# A Retrospective Study on the Safety of Waterjet (WJ) and Abrasive Waterjet (AWJ) Processing of High Explosive Ordnance

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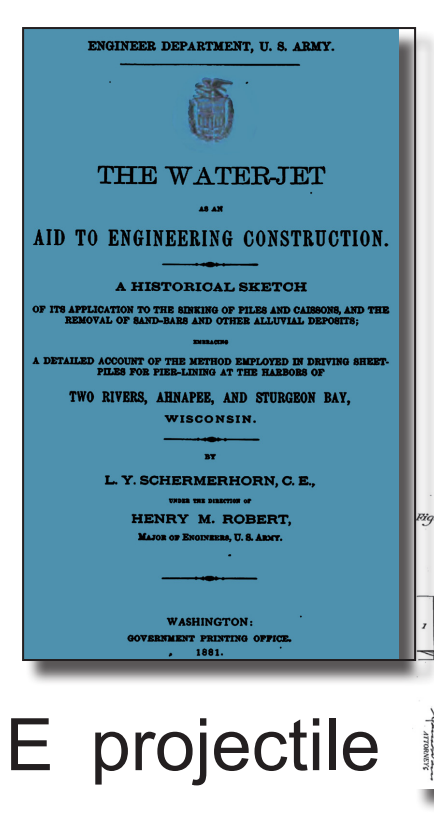
**BLUF -** (Bottom Line Up Front) Waterjets and Abrasive Waterjets have been shown to be **safe** for washing out and cutting munitions containing high explosives by theoretical and empirical testing for almost 100 years

# Background

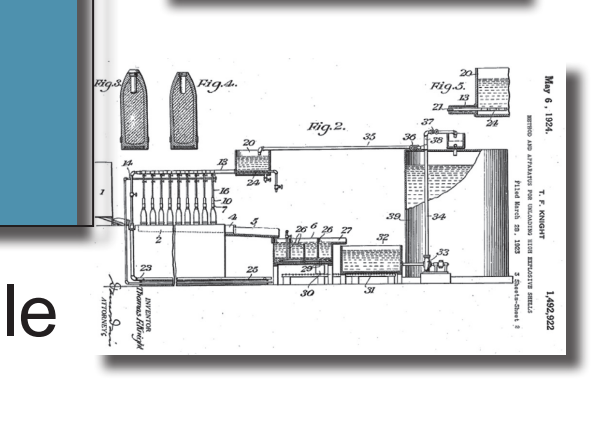
**1852 -** Lt. George **McClellan** (USACE) invents waterjets for a military civil engineering operation in Texas

**1853 -** Anthony **Chabot** reinvents WJ for hydraulic mining in California's Gold Country


ENGINEER DEPARTMENT, U. S. ARMY.
THE WATERJET AS AN AID TO ENGINEERING CONSTRUCTION.
A HISTORICAL SKETCH
L. Y. SCHERMERHORN, C. E.
HENRY M. ROBERT,
WASHINGTON:
GOVERNMENT PRINTING OFFICE.

**1870 -** Bvt. Brig. Gen. (ret.) Benjamin C. **Tilghman** awarded patent for abrasive waterjet cutter to cut stone and glass

**1879 - USACE** uses WJ for Mississippi River civil engineering projects for reshaping the river flow



**1923 -** Thomas **Knight** awarded WJ patent to washout HE projectiles

**1932 -** Howard **Deck** and Pasquale **DiCosmo** patent HE projectile washout system at Picatinny Arsenal

**1933 -** Charles **Fourness** and Charles **Pearson** develop WJ slitter for the commercial paper industry

**1940s -** Ammunition Peculiar Equipment (**APE-1300**) ***Explosive Washout Plant*** developed to washout HE projectiles

**1950s - Thiokol** (Redstone Arsenal) develops WJ solid propellant washout system for recovering rocket motors; **Aerojet**, **NSWC-Indian Head**, and **NSWC-Crane** quickly follow

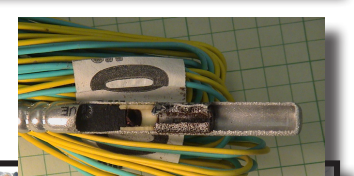
**1958 -** Billie **Schwacha** (North American Aviation) patents high-pressure AWJ for cutting exotic metals for the futuristic XB-70 ***Valkyrie*** bomber

**1960s -** Norman **Franz** and Eugene **Bryan** research high-pressure WJ for cutting wood under a U.S. FPL grant and restarts interest in high-pressure WJ

**1970s -** Mohamed **Hashish** and Gene **Yie** independently commercialize Franz's work into the modern high-pressure WJ and AWJ systems available today

**1980s -** Robert **Fairhurst** develops the abrasive slurry jet (ASJ); David **Summers** provides critical safety research on the impact of high-pressure waterjets on high explosives under contract to NSWC-Crane; Western Area Demil Facility installs South Tower *Hardware Hydraulic Cleaning Systerm* for projectile demilitarization; Richard **Hanson** invents PAN Disrupter (*MK40 MOD 0 Unexploded Ordnance Standoff Disrupter Tool*) which shoots a slug of water to disable terrorist bombs

**1990s -** Paul **Miller** uses high-pressure AWJ for cutting 172,000 HE projectiles; performs safety tests on HE at pressure of 1 GPa (147 ksi); DOE (James **Cruchmer**) independently confirms research



**1997 -** DOE (Brett **Board**) hazards analysis confirms AWJ safe to cut steel containers holding radioactive haz waste in flammable hydrogen-air atmosphere

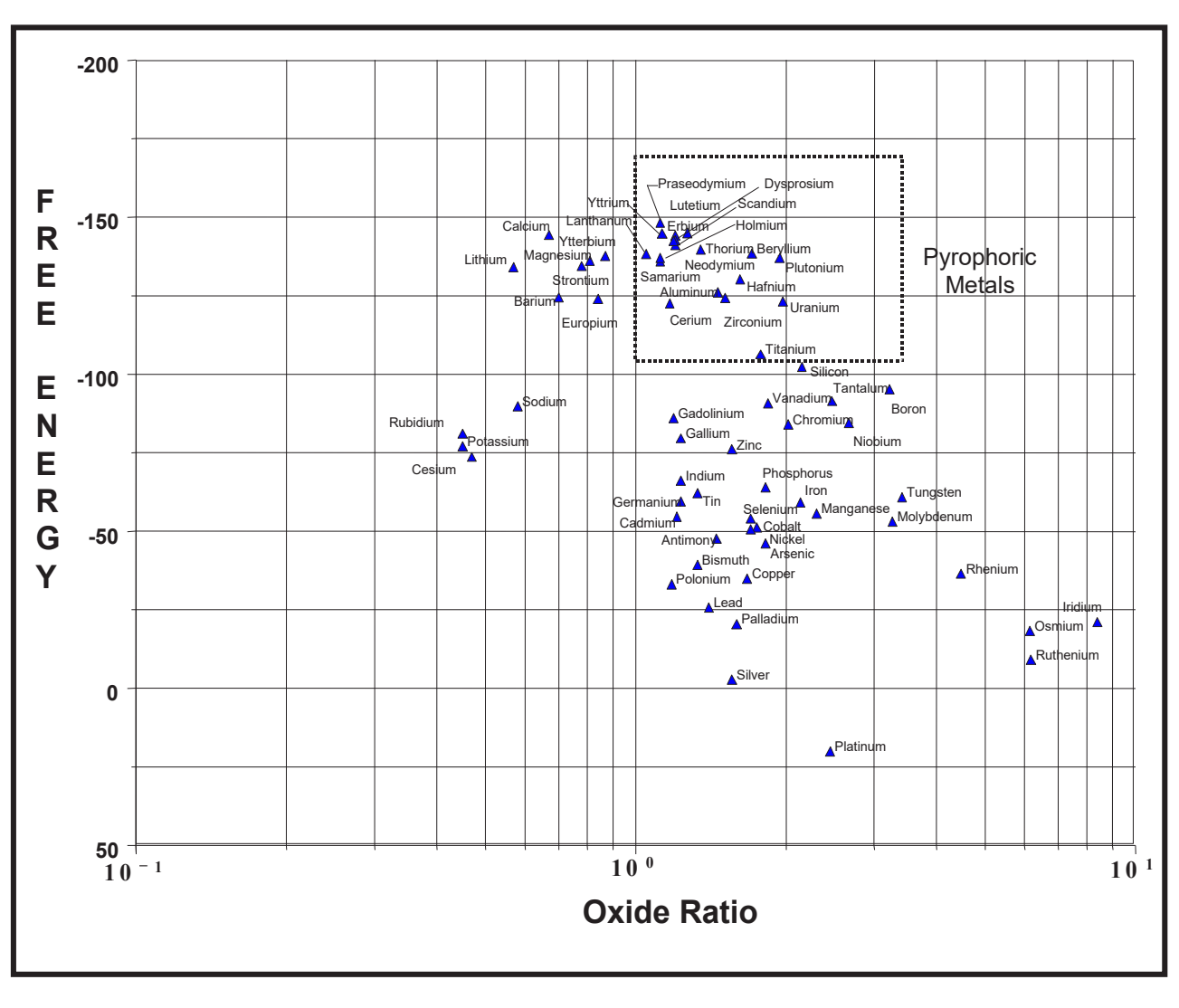
**2000 -** High-pressure AWJ+WJ projectile demilitarization line installed at **Crane Army Ammunition Activity** (CAAA) with 300,000 projectiles processed to date

## Ignition Safety Tests -

WJs and AWJs have been tested in flammable gas environments to determine the safety of cutting metals. One safety observation is that small sparks are occasionally seen when using abrasives in AWJs. Sparks of any nature are of great concern to safety personnel for both munition demilitarization and DOE facilities deconstruction. In the first case, high explosives and propellants are sensitive to ignition by sparks, and in the second case the radiolysis of water generates large quantities of highly flammable hydrogen and oxygen gases which can deflagrate if ignited. In both cases, the energy required for ignition is extremely low. Dahn and Reyes (1994) published that very fine TNT has a minimum-ignition-energy (MIE) of only 12 mJ. The ignition energies of hydrocarbons in an oxygen atmosphere have an MIE of only 0.002 mJ, while hydrogen in an oxygen atmosphere has an MIE of only 0.001 mJ according to NFPA 53 (1994).

The results of various empirical and theoretical studies confirm field experience that AWJs are safe to cut steels and most other metals around flammable gases, liquids, and solids. Research performed by Elvin and Fairhurst (1985), Board (1997), Miller (1999), and by Usman (2009) showed that ASJs and AWJs did not ignite hydrocarbons or hydrogen when cutting common steels. Miller (1999) also tested AWJ cutting of steel in a hydrocarbon-oxygen atmosphere as well as in a hydrogen-oxygen atmosphere.

Hillstrom (1973) showed that the chemistry and reactivity of the metal forming the mechanical spark played a significant role in the fuel ignition process and only some nineteen metals were effective pyrophoric materials. This is reflected in Bartknecht (1987) conversion graphs as some metals are much more capable of igniting flammables than others. In order to be an effective pyrophoric material, the metal had to produce sufficient heat from oxidation and the metal oxide coating forming on the metal particle had to be able to transmit that heat to the surrounding combustible gas or solid. Iron and steel were among those metals that were identified by Hillstrom (1973) as not being sufficiently chemically reactive and pyrophoric. Miller's (1999) research confirmed that cutting certain exotic metals, such as zirconium, with an AWJ could ignite hydrogen-air mixtures, but only with a low probability, while cutting steel in hydrogen-oxygen atmospheres would not ignite.



**Pyrophoric Metals**
Only certain metals can create pyrophoric sparks according to BRL (Hillstrom, 1973)

## Impact Flash -

Another concern safety researchers have noted is that the high velocity WJ or AWJ impact on a target can create a luminous discharge, known by researchers as an "impact flash." The luminescence observed during the impact process has been attributed to adiabatic compression, superheated ejecta, burning ejecta, or even detonating reaction products as shown in Bestard and Kocher (2010). All of these concerns focus on the formation of very hot thermal incandescence that could initiate and propagate an explosive reaction or are the products of an incipient reaction. It is well known in the safety profession that all of these events are possible with ever increasing impact force, but WJ can cause the observed "impact flash" even on non-explosive materials, and the targets show no post-impact heat affected zone.

Prevenslik (2003) showed that shocked argon caused the impact flashes, seen from WJ impacts on both inert and energetic targets, as all water contains dissolved argon gas unless freshly distilled. Anbar (1968) showed that water droplets dropped into air-saturated water at velocities as slow as 5 m/s (16 ft/s) create luminescent impact flashes – equivalent to a drop of only 1.3 m (4.25 ft). Winning and Edgerton (1952) detail the construction of an explosive argon flashlamp for photographing extremely high speed events. The initiation of a small explosive charge creates a shock wave in the argon gas, resulting in the intense light. The use of high-intensity explosive light sources has become standard practice in high-speed photography to generate extremely bright flashes of light. Sultanoff (1962), of the U.S. Army's Ballistic Research Laboratory, specifically states that argon luminescence is a function of the shock pressure and is not due to burning or due to the gas being heated to thermal incandescence.

Consequently, the flashes of light from WJ impact or water cavitation from commercial WJ systems are of no concern for safety personnel.

# Introduction

Waterjets (WJ) are a non-traditional technology that have evolved from a low pressure civil and mining engineering tool to a high pressure machining tool over the last 150+ years. Although still a novelty to many, they have been used for the demilitarization of high-explosive munitions for the last 95 years.

Later WJ variants using added abrasives, known as abrasive waterjets (AWJ), gave them the capability of cutting steels and other hard materials. AWJs have been used for the demilitarization of high-explosive ordnance for almost thirty years. This retrospective overview of WJ and AWJ safety analyses was performed to compile the available information for explosive safety professionals.

# Safety Studies

The two key questions that explosive safety professionals should ask regarding using high-pressure WJs on HE ordnance are:

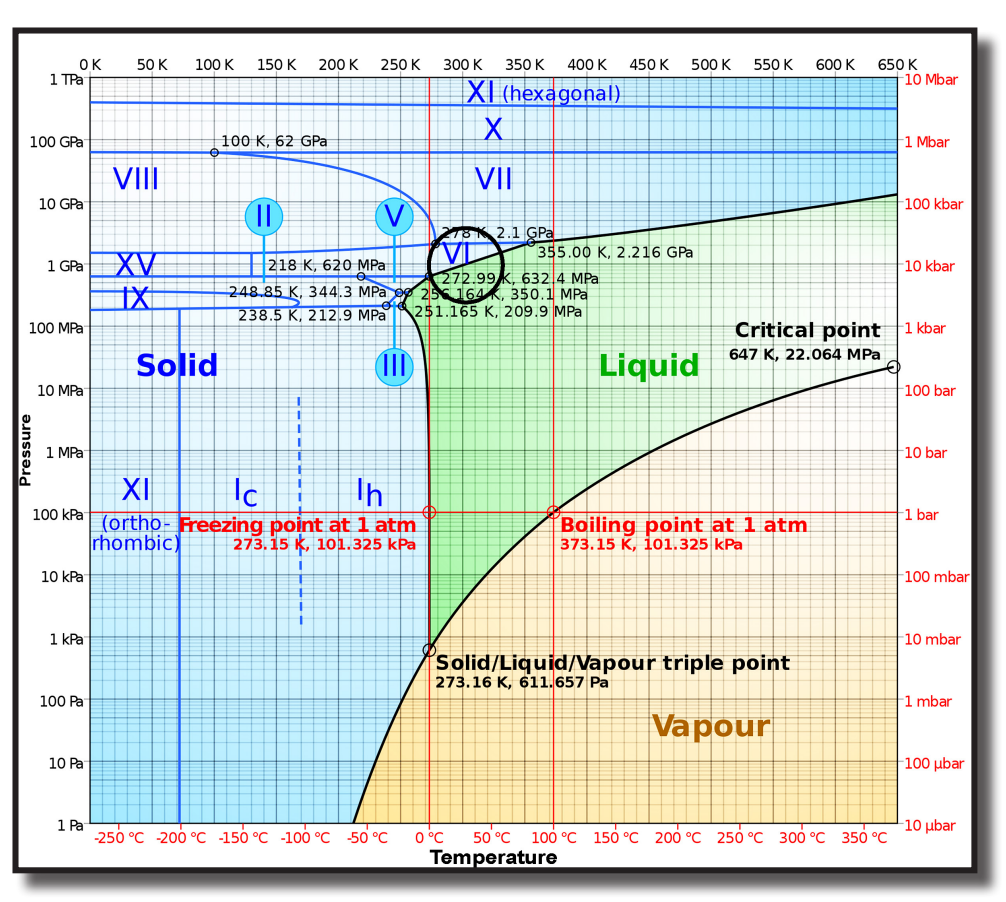
1) Can WJs ***ever*** initiate secondary high explosives or propellants?
**YES –** providing the WJ is sufficiently fast and is sufficiently large enough in impact area. Research by Summers, et al., (1988) has shown this.

2) Is initiating secondary high explosives ***likely*** with a commercial unit (rather than a research setup)?
**NO –** It is extremely unlikely that a commercial WJ can ever initiate secondary high explosives or propellants. Physics makes it functionally impossible to achieve the velocities or the large enough jet diameters required to detonate secondary high explosives with current commercial units.

## Explosive Safety Tests –

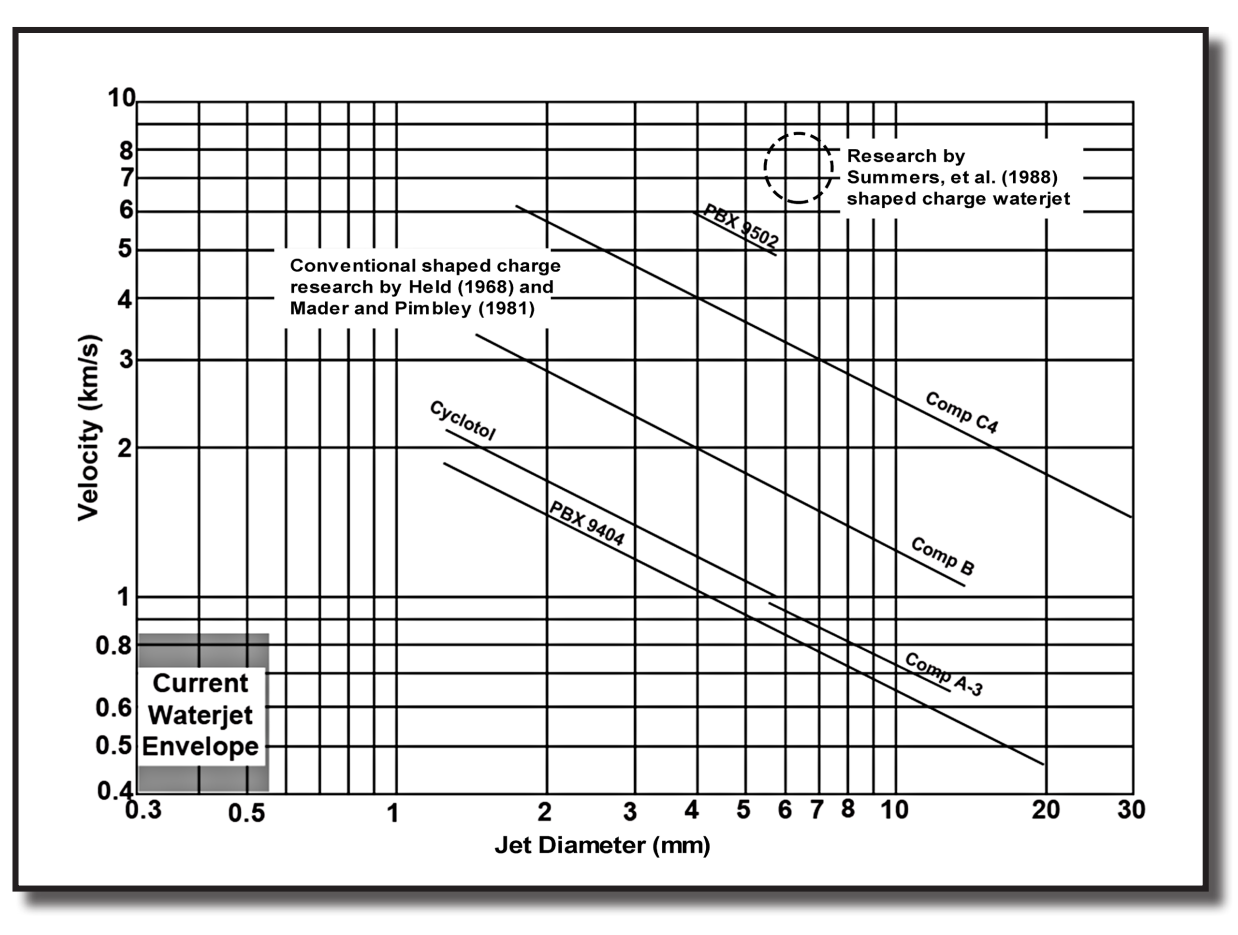
WJs and AWJs share many similarities with shaped charge jets and the same mechanics can be used to predict the reaction of explosives to jet impact. WJs operate at velocities of 0 - 1.5 km/s, as compared to explosive shaped charge jets which travel at velocities of 1 to 14 km/s. Extensive tests were conducted by LANL (Mader and Pimbly, 1981) and Summers, et al., (1988) in which they accelerated water using explosive shaped charges to velocities in excess of five times the sonic velocity of water in order to achieve a reaction in secondary high explosives. These tests do not reflect the realities of a commercial WJ system.

First of all, the discharge of water pumped through an orifice is limited by physics to subsonic flows, and supersonic speeds cannot be achieved by commercial WJ cutting systems due to choked flow conditions at the orifice. Secondly, since water at 1 GPa (147 ksi) freezes at 25°C (77°F) this effectively becomes the upper pressure limit for commercial WJs. The velocity of water at this temperature and pressure is approximately 1426 m/s (4680 ft/s), or very close to the published speed of 1496.65 m/s (4910 ft/s) for the sonic velocity of water (McSkimin, 1965).



**Physical Pressure Limits**
The maximum pressure a conventional WJ can achieve at room temperature (25°C) is 1 GPa because water freezes

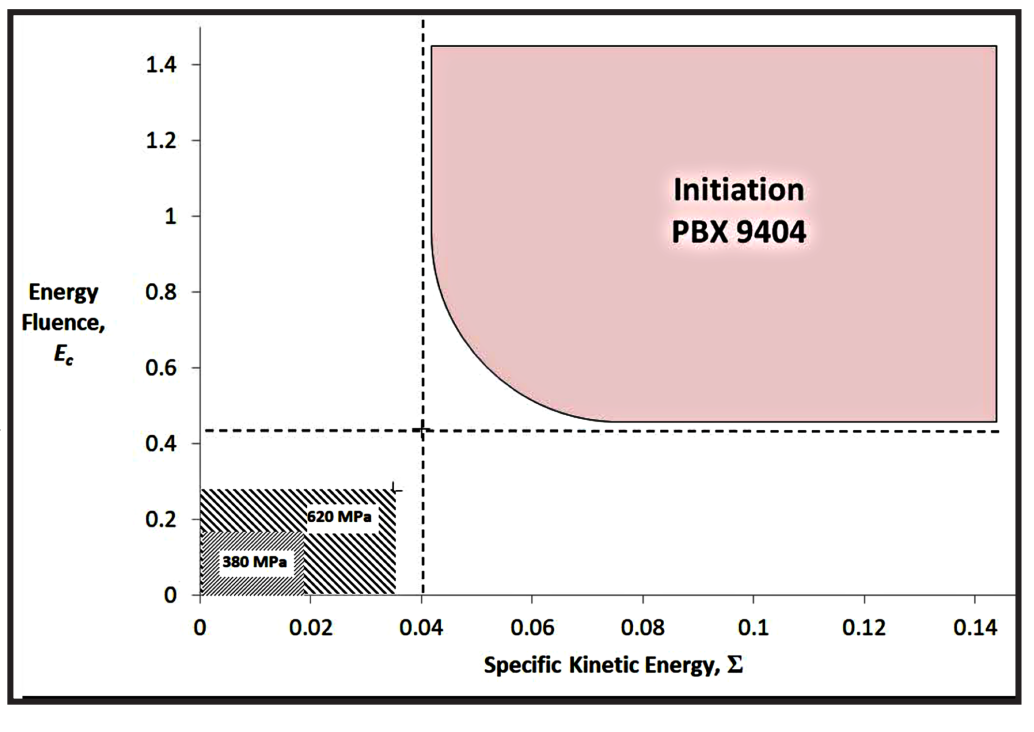
In addition, research on high explosive initiation has shown that both velocity and impactor diameter are critical parameters. Slade and Dewey (1957), Roslund, et al., (1974), Field, et al., (1982), Chan (1985), and Liddard and Roslund (1993) all showed that the impactor's velocity (V), diameter (d), and shape (round or flat nosed) act together to determine the probability of the explosive's initiating. The body of research confirms the predictive equation known as the Jacobs-Roslund equation (Roslund, et al., 1975). High-pressure WJs can only operate at relatively small (<1 mm) diameters.



**Relationship Between Velocity, Diameter, and Density**
Conventional WJs cannot achieve the velocities necessary for secondary explosive initiation, but explosively driven research waterjets can

Held's (1987) work focused specifically on copper-lined shaped charge jets and showed a relationship between the product of a shaped-charge jet's diameter (d) and velocity (V) squared ($V^2d$) and a specific explosive's detonating. Mader and Pimbley (1981) further refined Held's equation and showed that a specific relationship for initiation of a given explosive was based on the product of the density of the jet (ρ) in gm/cm$^3$, the square of the velocity ($V^2$) in mm/μs, and the diameter of the jet (d) in mm, or $\rho V^2 d$.

More recently, James (1996) of AWE-Aldermaston (UK) developed a critical energy criterion based on work performed by Walker and Walsey (1969) at Lawrence Livermore National Laboratory. The James Criterion establishes a threshold using the critical energy ($E_c$) defined by Walker and Wasley (1969) and the activation energy.



**Hugh James Graph**
WJs have significant safety margins for processing sensitive high-explosives

## Electrostatic Discharge (ESD) -

WJs can, unfortunately, generate electrostatic charges that are potentially hazardous to personnel and harmful to equipment and product as shown in Miller (2001). Several serious fires have been attributed to static discharge during WJ cleaning operations, and static electric arc discharge has been known to damage composite materials. The WJ industry's trend toward using higher velocity liquid jets and higher purity water increases the risk of electric spark generation.

It is a well-known phenomenon in engineering that flowing gases and liquids can generate large amounts of static electricity. The generation of static electricity from flowing gases and liquids even occurs during the operation of items expected to be "safe." A classic example is the generation of up to 5,000 volts during the discharge of a carbon dioxide fire extinguisher as described by Petrick (1968). Reif and Hawk (1974) showed that three very large crude oil carriers (VLCC), or oil-tankers, were destroyed in December 1969 from electrostatic discharge during routine washdown by jets of water.

## Accidents and Events -

There have been several explosions related to using WJs with energetics:

- Summers (1996) discussed a fire during a 103 MPa (15 ksi) washout test at MUST (Missouri University of Science and Technology) in the 1980s when a graduate student overtightened a WJ nozzle with a pipe wrench and broke the pipe. When pressurized, the broken nozzle became a projectile and struck the missile warhead resulting in a fire.
- A "puff" (non-propagating ignition) occured during testing of a 114 MPa (16.5 ksi) cryogenic liquid nitrogen (LN2) washout system, according to Spritzer (1999). The cause of the event is still undetermined (ESD?).

Some of the "***reported WJ accidents***" are not really related to the actions of the WJ at all. The following "accidents" are described here for clarification:

- Beaudet (1999) identified that DERA (Defence Engineering and Research Agency) – UK West Freugh, Scotland, reported an accident in 1995 while mechanically reprocessing explosives containing abrasive grit from a ASJ cut made three days earlier. This was a processing accident, not a WJ accident.
- Alliant Techsystems (ATK) had a low-order detonation of a U.S. Navy 8-inch/55-caliber high capacity projectile at their Elk River, MN, facility in 1996 during mechanical defuzing operations according to Beaudet (1999). Although ATK had AWJ systems available at the site but elected to use mechanical defuzing to reduce costs. This event had nothing to do with the WJ system.
- In 2000 Teledyne-Commodore had a fire related to their ammonia processing system. The system used a WJ converted to pumping anhydrous ammonia, but the fire was not related to the cutting of the M61 rocket but due to a secondary chemical reaction several minutes after being cut with the ammonia fluid according to Beaudet (2001).
- A 2000 lb (907 kg) WWII bomb detonated, according to Hall (2010), while bomb disposal technicians were attempting to put a WJ cutter in place in Göttingen (Germany) on June 1, 2010. The fuze was believed to be a UK Type 37 chemical-type time delay fuze and detonated as the WJ was being erected, not during operations.

## Material Incompatibility -

Not all materials are compatible with each other and testing should be performed using a differential scanning calorimeter (DSC) to determine the compatibility prior to process acceptance. Miller and Navarro (1996) showed that powdered aluminum, a common additive in military explosives, can react with water. Shidlovskii (1964) recognized that wet aluminum powder would spontaneously create an exothermic reaction and release hydrogen gas. The most effective control method was developed by Ursenbach and Udy (1962) who added phosphates to passivate aluminum powders used in slurry high explosives for the commercial blasting industry. Ursenbach and Udy recommended diammonium dihydrogen phosphate, trisodium phosphate, sodium dihydrogen phosphate, or mono-ammonium dihydrogen phosphate in quantities from 0.1% to 2.0% by weight in water.

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