23RD INTERNATIONAL SYMPOSIUM ON BALLISTICS
TARRAGONA, SPAIN 16-20 APRIL 2007

SCALING OF THE SHAPED CHARGE JET BREAK-UP TIME: A LINER THICKNESS EFFECT OBSERVED AND EXPLAINED

Eitan Hirsch[1] and Joseph E. Backofen[2]

[1]*retired from IDF, IMI, and RAFAEL, Tachkemony St.6, Netanya, 42611 Israel*
[2]*BRIGS Co., 2668 Petersborough St., Oak Hill, VA 20171, USA*

Experimental data and use of Vpl-based break-up models in three different shaped charge jet formation analytical computer codes reveal that Vpl – a measure relating a local variation in jet kinetic energy to local material strength during jet elongation – has an inverse dependence on liner thickness. This dependence appears to be affected by initial coupling of the explosive's detonation into the liner wherein the coupled energy changes the liner material structure and properties.

INTRODUCTION

Break-up of a shaped charge jet into a stream of particles is the major factor affecting target penetration as the particles subsequently become misaligned from a single line-of-action trajectory. Because this is such an important issue, many scientists have studied jet particularization to propose both theoretical and engineering models. In essence, however, all the models can be reformulated to one form suggested early-on by Trinks that break-up is a function of a local variation in jet-material kinetic energy versus its local material strength. (The terminology and constants used in the many formulas depend upon whether the scientists are using static, dynamic, localized, or general parameters that can be quantified by measurement.) Many scientists have also proposed interpretations for the parameters used in their break-up models. [1-3]

Equations (1) & (2) published in 1979 for straight-wall liners of constant thickness have well described jet break-up as well as particle formation and trajectory.

$$T_{breakup} = d_{initial} / Vpl \tag{1}$$

$$Vpl = \sqrt{\sigma / \rho} \tag{2}$$

Where $T_{breakup}$ is the break-up time in μsec beginning when the detonation wave reached the liner portion forming the jet segment whose initial diameter is $d_{initial}$ in mm and Vpl – the "plastic velocity" is the average velocity between adjacent particles in km/s.[4] In eq. (2), σ and ρ respectively represent the liner dynamic yield strength and density using consistent units.[4] In 1992, the authors extended application of eqs. (1) & (2) so that a single Vpl value – an average for an entire charge – could also describe break-up locally for charges having a wide range of local strain rate gradients.[5] In [5], Vpl were provided in a table for many different types of shaped charges showing that Vpl was affected by liner material, explosive, and manufacture processing.

This paper uses published experimental data and Vpl-based break-up models in three very different analytical computer codes – ISL-1D, SCAN, and BRIGS – to show that Vpl has an inverse dependence upon liner thickness when charge shape, explosive composition and quality of manufacture are held constant.[5-7] (ISL-1D, SCAN, and BRIGS each use a different modified-Gurney method for describing liner implosion; and, respectively, they use modified-PER, improved-PER, and non-PER jetting formulas.) The BRIGS detonation-driven-propulsion formulas describing initial liner motion appear to provide new additional insight into the importance of explosive-to-liner coupling to this Vpl dependence and jet break-up.[8,9]

ANALYSIS AND DISCUSSION

Comparisons Between Experimental Data And Calculations

Reference [6] provides experimental jet break-up data for shaped charges having five different liner thicknesses while charge manufacture, materials, and quality were held constant. Calculations also were performed for [6] using the ISL-1D analytical code and its Carleone jet break-up model – a model using Vpl written as Cp and much like the BRIGS variable-Vpl model as explained in [5]. The ISL-1D calculations showed that the five different liner thickness charges required five different ΔV = 0.6807 Cp values in order to match the experimental jet break-up behaviour.

For [7,10], calculations were performed using [6]'s Vpl values in the SCAN code. These calculations also matched the experimental jet break-up data as shown in Figure 1 implying the following relationship existed between jet break-up time, Vpl, and the liner thickness-to-explosive charge diameter thickness ratio (T_{Liner}/CD) with T_{Liner} and CD using comparable units.

$$1/\mathrm{Vpl} = 13.886 - 101.149\,(T_{Liner} / CD) \qquad (3)$$

Where 1/Vpl is the specific break-up time for a liner producing a unit jet diameter; and the ratio (T_{Liner}/CD) was chosen for the formula since it is well known that use of the same materials, same geometry, and same quality of manufacture in scaled charges produces comparable jets whose performance scales with CD. [11]

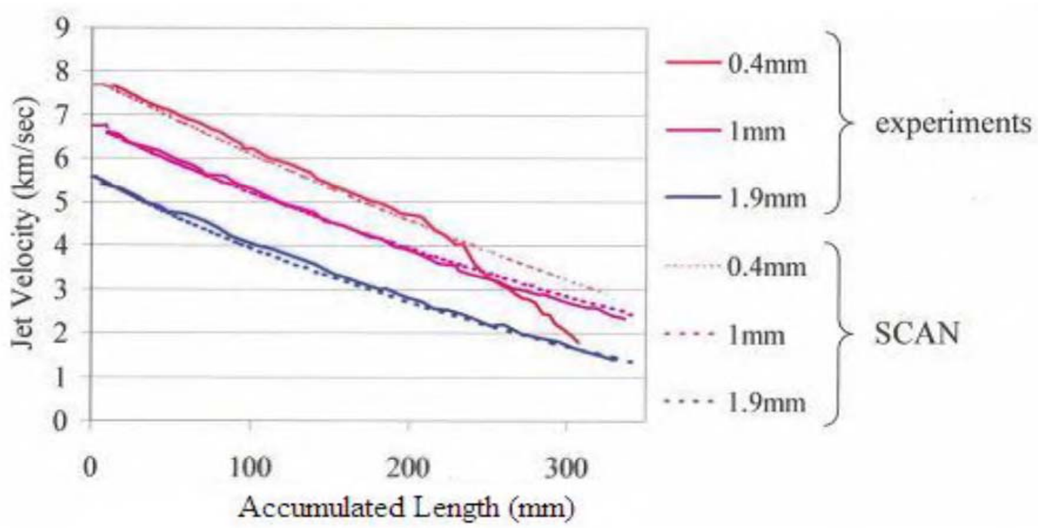

Figure 1. Comparison of SCAN code calculations to [6]'s data using the same Vpl values

BRIGS had matched the performance of [6]'s 1.00-mm liner thickness charge as early as 1987 using the 1979 Vpl model [12] and also the variable-Vpl model as described in [5]. However, the liners in the earlier charges were made by drawing copper sheet rather than by machining from bar stock as in [6].

Table 1. Comparison of [6]'s Experimental and Calculated Data for Five 45-mm Diameter Shaped Charges to BRIGS Calculations for These Charges [13]

T_{liner}	0.4	0.6	1.0	1.0	1.0	1.9	3.0
Vpl	0.077	0.080	0.085	0.090	0.095	0.105	0.140
V_{jet}	7.74	7.42	6.83	6.83	6.83	5.57	4.43
V_{air}	7.61	7.20	6.63	6.63	6.63	5.35	4.28
V_{exp}	7.7	7.2	6.6	6.6	6.6	5.4	4.2
# exp	53	61	40	40	40	34	26
# calc	68	70	67	63	55	48	30
L_{exp}	308	400	338	338	338	358	246
L_{ISL-1D}	280	334	--	338	--	392	208
L_{BRIGS}	309	359	404	385	360	388	295
$V_{tail\ exp}$	1.76	1.00	2.31	2.31	2.31	1.18	1.03
$V_{tail\ Brigs}$	2.58	2.15	1.64	1.64	1.64	1.06	0.74

The BRIGS calculations revealed that explosive initiation and charge geometry produced local strain rate gradients affecting jet break-up appearing in [6]'s experimental data.[13] These appeared to affect the size and separation of some particles for which [6] had noted that particle definition was a difficult process. Although both Vpl and calculation grid size were varied parametrically for [13], Table 1 only presents those calculations using the same calculation grid for all five charges as well as with three Vpl values for the 1.00-mm liner.

In Table 1, the jet tip velocities penetrating air (Vair) compare favorably to those in the radiography. However, none of the particle counts or summed jet lengths compare completely favorably between the experiments, the ISL-1D calculations, and the BRIGS calculations. Nevertheless, jet velocity versus accumulated length essentially overlays the data with variation of Vpl with liner thickness approximated by:

$$Vpl = 0.06796 + 0.021346\, T_{Liner} \tag{4}$$

There are many different reasons for the differences between the BRIGS calculations and [6]'s experimental data, some of which appear to be due to experimental measurement and others due to calculation methods. For example, particle counts can differ due to the way particles are read from flash radiographs such as counting two still joined / still stretching particles as one particle. This appears to have occurred for all five charges near regions in which the jet has a small localized compressive gradient. The summed jet length can also differ by how the lengths of the particles have been measured. For example, particles may have been measured from the faintest shadow of pointed tips of stretched particles to similarly pointed tails; or, conversely, the final total length can be understated when the jet particles have not yet been fully stretched and separated into individual particles. This latter may be the case for the charge with the 3.0-mm liner since it has a break-up time much later than the other charges.

Table 2. Comparison of Vpl Values For Three Different Analytical Computer Codes Producing Comparable Descriptions For Jets From Five Different Liner Thickness Shaped Charges

Liner Thickness (mm)	ISL-1D [6] ΔV	SCAN [7,10] Vpl	BRIGS [13] Vpl
0.4	0.077	0.0770	0.0765
0.6	0.080	0.0798	0.0808
1.0	0.085	0.0859	0.0893
1.9	0.105	0.1040	0.1085
3.0	0.140	0.1400	0.1320

Table 2 shows that eqs. (3) & (4) generate Vpl capable of producing jet descriptions comparable between [6]'s experiments and ISL-1D modeling, SCAN modeling and BRIGS modeling. These findings imply that for a specific explosive (Comp B in [6]'s experiments) and specific liner processing, there is a lower limit to Vpl and to a usable liner thickness. ([6] also notes that the jet became incoherent at a liner thickness of 0.25 mm.) However, only the inverse formulation in eq. (3) appears to open-the-door to an important scientific relationship.

Effect of Explosive-to-Liner Coupling

The BRIGS analytical package describes explosive charge performance using a two-step detonation propulsion model with: 1) initial motion imparted by a brisant shock-dominated process that depends upon intimate contact of an explosive with the propelled material, and 2) subsequent acceleration by a gas-push (gas-dynamic) process. Initial motion is envisioned as being caused by the higher-pressure region of a detonation front (i.e. envision the von Neumann spike or reaction zone region as being a finite thickness of solid material squeezed at high pressure). The gas-push process is envisioned similar to that assumed by Gurney modeling, wherein the gas volume expands from a "static" homogeneous "all-burned" high-pressure state into one wherein the velocities of the gases at the boundaries match those of inert boundary materials.

Previous work has shown that the initial velocity imparted to a cylinder or plate by the brisant 1st propulsion stage is a function of six quantities:

$$Vi = F(\rho_{ex}, \rho_{cyl}, R_{ex}, T_{cyl}, D, \Gamma) \quad (5)$$

Where:

V_i is the initial free-surface velocity (mm/μsec),
ρ_{ex} is the density of the explosive (g/cm^3),
ρ_{cyl} (or ρ_{plate} or ρ_{liner}) is the cylinder (or plate or liner) material density (g/cm^3),
R_{ex} (or t_{ex}) is the radius (or thickness) of explosive (mm),
T_{cyl} (or T_{plate} or T_{liner}) is the cylinder wall (or plate or liner) thickness (mm),
D is the detonation velocity (mm/μsec), and
Γ is the non-dimensional adiabatic coefficient for gas expansion.[8,9]

As described in [9], initial motion can be represented from eq. (5) in the form of an Energy Transference Ratio (ETRi) for grazing (side-on) propulsion, which also has been found to be approximately half the ETRi for normal (head-on) impact of a detonation front with a plate described in [8].

$$ETRi = (Vi / D)\,(\rho_{liner} / \rho_{ex})^{1/2} = 0.2085[3.75/(\Gamma + 1)](T_{liner}/C_{ex})^{-3/40} \quad (6)$$

Where: $C_{ex} = [(CD/2) - (T_{liner} + R_{inner})]$ with R_{inner} as the radius to the liner's inner surface; and 0.2085 [3.75 / (Γ+1)] can be replaced by A = 0.2085 when Γ = 2.75 or A = 0.211 for Comp B explosive for which Γ = 2.706.

Equation (6) also describes how energy is lost as the initial shock is driven through the liner because $ETRi^2$ is proportional to $(T_{Liner} / C_{ex})^{-6/40}$. The following are some of the processes that can affect such energy loss:

- Liner material phase transition such as well known to occur in iron [15],
- Compression and subsequent release fracture of liner material grains into smaller grains as well known to occur in copper at shock pressures comparable to those occurring during the 1st propulsion stage [16], and
- Liner heating induced as grains shear internally as well as past one another due to irregularities in the shock-wave structure.

Liner material grain size is well documented as affecting jet break-up. (See [3], [17], and [17]'s citations.) The effect of increased temperature on shaped charge jet elongation has also been demonstrated. (See [18] and [19].)

Equation (6) can be rewritten as:

$$Vi = A\,D\,(\rho_{ex} / \rho_{liner})^{1/2}\,(T_{liner} / C_{ex})^{-3/40} \quad (7)$$

Taking the derivative with respect to the liner thickness while holding the other parameters to include C_{ex} constant yields:

$$dVi / d(T_{liner}) = A\,D\,(\rho_{ex} / \rho_{liner})^{1/2}\,C_{ex}^{3/40}\,(-3/40)\,T_{liner}^{-43/40} \quad (8)$$

With [(43/40) ≅ 1], eq. (8) appears to indicate that a "fixed" amount of energy is imparted by an explosive's initial high-pressure propulsion stage. Examination of [8]'s data reveals that as the "Case 2" region (the region typical of explosive propulsion designs) approaches the "Case 3" region (representative of some very thin plates driven by long explosive charges), then (43/40) may approach (41/40) – a closer approximation to 1. This appears to imply that only a limited amount of explosive drives the 1st propulsion stage and that an explosive may have a limited "fixed" impulsive relationship affecting both initial liner motion and the shock-processed material properties that later affect jet break-up. And, according to eqs, (6) & (8), the effect of the explosive's "fixed" energy input decreases as liner thickness increases.

Since (43/40) is approximately 1, eq. (8) can be rewritten to imply that break-up time may be decreased using thicker liners and increased using thinner liners having the same metallurgical processing in accordance with:

$$1 / (dVi / d(T_{liner})) = \quad - B\, T_{liner} \tag{9}$$

Where B is analogous to (101.149 / CD) in eq.(3) and depends on the values of ρ_{liner}, ρ_{ex}, D, Γ, and C_{ex}. Equation (9) thus suggests a scientific finding for jet break-up being correlated with the change in the initial free-surface velocity as a function of liner thickness for at least [6]'s experiments. Since Vi is approximately twice the particle velocity imparted to the liner material by the first shock wave reaching the liner surface, this appears to link the relationships for Vi, particle velocity, and Vpl. This implies that explosive-to-liner coupling affects Vpl in a manner directly related to the particle velocity driven by the first shock passing through the liner for which one clear process probably involves change in grain structure. (See [16].)

Equations (3), (8) and (9) provide parameters expanding knowledge of how an explosive's detonation may affect σ in eq. (2) in agreement with previous understanding in [5] of the factors affecting Vpl. For example, the relationship $[D\, (\rho_{ex} / \rho_{liner})^{1/2}]$ can describe the effect of explosive "quality" – smaller Vpl (or longer breakup times) are provided by higher density, faster detonation rate explosives. In eq. (3), the term associated with liner thickness subtracts from a "constant" – a "constant" probably related to liner and explosive charge manufacturing "art" (or technology).

SUMMARY AND RECOMMENDATIONS

This paper has explored how jet break-up is affected by choices in shaped charge geometry, materials, and manufacturing in order to further understanding of the factors underlying jet break-up. To do so, it has used experimental work performed using five different thickness liners in consistent charge geometry and manufacture as described by three different computational models.

The dependence of the specific break-up time (1/Vpl) on liner thickness implies a strong influence of the explosion on the material close to the liner's free-surface from which a jet is formed. Experimental data on initial free-surface motion produced by explosive-to-liner coupling appears to be analogous indicating the effect of liner thickness as being affected by the magnitude of the initial shock on the liner material's metallurgical state. These findings suggest that experimental study of jet formation, jet break-up, and liner material response to explosive-driven shock loading need to be simultaneously combined because the data they provide are mutually completing.

REFERENCES

[1] W.P. Walters and J.A. Zukas, *Fundamentals of Shaped Charges*, Chapter 8, John Wiley & Sons, New York, 1989
[2] W.P. Walters and R.L. Summers, "The Velocity Difference Between Particulated Shaped Charge Jet Particles for Face-Centered-Cubic Materials", ARL-TR-8, US Army Research Laboratory, Nov. 1992
[3] M. Held, "Particulation of Shaped Charge Jets", *Proc.* 11th *Int. Symp. Ballistics*, Brussels, May 1989, Vol.II, pp. 1-10
[4] E. Hirsch, "A Formula for the Shaped Charge Jet Break-Up Time", *Propellants and Explosives*, Vol.4, 1979, pp. 89-94
[5] J.E. Backofen and E. Hirsch, "The Variable Vpl Model – A Strain Rate Sensitive Engineering Application of the Vpl Model", *Proc*. 13th *Int. Symp. Ballistics*, Stockholm, 1992, Vol.2, pp. 359-366
[6] P.Y. Chanteret and A. Lichtenberger, "About Varying Shaped Charge Liner Thickness", *Proc*. 17th *Int. Symp. Ballistics*, Midrand, South Africa, March 1998, Vol. 2, pp. 2-365 to 2-372
[7] E. Hirsch and D. Mordehai, "Shaped Charge Jet Break-Up Time Formula Confirmed", *Proc.* 19th *Int. Symp. Ballistics*, Interlaken, May 2001, Vol.II, pp. 811-818
[8] J.E. Backofen and C.A. Weickert, "The Effects of Plate Thickness and Explosive Properties on Projection from the End of a Charge", *Proc.* 16th *Int. Symp. Ballistics*, San Francisco, Sept. 1996, Vol.2, pp. 641-650
[9] J.E. Backofen and C.A. Weickert, "Initial Free-Surface Velocities Imparted by Grazing Detonation Waves", in *Shock Compression of Condensed Matter* – 1999, eds. M.D. Furnish, L.C. Chhabildas, R.S. Hixon, American Institute of Physics, 2000, Part 2, pp. 919-922
[10] E. Hirsch, "Scaling of the Shaped Charge Jet Break-Up Time", *Propellant, Explosives, Pyrotechnics*, Vol. 31, No. 3, 2006, pp. 230-233
[11] W.E. Baker, P.S. Westine, F.T. Dodge, "*Similarity Methods in Engineering Dynamics*", Southwest Research Institute, San Antonio, Texas, 1981, pp.194-199
[12] Private communications between P.Y. Chanteret and BRIGS Co., 1987
[13] J.E. Backofen, "Comparison of "Old BRIGS" Computer Code Calculations to Experimental Data and Calculations in the Scientific Paper "About Varying Shaped Charge Liner Thickness"", BRIGS Note 00-4, BRIGS Co., Oak Hill, VA, 1 Dec. 2000
[14] J.E. Backofen, "The Effect of a Detonation's 1st Propulsion Stage on Shaped Charge Jet Break-Up Time and the Hirsch Parameter, Vpl", BRIGS Note 05-3, BRIGS Co., Oak Hill, VA, 19 Aug. 2005
[15] J.E. Backofen, "The Influence of Geometry and Material Properties on an Explosive's Gurney Velocity and Energy", *Proc. New Trends in Research of Energetic Materials*, Univ. of Pardubice, The Czech Republic, April 2006, Part I, pp. 76-89
[16] E. Hirsch and J. Plesek, "A theoretical analysis of experimental results of shock wave loading of OFE copper relating the observed internal structure to the deformation mechanism", *Int. J. Impact Engng*. 32 (2006), pp. 1339-1356
[17] G. Andersson, B. Janzon, S. Karlsson, A. Watterstam, "A Study of Grain Size Effects on the Performance of Cold Pressed Shaped Charge Liners", *Proc.* 15th *Int. Symp. Ballistics*, Jerusalem, May 1995, Vol. 2, pp 259-266
[18] G.E. Markelov, "Effect of Initial Heating of the Jet-Forming Layer of Shaped-Charge Liners on the Ultimate Elongation of Jet Elements", *J. Appl. Mech. Tech. Phys*., Vol.41, No.2, 2000, pp. 231-234
[19] G.E. Markelov, "Effect of Initial Heating of Shaped Charge Liners on Shaped Charge Penetration", *J. Appl. Mech. Tech. Phys*., Vol.41, No.5, 2000, pp. 788-791