PROBLEMY MECHATRONIKI
UZBROJENIE, LOTNICTWO, INŻYNIERIA BEZPIECZEŃSTWA

ISSN 2081-5891 **8, 1 (27), 2017, 23-38**

PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

Development and Evaluation of Small Shaped Charge Jet Threats

Arthur DANIELS*, Stan DEFISHER, Greg STUNZENAS, Nausheen AL-SHEHAB and Ernest L. BAKER

U.S. Army Armament Research, Development and Engineering Center, Picatinny Arsenal, NJ 07806-5000, USA
**Corresponding author's e-mail address:arthur.s.daniels.civ@mail.mil*

Received by the editorial staff on 24 July 2015.
The reviewed and verified version was received on 13 April 2016.

DOI 10.5604/01.3001.0009.8992

Abstract. Because of their prolific nature on the battlefield, rocket propelled and gun-launched grenades are of particular concern to the soldier, particularly because of the severe reaction that occurs when a munition is hit by the shaped charge jet. As a result of the danger that such a detonation poses, it is necessary to more precisely understand the behaviour of munitions subjected to these types of devices. In response to these threats, standardized 81 mm and 40 mm shaped charge warheads were developed for use during threat assessment testing to act as a consistent, lower-cost representative of shaped charge projectiles commonly encountered on the battlefield, and to help quantify the interaction of these jest with explosive charges. The international standards for shaped charge jet threat testing uses the Held initiation criteria V^2D, where V is the jet velocity and D is the diameter. V^2D was computationally predicted using the high-rate continuum models CALE and ALE-3D. The surrogate warheads were test fired through aluminium target plates to strip off jet mass to adjust the V^2D to the threat munition.
Keywords: mechanics, shaped charge jet, surrogate warhead, Held's Criteria, V^2D

This work has been compiled from the paper presented during the 11th International Armament Conference on Scientific Aspects of Armament and Safety Technology, Ryn, Poland, 19 to 22 September 2016

1. INTRODUCTION

The shaped charge jet (SCJ) is one of the more menacing threats on the modern battlefield, and virtually all munitions detonate violently when hit by one. As a result of the danger that such a detonation poses, it is necessary to more precisely understand the behavior of munitions subjected to these types of devices. In response to these threats, standardized 81 mm and 40 mm shaped charge warheads [1, 2] were developed for use during threat assessment testing to act as a consistent, lower-cost representative of SCJ projectiles commonly encountered on the battlefield, and to help quantify the interaction of SCJ's with explosive charges, in both the cased and uncased configurations. The rocket propelled grenade (RPG) was considered the primary SCJ threat. The 81 mm surrogate warhead was developed and adopted both nationally and internationally as the standard for RPG threat evaluation.

Since most munitions will produce catastrophic effects when hit with an RPG, many munition systems automatically access their SCJ impact test as a fail, and don't bother to develop any mechanisms to mitigation this threat. Identification and adoption of a smaller-than-RPG shaped charge threat was developed to provides systems with a lesser, yet still realist SCJ threat that can be protected against, and therefore provide the system with incremental improvements. A 40 mm surrogate was developed to represent small gun-launched grenades.

Fig. 1. Low velocity grenade launchers and a variety of 40 mm grenades

The international standards for SCJ threat testing [3] uses the Held initiation criteria V^2D [4], where V is the jet velocity and D is the diameter.

Although not without debate [5], this value has been used as a metric for representing various classes of aggression when initiating a munition with a shaped charge warhead. The standards list four levels of threats based on V^2D, from large anti-tank missiles down to small top attack bomblets. The smallest of the threat categories is the top attack bomblet. Many countries have hand-held and platform mounted launchers for similar medium caliber grenades, so the bomblet category is a realistic threat. Figure 1 shows a number of examples of hand-held launchers and grenades.

2. MATERIALS AND METHODS

One measure of explosive sensitivity is gap testing which is a statistical measure of explosive shock sensitivity. In order to determine initiation from a point source, a shaped charge jet is used. [6]. Held's criterion is a correlation between a SCJ velocity and diameter to the detonation of an impacted explosive. Qualitatively similar to critical energy effluence, it shows that impacting an explosive charge with a jet having a V^2D value higher than it's measured value means the explosive will detonate.

Impacting with a lower V^2D means it will not detonate. Although these numbers are listed as single valued constants, care must be taken as a number of variables and factors mean that this number is somewhat variable. While it is known that the explosive critical diameter effects the reaction process in jet initiation [7], due to recent advances in the field of insensitive high explosives and non-ideal explosives with large critical diameters, there is interest in focusing on quantifying the effect of V^2D as a function of explosive critical diameter. Before this could be done, a well characterized, consistent jet had to be developed that would perform reliably so that it could be repeatedly altered to produce consistent values of various V^2Ds.

2.1. Background

Since the surrogates were intended to be more consistent, less expensive, and easier to procure versions of the threat munitions, a rear-initiated warhead design with a high-precision liner was used. An aluminium buffer plate was used to detune the over-performing SCJ to the appropriate V^2D level. This allowed designers to use a variable plate thickness to adjust V^2D and to experimentally validate the predicted responses of explosives subjected to these threats.

Experimental characterization of the jet tip diameter and velocity as a function of buffer penetration would have been prohibitively time consuming and expensive to evaluate. Computational advances made it possible to model these scenarios with a high degree of accuracy before the parts were manufactured.

Although modeling is much quicker, it is not without a financial or a temporal cost. This is particularly true for large three dimensional models that require a fine mesh resolution to accurately solve. To address this, analytical and other 2D based modeling techniques were utilized as a more general screening procedure to quickly get closer to the final V^2D value.

2.2. Warhead Modeling

V^2D for a typical RPG-7 can be determined experimentally by rear initiating the warhead and measuring the tip velocity and jet diameter from x-ray images. However, many 40 mm threat munitions include the use a forward-initiating point-detonating (PD) fuze that fires a spit back flyer plate through a hole in the liner apex. This type of initiation can negatively affect SCJ properties and produce inconsistent performance. PD fuzes also makes it difficult to experimentally measure V^2D because of the difficulties in trying to set off an impact fuze statically. Therefore, $\mathrm{V}^2\mathrm{D}$ was predicted computationally using CALE and ALE-3D to quantify the jet mass for the surrogate munition.

In addition, the jet profile of the 40 mm surrogate was modeled using both Comp-A5 and Comp A-3 explosives at various densities. Comp-A5 is a typical explosive used in the U.S. for high-volume loading of medium caliber warheads where a high-speed rotary press is used to press the shaped charge liners and explosive directly into the warhead bodies. However, Comp-A5 has very little binder material so it doesn’t have sufficient strength to be pressed into a free standing billet for subsequent machining. Since Comp A-5 has a higher binder content, it was used to allow for a precision warhead to be fabricated.

2.3. Modeling of Explosive TMD verses Density

The Theoretical Maximum Density (TMD) for Comp A-5 is 1.757 g/cc. As-pressed densities in production are generally around 90% of TMD. The TMD for Comp-A3 is 1.672 g/cc. As-pressed densities for the surrogate warheads averaged about 1.668 g/cc, or about 99.8% TMD. The jet profiles were modeled in CALE (by V. Gold) and ALE-3D (by G. Stunzenas). The output is displayed in Figure 2. Critical parameters, such as loaded density, were altered to generate an Equation-of-State (EOS) for each explosive. Modifying these parameters varies the degrees of detonation velocity and energy, which dictate metal pushing capabilities and blast output [8]. As-modeled densities for Comp A-3 were 1.665 and 1.64 g/cc, and for Comp A-5 were 1.71, 1.67 and 1.63 g/cc.

Velocities used to calculate V^2D were taken from the velocity verses position curves. Tip velocity did not consistently increase with explosive density as expected, but instead remained fairly consistent, ranging between 5.0 and 5.4 km/sec.

The jet diameters were measured from the scaled model output, however, variability in the diameter due to the measurement location is likely. In addition, non-uniformly shaped jet tips also introduce variations in tip diameters. As a result, jet diameter measurements were taken behind the jet tip. Necked-down regions of the jet were also avoided.

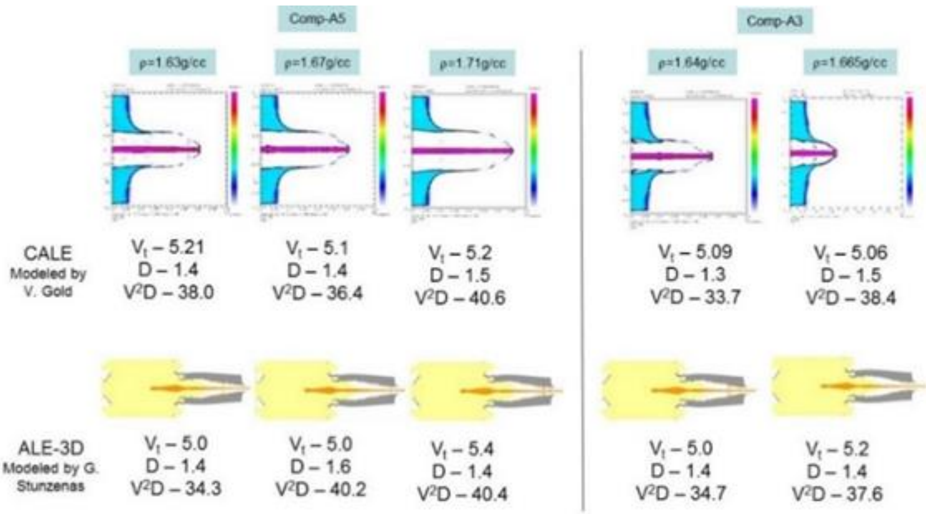


Fig. 2. CALE and ALE-3D models of surrogate warhead with Comp A-3 and A-5 explosives

This produced results that were fairly consistent ranging from 1.4 mm to 1.6 mm in diameter. As with the velocity measurements, there was no clear trend in jet diameter verses increasing explosive density, which also carried through to the calculated V^2D. V^2D's were generally in the 35-40 $mm^3/\mu sec^2$, with those for Comp A-5 being slightly higher than those for Comp A-3.

2.4. 40 mm Surrogate Buffer Plate Analytical Modeling

Prior to the computational power currently available, analytical models were the best tools designers had when attempting to predict SCJ penetration. Although surpassed in accuracy by modern computational tools, these models are not without value as they can sometimes be used to zero in on a design more quickly and efficiently than if continuum codes are used exclusively. The analytical model PENVET, developed by Dr. E. Baker at ARDEC, served as the basis for determining the jet velocities as a function of buffer plate thickness for the 40mm surrogate warhead before hydrocode modeling was used.

The general technique PENVET employs is to determine a virtual origin, a ductility factor, and break up time. After the jet breakup time is calculated, the aluminum buffer plate thicknesses were calculated for explicit values of velocity using Equation 1. In the scenarios of interest, velocity was varied from 3 to 8 km/s at roughly 1 km/s intervals. The following formula from Walters and Zukas and Dr. Baker's course notes [9-10] were used to solve for the penetration of the aluminum buffer that would result in the desired velocities:

$$P = \frac{1}{\gamma} * \left((1+\gamma) * (V_0 + t_b)^{\frac{1}{1+\gamma}} * S^{\frac{\gamma}{1+\gamma}} - V_{min} * t_b \right) - S \qquad (1)$$

Note that P is the penetration depth, γ is the square root of the ratio of target to jet density, V_0 is the jet tip velocity, S is the effective standoff distance, (i.e. the distance from the virtual origin to the target), t_b is the breakup time, and V_{min} is minimum jet velocity capable of penetrating that depth. In this scenario, a minimum tip velocity of 5.12 km/s was used as an average from prior calculations. Subsequent calculations resulted in the output collected in Table I.

This was then used to model the buffer plate scenarios that would result in specific discrete velocities ranging from 3-8 km/s. Both the 3 and 4 km/s velocities were determined to be broken during penetration. These results served as the starting point for continuum modeling.

Table 1. Velocity of 40 mm surrogate as a function of buffer thickness

Calculated Velocity (km/s)	**Buffer Thickness (mm)**
3	222.49
4	142.60
5	80.69
5.10	76.0
6	45.65
7	23.85
8	9.32

2.5. 40 mm and 81 mm Surrogate Buffer Plate Continuum Modeling

All prior results were calculated using Equation 1. Continuum modeling was also done using Lawrence Livermore National Laboratory's (LLNL) ALE-3D hydrocode. The initial model was setup as shown in Figure 3.

This problem was run in ALE mode using 40 nodes per cm. Although this number was increased up to 80 nodes per cm in 10 node per cm increments, there was virtually no change in the results with an appreciable increase in run time so this was taken as evidence of having achieved sufficient mesh resolution for all further calculations.

This mesh density resulted in 3-4 elements across the liner and a total of a little over 516k elements for the entire problem, including the air.

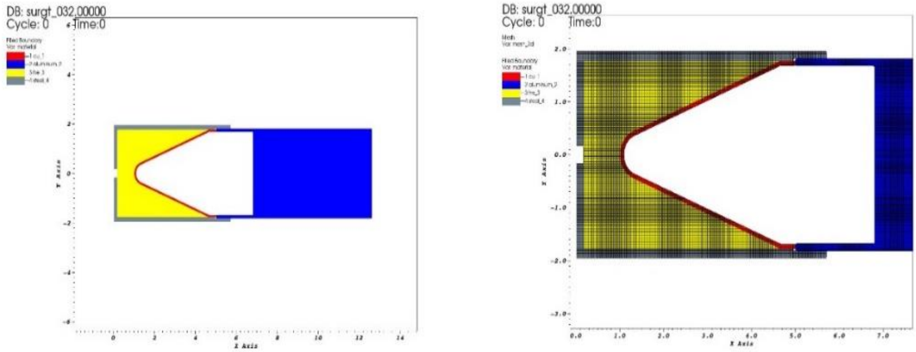


Fig. 3. As built surrogate time 0 and mesh plot

All non-energetics were modeled using the KO/SGEOS material database. Additionally, all copper and aluminum were modeled with a Gruneisen equation of state (EOS) and a Steinberg-Guinan constitutive model.

The Composition A3 HE was modeled using a JWL EOS at a density of 1.644 gm/cm^3 with parameters generated via the thermochemical equilibrium code JAGUAR.

The velocities of the jet tips at penetration were taken at the first point of separation of the back of the aluminum buffer as seen in Figure 4. This approach is subjective and an argument can be made for stating that penetration occurs sooner, but it was believed to be a consistent point from which to reliably select penetration velocities.

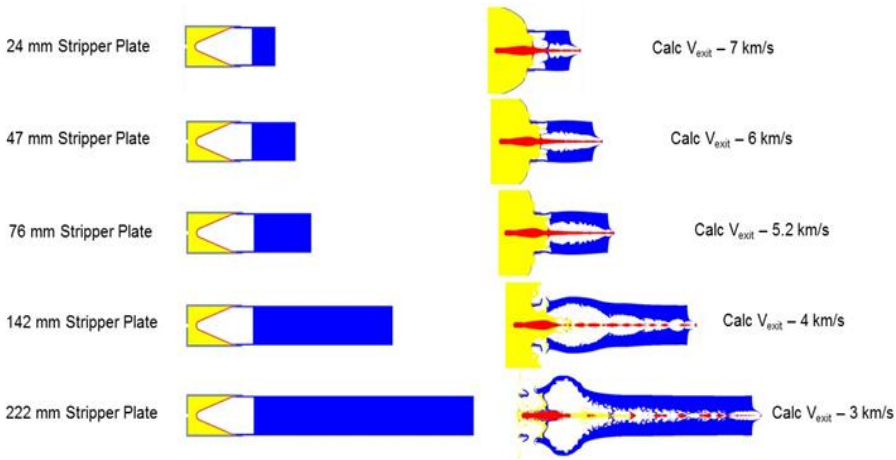


Fig. 4. Time zero and at the instant of penetration

In order to accurately characterize V^2D, it was necessary to measure the diameter at the point of penetration. It should be noted that there is a fair amount of room for debate about exactly which area should be used. As can be seen in close-up of the jet tip in Figure 5, the diameter varies appreciably, and attempts were made at being as consistent as possible. The values of velocity calculated using continuum modeling were generally in agreement with those calculated analytically, at least at the higher velocities. This was, perhaps, fortuitous because there was leeway in the choice of exact times that penetration occurred. The values are presented in Table 2.

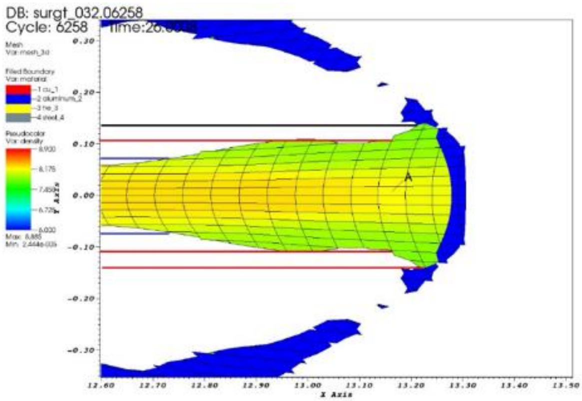


Fig. 5. Penetration mesh and V2D for various buffer plate thicknesses

Tip diameters are also presented along with corresponding V^2D values for jets modeled in ALE-3D.

Table 2. Computational Results – 40 mm Surrogate

Buffer thickness (mm)	**V_{tip} (km/s) Analyt**	**V_{tip} (km/s) Comp**	**D_{tip} (mm) Comp**	**V^2D (mm^3/μs^2) Comp**
222	3	1.5	0.5	1.1
142	4	3.4	1.6	18.5
76	5.1	4.9	2.2	52.8
47	6	6.1	1.2	45.4
24	7	7.3	1.6	85.3

The jet profiles of the 81 mm surrogate warheads were also modeled in ALE-3D through aluminum buffer plates are discrete thicknesses of 4, 5, 6, 7, 8, and 10 inches (102, 127, 152, 178, 203 and 254 mm).

The velocities, diameters and V^2D values are presented in Table 3. To date, experiment test shots have not been fired to confirm the model outputs, however, the computational values for the baseline 81 mm warhead with a 102 mm (4 inch) buffer plate matches previously reported experimental data [11].

Table 3. Computational Results – 81 mm Surrogate

Buffer (mm)	V_{tip} **(km/s)**	D_{tip} **(mm)**	V^2D **(mm^3/µs^2)**
102	**6.3**	**3.6**	**143**
127	**5.8**	**3.2**	**108**
152	**5.2**	**2.8**	**79**
178	**4.5**	**3**	**61**
203	**5.0**	**1.0**	**25**
254	**4.6**	**0.75**	**15**

3. RESULTS AND DISCUSSION

3.1. 40 mm Surrogate Warhead Jet Profile

The 40 mm surrogate warhead was fired without the buffer plate at a long stand-off to characterize the shaped charge jet. Flash radiography was used to capture jet images digitally using three 150 kV pulser heads. Experimental tip velocities were slightly lower than the modeled tip velocity (approximately 0.5-0.7 cm/µs). This may have been caused by jet erosion.

Although there was a reasonable correlation between tip velocity and the experimental data and models, the accumulated mass profile was lower for the fired warheads. It is not known what caused this difference, but it may have been due to scaling factors when modeling smaller diameter warheads. The accumulated mass curves, along with the long stand-off jet X-rays and a picture of the warhead on the test stand are shown in Figure 6.

The surrogate warheads were fired through a 76 mm aluminum target plate to strip off jet mass and adjust the V^2D to the actual munition. Tip velocities were measured based on known times, and jet diameters were measured from just behind the jet tip to provide a consistent measurement. Experimental tip velocities measured approximately 5 km/s and jet diameters measured approximately 1.3 mm, with an average V^2D of 34 mm^3/µs^2. Figure 7 is a typical X-ray of the jet tip at three different times after emerging from the aluminum buffer plate, along with actual measurements of four experimental test shots, which show consistent test results for velocity, diameter and V^2D

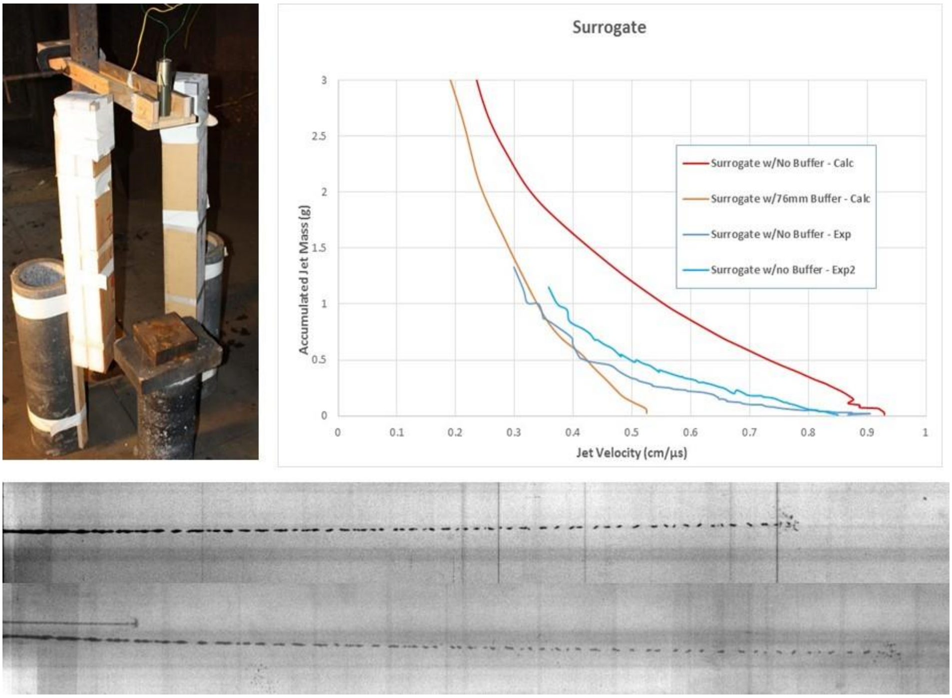
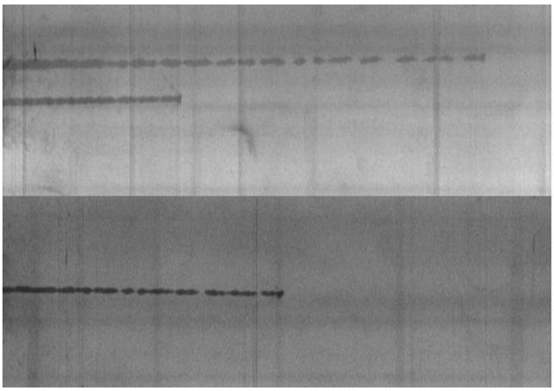


Fig. 6. Long stand-off jet X-rays, accumulated mass curves and surrogate warhead on test stand



	Vt	D	
	(km/s)	(mm)	V2D
	5.02	1.36	34.2
	5.11	1.30	33.9
	5.10	1.25	31.8
	5.11	1.41	36.7
Ave	5.09	1.33	34.2

Fig. 7. Typical flash X-ray of jet tips and experimental results of four test shots

3.2. Evaluation of Buffer Plate Diameter

The 40 mm surrogates were intended to be small, light-weight, and easy to fabricate and assemble. The buffer plates were design to screw into the body to hold the liner/explosive assembly, and to match the outside diameter of the warhead case to save on weight and space during shipment. However, when the warheads were fired during testing, it was noted that the buffer plates were shredded and produced several large fragments as well as spall. Generally, it is desirable to use a target plate of sufficient diameter to eliminate edge effects so a larger diameter buffer plate was tested to determine if this was occurring. In addition, while a gap was left in the buffer plate for the shaped charge liner collapse zone, it was not vented. Previous work on should-fired warheads with stand-off tubes indicated a possible effect on performance when the tubes were not vented, so vent holes were cut into a buffer plate to determine if the unvented cavity would change the results.

Figure 8 shows the standard, vented and the larger diameter buffer plate test and Figure 9 shows the results.

Fig. 8. Standard (c), vented (l) and larger diameter (r) buffer plate test setup

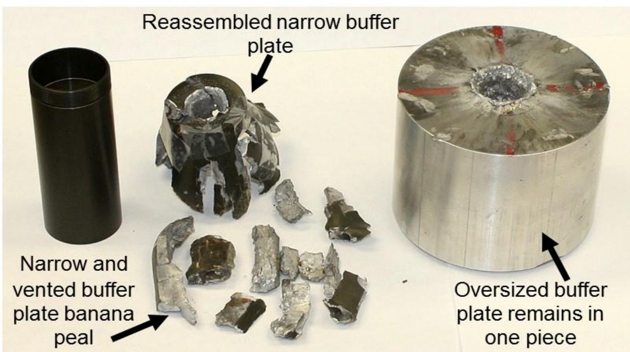


Fig. 9. Buffer plate test results

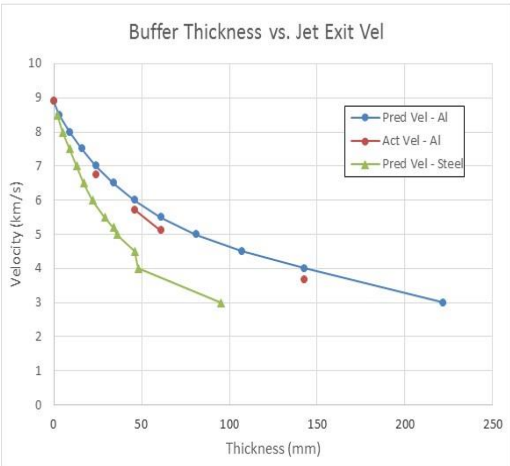
Both the vented and unvented narrow buffer plates ‘banana pealed’, while the larger diameter plate stayed intact. The measured tip velocities for the vented and unvented narrow plates were 5.11 km/s and 5.17 km/s respectively, and the measured tip velocity for the large diameter plate was 5.10 km/s. All velocities were within 1% of each other so no degradation was indicated.

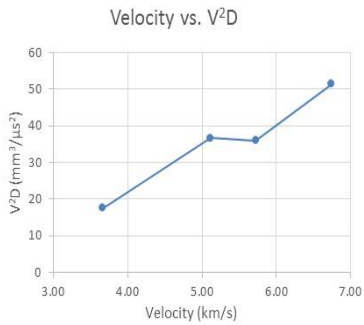
3.3. Variation of V^2D with Buffer Plate Thickness

While the 76 mm buffer plate was designed to produce a SCJ that replicates the 40 mm threat munition, there are applications where firing shaped charges with varying V^2D are beneficial, particularly when trying to quantify the sensitivity of explosives to SCJ impact and compare that impact energy to the explosive critical diameter.

Aluminum buffer plates were fabricated and tested to evaluate variation in V^2D produced by the 40 mm surrogate with different buffer plate thickness. The results, shown in Figure 10, demonstrate good agreement between the analytic modeling and the testing, within experimental error, and good agreement with continuum modeling and testing but generally for the highest velocities where the shortest amount of aluminum buffer was penetrated. Also shown is the corresponding increase in the V^2D with increasing velocity. Figure 11 shows the actual buffer plates with entrance and exit holes.

It was noted that the 23 mm and 46 mm buffers produced spall rings, which could potentially interact with an acceptor charge unless a spall blocker plate was used.





Vt (km/s)	D (mm)	V^2D ($mm^3/\mu s^2$)
3.7	1.3	17.6
5.1	1.4	36.7
5.7	1.1	36.0
6.7	1.1	51.5

Fig. 10. Test results of 40 mm surrogate firings through aluminium buffers plates

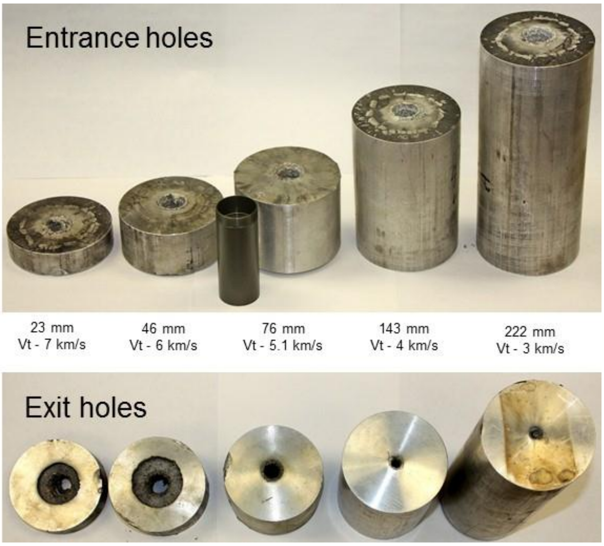


Fig. 11. Buffer plate entrance and exit holes

3.4. Critical Diameter Evaluation

As a result of the requirement to improve Insensitive Munitions (IM) performance, a variety of new, less sensitive energetic compounds have been produced over the last several years. A primary characteristic of these explosives is an ever increasing critical diameter, the minimal diameter which will support a self-sustaining detonation. It is not uncommon for these newer, more IM compliant high explosives, to have critical diameters greater than one inch and in some cases greater than several inches.

Although the relationship has not been conclusively established, a link is believed to exist between the critical diameter of a high explosive and the likelihood of detonation resulting from a shaped charge jet impact assuming a fixed set of jet parameters (i.e. jet tip velocity and diameter).

An effort is currently underway to quantify the effect of varying SCJ parameters of tip velocity and diameter against explosives of different critical diameter to see whether any trends in behaviour might be noted. Four different energetic materials were tested using the ARDEC designed RPG-7 surrogate with varying thicknesses of aluminum in an effort to reduce the velocity and diameter of the SCJ that the high explosive is exposed to. A typical test setup is displayed in Figure 12 showing the 81 mm warhead on the test stand, along with a close-up of the explosive billet being tested. Along with billet is a steel stripper plate on top and witness plates below, along with piezo pins and fiber-optic probes to capture time-of-arrival data of the detonation front.

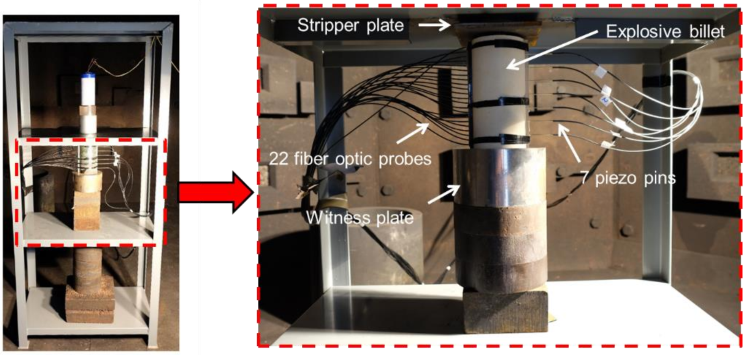


Fig. 12. Critical diameter testing. Test stand (left) and close-up of explosive (right)

To date, testing has been conducted against several ideal and non-ideal explosives and propellants. The non-ideal explosive was successfully bracketed between the 127-mm and 152-mm thick buffer plates indicating a V^2D of around 100 $mm^3/\mu s^2$ was required to initiate the explosive. The results are displayed in Figure 14 and show the difference in damage to the stripper and witness plates between a 'Go' and 'No-Go' reaction. Note that for the non-ideal go reaction, the witness plate was broken into multiple pieces from the detonative reaction, and even the stripper plate that was above the billet and subject only to the initial reaction of the explosive billet, was severely bowed. Figure 13 also displays the test hardware from the reaction of an ideal explosive. It can been see that the witness plate also received a high order detonative impact, however in this case, a large hole was blown through the stripper plate, indicating the upper portion of this billet demonstrated a significantly higher detonative response than the non-ideal billet. Time-of-arrival data also confirmed the difference in the run up to detonation.

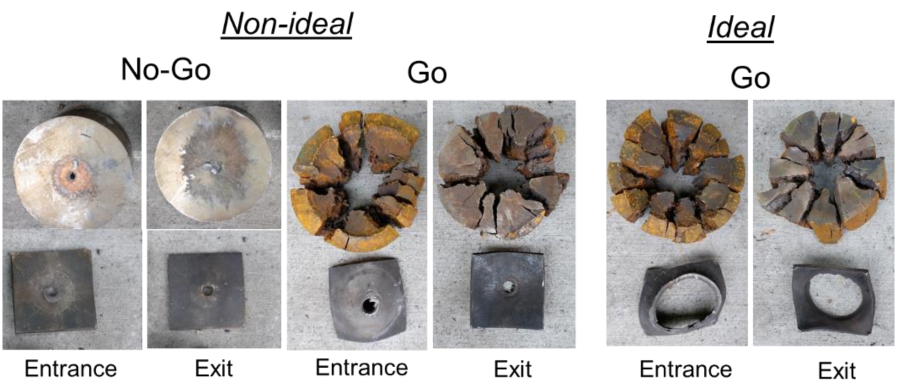


Fig. 13. Comparison of a 'Go' and 'No-Go' reaction for a non-ideal explosive and the difference between the detonation response of an ideal and non-ideal explosive

4. CONCLUSIONS

Shaped charge jet threats are commonly encountered and almost always induce a detonation when they impact explosive ordnance.

The U.S. previously developed a surrogate warhead to represent a more consistent RPG threat and is currently doing the same for a smaller gun-launched grenade. Since most munitions do not survive impact from an RPG SCJ, the 40 mm surrogate was designed to provide reliable performance for a smaller threat.

A series of discrete 40 mm surrogate buffer plates were modeled and tested. These were designed so that surrogate warheads would produce velocities ranging from 3-7 km/s. Analytical calculations were used to save time by guiding continuum modeling before conducting verification testing. Although there was good agreement between the analytical and continuum modeling for the highest jet velocities, agreement was less for the lowest velocity cases. For the analytical models, this was likely due to inherent assumptions and/or oversimplification (e.g. no constitutive behavior is assumed). For the continuum modeling, error was likely due to the fact that the accuracy of constitutive models, strength, and failure probably matters more on the lower end of velocity than it does at the higher end where the EOS is most important. The use of analytical modeling as a starting point from which to guide continuum modeling proved to be a valuable technique because it saved an appreciable amount of time.

There was reasonable agreement between modeled and experimental jet tip velocity, although as-modeled results predicted higher values than were measured experimentally. These noted differences could be attributed to erosion of the jet tip, since the jets need to be allowed to go sufficiently past the end of the buffer plates in order to calculate time differences from the jet X-rays. The difference between calculated and experimental jet diameters was more erratic. This most likely stems from the difficulties in trying capture a realistic diameter from the model output, and normal experimental error.

The influence of squaring the jet velocity, along with irregular jet diameters had a tendency to increase the differences in V^2D values.

It should be understood that values for Held's criterion should not be construed to be exact. It is likely more appropriate to think of these numbers as having error bands when considering whether or not a precisely characterized jet is likely to initiate a given explosive, and this applies equally to both the computational and experimental results. That being said, the development of consistently performing 81 mm and 40 mm surrogate warheads provides a valuable tool for evaluating the effect of jets of varying parameters on explosive initiation. It also allows designers to develop methods to mitigation the effect of prolific battlefield threats on munitions and make our soldier safer.

REFERENCES

[1] Baker L. Ernest, James Pham, Timothy Madsen, William Poulos, Brian E. Fuchs. 2013. Shaped Charge Jet Characterization and Initiation Test Configuration for IM Threat Testing. In *Proceedings of the 12th Hypervelocity Impact Symposium.*

[2] Baker L. Ernest, Nausheen Al-Shehab, Arthur S. Daniels, C. Frankovic, K.W. Ng, Timothy M. Madsen, Brian E. Fuchs, F. Cruz. 2014. Test Configuration Development for Small Shaped Charge Threat Insensitive Munitions Testing". In *Proceedings of the 28th International Symposium on Ballistics*, Atlanta, GA, USA.

[3] STANAG 4526 Edition 2 – Shaped Charge Jet, Munitions Test Procedure. NATO AC326 (2004).

[4] Held Manfred. 1989. Initiation Phenomena with Shaped Charge Jets. Paper presented at the *9th International Symposium on Detonation,* Portland, OR, USA.

[5] Werner Arnold, et al. 2015. Challenging v^2d. In *Proceedings of the 2015 Insensitive Munitions & Energetics Materials Technology Symposium*, Rome Italy.

[6] Held Manfred. 1980., "Initiation of Explosives: A Multi-Layered Problem of the Physics of Detonation". *Translation, Explosives Periodical* 16(5).

[7] Bussell T. J., M. C. Chick. 1992. *Flash Radiography Studies of Hypervelocity Projectile Interactions with Explosives*. Materials Research Laboratory, DSTO, MRL-TR-91-51.

[8] Stunzenas Gred, Ernest L Baker. 2010. A Comparison of Hydrodynamic and Analytic Blast Pressure Profiles, In *Proceedings of 2010 Structures Under Shock and Impact Symposium.*

[9] Walters W.P., J.A. Zukas. 1989. *Fundamentals of Shaped Charges*.

[10] Baker L. Ernest. 2015. *Lecture 11 Shaped Charges, Theory and Performance of Propellants and Explosives,* Stevens Institute of Technology *(lecture notes).*

[11] Baker L. Ernest, Nausheen Al-Shehab, Arthur S. Daniels, C. Frankovic, K.W. Ng, Timothy M. Madsen, Brian E. Fuchs, F. Cruz 2014. Test Configuration Development for Small Shaped Charge Threat Insensitive Munitions Testing". In *Proceedings of the 28th International Symposium on Ballistics*, Atlanta, GA, USA.