGE JETS

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Air cratering by shaped charge jets is calculated using two very different penetration rate and crater radius models. Comparison of calculations to experimental data demonstrates that both models produce penetration results representative of data from experiments. Calculations also show that jet erosion proceeds within a very thin layer to produce jet debris suitable for rapid combustion at the crater interface – the process producing the fiery tails that have long been observed during shaped charge experiments. However, the crater radius formulas are greatly different with little experiment data available from which to validate them or to choose which is better.

## INTRODUCTION

Shaped charge jet erosion and the resulting crater in air have long been controversial, little studied subjects for two principal reasons. Firstly, shaped charge researchers generally have long associated the tip of many jets with a compressive velocity gradient deemed sufficient to cause both a mushroom shape and the radial dispersing debris observed in high-speed photography and flash radiography. Secondly, jet tip erosion in air requires a velocity greater than a yet-undefined lower bound, is quite small, and is usually many times less than local jet stretching until the jet's tip separates from the rest of the jet.[1] Nevertheless, [1] and its many citations as well as subsequent experimental data since its publication continue to demonstrate that many jets do erode producing a crater in air while comparable jets do not erode when travelling in vacuum.[2-8] (Photography also shows that jet particles travelling inside the air crater do not erode and do not produce air-shock light emissions.)

This paper does not dispute that a compressive gradient in a jet (be it in the tip or elsewhere) can cause a jet to grow in diameter or to even penetrate itself. Compression-driven mushrooming of a jet's tip can be created and greatly exaggerated through the "Kernel" effect after impact with very thin foil switches such as used for taking flash radiography.[9] Held has photographed metal-jet compression so great that the jet penetrates itself with the debris flowing laterally as a disk having a lower radial velocity when penetrating air than when travelling in vacuum as shown in [2,3]. However, the experimental work in [7,8] has clearly shown that very-high-speed, stretching aluminum jets do erode in air in agreement with [1] versus not eroding in vacuum.[10]

During presentation of [1] and in the paper's subsequent epilogue, seven independent proofs were provided showing that a jet does erode while cratering air:

- Differences noted in photography of a jet tip travelling in air versus vacuum,
- Similar differences observed in low-voltage flash radiography,
- Measurements of jet tip velocity at different distances showing significant velocity loss when penetrating air,
- Smaller metal-target crater volumes at 20 charge diameter standoff in air versus the same standoff in vacuum,
- Air crater diameter observations similar to those for exploding wires,
- Airblast measurements, and
- Visual and photographic observation of jet debris combustion along the trajectory in air.

Aerodynamic drag measurements in wind/shock tunnels have also shown that drag is orders of magnitude too small to cause the above observations.[1]

This paper improves upon and compares [1]'s cratering model – a model that was suggested by experimental data but not validated – to a more general cratering model originally developed and validated for cratering of compressible and incompressible liquids and solids. [11]

## BACKGROUND, ANALYSIS, AND DISCUSSION

### The Cratering Model in [1] from [12]

Previously [1] and [12] explained the importance of modeling jet tip erosion to understanding experiment-based observations and the representation of shaped charge jets by computational modeling. The following equation was adapted in [12] to describe the penetration rate (U) of a jet having velocity (V) through air from earlier classical aerodynamic modeling.[12,13]

$$U = V / [1 + \sqrt{\{\rho_1/\rho_{jet}\}(\{1+\lambda_1\}/\{1+\lambda_{jet}\})}\ ] \tag{1}$$

Where U and V have comparable units (such as km/s), $\rho_1$ and $\rho_{jet}$ are the density of free-stream air and the jet, respectively in comparable units (such as g/cm$^3$), and $\lambda_1$ and ($\lambda_{jet}$ = 0, incompressible) are the compressibility of air and the jet, respectively:

$$\lambda_1 = 1 - (\rho_1 / \rho_2) \tag{2}$$

With the increased density ($\rho_2$) after the shock front provided by:

$$\rho_2 = \rho_1 [(\gamma + 1)\ M_1^2] / [(\gamma - 1)\ M_1^2 + 2] \tag{3}$$

Where the free-stream Mach number ($M_1 = V / Co$) uses the speed of sound Co = 0.335 km/s for air; and the effective adiabatic exponent γ is approximated by 1.25 (ratio of specific heats) to account for dissociation behind a strong shock wave as a result of the high air temperature. [14]

The effectiveness of these equations for describing jet erosion and air penetration was clearly validated by experiments in [7] and [8].

Reference [1] also used eqs. (1), (2), and (3) to provide a means to calculate an approximate crater radius in air by setting the jet-deposited kinetic energy equal to an equivalent detonation rate explosive's energy in an equation taken from the study of the effect of detonating cords on air.

$$R_{crater} = 2.05\ R_{jet} \sqrt{\rho_{jet} / X_{er}\ \rho_{air}} \tag{4}$$

Where $X_{er}$ is the distance within which 1-mm of jet is consumed and can be found from the penetration distance (P = (U/(V – U)) L; L = 1-mm) travelled during the time this jet piece erodes. When eq. (4) was created, the detonation cord impulse approximations caused the detonation rate to be cancelled from both the numerator and denominator. This approximation similarly caused V and U to be cancelled; but eq. (4) actually should include the ratio (V/U) as a multiplier.

The classical analyses in [13] contain equations describing a crater's radius during steady-state flow. However, these equations represent an energy balance derived from a local centreline flow pressure balance – an analysis that does not consider a total event energy balance. When the ratio (P/L) is included within [13]'s equations in order to account for a finite energy deposition event, such as a particle depositing its energy over a path length, then the following formula is produced – a formula nearly the same as eq. (4) when eq. (4) is modified to include (V/U):

$$R_{crater} = 2.5738\ R_{jet}\ (V/U) \sqrt{\rho_{jet}/\rho_{air}}\ \sqrt{L/P} \tag{5}$$

## The Cratering Model in [11]

The model in [11] was separately developed for the BRIGS software suite in order to define supersonic penetration of compressible and incompressible targets having hardness by compressible and incompressible jets also having hardness. The emphasis in [11], however, was on liquid and solid materials; and the model used a procedure that was different from that in [12] and [13]. In [11]'s model, the flows create and are driven by a "Kernel" – a "rigid" body that consists of stagnated-jet and stagnated-target materials. In [11], equations were assembled describing the effects on density and particle velocity of shocks in the jet and the target as well as motion of the shock and penetration front in the target. MathCad$^{tm}$ software was used to iterate the equations toward a solution where the target shock and penetration velocities were equal (steady-state) in a laboratory coordinate system. Conventional linear (Us = a + b Up) equations-of-state (EoS) represented the materials being studied where Us (shock velocity), Up (particle velocity) and "a" use comparable units, such as km/s.

Two EoS describing air's behaviour are available for use in [11]'s MathCad$^{tm}$ model.[15,16] Both EoS are comparable; but the EoS in [15] using $\rho_{air} = 0.0012$ g/cm$^3$, a = 0.230 km/s, and b = 1.09 probably represents conditions at a specific research location. The EoS in [16] is more general with these parameters being 0.00126, 0.2406, and 1.0602 for dry air at standard conditions. The EoS in [16] was chosen for comparisons between the two different models because it is also provided in a form for $\gamma$ suitable for use in eq. (3) as a function of particle (piston) velocity and the sound speed for the initial state of the air being compressed. (Substitution, however, had little effect on calculations using [12]'s model even though for $5 < V_{jet} < 20$ km/s , $1.213 > \gamma > 1.144$ instead of the former $\gamma = 1.25$ approximation.)

After performing MathCad$^{tm}$ studies representing different jet materials penetrating air, [11]'s formulas were simplified to the following:

$$\rho_2 = \rho_{air}\,[b / (b - 1 + \{a / V\})] \tag{6}$$

$$U_{flow} = V\,(\rho_{air} / \rho_2) \tag{7}$$

$$U_{pen} = (V - U_{flow}) / [1 + \sqrt{(\rho_{air} / \rho_{jet})(\rho_2 / \rho_{air})}\,] \tag{8}$$

$$U_{lab} = U_{pen} + U_{flow} \tag{9}$$

Where a "seed" value – a value 96% of the incompressible-air hydrodynamic penetration rate ($U_{hydro}$) – is substituted for V in eqs. (6) & (7) in order to provide a solution where the air penetration rate in the laboratory coordinate system ($U_{lab}$) was approximately equal to the shock wave velocity ($U_S$) in the free-stream air.

Three different crater radius formulas are available in [11] from which only the following has been selected because one of the others produces almost the same numerical results while the other is invalid for penetrations much greater than the penetrator's length:

$$R_{crater} = R_{jet}\sqrt{[51.02\,\rho_{jet}(V - U_{flow})^2 L/(P\,H_{air})] - [(H_{jet}/H_{air})(\{L/P\}+1)]} \quad (10)$$

Where $H_{jet}$ and $H_{air}$ represent the energy required to form an "indented" cavity into jet material and air in terms of Brinell hardness (BHN); and "steady-state" penetration occurs into compressed air that is moving forward behind the leading shock wave. Unfortunately, the values of $H_{jet}$ and $H_{air}$ are currently unknown due to their not having been measured under the prevailing conditions of jet penetration into air.

## Penetration Rate Comparisons

Table 1 contains a comparison between experiment data for aluminum jets from similar set-ups producing jets travelling in vacuum or air and information calculated using this paper's models. Very little change in calculated penetration rate is affected by using the $\gamma$ EoS instead of the $\gamma = 1.25$ approximation as can be seen in columns 4 and 5. As mentioned in [8], [12]'s model closely approximates the experiment data, although the calculations appear slightly high for V > 11 km/s. The new formulas extracted from [11]'s model provide results slightly lower than the experiment data. Although the experiments needed to validate the models are not easy to perform and contain experimental error, it is clear that air causes jet tip erosion which appears to be bounded by the two different models.

Table 1. Experiment Data and Model Calculations for Aluminum Jets Penetrating Air

| Experiment (km/s) | | Calculated Penetration Rates (km/s) | | | |
|---|---|---|---|---|---|
| $V_{vacuum}$ | $U_{air}$ | $U_{hydro}$ | $U_{[12],\,\gamma=1.25}$ | $U_{[12],\,\gamma\ EoS}$ | $U_{lab}$ |
| 8.3 | 8.0 | 8.12 | 8.06 | 8.02 | 7.78 |
| 9.2 | 8.8 | 9.00 | 8.94 | 8.89 | 8.61 |
| 10.3 | 9.9 | 10.08 | 10.00 | 9.96 | 9.63 |
| 11.4 | 10.9 | 11.16 | 11.07 | 11.03 | 10.64 |
| 12.2 | 11.6 | 11.94 | 11.85 | 11.81 | 11.38 |
| 12.7 | 12.0 | 12.43 | 12.33 | 12.29 | 11.84 |
| 19.6 | 18.4 | 19.19 | 19.03 | 19.03 | 18.21 |

Table 2 shows calculations for another means by which jet erosion can be quantified – the distance within which 1-mm of jet length may be consumed. This method produces large differences in calculated results showing that air as incompressible permits an eroding jet tip to travel 37% farther than predicted for compressible air using [12]'s model for 5 < V < 20 km/s. The model described by eqs.

(6) to (9) describes travel distances less that half those of [12]'s model, which is an effect caused by the calculated differences between the penetration rates even though these differences are small numerically. Unfortunately, the few experiments that might quantify such erosion yielded measurements for copper jet penetration into air ranging from 58 to 150-mm – a range too large for validating or improving either model. [1]

Table 2. Calculated Air Penetration Distances for 1-mm of Jet Erosion

| P (mm) | P for $U_{hydro}$ | P for $U_{[12], \gamma = 1.25}$ | P for $U_{[12], \gamma\ EoS}$ | P for $U_{lab}$ |
|---|---|---|---|---|
| Aluminum Jet | ~ 46.3 | ~ 33.7 | ~ 33.5 | 13.1 to 16.76 |
| Copper Jet | ~ 84.2 | ~ 61.3 | ~ 60.7 | 23.7 to 30.7 |

Both models describe jet erosion proceeding on the order of a very fine grain-size-scale layer (16 microns per millimeter of copper jet travel and 29 microns for aluminum jet travel) at velocities above 5 km/s. This erosion appears to require only a thin layer of the jet tip or a jet particle to be "strengthless" – an assumed requirement in both models and probably sufficiently caused by ultraviolet and infrared radiation from the bow shock wherein the aerothermochemistry affected radiation is a function of velocity.[17] (Such energy transport was measured during early 1990s rocket tests with the ultraviolet radiation being 15 times greater than available theoretical modeling [18]). As erosion is on the order of a liner-to-jet particle grain size, the even finer hot flow-turned debris will be capable of immediate combustion at the air crater interface consistent with photographic records.[1]

## Crater Size Comparisons

Table 3 contains calculations for copper and aluminium jet particles of 1-mm radius and 1-mm length arranged so that the results might be used to compare crater diameters to jet diameters measured in experiment records. The results produced by eqs. (4) and (5) in Table 3 are vastly different from those of eq. (10) for which two very-soft hardnesses were used to represent a "strengthless" jet penetrating three different representations of the energy required to displace a volume of air. When [1] was prepared, data from experiments using BRL 81-mm and M72 LAW shaped charges suggested that the ratio for a jet tip travelling at about 8 km/s might be on the order of 22. This was also suggested by photography reproduced in [1]. However, subsequent measurements from published photography such as that in [18-22] have ranged from 6.3 to 22 for comparable jet velocities. In light of the lack of well organized experimental data – data that should be produced using simultaneous synchro-streak photography with "soft" low-voltage radiography of the same jet passing at least two locations – it is impossible to judge among or to quantitatively validate the models. Thus, as stated in [22], "At the moment no theory exists which calculates the cavity expansions for jets in air and for their collapse processes, which would explain the visible shock waves or the reaction lights of the eroded copper materials with air”.

Table 3. Crater Radius Ratios Calculated for 1-mm Radius Jet Particles of 1-mm Length

| Jet Material | V (km/s) | Eq. (4) | Eq. (5) | Eq. (10) Hjet = 1.0 BHN | | Eq. (10) Hjet = 0.33 BHN | |
|---|---|---|---|---|---|---|---|
| | | | | Hair, 0.05 | Hair, 0.1 | Hair, 0.1 | Hair, 0.2 |
| Copper | 5 | 22.44 | 28.18 | 11.26 | 7.97 | 8.55 | 6.06 |
| | 10 | 22.51 | 28.26 | 22.34 | 15.80 | 16.08 | 11.38 |
| | 15 | 22.53 | 28.29 | 33.17 | 23.45 | 23.64 | 16.72 |
| Aluminum | 5 | 16.86 | 21.17 | 9.60 | 6.80 | 7.46 | 5.29 |
| | 10 | 16.91 | 21.23 | 20.50 | 14.50 | 14.81 | 10.48 |
| | 15 | 16.93 | 21.26 | 31.14 | 22.02 | 22.23 | 15.72 |

## SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Air cratering by a shaped charge jet can now be calculated using two different but comparable penetration rate and crater radius models that appear to qualitatively provide upper and lower bounds to experimental data. The first of these is based on classical aerodynamic analytical modeling and has been improved since previous publication by using a validated equation-of-state for air instead of the original approximation of $\gamma = 1.25$. The second has been simplified from a general model for the penetration of compressible and incompressible jets having hardness into compressible and incompressible liquid and solid targets also having hardness.

Neither model provides a validated, quantified estimate of the crater produced in air although they can still be used qualitatively to estimate a crater as well as the time and distance at which a crater may collapse back onto later jet portions to disturb the jet and/or its particles.[1] Thus, the models are still useful for guiding future experiments during which the data needed for model validation can be acquired. (As suggested in [1], air blast measurements can also be useful for quantifying jet erosion and crater formation.)

Further modeling work is needed. The depth of softness in a jet’s tip or a jet-particle’s forward facing surface still needs to be defined. Such modeling needs to quantify bow shock radiation generation and transport as a function of jet tip or jet particle velocity, gas density, and gas composition as well as heat flow within and softening of the jet material. The effective “hardness” of air – the energy required to dynamically open a temporary cavity in air similar to the residual indentation made during hardness testing of solid materials – remains to be quantified.

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