

THE MECHANISMS AND PARAMETERS OF ABRASIVE WATERJET (AWJ) CUTTING OF HIGH-EXPLOSIVE PROJECTILES

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ABSTRACT

Alliant Techsystems has researched sectioning high-explosive projectiles with abrasive waterjets (AWJ) and has examined the physical mechanisms of the process. In addition to performing parametric studies of waterjets, Alliant Techsystems has cut over 170,000 high-explosive projectiles under controlled conditions to evaluate the safety of the waterjet cutting process. Here, the various parameters that affect the safety and performance of the abrasive waterjet cutting process are described and the relative merits of the different options are compared. Specifically, the safety-critical parameters are the diameter of the jet stream and the velocity of the water. With these safety critical parameters, the likelihood of an initiation can be predicted for a given explosive using existing projectile impact models developed by various laboratories.

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INTRODUCTION

Background

Once the Defense Systems Group of Honeywell, Alliant Techsystems is now a fully independent company and takes its place as one of the largest designers and producers of conventional ammunition in the world. As part of our continuing effort for technical excellence, we have pursued a number of new technologies, including this field of waterjet cutting of explosives. The investigation of waterjets as an unconventional machining technology was in response to an internal need to safely cut high-explosive projectiles.

As supported by other papers presented by Alliant Techsystems at this Department of Defense Explosive Safety Board Seminar, we have established that waterjets are a safe method for working with high explosives. After a thorough tradeoff study, the use of waterjets was sanctioned within our company as fully meeting our needs for a safe and efficient method of cutting high-explosive ammunition prior to either explosive recovery or incineration. This research into the performance parameters and limits of safe operation has taken us almost two years to complete.

Our research was separated into both a theoretical portion and an empirical testing program. The testing operations were further split into seven specific phases, four of which will be discussed in this paper. Deliberate care was taken at each step to structure the test sequences in such a way as to ensure that the information gathered was statistically accurate. Although not exhaustive, this paper describes the mechanisms and parameters we found useful for operating waterjets, including the results of our safety test sequence of abrasive waterjet cutting approximately 170,000 high-explosive projectiles.

Definitions

Some definition of terms must first be made in order to prevent confusion with existing products that also have been used on explosives:

Waterjet (WJ) — A process utilizing high-pressure water, up to 410 MPa (60 ksi), forced through an orifice (Figure 1). The particle velocity of waterjets is usually very high, up to a maximum of 0.9 km/s, and is capable of directly cutting many low-yield-strength materials without the use of additional abrasives. In the United States, the major producers are Flow, Ingersoll-Rand, and Jet-Edge.

Abrasive Waterjet (AWJ) — A waterjet that, after the water passes through the orifice, entrains abrasive particles by aspiration and mixes them by mechanical action into the high-velocity stream of water inside a focusing tube (Figure 2). Depending on the abrasive and other parameters, abrasive waterjets can cut through virtually any material.

Abrasive Slurryjet (ASJ) — A system that utilizes mixed water and abrasive slurry, which is then pressurized and the slurry mixture forced through a nozzle (Figure 3). Although abrasive slurryjets are potentially more efficient than abrasive waterjets when operated at the same pressure, the current production equipment pressure levels are only about 20 percent that of abrasive waterjets and have a proportionally lower efficiency.

Cavitating Waterjet (CWJ) — An intermediate pressure, approximately 68 MPa (10 ksi), water stream process with a special nozzle that induces "natural cavitation" (vapor bubble formation) in

the water flow (Figure 4). The cavitating waterjet process involves the initiation, growth, and impact of vapor bubbles against the target material. The collapse of these vapor bubbles causes intense, localized impacts in a highly variable manner to erode the target material. It is important to note that cavitating waterjets are *not* the same thing as waterjets in the waterjet industry. Although cavitating waterjets have historically been used on explosives,¹ they are not related to the safety tests described in this paper and no extrapolation of results should be made simply because they have similar names.

Operational Description

The operation of a waterjet can be simplistically stated as a pump (Figure 5) that pressurizes water up to 410 MPa (60 ksi) and delivers the water through a small orifice, ranging in size from 0.13 mm (0.005 in.) to 1.32 mm (0.052 in.) in diameter, as a continuous stream. This continuous stream of water is traveling at velocities approaching 825 m/s (3000 f/s) and impacts the target material, causing erosion at a rate dependent on the mass and velocity of the water and the yield strength of the target material. As shown in Figure 1, the number of components used in a waterjet are few and appear deceptively simple. What is difficult to show in this diagram is the stress on the equipment and the precision machining necessary for the system to remain reliable over a long period. For instance, the typical waterjet orifice, (Figure 6), used in our operations is manufactured from sapphire, and some of them (for ultrahigh-pressure work) must be manufactured from diamond in order to withstand the stress.

The abrasive waterjet, (Figure 2), utilizes the basic waterjet concept and augments it with the introduction of abrasives aspirated through a venturi section. The abrasives and water are mixed in a short mixing tube, typically made of carbide or some ceramic, and the mixture discharged toward the target. The abrasive grains act as individual single-point cutting tools similar in action to that of a sandblaster. In the case of an abrasive waterjet, the grains of abrasive are accelerated by water instead of air to a high velocity (although significantly less than the jet velocity) and impacted upon the target material. The target is both cut and worn away by the abrasives and the machining debris is flushed away by the water stream.

TEST SETUP

Our parametric testing was performed on inert materials at all three major waterjet vendors' test facilities in the United States. These facilities included Flow International in Kent, Washington; Ingersoll-Rand in Detroit, Michigan; and Jet-Edge in Minneapolis, Minnesota. Although some minor explosive testing was conducted at the Ingersoll-Rand facility in Baxter Springs, Kansas, the majority of the explosive testing was performed at the Alliant Techsystems Proving Ground (ATPG) located near Minneapolis. The proving ground test site is the largest commercial explosive test facility in the world and has complete capabilities to test and analyze explosive events.

Equipment varied slightly among the three vendors, but basically consisted of a computer-controlled, programmable 3-axis table with at least a 75 kW (100 hp) waterjet pump attached. This setup allowed exacting control and measurement of the cutting process.

¹Summers, D., et al., "Considerations in the Design of a Waterjet Device of Reclamation of Missile Casings," *Proc. 4th U.S. Waterjet Conference*, Waterjet Technology Association, August 1987, pp. 51-56.

Testing on explosive materials was conducted in our remote explosive machining building at the Alliant Techsystems Proving Range with an Ingersoll-Rand 29.8 kW (40 hp) 40S *Streamline Intensifier*TM capable of sustaining pressures of approximately 340 MPa (50 ksi) through orifices ranging in size from 0.076 mm (0.003 in.) to 0.0356 mm (0.014 in.) in diameter. The orifices were manufactured from synthetic sapphire and supplied by the vendor. The abrasives were garnet, 150 micron (100 mesh) at a mass flow rate of between 0.23 kg/min (0.5 lb/min) and 0.7 kg/min (1.57 lb/min).

The waterjet machine was located behind a standard 30 cm (12 in.) reinforced concrete blast suppression wall in the operator control station. Plumbing for the high-pressure water was run through the wall in armored conduits to minimize damage to the plumbing and to protect the workers should a failure occur in the tubing. Water was supplied from drums to prevent introduction of uncontrolled variables into the test matrix.

PARAMETERS

Our goal was to cut high-explosive projectiles safely with little or no concern for such metrics as surface finish or efficiency, which may be of significant importance to other individuals. This difference in our emphasis may explain slight differences between our work and that of other published researchers.

The parameters we identified for cutting high-explosive projectiles fall into three broad categories: first, fluid parameters relating to the flow of the water and the decay of energy; second, abrasive parameters relating to the type and amount of the cutting grains; and third, general parameters that do not fit easily into either of the preceding categories. The parameters we identified as being of importance for safety are the diameter of the impact and the velocity of the impacting jet.

Fluid Parameters

The basic parameters relating to the hydraulics of the system are the pressure of the water and the size of the orifice. Within limitations, a generalization can be made that greater pressures and larger orifices will give the fastest cutting speeds, but not necessarily the highest efficiency. The pressure of the liquid is one of the most critical parameters, because pressure has a direct relationship to velocity and for every target material there is a minimum impact velocity required in order for the material to be cut in a reasonable amount of time.² Below this critical impact velocity, the removal rate of material is, for reasonable purposes, nonexistent. The velocity of the fluid (Figure 7) can be approximated by the formula:³

$$V_{jet} \equiv \sqrt{2p/\rho} \quad (1)$$

where V_{jet} = Jet velocity in m/s
 p = Pressure in kilopascals
 ρ = Density of the fluid in gm/cm³

²Hashish, M., "A Model for Abrasive-Waterjet Machining," *Trans. ASME J. Eng. Materials and Technology*, Vol. III, April 1989, pp. 154-162.

³Adapted from: Hashish, M., "Pressure Effects in Abrasive-Waterjet Machining," *Trans. ASME J. Eng. Materials and Technology*, Vol. III, July 1989, pp. 221-228.

We found that the speed of cutting is proportional to the pressure delivered by the waterjet. For this reason we elected to operate at maximum pressures on our current operations. This observation closely follows the published data for the depth of cut in other research efforts.^{4, 5}

The second most important hydraulic equation is the size of the orifice which, in turn, dictates the mass flow of the water in the jet stream. The mass of water can be approximated by the formula:

$$m = \rho * A_o * V_{jet} \quad (2)$$

where m = Mass flow rate
 A_o = Orifice area

Our efforts showed that the increase in orifice size significantly increased the cutting rate of the process. A drawback to increasing the orifice size is the increase in water flow consumption, which may be of concern to some projects. However, our waterjet uses only 8.2 l/min (2.2 gpm) operating at the maximum limits of the equipment. This is significantly less than that of previous systems used on washing out high explosives with a consumption rate of up to 187 l/min (50 gpm).⁶ The low rate of water consumption is of particular importance to us as part of our efforts is to recycle as much water as possible. Calculations indicate that almost 50 percent of the water used can be recycled back into the system for reuse. The remainder of the water is lost through evaporation and drag-out by the abrasive disposal process.

Safety

These two parameters of jet velocity and orifice size are also the critical parameters for safely impacting high explosives. As more fully described in a separate paper presented to the Department of Defense Explosive Safety Board on our waterjet safety tests, we identified that the most serious concern was the hazards associated with the impact of high-velocity water on explosives.

Various papers have been written about the impact of projectiles on different explosives. Weiss and Litchfield⁷ alone cite more than 25 papers on the topic prior to 1967. One of the most applicable works on the effects of projectile impact was that of Slade and Dewey⁸ of the Ballistic Research Laboratory at the Aberdeen Proving Grounds. Andersen's⁹ work became very applicable to our analysis as he identified mathematically why the impact of small-diameter, high-velocity jets of water were not initiating the explosive as data from explosive properties manuals would have suggested.

⁴Chalmers, E., "Effect of Parameter Selection on Abrasive Waterjet Performance," *Proc. 6th American Waterjet Conference*, Waterjet Technology Association, August 1991, pp. 345-354.

⁵Hashish, op. cit., July 1989.

⁶Personal communication.

⁷Weiss, M., and Litchfield, E., *Projectile Impact on Initiation of Condensed Explosives*, Report 6986, Bureau of Mines, Pittsburgh, PA.

⁸Slade, D., and Dewey, J., *High Order Initiation of Two Military Explosives By Projectile Impact*, BRL Report No. 1021, AD145868, 1957.

⁹Andersen, W., "Critical Energy Relation for Projectile Impact Ignition," *Combustion Science and Technology*, Vol. 19, 1979, pp. 259-261.

Weiss and Litchfield showed that the critical velocity necessary for explosive initiation was very dependent on the diameter (as shown in Figure 8) of the impacting projectile and further identified that the shape of the projectile had a significant effect (Figure 9). This information was expanded upon by Andersen in the form of his equation identifying the role of the projectile diameter. His formula was given as:

$$V_i = \sqrt{A^2/d + B^2} + B \quad (3)$$

where V_i = Critical impact velocity, m/s
 A = Detonation velocity / e
 d = Projectile diameter, mm
 B = $f / 2e$
 e, f = constants for a particular explosive

Andersen identifies that for pressed TNT impacted by a cylindrical, flat-nosed steel projectile, the value of $e = 4.094 \times 10^5$ cm/sec and $f = 1.052 \times 10^{10}$ (cm/sec)².

The acoustic impedance mismatch was also identified by Andersen as being important to the initiation function. The acoustic impedance difference between steel/TNT and water/TNT is a factor of about 3.85.¹⁰ This factor means that a steel projectile is capable of transmitting the shock front into a piece of TNT more efficiently by a factor of 3.85 over that of water.

Table 1 represents some common explosives and the estimated velocities for the 50 percent initiation point for a flat-nosed steel projectile based on the above works. In Figure 10 through Figure 14, we show the theoretical shift of critical velocities from the use of steel to water projectiles for the various listed explosives. Since each explosive has its own characteristic critical velocity for a given impact source, there will therefore be some critical impact function as the combination of orifice size and waterjet velocity, determined by the water pressure. In many cases the velocity will exceed the sonic velocity of water and act as a natural limit to being pumpable. In other cases the necessary pressure may exceed the freezing point of water at operational temperatures. Water freezes at room temperatures¹¹ under highly elevated pressures, as shown in Figure 15, and would provide another natural limit to a "runaway" condition.

Table 1. Projectile Impact V50 Velocities for Square Edged Projectiles.
Adapted from reference 17.

PETN	310 m/s
HMX	445
RDX	455
COMP B	1470
TNT	1745

¹⁰Lopatin, C., "Detonation of Explosives by Jets of Propylene Glycol Mixed with Glycerin," Alliant Techsystems Interoffice Correspondence CML 92043 to Paul Miller, February 20, 1992.

¹¹Bridgman, P., "Water, In the Liquid and Five Solid Forms, Under Pressure," *Proc. Am. Acad. of Arts and Sciences*, Vol. 47, No. 13, January 1912, pp. 441-558.

The use of abrasive waterjets to cut high explosives in steel projectiles appears to be safe to at least the 0.99998 safety level. In the interest of time, additional safety related information is contained in a separate paper.

Abrasive Parameters

Choosing abrasive grains is not as simple as picking a particular hardness and then proceeding with abrasive cutting. Abrasive parameters include not only the abrasive's composition but also its physical structure, size, and mass flow rate.

Abrasive composition falls primarily into the type of abrasive used. Chemical composition, in itself, is not really sufficient to specify an abrasive grain, since one type of "garnet" abrasive may not perform like that of a "garnet" abrasive from another source. This difference may be due to slight variations in the crystalline structure, the ability to fracture into fresh cutting surfaces (known in the industry as "friability"), and the presence of contamination. The substitution of alternative materials could be a nightmare if an overzealous purchasing agent decided that he could "save" some money without consulting Engineering first.

The type of abrasives commonly used in abrasive waterjets is shown in Table 2. Most industrial users rely on garnet abrasives as the cost is low and the performance is good. The testing performed at all three vendors used "Barton" garnet, and our current operation also utilizes this material as it seems to be the most efficient and least expensive for our purposes.

Table 2. Abrasives Used In Abrasive Waterjet Cutting. Adapted from reference 13.

Abrasive	Knoop Hardness
Silicon Carbide	2500
Aluminum Oxide	2100
Garnet	1350
Silica	700
Steel Shot	600
Glass	500
Copper Oxide (Slag)	—

These abrasive grains have a typical hardness, defined by Knoop hardness numbers, which is only a partial indication of how the abrasive will behave cutting materials. Logically, the harder target materials require abrasive grains that are harder than they are. But these abrasive grains do not have to be significantly harder to be effective. Although aluminum oxide is the abrasive of choice in the grinding wheel industry and garnet abrasives are considered too soft for metal cutting,¹² the waterjet industry uses these abrasives in radically different ways. Garnet is the material of choice for abrasive waterjets, while aluminum oxide is almost a specialty item. The primary reasons why

¹²King, R., and Hahn, R., *Handbook of Modern Grinding Technology*, Chapman and Hall, NY, 1986, p. 291.

garnet is used more frequently is because garnet cuts 90 percent as well as aluminum oxide, but only costs 10 percent as much.¹³ The improvement in cutting capability can be easily explained by the fact the abrasives are traveling very fast; any disadvantage garnet may have at normal grinding wheel speeds is overcome by the high velocity of the abrasive waterjet. Normally, grinding wheels operate with a surface particle speed of approximately 35 m/s,¹⁴ while an abrasive waterjet particle is traveling at over 600 m/s.¹⁵ At the present time, the garnet that we use for abrasive waterjet cutting only costs about \$0.55/kg when purchased in multiple-bag increments.

Abrasive grain size also can be tailored for the type of material cut. We have not had any problem with cutting metals from titanium (Ti-6Al-4V) to aluminum with garnet abrasives of 150 micron (100 mesh) particle size. This particle size was suggested by the vendor and substantiated by literature as the most efficient for cutting steel.¹⁶ Larger particles are more efficient for softer metals such as aluminum and cast iron. For those applications where surface finish may be important, the finer grain size also yields a better surface quality. One other precaution that may be worth noting is that the size of the sparks created by the impact of abrasive on steel are proportional to the size of the swarf (metal chip) removed. Our investigations have shown that, based on mathematical models available for spark ignition, the sparks we have generated too small (Figure 16) to ignite the explosive materials.¹⁷ Increased abrasive grain size used for cutting may create larger swarf and reduce the safety margin of the process.

The mass flow rate is the last abrasive parameter that must be specified. For any given material, there will be an optimum mass flow rate that is approximately 85 percent of the maximum cutting rate.¹⁸ This abrasive mass flow rate is chosen as it the most cost effective. Exceeding the maximum cutting flow rate reduces the cutting efficiency significantly at the cost of large amounts of abrasive material. For this reason, the logical approach should be to start off with less than ideal flow rates and gradually build up to an appropriate operating rate, rather than to jump in with the "more is better" philosophy.

Cutting Approach

We tried cutting both laterally across the projectiles, as one would do with a saw, and cutting rotating projectiles (Figure 17) like a lathe. The rotational method was significantly faster than the lateral cutting method for larger projectiles as the abrasive waterjet loses energy rapidly after penetrating the metal casing. Too fast a cutting speed on a lateral cut will prevent the jet from cutting through the opposite casing wall. An average speed for cutting 4.2 in. high-explosive mortar projectiles, loaded with Comp B, was 33 seconds by the rotational method. The lateral cutting method for the same projectile was 57 seconds.

¹³Hashish, M., *Optimization Factors in Abrasive-Waterjet Machining*, Flow International.

¹⁴King, R., and Hahn, R., *ibid.*

¹⁵Chen, W., and Geskin, E., "Correlation Between Particle Velocity and Conditions of Abrasive Waterjet Formation," *Proc. 6th American Waterjet Conference*, Waterjet Technology Association, August 1991, pp. 305-313.

¹⁶Hashish, M., "A Modeling Study of Metal Cutting With Abrasive Waterjets," *Trans. ASME J. Eng. Materials and Technology*, Vol. 106, January 1984, pp. 88-100.

¹⁷von Jouanne, R., *A Computer Model for the Ignition of Methanol/Air Mixtures*, Master's Thesis, Southern Illinois University, Carbondale, Illinois, July 1987.

¹⁸Chalmers, E., *loc. cit.*

We also showed that there was very good control over the depth of cut when using abrasive waterjets on a rotating projectile. We demonstrated that the depth of penetration could be tailored to cut up to the explosive without impacting the reactive materials. However, we abandoned this delicate approach of case slitting without explosive involvement once we demonstrated that the explosive was not going to react to the effects of waterjet impact. In addition, we currently use the lateral cutting method (Figure 18 and Figure 19), which is slower in cutting speed, because the simplicity of the system and the rapidity of loading the projectile feed trays outweighed any speed advantage that rotational cutting may have had.

CONCLUSIONS

Waterjet cutting of high-explosive materials, either by plain water impact or by abrasive waterjet impact, is a demonstrated safe procedure. Parameters such as water pressure, orifice size, and abrasive size can be chosen to perform in a safe operating region, based on existing projectile impact models, for all secondary high explosives from PETN to TNT. Other parameters can be used to optimize the performance of the system and tailor it to the individual operation needs.

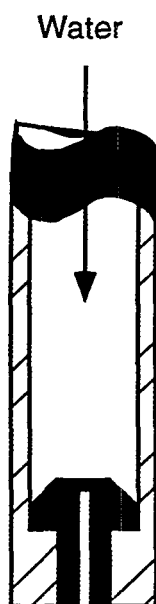


Figure 1. Waterjet

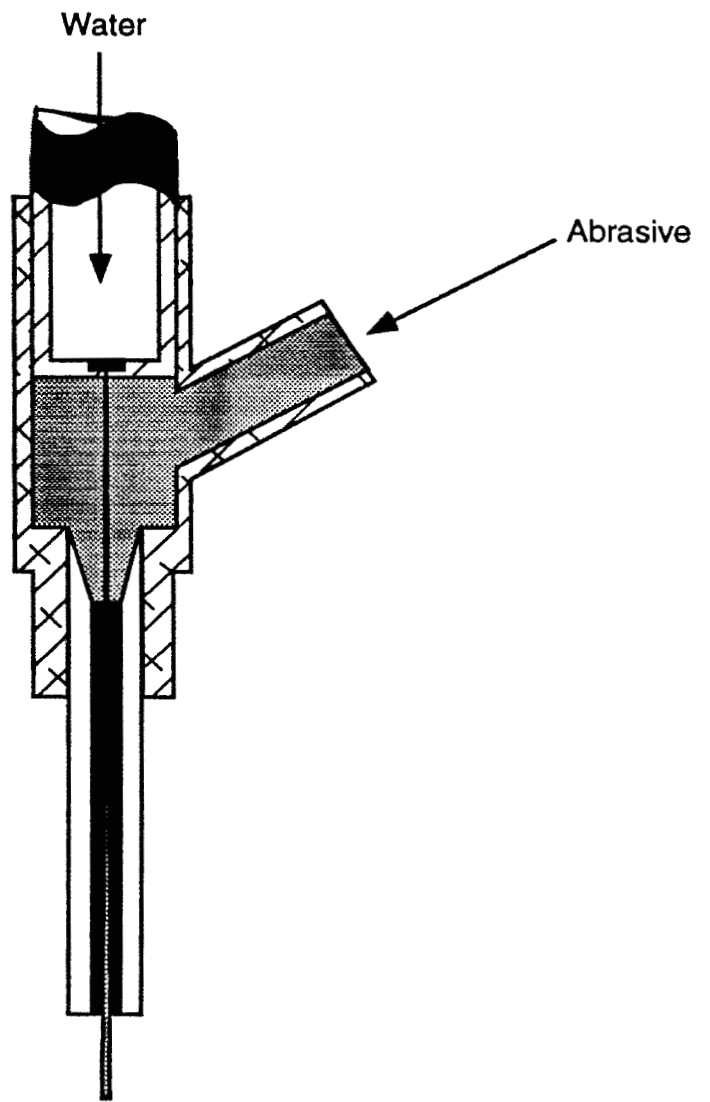


Figure 2. Abrasive Waterjet

Water/abrasive mix

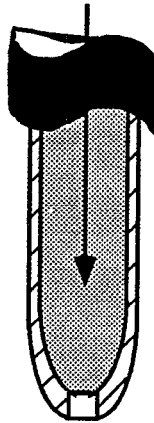
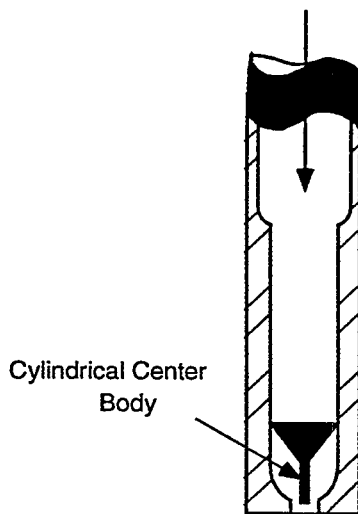


Figure 3. Slurry Jet

Centerbody Cavijet®
Induces cavitation by
flow separation.



Organ-pipe Stratojet
Cavitating Jet Configuration



Figure 4. Cavitating Waterjets

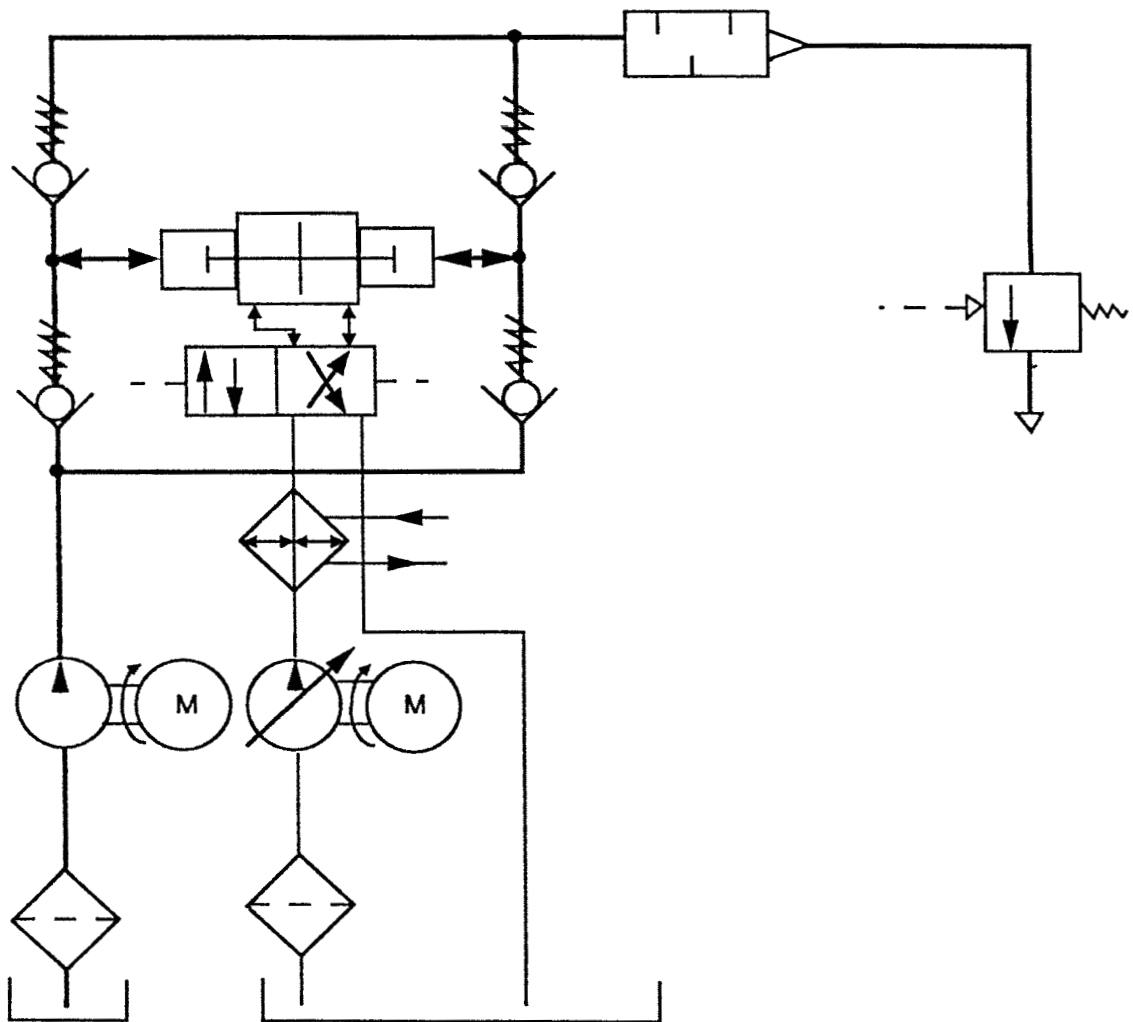


Figure 5. Waterjet Schematic

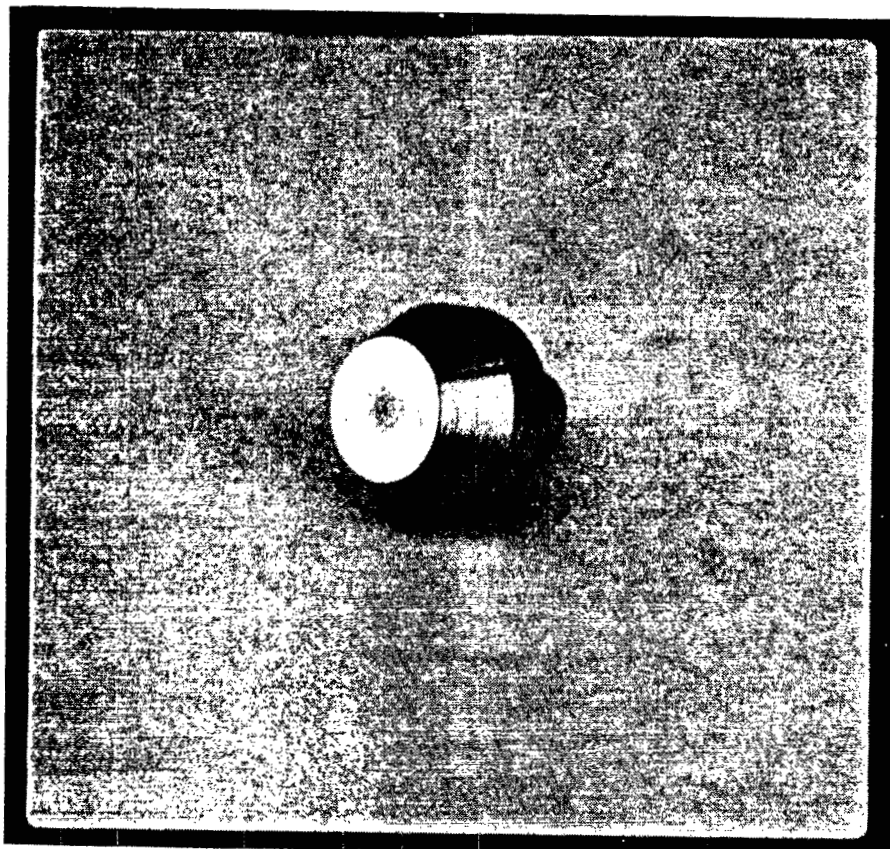


Figure 6. High Pressure Orifice

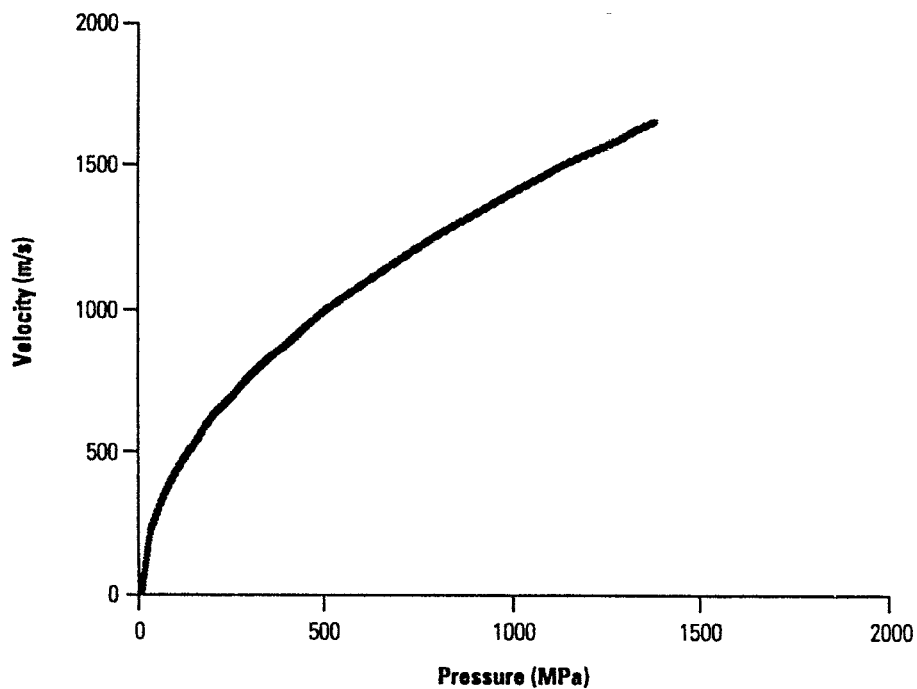


Figure 7. Velocity of Jet Stream vs. Pressure

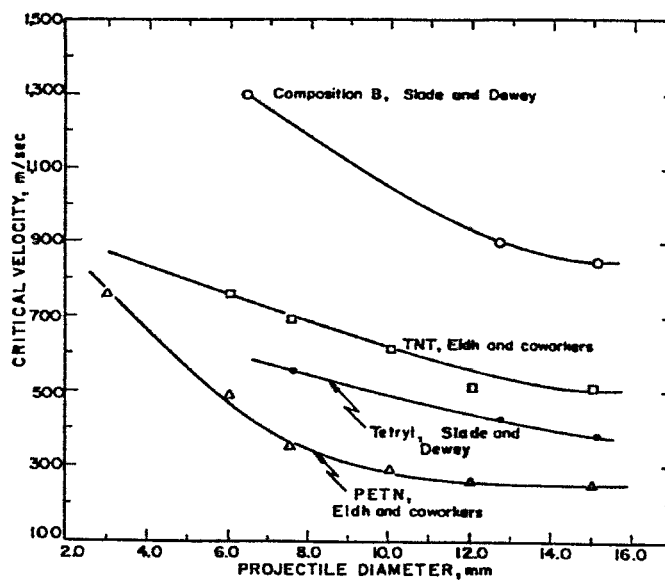


Figure 8. Critical Velocity vs. Projectile Diameter, from Bureau of Mines RI6986

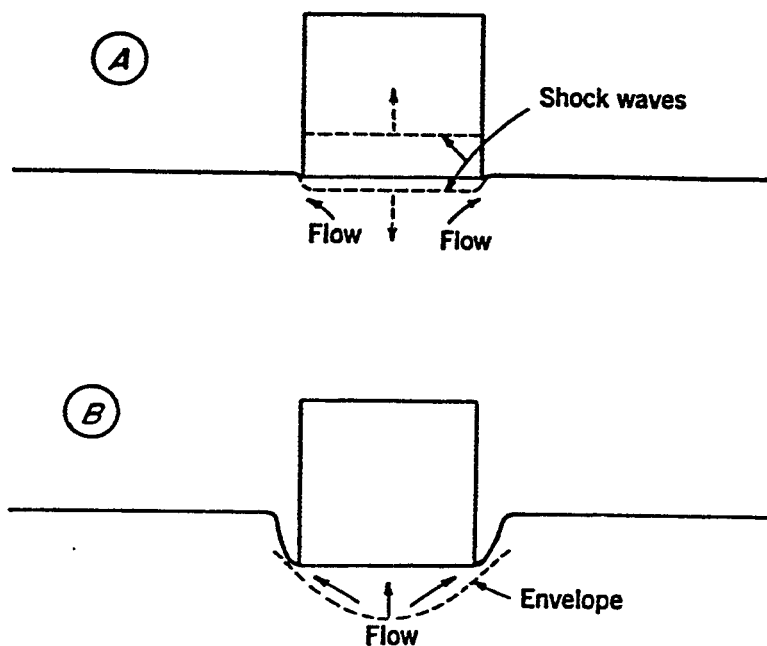


Figure 9. Projectile Impact. A: Position of shock waves in projectile and explosive and flow pattern in explosive after less than 1-mm penetration. B: Steady-state penetration of explosive by projectile. From Bureau of Mines RI-6986

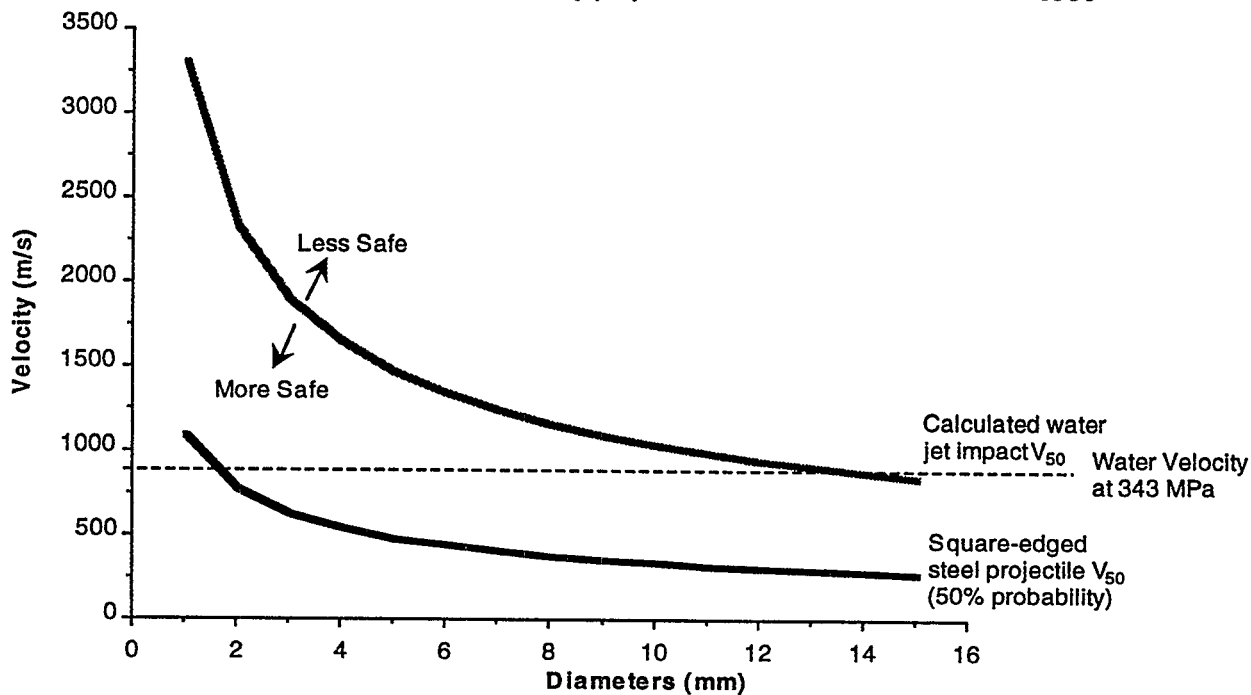


Figure 10. Projectile Impact Velocity vs. Diameter: PETN

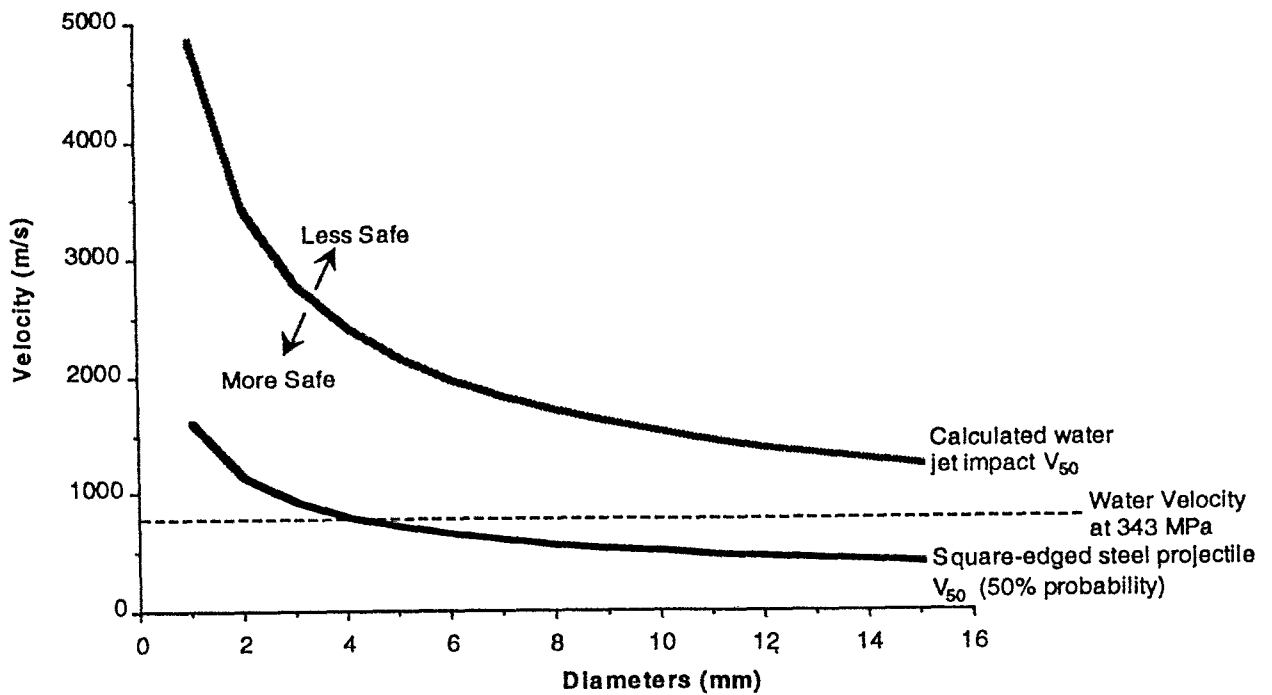


Figure 11. Projectile Impact Velocity vs. Diameter: RDX

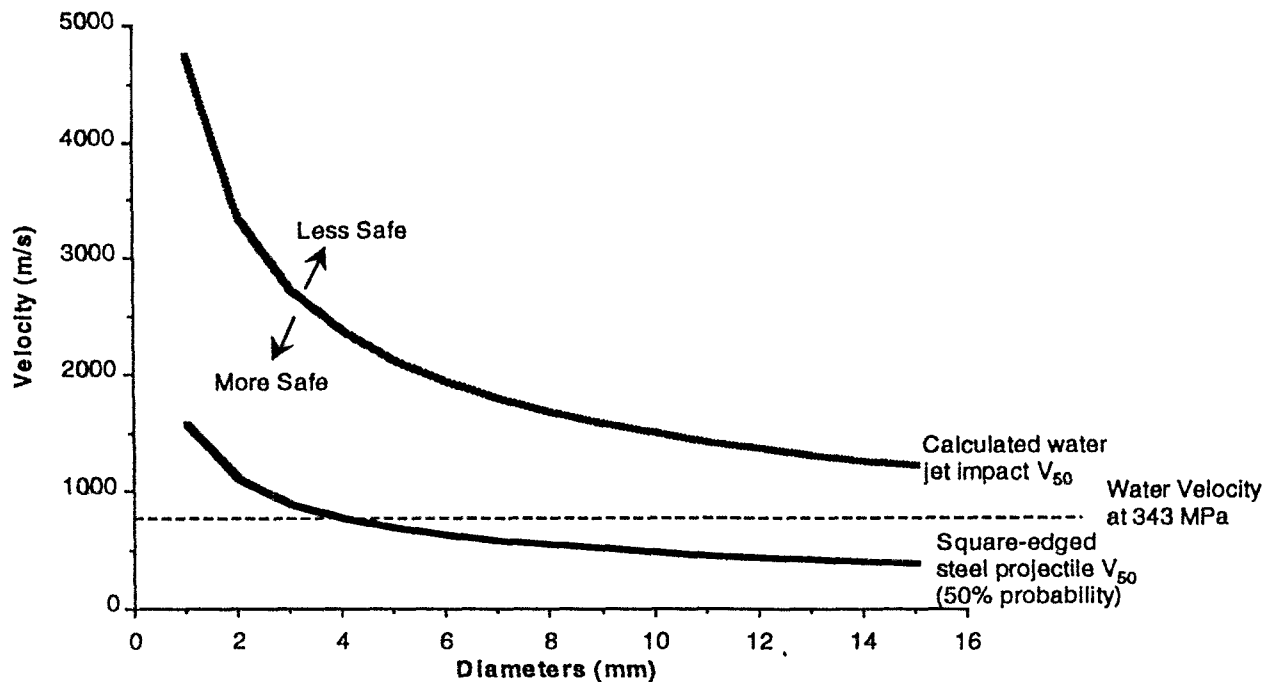


Figure 12. Projectile Impact Velocity vs. Diameter: HMX

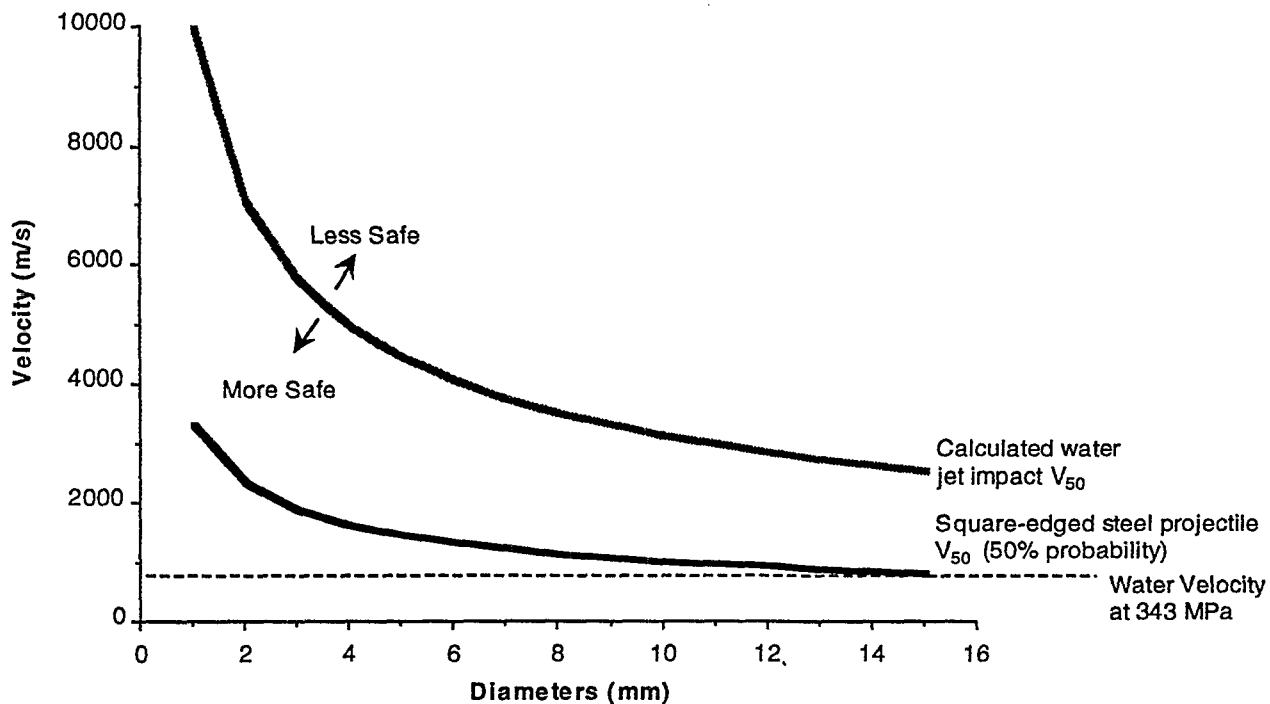


Figure 13. Projectile Impact Velocity vs. Diameter: Composition B

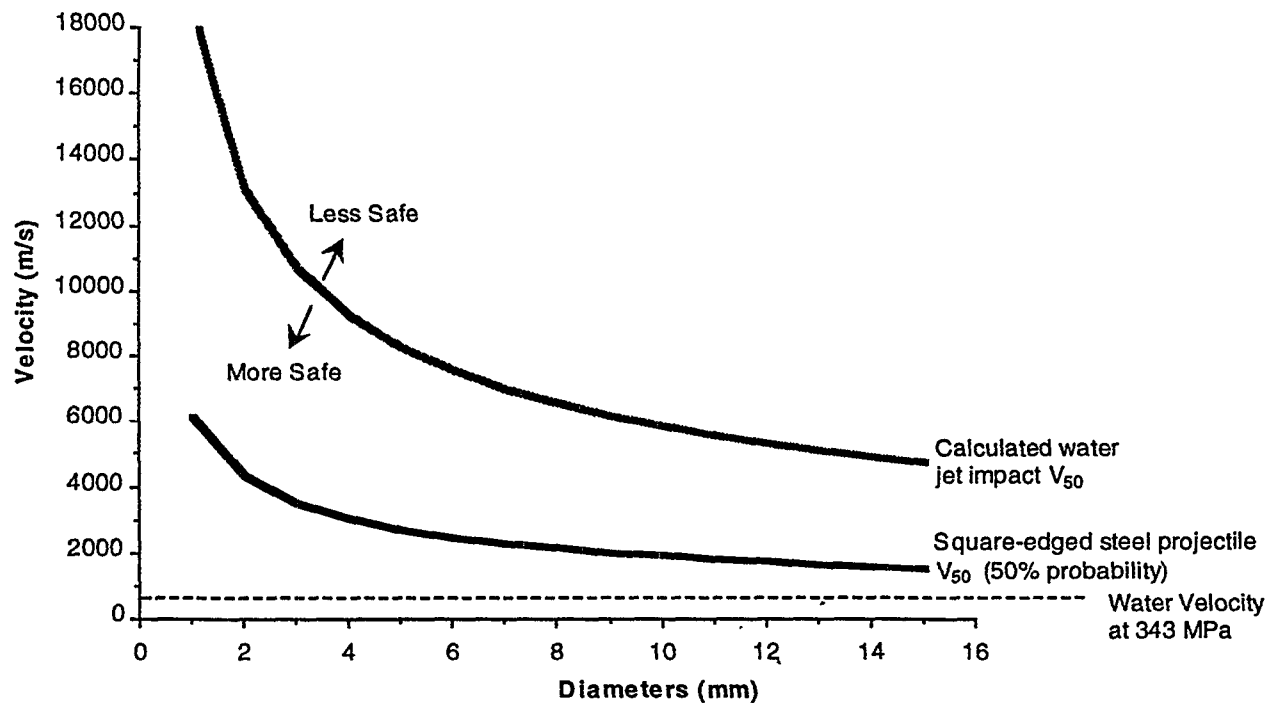


Figure 14. Projectile Impact Velocity vs. Diameter: TNT

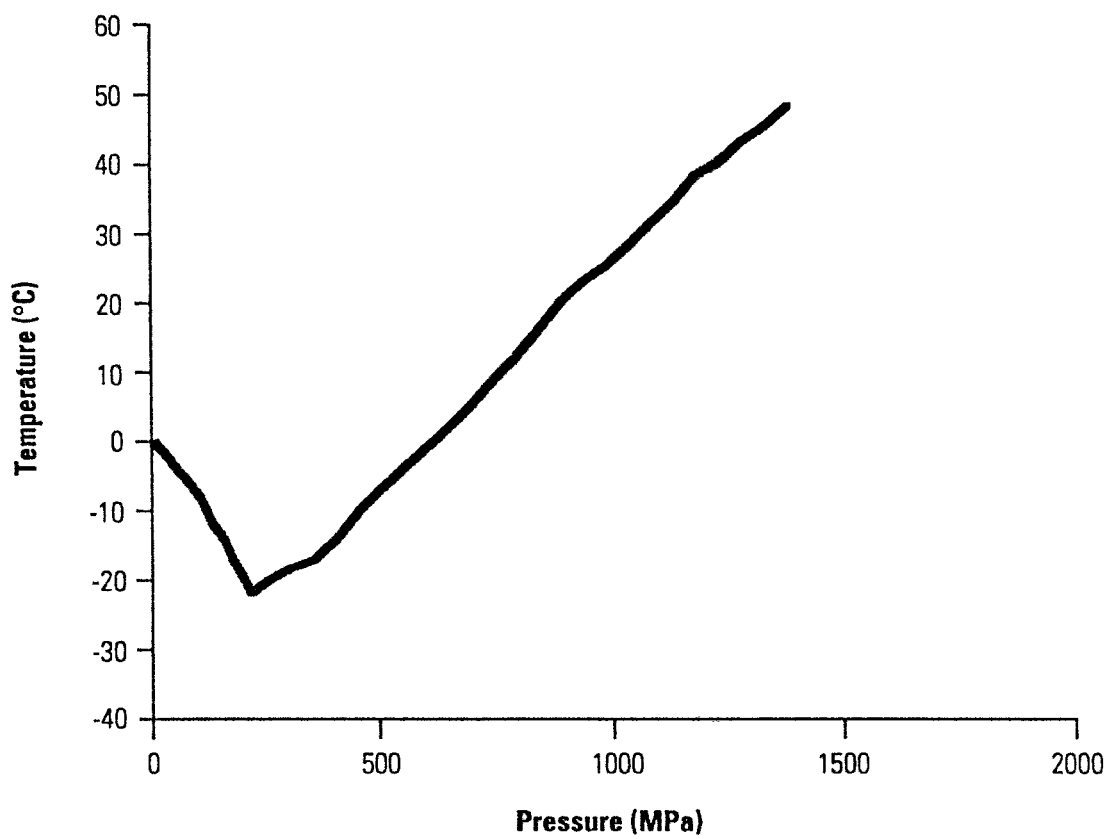


Figure 15. Freezing Point of Water vs. Pressure

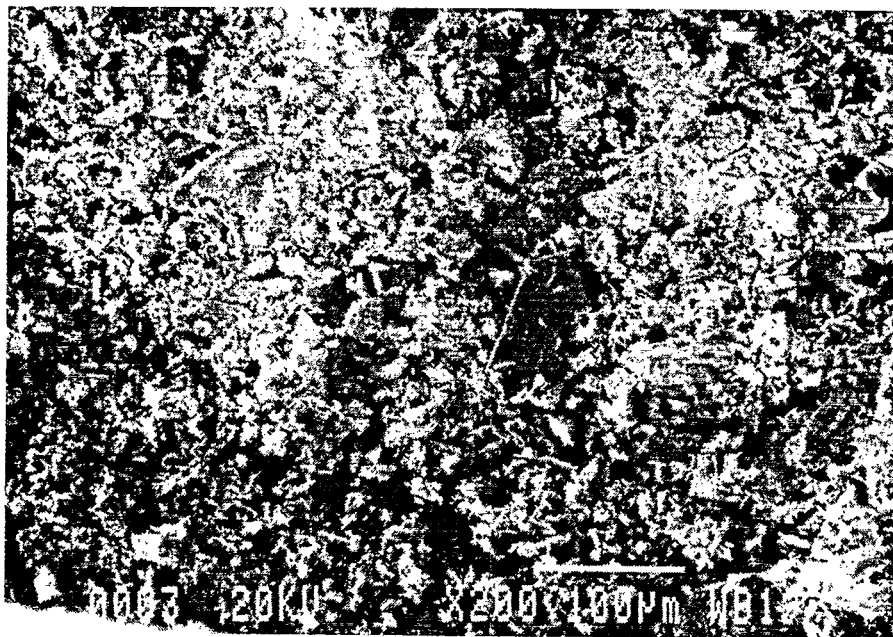


Figure 16. Typical Abrasive Waterjet Swarf

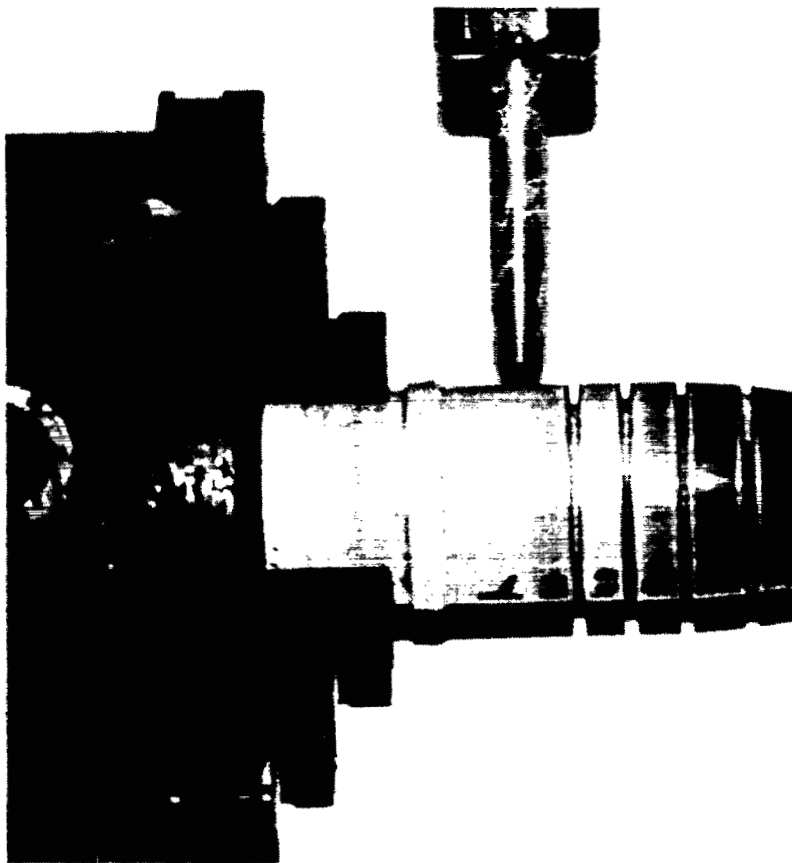


Figure 17. Rotational Cutting with Abrasive Waterjets

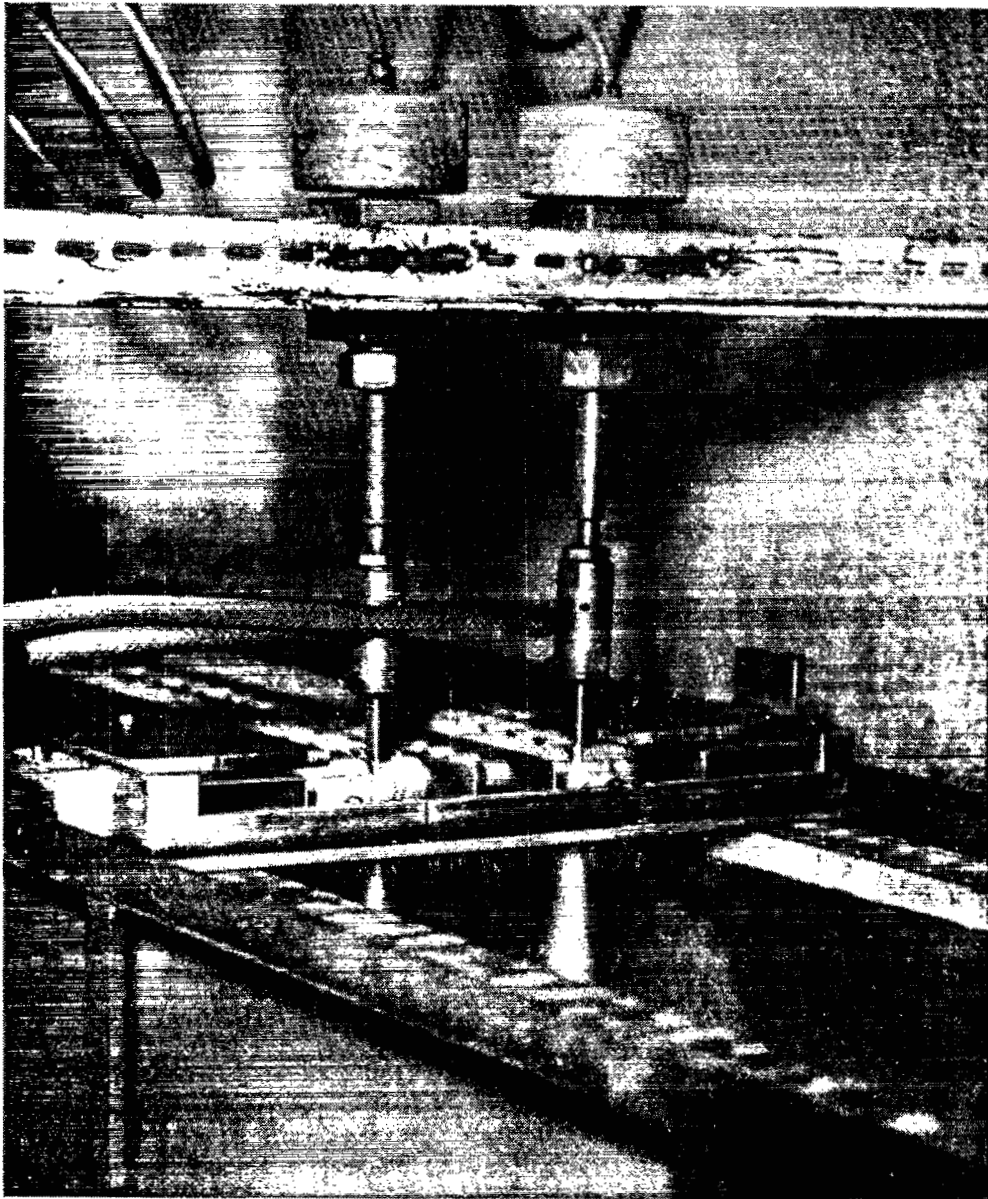


Figure 18. Abrasive Waterjet Cutting 30mm HEI Projectiles

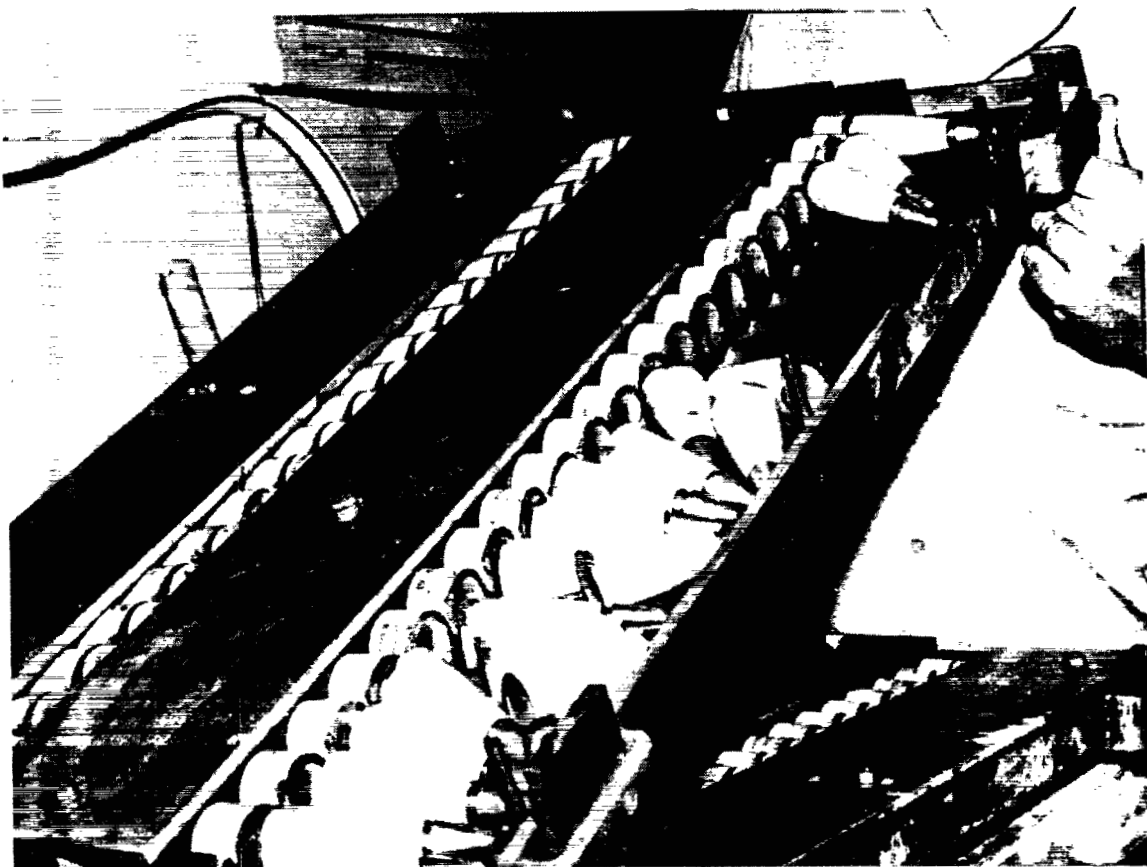


Figure 19. Laterally Abrasive Waterjet Cut 30mm HEI Projectiles