

Decontamination and Dismantling (D&D) of Explosive Contaminated Process Piping in High Explosive Load Lines

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Abstract

Large amounts of piping and related equipment contaminated with high explosives recently had to be removed from several facilities as part of major facility refurbishments and upgrades. Some of these pipes, pumps, and process vessels had been in service up to 75 years and were known to contain a variety of explosive materials. The majority of the components were process vacuum line systems that were installed in order to capture and remove explosive materials generated during the milling of projectile fuze pockets in pressed or cast explosives or the machining of explosive billets. Two of the load-lines had vacuum piping that had been installed in the early 1940s. They were known to be contaminated with various explosive materials from the Second World War through Vietnam. The third production line was built in the 1960s and had process lines that were believed to contain pyrotechnic or toxic chemicals of unknown composition and reactivity.

A preliminary hazards analysis of a number of decontamination and dismantling (D&D) 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. This analysis allowed management and engineers to evaluate design and operational risks, cost, and schedule impact while meeting all of the safety requirements. Among the various processes evaluated were manual disassembly, bandsawing, rotary displacement cutting, diamond wire sawing, rotary lathe cutting, abrasive waterjet cutting, and hydraulic shearing. Traditional disposal methods, such as burning out the facility, were not acceptable on environmental grounds as the facilities contained asbestos paneling that would have become a downwind airborne hazard. In addition, the facilities were slated to be reutilized, not destroyed, and had to have minimal or no collateral damage. The location and clearance around the piping and equipment had to be evaluated as some of the processes would not have sufficient access to safely section the targeted items. Also, the post-cut processing of the contaminated piping had to be evaluated to prevent an initiation of the contaminants while the piping and equipment was being removed.

Approximately 600 cuts were ultimately required to safely section the piping, and large amounts of explosive were found in the piping validating the time and effort spent on the hazards analysis. The projects were all completed without incident and with minimal impact on the facilities.

1 Introduction

Modernization of several explosive processing facilities recently required the decontamination and dismantling (D&D) of contaminated process piping and related systems. Some of these pipes, pumps, and process vessels had been in service up to 75 years and were known to be contaminated with a variety of explosive materials. The majority of the components were process vacuum lines that were installed to remove finely divided explosive chips, dusts, and shavings generated during the milling of fuze pockets in pressed or cast explosives. Two of the load-lines had vacuum piping that had been installed in the early 1940s for operation during the Second World War. The units, known as “vacuum accumulator collection systems,” were actively used for processing explosive munitions through the end of the Vietnam era. The third production line was a research and development process line built in the 1960s that was believed to contain pyrotechnic or toxic chemicals of unknown composition and reactivity. The operation had been shut down, presumably in the 1970s, and still contained in-process materials.

Prior to dismantling these systems a thorough safety hazards analysis was performed to determine what cutting technologies were applicable for the D&D of the explosive contaminated process piping and a corresponding risk assessment.

2 Background

Piping is a ubiquitous part of modern facilities infrastructure and is seemingly present regardless of the end product being produced. Much of the piping is innocuous and carries only water or steam. Many facilities, however, transport hazardous materials such as compressed gases, flammable substances, and toxic chemicals through the buildings using piping.

“Line breaking” is defined in OSHA (29 CFR 1910.147, 2017) as: “the intentional opening of a pipe, line, or duct that is or has been carrying flammable, corrosive, or toxic material, an inert gas, or any fluid at a volume, pressure, or temperature capable of causing injury.” Many unnecessary accidents have occurred by improper line-breaking. A quick search of Sanders (1999) or OSHA (Occupational Safety and Health Administration), Center for Chemical Process Safety (CCPS 2018), or U.S. Chemical Safety Board (CSB 2018) websites can supply more than sufficient horror stories based on improper line breaking procedures.

On three separate instances Gradient Technology was requested to provide hazards analyses for line breaking of piping systems that were known or suspected to contain high explosive or energetic materials as part of facilities modernization. The modernization aspect prevented the standard practice of controlled burning of a facility to decontaminate it by thermal treatment. CSWAB (2006) estimated that the U.S. Army burned some 327 buildings in the early 2000s to decontaminate them. Although thermal decontamination is highly effective and safe, it would have done irreparable damage to the structures that were slated to be modernized. Consequently, an alternative method of decontamination and dismantling explosive contaminated piping was required that would provide adequate safety and risk levels.

3 Hazards Analysis

Prior to deciding on a particular method of decontaminating and dismantling the piping systems a hazards analysis was performed. The primary goals of the hazards analysis were to identify all relevant hazards and develop a risk assessment based on the likelihood of an adverse outcome and consequence of the hazard.

3.1 Explosive Contamination

These pipes were known to have been used either for the vacuum transfer of explosives or for the processing of hazardous materials of unknown composition. Multiple types of explosives were known to have been used at two of the three facilities and the third facility was a research and development (R&D) operation with no known records. R&D operations can be highly problematic as any number of undocumented materials might be present in some quantity.

Besides the known explosive contamination in the piping, explosive chemicals can react over time to form highly sensitive explosive derivatives. A classic case in point is operations handling picric acid or ammonium picrate (Explosive D). Hopper (1938) shows that secondary picrates can be formed by the corrosive action of picric acid or ammonium picrate explosives on metals, as shown in

Table 1. Some metal picrates have impact sensitivities equal to those of primary explosives. This corrosion can occur either on the inside or the outside of the piping or both. Urbanski (1964) describes a disastrous fire at the Huddersfield (UK) explosive processing plant where the outside of a pipe was struck by a plumber igniting the external explosive contamination. This happened to be a steam pipe that was considered inert, but wasn't. Consequently, all piping in explosive operations should be considered contaminated for the purpose of a hazards analysis unless proven otherwise.

Table 1 – Relative Drop Test Sensitivity of Metal Picrate Corrosion Products and Reference Explosives

PA Height (cm)	Explosive
5	Lead picrate (anhydrous)
10	Nickel picrate (anhydrous)
12	PETN (reference)
20	RDX (reference)
31	Copper picrate (anhydrous)
33	Picric Acid (reference)
35	TNT (reference)
35	Ferrous picrate (anhydrous)
*	Calcium picrate
*	Magnesium picrate
43	Ammonium picrate (anhydrous)
92	Chromium picrate
92	Ferric picrate

*classified only as being “less sensitive than TNT.”
derived from: Hopper (1938)

3.1.1 Energetic Ignition Methods

There are a number of different methods for the ignition or initiation of propellants, explosives, and pyrotechnics (PEP). Field, et al. (1982) categorized a number of ignition mechanisms from the mechanical deformation of explosive materials:

- Adiabatic compression of trapped gas spaces by impact
- Viscous heating of material being sheared by extrusion between impacting surfaces
- Friction between impacting surfaces, crystals, or grit particles
- Adiabatic shear of material during mechanical failure
- Electrostatic discharge
- Hot particle ignition
- Exothermic self-sustaining reaction.

Although a number of different ignition mechanisms are recognized by various researchers, the convective, conductive, and radiative thermal mechanisms predominate according to Kuznetsov, et al. (2004). The various initiation mechanisms related to the pipe cutting processes can be lumped into impact, shear, ESD, and thermal sources.

Impact – The impact of dropped tools on a contaminated pipe can be sufficient to ignite explosive contamination. Contaminated piping can either be struck by another tool or it can be dropped accidentally during dismantling. Pape, et al. (1982) estimate that the likelihood of a person’s accidentally dropping an item is 1×10^{-3} / operations.

If a tool or pipe is dropped during maintenance operations, the stimulus level is given by the energy of the tool at the moment of impact distributed over the impact area. Assuming a tool weighing 0.227 kg (0.5 lb) was dropped from a height of 1 meter and impacted an area of 1 mm x 1 mm (1×10^{-6} m²), the impact stimulus level would be about 2.26×10^5 J/m². Increasing the mass or the drop height increases the energy. A 3.05m (10 ft) length of DN 100 (4 in NPS) nominal Schedule 40 pipe with flanges weighs approximately 47.09 kg (103.82 lb). The impact energy for such a pipe dropped 3.05m (10 ft) from an overhead pipe rack would generate 6.16×10^7 J/m².

Shear – Similar to impact initiation is initiation by shear or crushing. When PEP is deformed between two hard surfaces the energetic material may react violently, as shown in Parker, et al. (2013). They showed that even a 2.2 m/s (7.3 ft/s) impact on an angled glass plate could initiate PBX 9501 from shear.

ESD – Electrostatic discharge (ESD) is yet another common initiation mechanism and is usually caused by moving objects accumulating a differential electrical charge. Ungrounded humans can accumulate sufficient ESD to be hazardous around most, if not all, energetic and flammable materials. Flowing gases and liquids are another serious

ESD generation hazard, as shown in Eichel (1967), ESCIS (1988), and Helerea, et al. (2012). Consequently, piping and personnel must have adequate grounding during D&D operations.

Thermal – Heat insult is a very common method to initiate explosive reactions in PEP. The temperatures that explosives can be exposed to vary with both the chemistry of the energetic and the duration of the exposure. RDX is much more sensitive to temperature than TNT as shown in Weinheimer (2002). He gives the 1 second autoignition temperature (AIT) for RDX as 316° C (601 °F) while TNT’s AIT is substantially higher at 520 °C (968 °F).

A relative risk analysis can then be generated by knowing both the insult temperature and the reaction rate for the explosives. If the applied heat yields a time to explosion that is unacceptably short, then the level of heat may be judged as excessive.

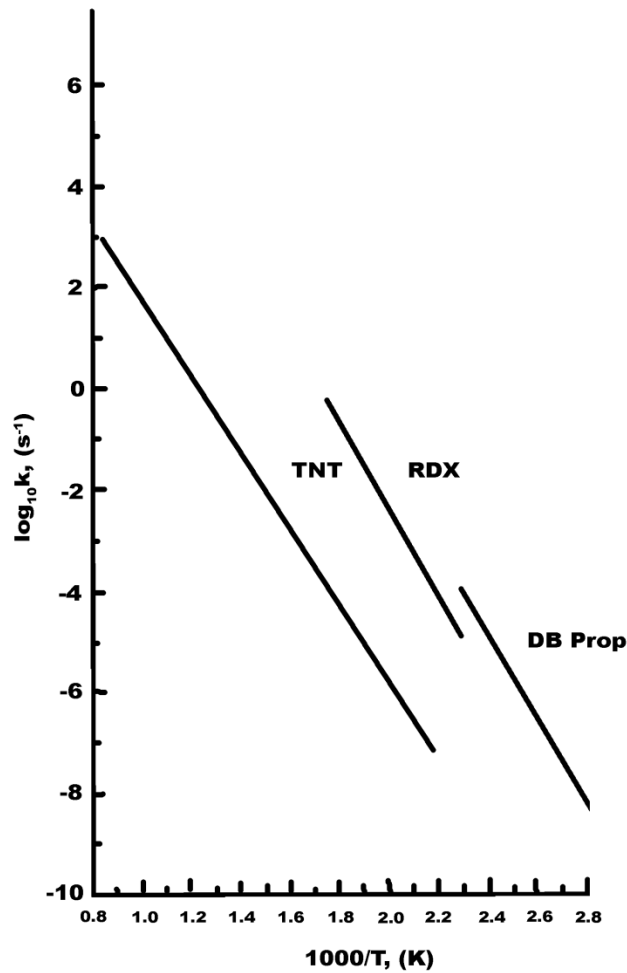


Figure 1 – Temperature vs. Time to Explosion for TNT, RDX, and Double Based (DB) Propellant
(adapted from Kondrikov and Alyoshikina (2002))

3.1.2 Consequences of Adverse Event

The consequences of an adverse event while handling piping containing energetic materials was determined to be either fire or explosion. Flammable solids, liquids, and gases can ignite within the pipe and accelerate to disastrous

pressures, as shown by Proust (1996), Thomas (1999), and Lunn (2001). Their research involved only flammables, not energetics, and still show the catastrophic consequences of fires within pipes.

The reference size pipe for the above mentioned analyses was the DN 100 (4 inch NPS) Sch 40 which has a cross sectional area of 82.08 cm² (12.73 in²) according to Nayyar (1999). This gives the internal volume of 8.2x10⁻³ m³/m (152.7 in³/ft), or the equivalent of up to a maximum of 13.5 kg TNT per meter (9.1 lb/ft) for a full pipe [14.9 kg/m (10 lb/ft) for RDX] assuming the piping is plugged (worst case).¹ Using the above referenced 3.28 m (10 ft) length of pipe as an example, up to 41.3 kg (91 lbs) of TNT [45.5 kg (100 lbs) of RDX] could hypothetically be found in that length of pipe. Although these numbers are large, the reality is that explosive contamination may extend for several hundred meters down the entire length of pipe. The initiation at any one place will precipitate a near simultaneous detonation of the entire length of pipe. This technique is commonly used in the commercial blasting industry for non-electric fusing where small diameter plastic tubing is dusted internally with energetic. An initiation at one end of the tube provides a shock front at approximately 2,100 m/s (6,500 ft/s) to the other end of the tube. Proust (1996) shows the shock tube effect is extremely violent with coal dust. High explosive or propellant dust would only be more energetic.

Assuming that only the one 3.28 m (10 ft) length of pipe detonated, the significant damage radius would be approximately at the NEWQD 7.15Q (K18) quantity distance or 24.7 m (81 ft) for TNT or 25.5 m (84 ft) for RDX. Functionally, an accident with only one piece of pipe would destroy the entire building.

3.1.2.1 Value of Human Capital

The corporation for which the author worked over forty years ago placed the value of human life, for risk-benefit purposes, at approximately \$0.4 million. The determination of this value is based on a large number of variables as outlined in Moran and Monje (2016). The Consumer Product Safety Commission (CPSC) (Raich, et al., 2018) currently uses the value of a statistical life (VSL) as \$8.7 million (2014 dollars). Applebaum (2016) gives the EPA's VSL as \$9.1 million (2015 dollars) and Moran and Monje (2016) show the DOT places the VSL at \$9.6 million (2016 dollars). They further show the low and high estimates range from \$5.4 million to \$13.4 million respectively. A value of \$10 million is used in this analysis as a "round figure" based on these official government computations.

3.1.2.2 Value of the Facility

The value of the facility, based on the expected damage caused by a pipe explosion during dismantling, was defined as \$5 million based on costs extrapolated from data by Plotner (2015).

3.1.2.3 Operational Risk Value

The generally held safety procedure of a "2-person rule" for working with high-explosives meant placing 2 persons at \$10 million VSL at risk in addition to the \$5 million facility value for each operation for a combined risk value of \$25 million. Naturally, each situation may be different and these numbers were taken only as an estimate.

3.1.3 Decontamination

Most industrial piping systems can be easily bled down and purged with air or inert gases to render them safe for disassembly. Workers can still be at risk from opening pipes that contain residual high pressures or toxic materials. Typically, a "double-block and bleed" (DBB) system is used on pipes consisting of two valves that isolate a section of pipe upstream of the work area and a bleed valve that is used to depressurize and drain the blocked off section. Combined DBB spools are commercially available allowing a single spool to contain both blocking valves as well as the bleed valve. According to Haywood (2004) once isolated and drained, the pipe section should be mechanically isolated using a spade blind, a spectacle blind, or even a blind flange to physically block the end of the pipe.

Other piping systems may not be as easy to decontaminate prior to dismantling. Some piping systems carry hazardous liquid or solid materials that are much more difficult to purge. Typical industrial accident reports include flammable materials ignited from using inappropriate equipment to cut the piping or from contact with hot surfaces. Solid materials in pipelines are especially difficult to remove as thin layers of material can coat the entire inside of the pipe.

Air or inert gases are usually insufficient to completely clean the contents of pipes that carried liquid or solid materials. In some cases the internal blockage of the pipelines' byproducts or residues can prevent the flow of purge

gases or liquids. This is actually more common than one might think, as shown in CSB (2001). Liquid flushing agents are often required and large volumes of liquids may be necessary to purge the pipes.

Pigs – Mechanical abrasion and physical displacement of solids in pipelines by inserted plugs can also be used to clean the pipes by forcing the plugs under pressure through a pipe. The petrochemical industry routinely uses these mechanical plugs, known as “pigs” in the industry, to physically clean and purge process piping according to Davidson (2002).

Pigs used for mechanically purging and cleaning a pipeline are typically fabricated from 0.03 gm/cm³ to 0.16 gm/cm³ (2 lb/ft³ to 10 lb/ft³) open cell polyurethane foam with a urethane coating. Alternatively, there are also fully molded urethane pigs that are used for liquid removal.

In other cases the use of mechanical abrasion may not be acceptable, such as in the cleanout of energetic materials in suction and vacuum accumulator lines found in explosive processing plants. In these cases the friction and shear sensitive materials may ignite even when abraded by relatively soft “pigs.”

3.1.4 Decontamination of Energetics

The decontamination of piping contaminated with energetics may be too complex to completely remove all of the risks. It is reasonable to assume that leakage at flanges due to deteriorated gaskets over time may have contaminated both flanges and bolts. Rinsing the bolts and flanges may reduce some of the contamination as long as secondary corrosion hasn't occurred. Flushing the inside of piping systems with large quantities of solvents may be possible, but may also introduce a number of collateral risks and unintentional problems. Common solvents are unlikely to remove corrosion byproducts, and the use of mechanical abraders has high risk associated with it.

For the purpose of this hazards analysis no attempt at decontamination of the piping internals was considered, but external decontamination was considered.

3.2 Dismantling Processes

The historic process for dismantling process piping was to have workers physically disassemble the piping system. Early accidents with explosive contamination in the threaded ends of piping led to the prohibition of threaded joints in ammunition activities. For example AMC-R 385-100 (1995) and Englund (2007) prohibit threaded joints in hazardous locations and recommend flanged and bolted construction.

The ordnance facilities under consideration in this analysis were designed to have maintenance personnel manually disassemble the flanged connections and physically clean out the piping. Although this was always the intent, it was unknown how often or even whether this practice was ever carried out. All of the piping inspected prior to D&D appeared to have been untouched since its original installation. Manual disassembly of contaminated systems could be attempted in cases where the explosive contaminant was known and sufficient solvent or fluid could be applied to bolt and gasket surfaces to prevent ignition during disassembly. Cleaning gasket surfaces to prevent shear or friction initiation during sliding one flange across the other, however, would be difficult.

The manual process was ruled out due to the lack of information on the explosives used and the condition of the flange faces, all of which would cause an unnecessary risk to personnel. The excessive risk of manual disassembly forced the decision to remotely cut the piping in order to remove it. The cost of replacing the pipe, where necessary, was so inexpensive as to be negligible as compared to the risks associated with trying to manually decontaminate the system.

3.2.1 Pipe Cutting Techniques

The Department of Energy (DOE) has published several documents on the removal of piping systems, primarily from retired nuclear reactors. These documents are shown in Manion and LaGuardia (1980), Anon (1994), Anon (1998b), Anon (2000a), and Taboas, et al. (2004). The DOE's main concern is not fire or explosion as much as it is radioactive contamination. This is not to say that fire or explosion is not a concern, however. Water exposed to radiation does undergo radiolysis and breaks down into its constituent hydrogen and oxygen, and hydrogen is extremely flammable and has a minimum ignition energy that is orders of magnitude lower than high explosives.

This hazards analysis evaluated a number of pipe cutting techniques identified by the DOE even though not all of them were applicable for cutting explosive contaminated piping. (They may be of use for cutting other non-hazardous pipes in non-hazardous areas, though.)

Thermal Cutting – Among the quickest and least expensive methods for cutting pipe are thermal processes. These processes were identified in Manion and LaGuardia (1980), Anon (1994), and Taboas, et al. (2004) as:

- Oxygen Burner (Oxy-Acetylene or Oxy-Fuel Cutting)
- Plasma Arc Cutter
- Thermite Reaction Lance
- Laser Cutting
- Electro-Discharge Machining (EDM)
- Metal Disintegration Machining (MDM)
- Arc Saw.

Although inexpensive and effective the thermal methods were deemed completely unacceptable for use around energetics and flammable materials and discarded from further evaluation.

Explosive Cutting – Although it may at first sound inconceivable to use flexible linear shaped explosive charges for cutting piping in flammable or explosive areas, it is actually a common process in the oil and gas industry. Porter and Kline (1947) show that this technique can be used for cutting high-explosive ordnance, and later Mock (1977) adapted the technique for cutting petroleum pipe lines. Hazelton, et al. (1981) provide good information on the use of explosive cutting in the DOE D&D of nuclear facilities.

Despite the extensive use of explosive cutting charges in the oil and gas industry, and although it is possible to manage the likelihood of detonating explosives in piping to be removed, the risks of using explosives for cutting piping for this application far outweighed the benefits.

Shear Cutting – Hydraulic shears are routinely used to cut through metals. The Hurst corporation's portable hydraulic shear is a standard tool used in vehicle rescue work and is known by the tradename "Jaws of Life." According to Anon (1998b) the cutting limit of the portable shear is DN 50 (2-in NPS) pipe and is best used on conduit and lighter piping. Larger shears are available, but are not portable. Some concern was raised as the crushing action of the shears must be considered as well as the adiabatic shear of the metal during cut-through. As an analogy, Rontey (2007) warns that cutting even plastic shock tube should be accomplished using non-metal to metal shears, i.e. anvil-style shears, to avoid the possibility of a friction ignition when using metal-on-metal scissors. Shear cutting is quick and inexpensive and may have other applications but it appears to be too risky for explosive contaminated pipe.

Mechanical Cutting – A number of mechanical processes were identified by Manion and LaGuardia (1980), Anon (1994), Anon (1998b), Anon (1999), and Taboas, et al. (2004). These involve various types of mechanical saws, such as bandsaws, reciprocating saws, and oscillating (guillotine) hacksaws. Rotary saws are also used for cutting pipe. These saws are similar in design to circular woodworking saws but with different style teeth.

Rotary lathe tools that can be clamped to the pipe are also available for larger pipe sizes. Known as "clam-shell" or "split-frame" cutters by Anon (1998b), these tools cut a groove in the pipe as the cutting head spins around. The cutting tools are progressively fed deeper into the cut until the pipe is cut through. Anon (1998a) details the use and testing of this type of cutter.

One of the major drawbacks to using mechanical cutting tools is the heat transferred to the swarf (metal chips). The swarf from various cutting tools such as bandsaws, rotary lathes, and circular saws all behave in roughly the same manner according to Shaw (2005). Shaw (2005) provides a number of predictive methods and actual measurements of tool-chip interface temperatures, as shown in Figure 2, from machine tool processes, with 380 °C (716 °F) to 1000 °C (1830 °F) as a nominal range for production operations. Al Huda, et al. (2002) showed that water soluble coolant at a rate of 5.4 l/min (1.43 gpm) with a heat transfer coefficient of 21,000W/(m² K) dropped the cutting tool temperatures, as shown in Figure 3, by approximately 30 °C (86 °F) at the tool-chip interface.

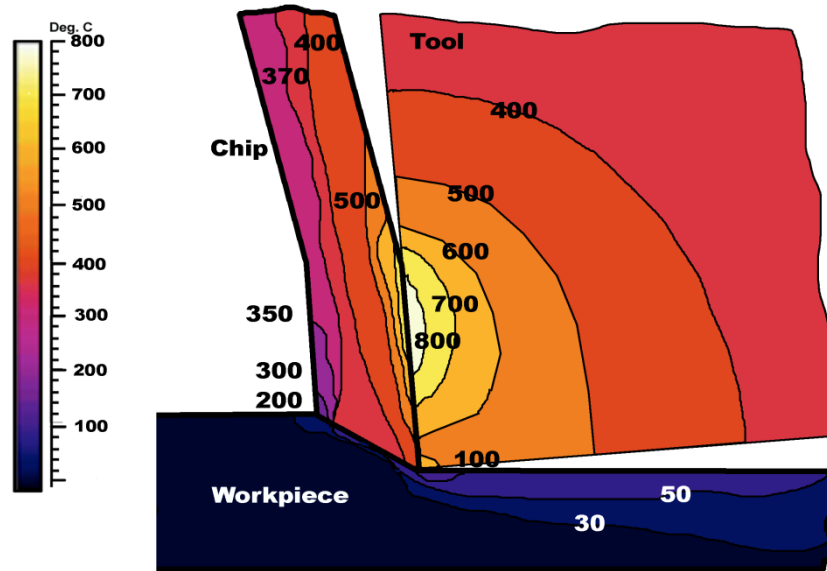


Figure 2 – Tool – Chip Interface Temperature

(Adapted from Shaw (2005))

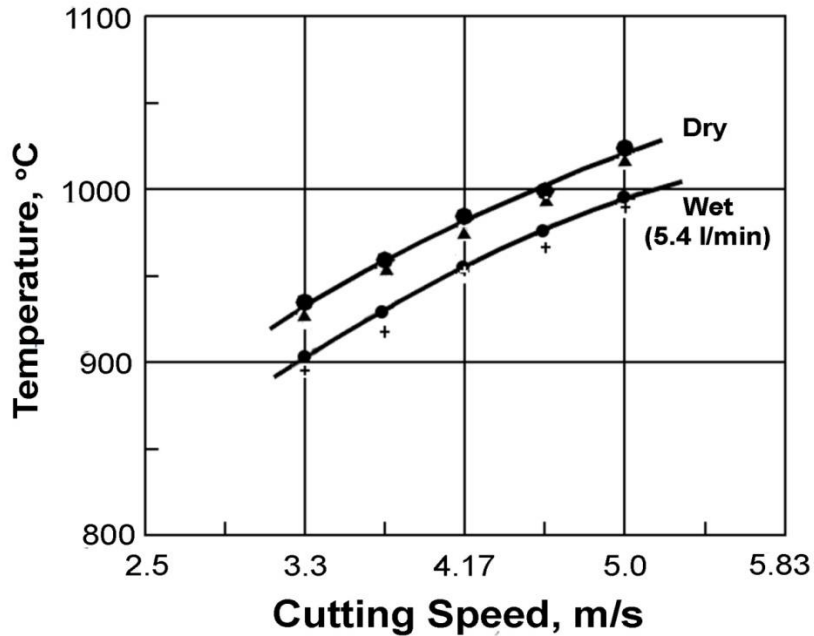


Figure 3 – Tool – Chip Interface Temperature - Wet vs Dry Cutting

(Adapted from Al Huda, et al. (2002))

The temperature of the swarf from rotary lathe tools can also be estimated from a comment in Anon (1998b) where it's stated that "Workers can watch the cut and when the metal turns blue it indicates that the metal is very thin and thermally hot. Break-thru is about to occur." The color of the swarf is due to optical interference that depends on the thickness of iron oxide produced on the surfaces of the swarf according to Shaw (2005). Zaereth (2012) provides a rough temperature based on steel color, as shown in Figure 4, which gives a "blue" color at approximately 310 °C (590 °F).

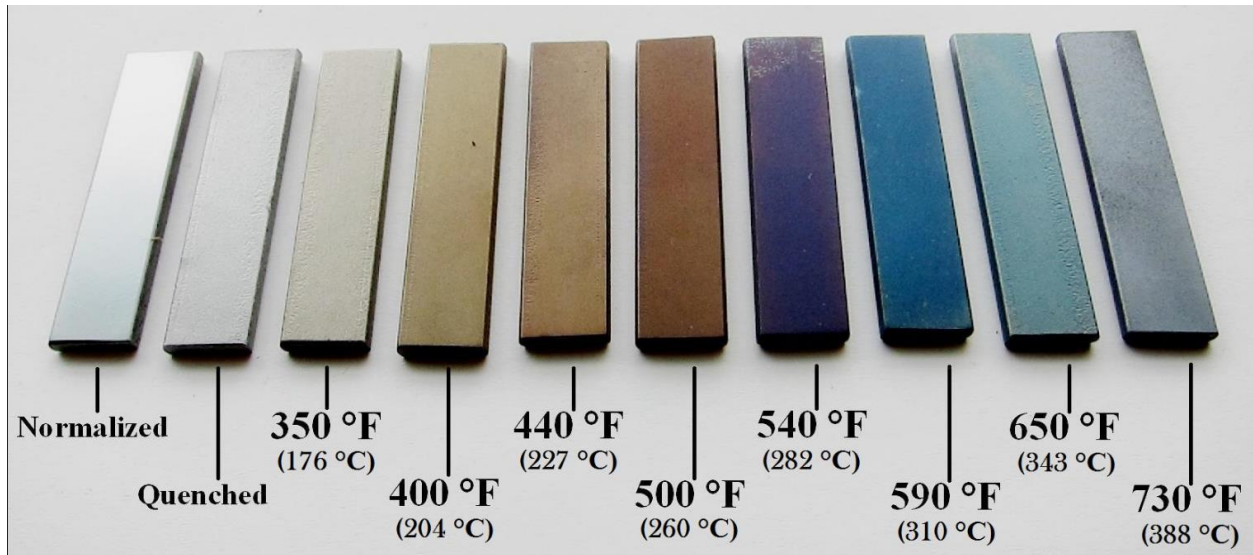


Figure 4 – Rough Temperature of Steel by Color

Swarf temperatures above 121 °C (250 °F)ⁱⁱ are generally considered as too hot for use around high explosives, but there are exceptions when a hazards analysis shows the process is “safe enough.” Weinheimer (2002), as stated above, gives the 1 second AIT for RDX as 316° C (601 °F) and 520 °C (968 °F) for TNT. The AITⁱⁱⁱ of various chemicals can be found in Setchkin (1954) and Zabetakis (1965). Kerosene’s (diesel fuel’s) AIT, for example, is reported as 227 °C (441 °F) by Setchkin (1954), and JP-4’s AIT is reported as 242 °C (468 °F) by Zabetakis (1965).

Displacement Cutters – Roller or displacement pipe cutters are also available. These cutters are larger versions of the shop “pipe cutter” normally used for cutting copper and steel pipe. Surprisingly large pipe can be cut using specialty cutters if sufficient manpower is available. Although seemingly benign, the “breakthrough” area gets very hot as the metal gets very thin when using displacement cutters. Adiabatic shear of the metal has also been shown to be an ignition source.

Abrasive Cutting – Manion and LaGuardia (1980), Anon (1994), Anon (1998b), and Taboas, et al. (2004) identify a number of abrasive cutting techniques capable of cutting pipe. Most common are abrasive disk cutters (“abrasive saws”) where a wheel of abrasive material is used to cut the piping, similar to that shown in Figure 5. The hot area where the wheel contacts the material and the immense spray of sparks and swarf are considered unacceptable for use around high explosives. A number of accidents have understandably been reported from using abrasive saws on ordnance.



Figure 5 – Abrasive Saw Cutting Inert Bomb Skin

Other abrasive cutting techniques include diamond wire saws, abrasive jet machining (AJM), and abrasive waterjet (AWJ) cutting. Diamond wire saws are routinely used for cutting stone and marble but can also be used to cut carbon steel and stainless steels as shown in Anon (2000b). The actual cutting process appears benign as it generates low temperature swarf, but the overall process has issues with the diamond impregnated wire snapping when fatigued, bent, jammed, or tangled. Snapping the highly tensioned wire may release sufficient stored energy to initiate sensitive explosives.

AJM cutting uses compressed gases to accelerate abrasive materials that cut or abrade away metal much like a sand blaster. The process appears to be relatively safe, but has a very slow material removal rate and consumes large amounts of abrasive.

AWJs use high pressure water instead of air to accelerate abrasives to erode and cut stone and metal. They are commonly used in the granite and stone countertop market and are also found in machine shops for cutting metals. AWJs have been used on high explosive ordnance since at least 1991 (Miller 1992) and have continued to be used for cutting high explosive ordnance ever since. At least 420,000 projectiles have been cut without incident to date (the actual number is likely many times higher with numbers of two million commonly found).

Anon (1994) identifies AWJs as an effective cutting tool that can “cut virtually all materials” and “does not create any fire hazards.” Board (1997) performed a hazards analysis on using AWJ for cutting steel in flammable hydrogen environments for the DOE and concurs that an AWJ will not ignite hydrogen in air. AWJs were later successfully used by the DOE to cut steel and concrete in nuclear waste storage tanks containing hydrogen gas at Hanford, WA. This project and other DOE efforts are detailed in Anon (2011) and Boing (2012). Although AWJs are a messy process, as they use both water and abrasive grit, they are considered one of the safer, if not the safest, method for cutting metals in hazardous environments.

3.3 Results of Hazards Analysis

The hazards analysis for this project identified a number of possible pipe decontamination and dismantling methods. Although manual disassembly was highly attractive on the basis of per item cost, the risk was too high to be acceptable. Rotary displacement cutters were also attractive, but had sufficient risk to restrict their acceptance.

Abrasive waterjet cutting was finally decided on as the pipe cutting method of choice based on the following factors:

- 1) The company had experience using AWJs

- 2) AWJs had a much lower risk of igniting either explosives or hazardous chemicals than other cutting technologies
- 3) AWJs could cut through any combination of materials encountered
- 4) AWJs could be remotely controlled without modification
- 5) AWJs didn't require touching the pipe in order to cut it
- 6) AWJs were independently vetted for safety by the DOE.

Consequently, AWJs in this hazards analysis provided the lowest net risk for cutting explosive contaminated pipe.

4 Cutting Operations

Prior to any of the three pipe cutting operations a thorough survey of the piping layout was undertaken. Pipe lengths, estimated weights, and topology (bends, etc.) were taken into account as the piping had to be removed very gently once cut and then removed from the building through doorways. Each pipe cut was planned and marked to allow an orderly cutting schedule.

One or more commercial shoring posts were used to mount the AWJ cutting head in close proximity to the pipe location to be cut. A pneumatically driven motor was used to drive a linear motion stage carrying the AWJ cutting head across the pipe at the cut point. Closed circuit television (CCTV) cameras were strategically placed in various locations to allow the operators to remotely view the cutting process, as shown in Figure 6. The operator's location was connected with fiber optic cable to the cutting station several hundred meters away and could have been even further if necessary.

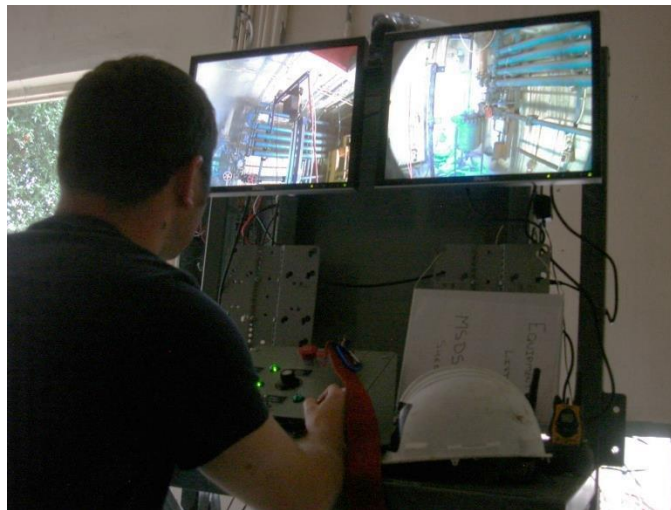


Figure 6 – Operator's Control Location

Special precautions were necessary to prevent the sliding or banging of the cut pipe ends as they were considered potential initiation mechanisms. The details of the immobilization protocol were suggested by EOD personnel who provided independent technical oversight with the first project. A series of ropes were rigged to additional shoring posts to immobilize the pipes so they would not shift once cut. The AWJ does put a small amount of force on the surface being cut, approximately 53.9 N (8 lbf), but the pipe was often under mechanical stress from the initial installation and DN 100 (4in NPS) Sch. 40 pipe is heavy, weighing approximately 4.08 kg/m (10.382 lb/ft).

The small size of the AWJ cutting head, approximately 12.5 cm (5 in) long x 38 mm (1.5 in), allowed cutting the pipe within a short distance from where the pipes penetrated the substantial concrete dividing walls. In areas where the jet could overshoot the target and impact important items, a sacrificial stainless steel plate was used to absorb the jet energy and safely deflect the jet to avoid collateral damage.

AWJs are messy and consume approximately 3.8 l/min (1 gpm) of water and 1 kg/min (2.2 lb/min) of 300 micron (50 mesh) [nominal] hard rock garnet abrasive. Garnet abrasive was chosen due to low cost, lack of free silica, and

no tendency towards piezoelectric sparking. Assuming that a nominal cut would take 5 minutes, approximately 19 liters (5 gal) of water and 5 kg (11 lbs) of abrasive had to be vacuumed up after each cut. A large piece of expendable 0.15 mm (6 mil) plastic sheeting was used to contain the overspray and to collect the spent water, abrasive, swarf, and energetic wastes. An explosion-proof wet-dry portable vacuum was used for collecting the waste, and the waste was packaged up for disposal at the facility burning grounds.

The AWJ nominal water pressure was 380 MPa (55 ksi) with a 0.46 mm (0.018 in) / 1.37 mm (0.054 in) orifice / focusing tube combination. A standard commercial diamond orifice and a boron carbide focusing tube were used. The focusing tube provides approximately 40 hours of cut time between replacements while the orifice has a lifespan of about a year. Using this combination, the waterjet velocity was calculated at approximately 800 m/s (2600 f/s).

The high velocity of the AWJ allowed up to 10 cm (4 inch) standoff from the pipes. Longer standoffs were possible, but were considered unnecessary. The cutting action of the jet continued for approximately 0.5 m (19.7 in), allowing pipe up to 0.45 m (18 in) to be cut with a single lateral pass. Larger diameter tanks and pipes could be cut with a circular tracking device that would allow the AWJ cutting head to cut circumferentially. This technique has been used to cut Mk84 GP bombs in the past, but was not found to be necessary on any pipe cutting operation to date.

The cut lengths of pipe were packaged by covering all openings with conductive plastic and securely taping them in place. These pipe lengths and associated vacuum pumps and accumulators were palletized and taken by facility explosive waste management personnel for destruction at the local burning grounds. Although it was possible to use high pressure water to wash out the interiors of the pipes to decontaminate them, the authorities having jurisdiction preferred to have the scrap thermally treated prior to recycling.

5 After Action Comments

In all, approximately 600 cuts were made over a period of several weeks. No event, mishaps, or injuries were recorded. An estimated 1000 m (3300 ft) of explosive contaminated pipe were removed. The primary explosive contaminant was determined to be Comp A-3 (91% RDX/9% wax), with Explosive D (ammonium picrate) coming in second. In some cases the pipes were completely filled with explosive residue, shown in Figure 7, validating the worst case assumptions and concerns made during the hazards analysis.



Figure 7 – Typical Comp A-3 Explosive Filled Pipe

Abbreviations

AIT	Autoignition Temperature
AWJ	Abrasive Waterjet
DN	Diamètre Nominal
EOD	Explosive Ordnance Disposal
GP	General Purpose
NPS	Nominal Pipe Size
RDX	Research and Development eXplosive (1,3,5-Trinitroperhydro-1,3,5-triazine)
Sch	“Schedule” [from the schedule found in ASME B36.10M (2010)]
TNT	Trinitrotoluene (2-methyl 1,3,5-trinitrobenzene)
WJ	Waterjet

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ENDNOTES

ⁱ Assuming a maximum density of 1.65 gm/cc for TNT (1.82 gm/cc for RDX). It is not realistic in practice, but allows a greater safety margin.

ⁱⁱ Based on AMC-R 385-100 (1995) para. 5-14(a).

ⁱⁱⁱ Formerly known as the "self-ignition" temperature (SIT).