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CUTOFF VELOCITY IN PRECISION SHAPED CHARGE JETS

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Every shaped charge jet has a last particle that contributes to penetration depth. Estimating the speed of this particle, or "cutoff" velocity of the jet, is a key factor in predicting penetration performance for a given shaped charge. Many of the traditional penetration models use an assumed random distribution for deviations in drift speed to determine if individual particles contribute to penetration. This paper describes an alternate, non-statistical approach for modeling cutoff where the penetration process is viewed as ending fairly abruptly in precision devices once the jet collides with the side of the hole. Direct comparison between particles in flight and their individual contributions to penetration depth are made. The importance of local hole shape ("scalloping") is discussed, and a simple empirical cutoff model that agrees with RHA penetration data at short and long standoff is described.

INTRODUCTION

The penetration of a shaped charge jet into a semi-infinite homogeneous target depends on the cumulative length of jet elements that interact effectively with the bottom of the hole. It would improve our understanding of the process if we knew which portions of the jet actually contribute to penetration and what associated circumstances lead to the final observed penetration depth.

It is common during the investigation of new shaped charge designs to take flash radiographs (x-rays) of the jet at a longer standoff than at the one of interest for performance testing, for example at 20 charge diameters (CD) instead of 6 CD. These jet characterization x-rays provide images of individual particles that give critical information about the jet including its speed, mass, breakup time, straightness, and total length, that are not readily available at shorter standoff. One of the most important observations to be accounted for concerns the total particle length evident in an x-ray of a fully particulated jet. This total length, if only adjusted for jet/target relative density according to hydrodynamic penetration theory [1], almost always corresponds to a much greater penetration depth than is actually achieved in the target. A partial explanation, valid for tests conduc-

Home
Table of Contents

ted with the targets positioned at short to intermediate standoff, is that the early part of the jet did not have sufficient time to reach the full particle length observed in the longer standoff x-ray. Usually this adjustment will account for some, but not all, of the discrepancy as shown in Table 1. This suggests some of the jet particles do not contribute effectively to increasing penetration depth.

Table 1. Examples showing substantial portion of jet is not used to increase penetration depth

CONDITIONS		
Type of Jet	Copper Jet 1	Copper Jet 2
Standoff, CD	6.0	20

RESULTS		
Parameter	**Penetration, CD**	
Penetration if total particle length seen in jet x-ray contributed fully	9.5	11.9
Penetration if jet length is adjusted for particle time of flight	8.9	11.9
Measured Penetration Depth	7.7	5.9

Many of the traditional shaped charge jet penetration models [2] attempt to account for the apparent ineffectiveness of some of the jet particles by assuming that there is a random-type distribution in lateral "drift" speed along the jet. This causes sufficiently wayward particles to hit the side of the penetration hole and not contribute to depth, leaving the rest of the jet more or less undisturbed. Several limitations exist with this approach. First, it is our experience that jets produced from precision (low-drift) shaped charges normally do not exhibit random lateral deviations from particle to particle, but more commonly show non-random, continuous deviations from centerline, along slightly "curved" arcs for example. Second, analysis of particle interactions with the side of the target hole indicates that particles arriving after an earlier collision event encounter interference. Finally, random drift models usually have difficulty in predicting penetration over a wide range of standoffs without continuously changing some basic assumption for the jet, such as its average drift speed.

The present investigation suggests that an alternate explanation is more appropriate for high-precision jets. It supports the idea that such jets achieve their penetration by using particles from the tip down to a final "cutoff" particle, after which penetration ends fairly abruptly. Spacing between the particles, which affects local hole profile shape, and lateral particle drift are important in determining the cutoff velocity of the jet which increases monotonically with standoff. This view accounts for all of the observed jet particle length in a straightforward manner, is consistent with other experimental data, and allows one to model penetration over a wide range of standoffs without making artificial changes to the properties of the jet.

EXPERIMENTAL DATA

Key experimental data supporting the idea of a sharp cutoff velocity for shaped charge jets has come from tests where the target standoff was sufficiently long that the jet was completely particulated prior to impacting an RHA target. Flash x-rays at various times and viewing angles were taken to characterize the jet (particle speed, length, etc.). The RHA blocks were sectioned to obtain a detailed hole profile. As Figure 1 shows, it is possible to clearly identify jet particles in the x-ray with their corresponding location in the hole profile based on the unique sequence of particle shapes and lengths. In another test, the full-length x-ray and cut-block data show that all of the particles from the tip down to a last contributing particle were responsible for the penetration depth (Figure 2). The rest of the particles in the jet that came after "cutoff" did not contribute appreciably to the final depth. Time-of-arrival (TOA) data was obtained from timing screens placed between the RHA blocks (Table 2). The velocity of the particle that penetrated the last RHA block based on TOA data was consistent (usually within a few tenths of a km/s) with that obtained from the x-ray.

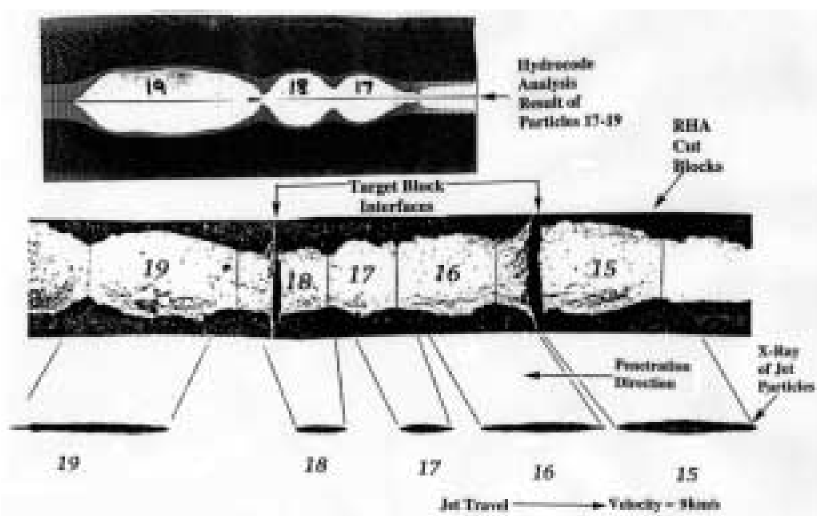

Figure 1. Scallops formed in RHA by spaced jet particles.

In cases where the cutoff velocity was observed to be much different than normal for a given charge at a certain standoff, the jet exhibited some anomaly. When the jet tail was noticeably off-line (or sometimes a large-diameter particle was present), higher than normal cutoff velocity resulted. On the other hand, a crooked jet tip could actually result in an abnormally low cutoff velocity. In this case, however, the penetration depth was also low since the front of the RHA stack had to be re-penetrated. As a consequence, the dis-

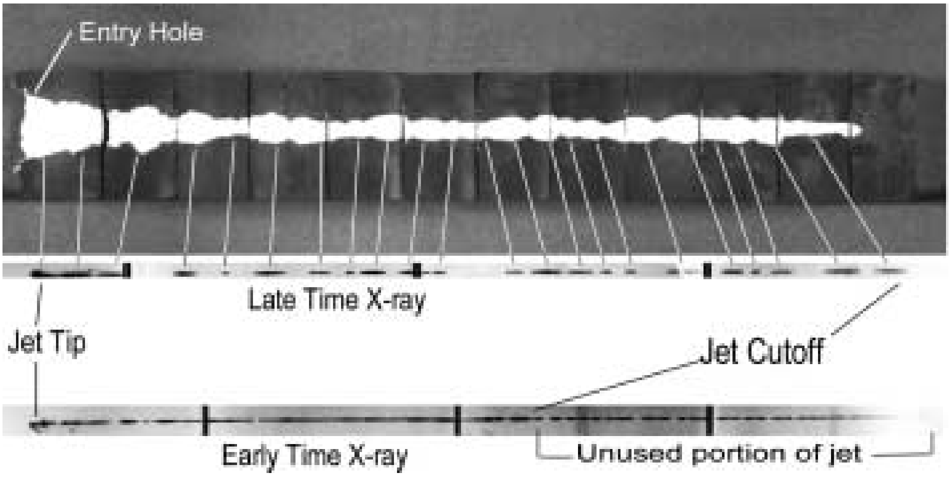

Figure 2. Correlation of particles in X-ray with scalloped holes in target.

Table 2. Typical TOA data for RHA penetration test

TOA No.	TOA Times, ms	Vjet/Vtip, calc.
1	466.8	1
2	480.8	0.98
3	497.1	0.97
4	514.1	0.95
5	543.8	0.91
6	568.5	0.88
7	602.3	0.84
8	622.3	0.82
9	650.0	0.80
10	677.9	0.77
11	710.5	0.75
12	751.8	**0.71**
13	Penetration stopped between 12 & 13	
	Vcutoff/Vtip from X-ray =	**0.68**

tance to the bottom of the hole (and particle time of flight) was reduced and lower than normal jet velocities contributed to the penetration.

Hydrocode analysis was performed using PISCES 2DELK [3] to model a few selected particles in the jet. Their predicted penetration hole pattern (included in Figure 1) agrees reasonably well the cut block data, and confirms the implicit assumption that each scallop in the target is produced by one jet particle.

The same sharp cutoff mechanism appears to apply in shorter standoff situations where the penetration is characterized by continuous penetration in the beginning followed by particulated penetration at the end (Figure 3). This explains why normally, if changes to the jet, e.g., in breakup time, are introduced above the known cutoff velocity but below the continuous regime, penetration is affected. Conversely, if the changes are made below cutoff, penetration is essentially unaffected.

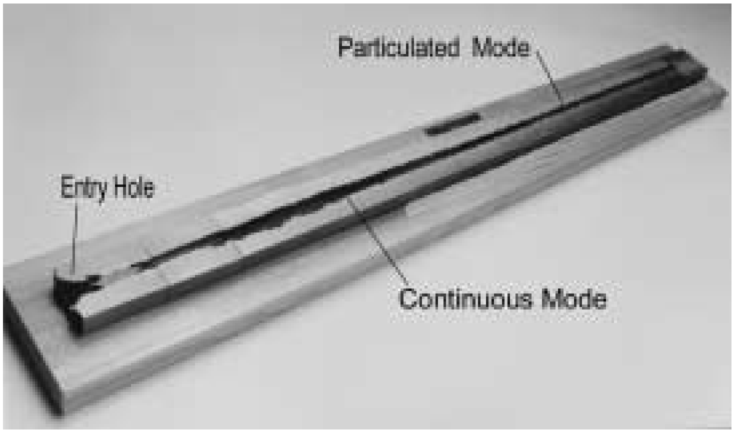

Figure 3. Hole profile created by jet at intermediate standoff.

Cutoff velocity was determined for a variety of experimental jets and, in general, it was observed to increase as standoff increased. Figure 4 shows this trend for a typical copper trumpet liner design loaded with LX-14 explosive. Cutoff velocity is also affected by the fabrication precision of the shaped charge, jet breakup time, jet speed, and jet/target dynamics. All of these factors influence the jet particle's lateral drift and interaction with the side of the target hole that ultimately leads to termination of the penetration process.

INTERPRETATION OF THE RESULTS

The one-to-one matchup of individual particles in the x-ray with the "scalloped" hole pattern in the sectioned RHA blocks provides the most compelling evidence for the idea of a sharp cutoff velocity for a shaped charge jet. Each particle above cutoff clearly contributed to penetration depth. Particles below this effective cutoff velocity did not contribute significantly to penetration. Instead, they were apparently consumed during the smoothing or "reaming" of the hole, especially at the bottom. This is further supported by the TOA data where the calculated particle velocity in the last block penetrated agrees with the cutoff velocity obtained from the x-ray data.

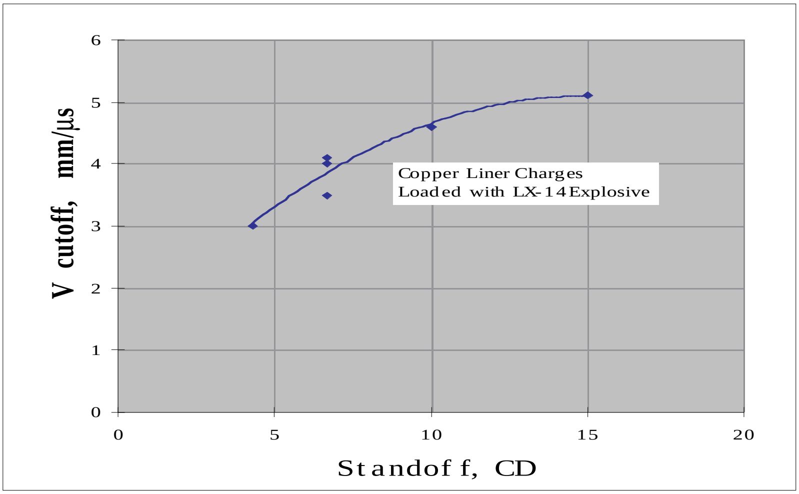

Figure 4. Variation of jet cutoff velocity with target standoff.

A mechanism for sharp cutoff is suggested from numerical simulations and from the cut block data itself. Unless penetration is entirely continuous, a series of connected scallops near the bottom of the hole can usually be seen (ref. Figures 2, 3). It is likely that the scallops had much smaller entry holes during the penetration process (prior to erosion) than are evident in the recovered RHA cutblocks. One possible mechanism contributing to cutoff is that as the spacing between the particles increases, the entry holes in the scallops are able to narrow down more, presenting a smaller opening for the next particle. At some critical point, the entry hole is small enough relative to the drift of the next particle that contact with the crater lip is made.

PISCES 2DELK was used to model incident jet particles that were off-center by some fraction of their diameter and allowed to interact with a pre-scalloped hole pattern (Figure 5). These simulations were done assuming plane strain (ε_z=0) symmetry and are expected to somewhat over-predict the full three-dimensional particle response. When the particle drift is about 50–100% of a jet diameter off centerline, the collision with the hole opening appears to be significant. The interaction in this case is predicted to be great enough to cause the affected particle to ricochet to the opposite side of the hole and effectively “block” or hinder further penetration. It is sometimes possible to actually see evidence of this type of termination event in the cutblocks (Figure 6). These calculations, although only qualitative, suggest that the scalloped edges play a significant role in terminating jet penetration.

PENETRATION MODEL

Based largely on data of the type presented here, an empirical sharp cutoff velocity model has been developed by Hancock [4]. It imposes a cutoff criterion based on average penetration speed, U, which decreases as the space between jet particles increases. When the penetration speed falls below a certain minimum level, U_{min}, penetration is stopped. The approach is an extension of constant U_{min} models [5] in that U_{min} is made a function of lateral particle drift:

$$U_{min} = U_o(1 + b\delta_r/r_b)$$

where U_o and b are constants, δ_r is the radial particle drift, and r_b is the jet particle radius at breakup. This equation normalizes the drift to particle radius, instead of maximum or average crater width, based on our observations that cutoff is sensitive to drift distances which are on the order of particle size. This empirical model is able to provide reasonable agreement with penetration data over a wide range of standoffs, as shown in Figure 7, while keeping particle drift speed fixed.

CONCLUDING REMARKS

It should be emphasized that the data presented here supporting a sharp cutoff velocity are for precision jets with low drift velocities, where penetration is repeatable to within a few particle lengths. This simple picture does not necessarily apply to lower precision charges, which have higher drift velocities and may be subject to complex re-penetration scenarios.

ACKNOWLEDGEMENT

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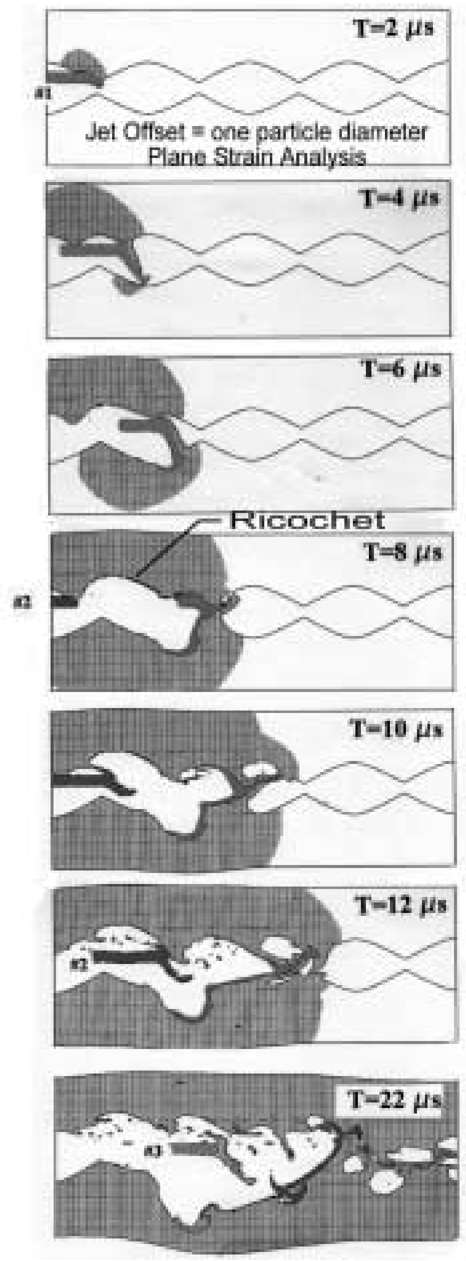

Figure 6. Evidence of jet particle ricochet near end of penetration.

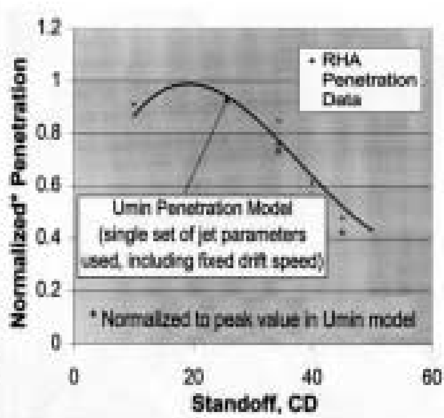

Figure 5. Simulation of offset jet particles interacting with "pre-scalloped" hole.

Figure 7. Comparison of Umin penetration predictions with data.