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

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Abstract

Waterjets (WJs) have been used for the demilitarization of high-explosive ordnance for over ninety years and abrasive waterjets (AWJs) have been used for cutting high-explosive munitions for about thirty years. This study reviewed the process safety of the technologies from the early low-pressure systems to the physical limits of the systems at 1,000 MPa (147 ksi[1]). Several major safety studies focusing on processing over 700,000 projectiles were distilled into this summary.

A summary of various hazards analyses on WJ and AWJ processes provided a probabilistic risk assessment to determine what could go wrong, how likely the failure was, and what would be the likely consequences of the failure. The summary analysis looks at initiation mechanisms, such as shock, impact, electrostatic discharge (ESD), piezoelectric discharge (PED), friction, shear, thermal particle, and autothermal decomposition.

1 Introduction

Waterjets (WJs) 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.[2] Although still a novelty to many, they have been used for the demilitarization of high-explosive munitions since at least the 1920s. Later WJ variants using added abrasives, known as abrasive waterjets (AWJs), gave the technology 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.

2 Background

The invention of the first WJs is generally credited to Lt. George McClellan, U.S. Army Corps of Engineers (USACE), as shown in Schermerhorn (1881), who argued that McClellan first used WJs on February, 1852, at Decrow's Point, Matagorda Bay, Texas, for civil engineering projects. As with most inventions the origin is somewhat clouded in history. Alternative arguments on the initial inventor, according to May (1970), variously give credit for the waterjet to Anthony Chabot, Edward Matteson, and/or Eli Miller on March 7, 1853, for hydraulic mining of gold at the French Corral mine in Nevada County, California, near the town of Dutch Flat (Hittell, 1898). The introduction of hydraulic mining to the California gold fields had an immediate and enduring impact.

The volume of water used on the gold field hydraulic mining monitors can be inferred from Bowie (1878) who mentions “nine-inch nozzles under 450-foot pressure” (0.23 m nozzle at 1.35 MPa [195 psi]) that operated 24 hours a day. Lindgren (1911) stated that the monitors *typically* delivered about 19,000 liter/min (5,000 gpm).

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[1] ksi is 1000 psig.

[2] WJs work by expelling pressurized water through an orifice to form a high-speed jet stream. Unfortunately, the term “waterjets” is so broadly defined that there are at least nine different technologies all identified as “waterjets” that are only minimally related to each other. For example, the marine propulsion technology, such as is used to power jet-skis and the Navy “Patrol Boat, Riverine (PBR) Mk II,” is probably the most common “waterjet” reference in DTIC.

The USACE continued to use low pressure WJs for civil engineering projects and for improvements of the Mississippi River waterway at least through the 1920s, according to Elliot (1932). The Russians started using WJs for mining coal in 1934, according to Muchnik (1956), as did the U.S. Bureau of Mines in 1959, according to Buch (1965). According to Summers (1995) WJs are still used for hydraulic mining today, although their use is somewhat limited by environmental restrictions.

Starting in the 1930s commercial industry began using higher pressure WJs for cutting paper, according to Fourness and Pearson (1933). The paper industry continues to be a major user of high-pressure WJs as the jet cutting stream never dulls and doesn't tear fragile paper products. Johnson (1956) commercialized WJs for cutting plastics and soft materials. Many car interiors are currently cut using WJs, according to Summers (1995). WJs also became more entrenched in industry as pressure washers for cleaning equipment and ships. Probably the most common WJ systems people encounter today are the pressure washers for cars and equipment available at home improvement centers.

In the early 1960s Franz and Bryan (1963) performed commercial research using 393 MPa (57 ksi) WJs for cutting wood. This research spurred the expansion of WJs into much higher pressures, as shown in Hashish (1977) and Hashish (1978). The commercial high-pressure WJ industry has since rapidly expanded into cutting everything from toilet paper to advanced aircraft metals and composites (Summers, 1995). Franz's (1968) contribution to the WJ industry was so significant that he is often erroneously given credit for "inventing" the WJ. At best he only "reinvented" an existing process, but he can be credited with greatly popularizing it.. As with all large leaps in technology the concept was unknowingly reinvented repeatedly by different researchers over time.

AWJ

AWJs, also known as "entrainment abrasive waterjets," work by using a venturi section to entrain abrasive into the high velocity jet stream. The abrasive is accelerated by the jet stream and performs almost all of the cutting action. The inventor of the AWJ is a little easier to identify as Bvt. Brig. Gen. (ret.) Benjamin C. Tilghman was awarded a patent for entraining abrasives into a high velocity stream of water in 1870 for cutting stone (Tilghman 1870). Tilghman envisioned using high velocity air, water, or steam as the accelerating medium. His patent also gives us the common "sand blaster" using air as an alternative medium for accelerating the abrasive.

Some 80 years later AWJs were "reinvented" using 690 MPa (100 ksi) oil and abrasive by Schwacha (1958) to cut exotic metals for the futuristic XB-70 *Valkyrie* bomber at *North American Aviation*. Hamburg (1969) states that Franz also used abrasives entrained in a WJ. Critical process research by Yie (1982) and Hashish (1984) significantly improving the AWJ venturi mixing head (also known as the "cutting head") allowed AWJ to begin to achieve its real potential as a controllable cutting system. Consequently both gentlemen are often incorrectly attributed as the inventors of AWJs; they did, however, make the system more practical and commercially available. Many commercial and military fabrication shops now utilize CNC-driven AWJ systems for cutting metals, composites, stone, glass, and ceramics that are directly descended from their work.

Abrasive Slurry Jet (ASJ)

An alternative abrasive cutting process, known as an abrasive slurry jet (ASJ), operates by premixing a slurry of abrasive and water (typically with a suspension agent added) and pressurizing the slurry mixture to high pressures and ejecting it through an orifice. The ASJ system was developed in the UK in the early 1980s and is still popular in Europe. Fairhurst (1982) is generally given credit for developing the ASJ system, but Brown and Roebuck (1960) disclosed using a similar system of pressurized abrasive slurry and forming jets to perforate oil wells some twenty years earlier.

The ASJ has both distinct advantages and disadvantages when compared to the AWJ. It can operate at much lower pressures than an AWJ and has a higher overall efficiency. It does, however, require large pressure vessels for pressurizing the abrasive slurry and the maintenance issues are significantly greater. Consequently, the ASJ is rare in the United States.

Military Applications of WJs

In the 1920s civilian contractors started utilizing WJs to demilitarize surplus World War I munitions (Knight, 1923), and the military followed soon afterwards (Deck and Di Cosmo, 1932). According to Zajicek and Ansell (1990) these early WJ washout systems evolved into the *Ammunition Peculiar Equipment* (APE)-1300 *Ammunition Washout and Reclamation System* in the 1940s. The very low pressure of 0.62 MPa (90 psi) and the high volume of water used by these early systems, however, limited their production rate and created large amounts of contaminated water. The large volumes of water created an environmental issue that is still being addressed.

In the recent past, military combat engineers have successfully used WJs for tactical military applications. According to Kopets (2003) the Egyptian army overran the Israeli *Bar Lev* Line during the *Yom Kippur War* (October, 1973) using WJs (also called “water cannons”). Pankove and Louie (2005) detail how five Egyptian armored divisions crossed the Suez Canal and breached the 18 m (60 ft.) high earthworks in less than 2 hours using the WJs.

The use of medium pressure (13.8 MPa to 100 MPa [2 ksi to 15 ksi]) WJs for the demilitarization of rocket motors was first used by *Thiokol* at Redstone Arsenal in 1954, according to Padgett (1962). Kwak, et al. (1990) stated that the Thiokol system used 69 MPa (10 ksi) water at 454 liter/min (120 gpm). *Aerojet* and *Thiokol* both used medium-pressure, high volume WJ systems to remove up to 454 kg/hr (1,000 lb/hr) of propellant from rocket motors, according to Zajicek and Ansell (1990).

Zeidman, et al. (1979) described the *Hydraulic Cleaning System* at the *Western Area Demilitarization Facility* (WADF) as using 69 MPa (10,000 psi) water at 300 liter/min (80 gpm) for the washout of projectiles loaded with *Comp A-3* (RDX/Wax 91/9). TM 9-1300-277 (1982) also described both a 34.5 MPa (5,000 psi) WJ system at NAVSURFWARCENDIV-INDIAN HEAD (NSWC-Indian Head) and a 62 MPa (9,000 psi) system at NAVSURFWARCENDIV-CRANE (NSWC-Crane) for the washout of rockets and projectiles respectively.

Hanson (1978) developed the precursor for the PAN (*Percussion Actuated Non-electric*) disrupter [MK40 MOD 0 *Unexploded Ordnance Standoff Disrupter Tool*] used by civilian and military explosive ordnance disposal (EOD) teams that shoots a slug of water at approximately 152 m/s (500 ft/s) to rip open packages and disrupt the explosive firing train. Cherry (1989) further developed this device into the current system used today, according to German (1998). The PAN typically uses a highly modified 12 ga. (18.5 mm [0.729 in] bore diameter) shotgun shell with various explosive and projectile loads, according to Anon (2012).

In the late 1970s Los Alamos National Laboratory explored the impact of high velocity jets of water and metals into high explosives as detailed in Mader and Pimbley (1981). According to Kwak, et al. (1990) in 1982 the U.S. Navy funded their own research on WJs with Missouri *Rolla School of Mines*, now *Missouri University of Science and Technology* (MUST) to determine the safety of high velocity water impact on explosives and propellants. Summers and Worsley (1983) detail the specialized safety tests on the washout of high explosives for the U.S. Navy. Summers, et al. (1988) later tested high velocity WJs, either shot with an explosive charge in an “explosive derringer” or as a gelled shaped charge jet, impacting into various high explosive substances at velocities up to 11.62 km/s. NSWC-Crane installed a 34.5 MPa (5,000 psi) x 190 liter/min (50 gpm) WJ washout facility designed by MUST in the mid-1990s called the *Waterjet Ordnance and Munitions Blastcleaner with Automated Tellurometry* (WOMBAT), according to Fossey, et al. (1997).

By the early 1990s high pressure AWJ systems operating at 380 MPa (55,000 psi) were being used to cut high explosive projectiles, typically containing *Comp A-5* (RDX/Stearate 99/1), according to Miller (1992a). In 1991 Miller (1992b) tested PETN and TNT high explosives with WJs at pressures to 1 GPa (147 ksi) without incident. Cruchmer, et al. (1995) of the Department of Energy (DOE) independently repeated and confirmed Miller’s work. The DOE uses high pressure WJs on projects as diverse as the decontaminating nuclear fuel canisters (Crystal, 1995), cutting radioactive waste storage tanks (Board, 1997), and cutting explosives and dismantling special weapons (Crutchmer, et al., 1995).

High-pressure WJ demilitarization facilities using 380 MPa (55 ksi) water were also installed by Alliant Techsystems in Elk River, MN, Ichnya (Ukraine), and Dobrush (Belarus) (Miller, 1994). Hundreds of thousands of high explosive projectiles have since been safely cut using high pressure WJ at these facilities operating at 380 MPa (55 ksi) without incident.

In 2000, Crane Army Ammunition Activity (CAAA) installed an automated high pressure AWJ demilitarization line for demilitarizing fuzed *Explosive D* filled U.S. Navy projectiles ranging in size from 3-in/50-cal to 8-in/55-cal, according to Miller and Burcham (2002). To date over 250,000 projectiles have been cut without incident by this AWJ system (Smith, 2015), and approximately 300,000 have been washed out using WJs at 380 MPa (55 ksi) . This operation is currently ongoing and was recently awarded a follow-on contract to process an additional 20,000+ projectiles ranging in size from 3-in/50-cal to 8-in/55-cal.

3 WJ Safety

There have been a number of accidents, fires, and explosions attributed to using WJs. The vast majority of the injuries and deaths are in the "low" and "medium" pressure civilian systems (under 200 MPa [30 ksi]). WJs are fully capable of cutting steel and can cut flesh and bone as easily as a bandsaw. In fact, WJs are extensively used in the meat packing industry for the sanitary cutting of meats, as shown in Wang and Shanmugam (2009).

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

- Mader and Pimbley (1981) discussed Campbell's research intentionally firing shaped charges with water against explosives as part of research on jet initiation of energetics.
- Summers (1996) discussed a fire during a 103 MPa (15 ksi) washout test at MUST 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.
- Summers (1988) used shaped charge jets with water to initiate 50 explosive samples out of the 212 samples tested. The lowest velocity that caused a reaction was 7100 m/s. This was a research test and was trying to determine which explosives would react at what velocity.
- Two lead azide test samples (approximately 25 mm – 1 inch in diameter) detonated during sensitivity testing in 1992, according to Beaudet (1999). This was a research test and was trying to determine which explosives would react with 308 MPa (55 ksi) WJs.
- A rocket propellant had a non-propagating "puff" during testing of a 114 MPa (16,500 psi) cryogenic liquid nitrogen WJ washout system, according to Spritzer (1999). The cause of the event is still undetermined.

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 WJ cut made three days earlier. This was a processing accident, not a WJ accident.
- Alliant Techsystems 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 Alliant Techsystems had AWJ systems available at the site it 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 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 Type 37 chemical-type time delay fuze and detonated as the WJ was being erected, not during operations.

Impact Initiation of Explosives

The DOD, DOE, and industrial researchers have all studied the safety of WJ impacts on high explosives since the late 1970s. Initial DOD research showed that WJs were considered too dangerous for use on high explosives based on research reported by Worsey and Summers (1984), Wilken, et al. (1992), and Giltner, et al. (1993). On the contrary, the DOE (Mader and Pimbley, 1981, Carlson, et al., 1993, and German 1999) as well as industry (Hanson, 1978 and Miller, 1992a) concluded that commercial WJs and/or AWJs are safe for use on secondary high explosives. The extreme dissimilarity between the two views can be traced to a difference in how the research was conducted and evaluated.

The two key questions that explosive safety professionals should ask are:

1) Can WJs ***ever*** initiate secondary high explosives or propellants?
    <u>YES</u> – 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)?
    <u>NO</u> – It is extremely unlikely that a commercial WJ can 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.

Note: Sensitive primary explosives should be assumed to initiate using commercial WJ units but sufficient research has not yet been performed.

Explosive Safety Tests – Worsey and Summers (1984) and Summers, et al. (1988) 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 25º C (77º 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).

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 initiating. The body of research confirms the predictive equation known as the *Jacobs-Roslund* equation (Roslund, et al., 1975).

Held (1968) and Mader and Pimbley (1981) documented research on the initiation of high explosives by high velocity shaped jets and showed that a modification to the *Jacobs-Roslund* velocity-diameter equation was required to accurately predict the probability of explosive initiation. 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 $\rho V^2 d$. (The archaic CGS units were retained to allow comparison with published data.) Cherry (1999) and others would later confirm this relationship.

Mader and Pimbley (1981) showed empirical test results that gave very close correlation to the equation's prediction to initiate sensitive PBX-9404with a required $\rho V^2 d$ product of 142 mm^3/µs^2 using copper jets[3] and 150 mm^3/µs^2 for WJs. Although a true shock-Hugoniot based computer modeling simulation will be more accurate, as shown by

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[3] Converted from the published V^2d number of 16 mm^3/µs^2 using copper with a density (ρ) of 8.903 gm/cm^3

Bouvenot (2011), the Mader and Pimbley (1981) estimation is sufficiently accurate for qualitative safety calculations.

Mader and Pimbley (1981) defined the CV (critical value) numbers for two explosives, PBX-9404 and PBX-9502, and a value for Comp B was extrapolated from Lawrence and Starkenberg (1997). Those CV numbers, along with an index of "relative susceptibility" of explosives to impact according to their "relative stimulus input factor," as calculated by Petersen (1981), for comparison are shown in
Table **1**:

Table 1
***CV* Number vs. Explosive Susceptibility**

Explosive	**CV**	**Petersen**
Exp D pressed		190
TNT cast		174
Comp A-3 pressed		102
Comp B pressed	890	100
PBX 9502	800	91
PBXN-103		87
PBX 9404	150	68
Comp A-5 pressed		65

Given that WJs (and AWJs) are functionally limited to approximately 1 GPa as water at that pressure freezes at 25º C (77º F), according to Lide (2005) we can determine the maximum (worst case) $\boldsymbol{\rho V^2 d}$ CV product for a commercial WJs at the maximum current ratings can be calculated as:

ρ = 0.997 gm/cm^3 at 25º C
V = 1.4 mm/μs[1] (jet velocity of water at 1 GPa)
d = 1.09 mm.[4]

The maximum CV product of a WJ is limited by physics to approximately 2.21 (gm/cm^3 mm^3/μs^2), as compared to the 150 (gm/cm^3 mm^3/μs^2) required to initiate PBX 9404. This is consistent with the theoretical conclusions of Carlson, et al. (1993) and with the experimental work by Miller (1992b) using 1 GPa WJs on PETN, essentially the most sensitive secondary explosive.

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:

$$\Sigma = \Sigma_c + \frac{E_c}{2\rho_o w_t \tau}$$

where: $\boldsymbol{\Sigma}$ = Specific energy in shock (MJ/kg)
$\boldsymbol{\Sigma}_c$ = Explosive activation energy constant = 0.04 MJ/kg for PBX-9404
E_c = Explosive critical energy constant (Walker and Wasley) = 0.44 MJ/m^2 PBX-9404
ρ_o = Ambient density of the explosive = 1.84 gm/cm^3 for PBX-9404
w_t = Shock velocity in the HE = $c + S\,u_p$
c = Sound speed in the shocked explosive = 2.43 mm/μs for PBX-9404
S = Slope of the shock Hugoniot = 1.57 for PBX-9404
u_p = Particle velocity
$\tau = d / 18c$ round nosed projectiles $d / 6c$ flat nosed projectiles, $d / 2c$ for shock
d = Diameter of the projectile (jet).

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[4] An orifice of this diameter would require a pump with an incredible 1.35 MW (1800 hp) shaft power.

James (1988) and Peugeot, et al. (1998) showed that most published data on jet impacts into bare explosives support the assumption that the results from round-nosed rods better fit the experimental results for jets than flat-nosed cylinders. James (2014) added that the use of the *d* / 18*c* term gives a constant value of E_c that follows the detonation threshold at relatively high pressures which result from small diameter projectile impacts. Hrousis, et al. (2009) and Gresshoff and Hrousis (2010) showed that the *James Criterion* could accurately quantify a margin against initiation (or non-initiation) as a generalized "Probabilistic Threshold Criterion" (PTC). Figure 1 shows that commercial WJs cannot achieve the energy required for the 50% initiation threshold for PBX 9404.

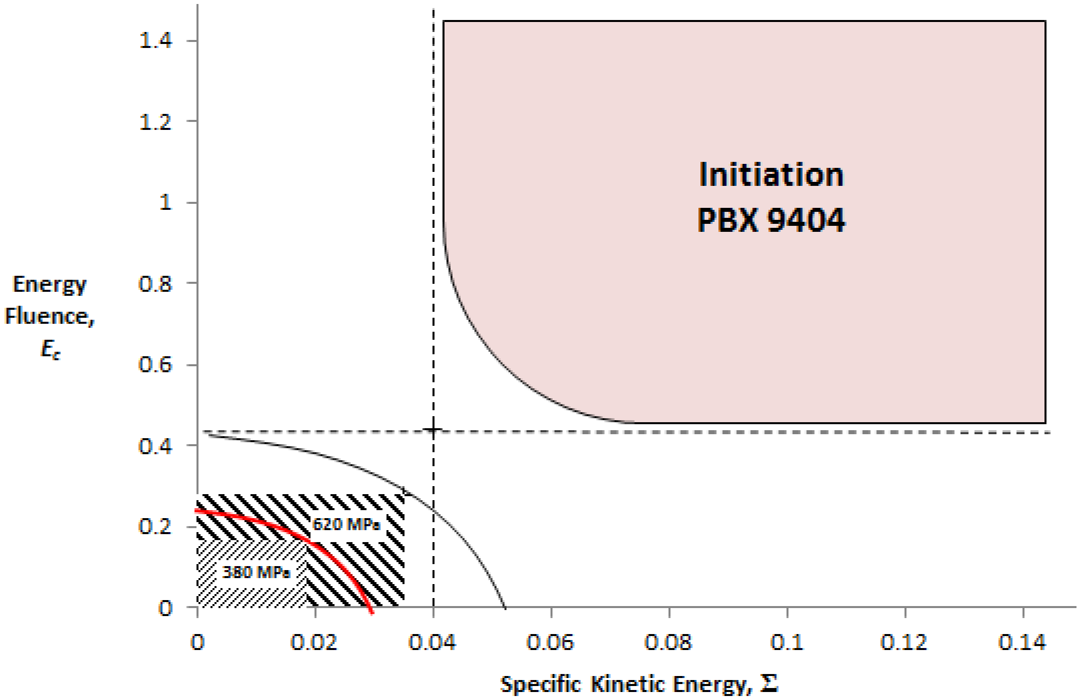

Figure 1 – James Criterion vs. WJ Physical Limits

James Criterion vs. WJ Envelope at 380 MPa and 620MPA

The take-away message about impact initiation of secondary high explosives by WJ impact is that it is extremely unlikely using conventional commercial equipment. In fact, high-pressure WJs and abrasive WJs may be the safest method for cutting high explosives.

Spark Initiation of Flammables and Combustibles

One safety observation is that small sparks are occasionally seen when using abrasives in waterjets (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 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. As previously stated, the MIE for stoichiometric hydrogen in oxygen is only 0.001 mJ. The research on AWJ confirms the conclusions of Silver (1937), Patterson (1940), Barnett and Hibbard (1957), Finnerty and Schuckler (1975), Chen, et al. (2011), Roth, et al. (2013), Coronel and Shepherd (2015), Melguizo-Gavilanes, et al. (2015), Coronel (2016), etc., on the inability of small steel particles and sparks to ignite hydrocarbons in air.

The mechanisms for why WJ sparks won't ignite flammable gases and solids while electric sparks will is a product of several phenomena. First of all, mechanically formed metal sparks are the combustion of fine pieces of abraded metal oxidizing in the surrounding atmosphere. These sparks are significantly different from electrically formed sparks in many ways, and the initiation mechanisms from the two processes are unrelated. Bartknecht (1987) gives a conversion graph for mechanical to electrical spark equivalence based on the base metal of the spark. Magison (1972) in his book on *Electrical Instruments in Hazardous Locations* provides ample details on the inability of small mechanical sparks to ignite flammable solids and gases.

Scull (1951) of NACA (now NASA) stated:

> "…Ordinary white friction sparks produced by grinding steel in air are actually small metal particles, which oxidize or burn in air after being initially heated by being torn off in the grinding process. These sparks will not ignite petroleum vapors unless the metal is held to the wheel for a long time to preheat the metal and thereby increase the thermal energy of the spark…"

Secondly, the particle size for WJ sparks is significantly less than 1 mm (0.039 inch). Silver's (1937) and Paterson's (1940) test data show that the smaller and the faster the travel speed of the particles, the hotter the particles must be in order to ignite the hydrogen – air mixtures. The studies show that the temperature required for thermally hot particles to ignite hydrogen – air mixtures goes up significantly for particles smaller than 4.0 mm in diameter. For 2.0 mm diameter metal particles, the temperature required to give the 50% ignition probability in hydrogen – air mixtures is 930º C as compared with the NFPA 325 (1984) stated hot plate ignition temperature of 500º C.

Finally, 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 the 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 has to both produce sufficient heat from oxidation and the metal oxide coating forming on the metal particle has to be able to transmit that heat to the surrounding combustible gas or solid. Iron and steel are among those metals identified by Hillstrom (1973) as not being sufficiently chemically reactive and pyrophoric. Miller's (1999) research confirmed that cutting certain exotic metals with an AWJ, such as zirconium, can ignite hydrogen-air mixtures, but only with a low probability, while cutting steel in hydrogen-oxygen atmospheres will not ignite.

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 WJs can cause the observed "impact flash" even on non-explosive materials and the targets show no post-impact heat affected zone.

Researchers during the 1990s, who were unfamiliar with the use of *argon flashlamps*, tried to explain the bright flashes they saw in ultrasonically induced cavitation of water as being some sort of high temperature thermal event approaching fusion temperatures. Carlson (1992) reported that "18,900 K are observed in pure water" (33,560° F) cavitation bubbles based on the luminous discharge spectra, while Lewia (1992) argues the temperature is 16,202 K (28,700° F). Hilgenfeldt, et al. (1999) state that the adiabatic compression of gas bubbles in liquids creates a single bubble sonoluminescence (SBSL) temperature from 20,000 to 30,000 K (35,540 to 53,540° F), implying that bubble compression is capable of creating temperatures suitable for nuclear fusion. Hollywood similarly released a science-fiction movie loosely based on the concept of sonoluminescence creating a runaway thermonuclear event titled *Chain Reaction* (1996). The researchers' problem was that they mistook the ***photon discharge spectra*** of shocked argon gas dissolved in water for the emission spectra of a hot blackbody radiator.

Prevenslik (2003) showed that the photon emission was created by an electron cascade, known as the *Becquerel* effect. The *Becquerel* effect yields the same photon energy emissions as adiabatic heating, but at a more manageable 50 K (122° F) temperature rise. Prevenslik's mechanisms also explained 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. Their measurements show that the flashlamp, also known as an "argon candle," "argon flash bomb," or "argon flash," produces an extremely brilliant flash of approximately 2.472×10^9 lumens (200 million candlepower) for a short period of time. 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's being heated to thermal incandescence**.

Alternatively, Bonora, et al. (2014) have also showed that the deformation of solids by any mechanical action can give off light, known as mechanoluminescence (ML). In addition, light emissions have been documented since 1605 from the mechanical actions on solids, such as the application of stress that causes fractures (fractoluminescence), pressure that results in elastic deformation (elastic luminescence), or by surface rubbing (triboluminescence).

Consequently, the flashes of light from WJ impact or water cavitation from commercial WJ systems are of little concern for safety personnel.

Electrostatic Discharge

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.

Fortunately, there are established ways to control static electricity that are quite effective:

1. Always bond all components together with a grounding cable and have a secure connection to ground.
2. Use conductive piping and hoses. Be careful that gaskets do not insulate the piping from the system.
3. Minimize fluid velocity by using larger diameter piping or hoses. A rule of thumb, given by ESCIS (1988), is $1\ \text{m} \times \text{s}^{-1}$ maximum fluid velocity.
4. Use humidity to minimize static buildup if it is appropriate for the hazardous material in the area.
5. Eichel (1967) suggests using ionization (either electrically or radioactively) to minimize static buildup.
6. The use of additives to the spray stream to increase the conductivity of the liquid may also be useful (Eichel, 1967).

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. As previously discussed, Beaudet (1999) mentioned the chemical reaction between ammonia and nitro-compounds as causing a fire in a test facility. 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. Johansson and Persson (1971) documented the destruction of the Swedish Match

Company facility from an aluminum / water reaction. Cutler (1959) of the U.S. Army's Chemical Warfare Laboratories wrote on the manufacturing of pyrotechnics:

> "Aluminum powder and magnesium powder, particularly, react vigorously with water. If a drop of water should fall into a pyrotechnic mixture containing a reactive metal powder and the mixture is subsequently consolidated or cured into a cake or grain, an explosion may result. The reaction between the metal and the water is exothermic and produces hydrogen as a decomposition product."

Other reactive or pyrophoric metals, as identified by Hillstrom (1973), should react in much the same manner. The pyrophoric materials' swarf would also react with a WJ using water or certain other fluids. These reactions are not specific to WJs, as the use of water, alcohol, or chlorinated coolant with bandsaws is just as reactive.

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 (1962) 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. Alternatively, the use of non-reactive motive fluids in the WJ would also prevent any reactions. The use of mineral oil for cutting metals was shown by Schwacha (1958) to be effective.

4 Conclusions

Neither WJs nor AWJs are a panacea for cutting explosives or explosive ordnance, but they are effective tools that are available for engineers to use. As with any technology there are advantages and limitations that should be thoroughly researched and understood prior to use. WJs and AWJs have shown an excellent safety record in use around hazardous materials. At least 700,000 high-explosive munitions have been cut or washed out with WJ or AWJ at pressures above 380 MPa (55 ksi), with an additional unconfirmed number in excess of two million rounds. AWJ may be one of the safest methods of cutting metals and composites when energetics are present.

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