DEMONSTRATION PLAN

Cut and Capture System Technology for Demilitarization of Underwater Munitions – Tank Test

ESTCP Project MR18-5116

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Munitions are encountered in a variety of underwater environments as unexploded ordnance (UXO) or munitions and explosives of concern (MEC). These items can cause unacceptable explosive risk to critical infrastructure, recreational divers, and fishermen. The ordnance can also wash up on-shore and place people at serious risk of death or injury from an explosion. The purpose of this demonstration is to validate an underwater suite of tools that can be used to demilitarize underwater UXO or MEC. Note that only inert target items will be used in this demonstration.

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Acronyms

ASJ abrasive slurry jet

AWJ abrasive waterjet

DMM discarded military munitions

DOD Department of Defense

DVR digital video recorder

EOD explosive ordnance disposal

HC high capacity

HMI human-machine interface

KMT Karolin Machine Tool Company

MDAS Material Documented as Safe

MTBF mean time between failures

NSA Naval Surface Activity

RDX Research Department eXplosive or Royal Demolition eXplosive

RMS root mean square

TNT Trinitrotoluene

UXO unexploded ordnance

WJ waterjet

Nomenclature

d_2	orifice diameter
gpm	gallons per minute
hp	horsepower
in	inch
kN	kilonewton
ksi	thousand pounds per square inch
lb	pound
m	meter
min	minutes
mm	millimeters
$p_{1,ga}$	gage pressure
P	power
psi	pounds per square inch
$\dot{Q}$	voluemtric flow rate
RPM	revolutions per minute
$wt\%$	weight percent

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Gradient Technology would like to acknowledge the support of ESTCP throughout this demonstration. We would like to thank Dr. Mike Richardson for attending the demonstration and providing valuable insight. In addition, numerous Gradient Technology, Delta SubSea, and Leidos personnel facilitated this demonstration and their efforts are appreciated.

Abstract

Introduction and Objectives

Munitions are encountered in a variety of underwater environments as unexploded ordnance (UXO) or discarded military munitions (DMM). The objective of this demonstration was to validate an underwater suite of tools that can be used to render safe underwater UXO and DMM. Testing was conducted on inert Navy 5-inch/38-caliber projectiles in a test tank.

Technology Description

The proprietary technology for underwater demilitarization of munitions utilized a suite of tools that accomplished the following: 1) cleaned a munition of external bioencrustations using a high-pressure waterjet cleaning tool, 2) positioned a cut and capture apparatus on the munition, 3) cut an access hole in the side of the munition using a high-pressure entrainment-style abrasive waterjet cutting head, 4) removed the resulting plug, 5) washed out the internal contents of the munition using a high-pressure washout head, and 6) captured the effluent generated during operations without leakage to the environment.

Performance Assessment

A total of 48 inert projectiles were processed during the demonstration. Three pipes were also covered with concrete 1.5 *inches* thick for testing the cleaning tool's effectiveness. The cleaning head had no issue in removing all of the concrete down to the original pipe surface in one pass.

Positioning and attaching the tool package on a projectile was readily achieved and a 3D-printed attachment boot provided a tight seal against the projectile and prevented leakage to the surroundings. Following attachment of the tool package to the projectile, the cutting of an access hole in the side of the projectile was accomplished in approximately 2 minutes. The effluent generated was successfully transferred to a collection tote without leakage to the environment. The resulting cut plug was also reliably removed.

A total of 19 inert projectiles, each containing 5.0 *pounds* of microcrystalline cellulose, were used for testing high-pressure waterjet washout. Complete washout was achieved in less than 10 minutes through the use of a multi-orifice washout head. Again, the effluent generated was successfully transferred to a collection tote without leakage to the environment.

Therefore, this demonstration has shown that Gradient Technology's high-pressure waterjet demilitarization technology can be utilized underwater in a highly controlled environment where much of the supporting equipment is located above water.

Implementation Issues

In this demonstration, the projectiles were positioned horizontally and were processed in that specific orientation relative to the tool. The equipment, as currently configured, is thus only capable of demilitarizing items that rest on their sides. This limitation was recognized but accepted so that the core of the technology could be validated. Additional efforts can now be focused on manipulating the tool underwater to demilitarize ordnance in varying positions.

Executive Summary

Introduction

Munitions are encountered in a variety of underwater environments as unexploded ordnance (UXO) or discarded military munitions (DMM). These items can cause unacceptable explosive risk to critical infrastructure, recreational divers, and fishermen. The ordnance can also wash up on-shore and place people at serious risk of death or injury from an explosion. The purpose of this demonstration was to validate an underwater suite of tools that can be used to demilitarize underwater UXO or DMM in an environmentally friendly manner. Note that only inert target items were used in this demonstration.

Objectives

The objective of this demonstration was to validate an underwater suite of tools that can be used to render safe underwater UXO and DMM. Testing was conducted on inert Navy 5-inch/38-caliber projectiles in a test tank. The suite of tools tested accomplished the following objectives:

1. **Clean** an inert munition of external bioencrustations using a high-pressure waterjet cleaning tool and three-axis underwater gantry,
2. **Position and attach** a cut and capture apparatus on the target item using a three-axis underwater gantry,
3. **Cut** an access hole in the side of the target item using a high-pressure entrainment-style abrasive waterjet cutting head and remove the resulting steel plug with a magnetic head,
4. **Wash out** the internal contents of the target item using a high-pressure washout head, and
5. **Capture** the effluent generated during high-pressure cutting and washout using a continuous flush and capture tank.

Technology Description

Gradient Technology has extensive experience in using high-pressure abrasive waterjets (AWJ) to demilitarize munitions on land. The onshore use of AWJs is a well-proven technology for cutting munitions and capturing their contents. Since 1991 AWJs have been used to safely demilitarize munitions without incident. Currently, Gradient Technology is utilizing a fully integrated and automated high-pressure waterjet projectile accessing and washout system at NSA-Crane. This system was designed, fabricated, integrated, and installed by Gradient Technology and has been operating since 2001. This projectile accessing system, shown in Figure ES 1, uses high-pressure abrasive waterjets with garnet abrasive to cut out the corroded base fuzes from large caliber U.S. Navy projectiles containing Explosive D and sensitive picrate salts, the corrosion products of the filler. In a second processing step, high-pressure waterjets at 55 *ksi* are used to completely wash out the explosive contents of the projectiles. This one processing line alone has processed over 300,000 projectiles, ranging in size from U.S. Navy 3-inch/50-caliber to 8-inch/55-caliber projectiles, to date without issue.

Figure ES 1: Automated AWJ cutting and washout system processing 8-in/55-cal HC rounds.

Over the past ten years, Gradient Technology has been adapting this AWJ technology for use underwater. This adaptation has involved the integration of a variety of tools into a package that can be deployed and operated from the surface. It is this suite of tools that was demonstrated.

The proprietary technology for *in situ* demilitarization of munitions utilizes the following tools/technologies:

1. Three-axis underwater gantry for moving the tool package around the target item,
2. High-pressure waterjet cleaning tool for removing the bioencrustations or debris from the surface of the target item,
3. High-pressure entrainment-style abrasive waterjet cutting head for cutting an access hole in the side of the target item,
4. Magnet for removing the steel plug resulting from cutting,
5. High-pressure washout head for removing the internal contents of the target item, and
6. A continuous flush and capture tank for capturing the effluent generated during high-pressure cutting and washout operations.

A three-axis underwater gantry holds the tool package and allows for positioning it near or on the target item. The gantry and tool package are shown in Figure ES 2. This gantry allows for movement of the high-pressure waterjet cleaning tool for removing the bioencrustations or debris from the surface of the item of interest.

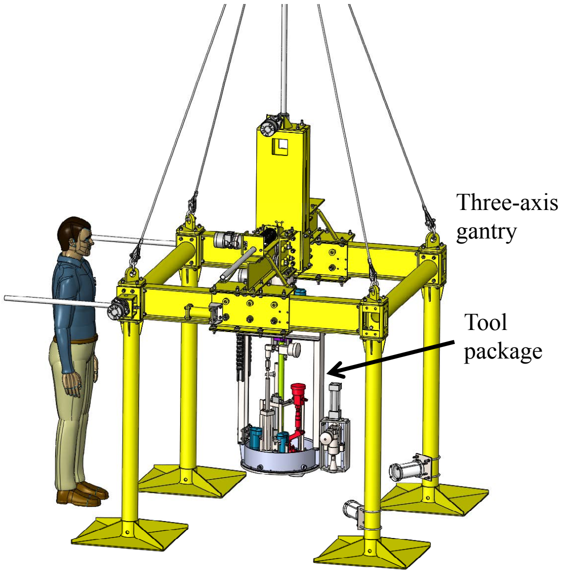


Figure ES 2: Integrated system consisting of a three-axis underwater gantry and the tool package (computer model).

The high-pressure entrainment-style abrasive waterjet cutting head used for cutting an access hole in the side of the target item utilizes approximately two gallons per minute of 55 *ksi* water and directs a single jet of water at the surface to be cut. Garnet abrasive is introduced into the high-pressure water stream via the Venturi effect at a rate of approximately one pound per minute. The abrasive is subsequently accelerated and impinges on the surface and erodes the material to be cut. The operating principle is captured in the schematic shown in Figure ES 3 (M. Hashish, *The Effect of Beam Angle in Abrasive-Waterjet Machining*, Journal of Engineering for Industry 115 (1993) 51).

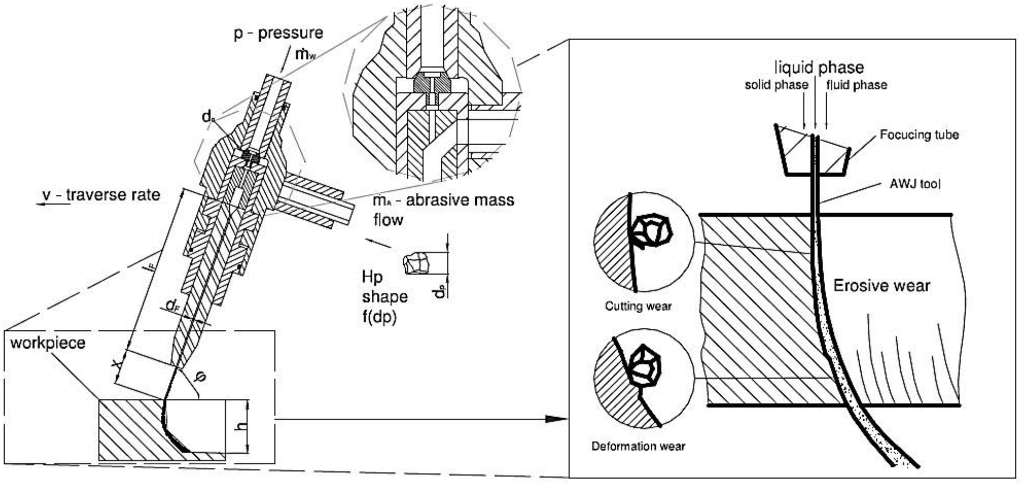


Figure ES 3: The high-pressure entrainment-style abrasive waterjet cutting principle (M. Hashish, *The Effect of Beam Angle in Abrasive-Waterjet Machining*, Journal of Engineering for Industry 115 (1993) 51).

The high-pressure washout head generates a high velocity water stream similar to the cleaning tool. This washout head is, however, smaller and is articulated into the target item via the access hole provided by the cutting operation. The high velocity water streams are used to erode the material inside the target item so that small pieces of the material can be flushed out of the internal cavity. The high-pressure washout head used in this demonstration contained three orifices used to direct jet energy at the inert fill to remove it.

Figure ES 4 is a representation of the tool package that contains the high-pressure entrainment-style abrasive waterjet cutting head, magnet, and high-pressure washout head all located on a turret. The high-pressure waterjet cleaning tool is attached external to the tool package. This tool package utilizes a turret and a multitude of servo motors to allow for turret rotation/translation and appropriate tool control. In addition, the piping for the continuous flush and capture tank equipment for collecting the effluent generated during high-pressure cutting and washout operations is attached to the tool package below the turret.

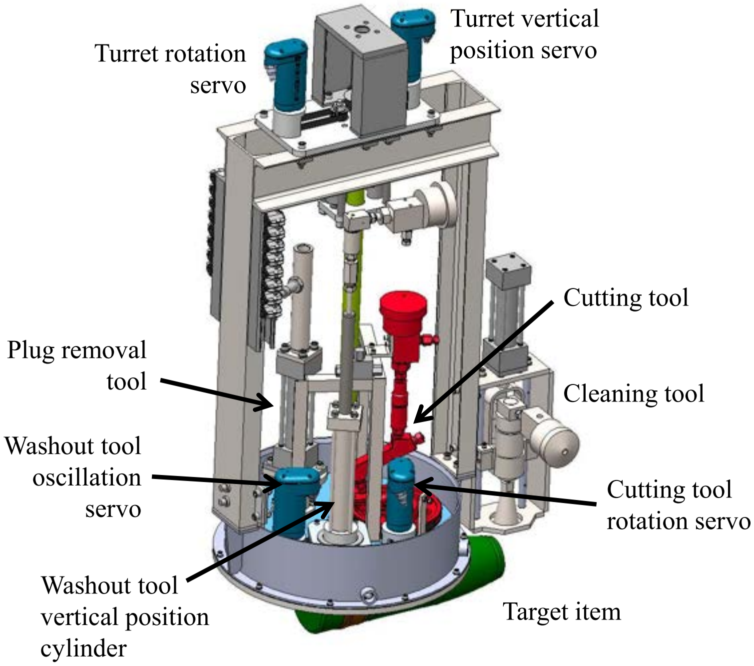


Figure ES 4: The integrated underwater tool package for *in situ* demilitarization of munitions (computer model).

The tool package shown in Figure ES 2 is lowered from the surface and placed over the item of interest. All support equipment for the system is located above water. This equipment includes:

1. High-pressure waterjet intensifier pump for generating high-pressure water,
2. Abrasive hopper for containing the required abrasive and delivering it to the abrasive feeder,
3. Abrasive feeder that dispenses abrasive at a controlled rate into a plastic line that is routed down to the cutting head,
4. Crane for lowering the equipment into the test tank, and a
5. Control panel housing all control hardware for operations.
6. Human-machine interface (HMI) for operating the equipment.

In addition to this equipment, a water source, electrical power source, and compressed air source are required. A simplified overall process schematic is shown in Figure ES 5.

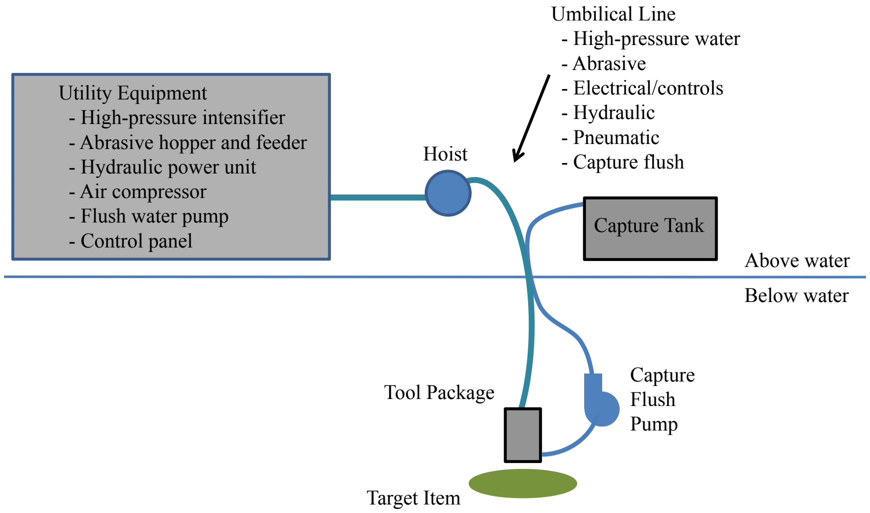


Figure ES 5: Overall process schematic of the system demonstrated in the test tank.

Overall, a majority of the technology pieces contained in the tool package have been successfully utilized above water for demilitarization. Over the past ten years, Gradient Technology has adapted this technology for the underwater environment. The purpose of this demonstration was to validate the integrated tool package in a controlled environment underwater.

Performance Assessment

A total of 48 inert projectiles were processed during the demonstration. Three pipes were also covered with concrete 1.5 *inches* thick for testing the cleaning tool's effectiveness. The cleaning head had no issue in removing all of the concrete down to the original pipe surface in one pass.

Positioning and attaching the tool package on a projectile was readily achieved and a 3D-printed attachment boot provided a tight seal against the projectile to prevent leakage to the surroundings. Following attachment of the tool package to the projectile, the cutting of an access hole in the side of the projectile was accomplished in approximately 2 minutes. The effluent generated was successfully transferred to a collection tote without leakage to the environment. The resulting cut plug was also reliably removed.

A total of 19 inert projectiles, each containing 5.0 *pounds* of microcrystalline cellulose, were used for testing high-pressure waterjet washout. Complete washout was achieved in less than 10 minutes through the use of a multi-orifice washout head. Again, the effluent generated was successfully transferred to a collection tote without leakage to the environment.

Therefore, this demonstration has shown that Gradient Technology's high-pressure waterjet demilitarization technology can be effectively utilized underwater to demilitarize ordnance.

Implementation Issues

In this demonstration, the projectiles were positioned horizontally and were processed in that specific orientation relative to the tool. The equipment, as currently configured, is thus only capable of demilitarizing items that rest on their sides. This limitation was recognized but accepted so that the core of the technology could be validated. Additional efforts can now be focused on manipulating the tool underwater to demilitarize ordnance in varying positions.

1 Introduction

Munitions are encountered in a variety of underwater environments as unexploded ordnance (UXO) or discarded military munitions (DMM). These items can cause unacceptable explosive risk to critical infrastructure, recreational divers, and fishermen. The ordnance can also wash up on-shore and place people at serious risk of death or injury from an explosion [1]. The purpose of this demonstration was to validate an underwater suite of tools that can be used to demilitarize underwater UXO or DMM in an environmentally friendly manner. Note that only inert target items were used in this demonstration.

1.1 Background

Demilitarization of underwater munitions currently requires either *in situ* remediation through use of countercharges or jet perforators placed by explosive ordnance disposal (EOD) divers or by the recovery of the hazardous ordnance for demilitarization on the surface. *In situ* detonation is most frequently used, but completely destroys the local marine ecosystem (e.g., protected or sensitive corals, fish, and mammals), kills or damages marine flora and fauna out to tens of meters, as shown in Jennings and Polunin [2], and can severely injure or deafen marine mammals, such as whales, dolphins, and porpoises out to 5 kilometers, as shown in Ketten [3], Klima et al., [4], and Yelverton et al., [5].

Use of *in situ* detonation is often constrained by potential blast effects that will damage sensitive habitats and cultural resources (e.g., shipwrecks) and blast acoustics that may harm sensitive biota (e.g., marine mammals) according to Keevin and Hempen [6]. It is often preferable to leave munitions in place from an explosives safety and environmental protection perspective unless such munitions pose an unacceptable risk to human safety. Even then it is often preferable to leave the munition casings in place but remove or reduce the explosive hazard in order to mitigate the potential risk of damage to the local microbiome such as coral reefs. The ecotoxic potential, as shown in Lotufo and Kuperman [7] and Sunahara, et al., [8], for the environmental release of organic chemical fillers (e.g., nitroaromatic and nitramine explosives such as TNT and RDX) from continuously corroding munitions also must be addressed.

Recovery of live munitions from the subsurface may result in an unintended detonation from activating the fuzing mechanism which may also destroy the maritime environment. Furthermore, recovery by divers places personnel at risk from both the ordnance and from repetitive and extended dive times. Each of these scenarios is undesirable and has high risk associated with them.

A technology that utilizes high-pressure waterjets to render a munition safe *in situ* could reduce the risk to response workers and the public and avoid potentially significant and costly environmental impact. Such a technology would be highly beneficial to the U.S. Department of Defense (DOD) as it begins to address underwater munitions at places with sensitive marine environments and high public access, like Culebra, Vieques, and Hawaii. In this demonstration, Gradient Technology demonstrated its high-pressure waterjet demilitarization technology in an underwater environment.

1.2 Objective of the Demonstration

The objective of this demonstration was to validate an underwater suite of tools that can be used to render safe underwater UXO and DMM. Testing was conducted on inert Navy 5-inch/38-caliber projectiles in a test tank. The suite of tools tested accomplished the following objectives:

1. **Clean** an inert munition of external bioencrustations using a high-pressure waterjet cleaning tool and three-axis underwater gantry,
2. **Position and attach** a cut and capture apparatus on the target item using a three-axis underwater gantry,
3. **Cut** an access hole in the side of the target item using a high-pressure entrainment-style abrasive waterjet cutting head and remove the resulting steel plug with a magnetic head,
4. **Wash out** the internal contents of the target item using a high-pressure washout head, and
5. **Capture** the effluent generated during high-pressure cutting and washout using a continuous flush and capture tank.

1.3 Regulatory Drivers

The demonstrated technology offers an environmentally friendly alternative to explosive remediation practices historically utilized to render safe underwater UXO and DMM.

2 Technology

Gradient Technology has extensive experience in using high-pressure abrasive waterjets (AWJ) to demilitarize munitions on land. The onshore use of AWJs is a well-proven technology for cutting munitions and capturing their contents. Since 1991 AWJs have been used to safely demilitarize munitions without incident. Currently, Gradient Technology is utilizing a fully integrated and automated high-pressure waterjet projectile accessing and washout system at NSA-Crane. This system was designed, fabricated, integrated, and installed by Gradient Technology and has been operating since 2001. This projectile accessing system, shown in Figure 1, uses high-pressure abrasive waterjets with garnet abrasive to cut out the corroded base fuzes from large caliber U.S. Navy projectiles containing Explosive D and sensitive picrate salts, the corrosion products of the filler. In a second processing step, high-pressure waterjets at 55 ksi are used to completely wash out the explosive contents of the projectiles. This one processing line alone has processed over 300,000 projectiles, ranging in size from U.S. Navy 3-inch/50-caliber to 8-inch/55-caliber projectiles, to date without issue.

Figure 1: Automated AWJ cutting and washout system processing 8-in/55-cal HC rounds.

Over the past ten years, Gradient Technology has been adapting this AWJ technology for use underwater [9–12]. This adaptation has involved the integration of a variety of tools into a package that can be deployed and operated from the surface. It is this suite of tools that was demonstrated.

2.1 Technology Description

The proprietary technology for *in situ* demilitarization of munitions utilizes the following tools/technologies:

1. Three-axis underwater gantry for moving the tool package around the target item,
2. High-pressure waterjet cleaning tool for removing the bioencrustations or debris from the surface of the target item,
3. High-pressure entrainment-style abrasive waterjet cutting head for cutting an access hole in the side of the target item,
4. Magnet for removing the steel plug resulting from cutting,
5. High-pressure washout head for removing the internal contents of the target item, and
6. A continuous flush and capture tank for capturing the effluent generated during high-pressure cutting and washout operations.

A three-axis underwater gantry holds the tool package and allows for positioning it near or on the target item. The gantry and tool package are shown in Figure 2. This gantry allows for movement of the high-pressure waterjet cleaning tool for removing the bioencrustations or debris from the surface of the item of interest. Figure 3 shows the high-pressure waterjet cleaning tool that delivers approximately two gallons per minute of 55 ksi water in a plurality of jets directed at the surface to be cleaned.

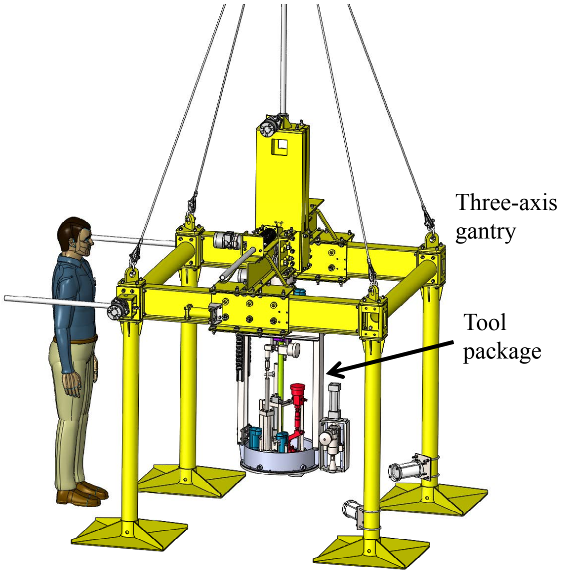


Figure 2: Integrated system consisting of a three-axis underwater gantry and the tool package (computer model).

Figure 3: High-pressure waterjet cleaning tool.

The high-pressure entrainment-style abrasive waterjet cutting head used for cutting an access hole in the side of the target item utilizes approximately two gallons per minute of 55 *ksi* water and directs a single jet of water at the surface to be cut. Garnet abrasive is introduced into the high-pressure water stream via the Venturi effect at a rate of approximately one pound per minute. The abrasive is subsequently accelerated and impinges on the surface and erodes the material to be cut. The operating principle is captured in the schematic shown in Figure 4 [13].

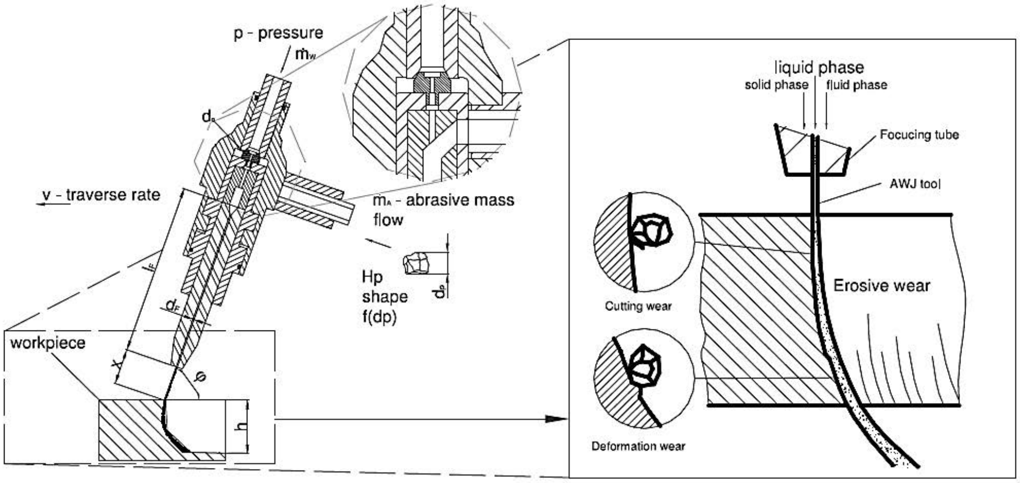


Figure 4: The high-pressure entrainment-style abrasive waterjet cutting principle [13].

The high-pressure washout head generates a high velocity water stream similar to the cleaning tool. This washout head is, however, smaller and is articulated into the target item via the access hole provided by the cutting operation. The high velocity water streams are used to erode the material inside the target item so that small pieces of the material can be flushed out of the internal cavity. The high-pressure washout head used in this demonstration contained three orifices used to direct jet energy at the inert fill to remove it.

Figure 5 is a representation of the tool package that contains the high-pressure entrainment-style abrasive waterjet cutting head, magnet, and high-pressure washout head all located on a turret. The high-pressure waterjet cleaning tool is attached external to the tool package. This tool package utilizes a turret and a multitude of servo motors to allow for turret rotation/translation and appropriate tool control. In addition, the piping for the continuous flush and capture tank equipment for collecting the effluent generated during high-pressure cutting and washout operations is attached to the tool package below the turret.

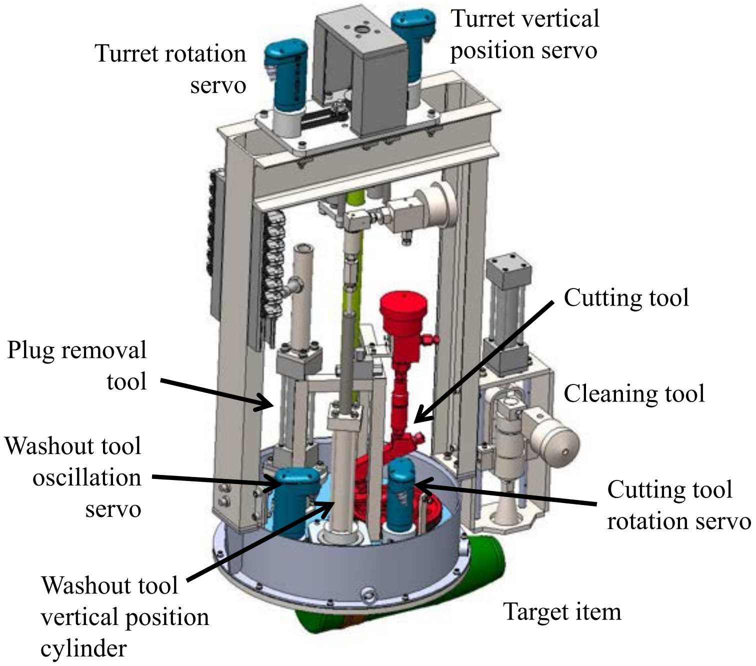


Figure 5: The integrated underwater tool package for *in situ* demilitarization of munitions (computer model).

The tool package shown in Figure 2 is lowered from the surface and placed over the item of interest. All support equipment for the system is located above water. This equipment includes:

1. High-pressure waterjet intensifier pump for generating high-pressure water,
2. Abrasive hopper for containing the required abrasive and delivering it to the abrasive feeder,
3. Abrasive feeder that dispenses abrasive at a controlled rate into a plastic line that is routed down to the cutting head,
4. Crane for lowering the equipment into the test tank, and a
5. Control panel housing all control hardware for operations.
6. Human-machine interface (HMI) for operating the equipment.

In addition to this equipment, a water source, electrical power source, and compressed air source are required. A simplified overall process schematic is shown in Figure 6. Finally, Figures 7 – 10 contain a variety of photographs acquired during the demonstration that highlight the technology and equipment utilized in this demonstration.

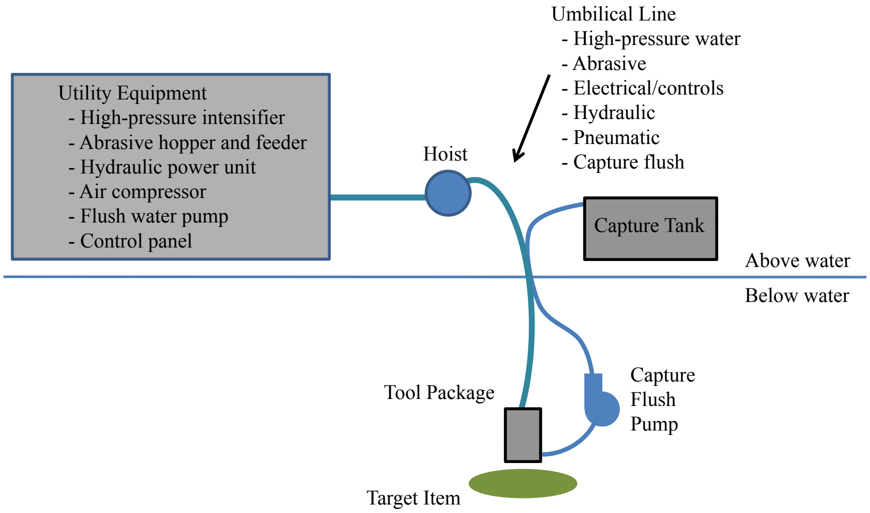
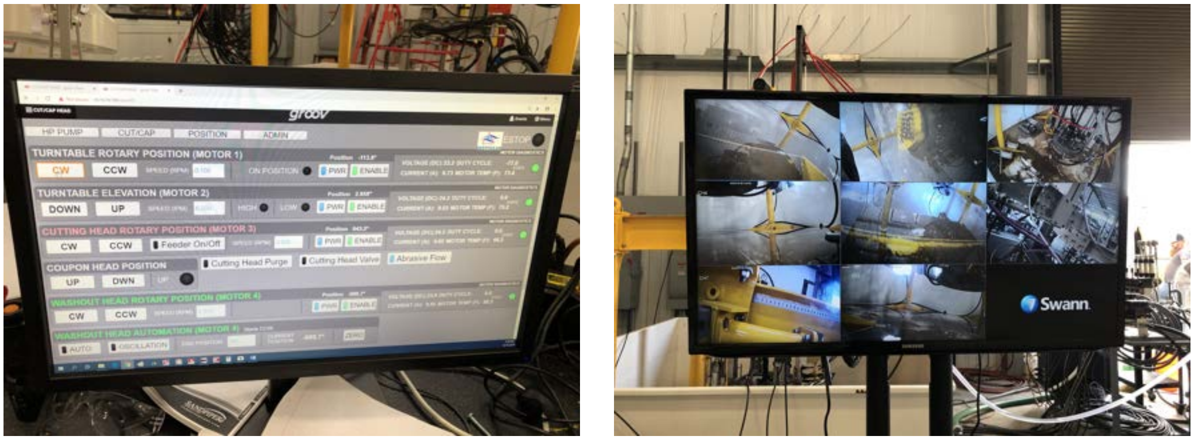


Figure 6: Overall process schematic of the system demonstrated in the test tank.

(a) Equipment layout in Delta SubSea's tooling shop.

(b) Abrasive feed system, high-pressure intensifier, and tool package inside the shop test tank.



(c) Control system human-machine interface (HMI).

(d) Camera monitor display.

Figure 7: Shop tank testing equipment layout and control system.

(a) KMT 100 *hp* high-pressure intensifier.

(b) Tool package inside the shop test tank.

(c) Tool package above an inert projectile after testing.

(d) Tool package gantry and high-pressure tube routing.

Figure 8: Shop tank testing equipment.

(a) Tool package located in the shop test tank before hoisting into the large test tank.

(b) Tool package being hoisted into the large test tank.

(c) Tool package after placement inside the large test tank as seen through the observation window.

(d) Processed inert projectiles after removal from the large test tank.

Figure 9: Large test tank demonstration pictures.

(a) Abrasive hopper positioned by the large test tank.

(b) Capture tank located near the large test tank.

(c) Control system used to operate the tool package.

(d) Operational container used to control the tool package and view cameras during operation.

Figure 10: Large test tank equipment.

Overall, a majority of the technology pieces contained in the tool package have been successfully utilized above water for demilitarization. Over the past ten years, Gradient Technology has adapted this technology for the underwater environment. The purpose of this demonstration was to validate the integrated tool package in a controlled environment underwater.

2.2 Advantages and Limitations of Waterjet Technology

The high-pressure entrainment-style abrasive waterjet system used in this demonstration uses a specialized cutting head that entrains (mixes) the abrasive and water together less than 3 *inches* from the cutting tip using a Venturi-type mixer. These entrainment waterjets have much higher reliability and uptime than premixed abrasive slurry jet (ASJ) systems and are now the industry standard in North America. The ASJ systems require pressurizing tanks of liquid abrasive slurry to high pressures and then piping the abrasive mass through the pipes and valves to the cutting tip. The system pressure is generally limited to the fatigue limits of the pressure vessels holding the abrasive slurry. The entrainment style cutting head, on the other hand, allows extremely high water pressures to be used in AWJ when compared to ASJ systems (up to 100 *ksi* vs 10 *ksi*) with accompanying proportional increases in cutting efficiency. The abrasive in an AWJ doesn't drop out of suspension and plug the piping and valves like in an ASJ since it is added by entrainment and not held in slurry form.

3 Performance Objectives

There were six main performance objectives for the demonstration. They contain both qualitative and quantitative metrics as shown in Table 1. The results shown in the table are for the second phase of the demonstration in the large test tank aside from the cleaning of the target; this test was completed in the shop test tank. Note that the first phase of testing in the shop test tank was beneficial in that it allowed for the performance objectives to be met when operating in the large test tank. The results for each performance objective are explained in detail following Table 1.

Table 1: Performance Objectives

Performance Objective	Metric	Data Required	Success Criteria	Results
Quantitative Performance Objectives				
Equipment reliability	Failure rate per hour Major: Requires repair Minor: Requires reset	• Hours operations • Number of major failures • Number of minor failures	$MTBF_{major} > 3\ hr$ $MTBF_{minor} > 1\ hr$	There were no equipment failures.
Cleaning of the target	Percentage of area reduced to 6.35 *mm* RMS or less	• Initial target area • Post-WJ area RMS	90% average acceptable RMS	The cleaning head removed all concrete (1.5 *in*).
Waterjet washout of munition constituents	Percentage of material removed	• Initial mass • Post-washout mass	80% average removal	More than 95% was removed. Some tests yielded 100% removal.
Qualitative Performance Objectives				
Capture of munition constituents	Percentage of material captured	• Initial fill mass • Mass captured	80% average capture	More than 95% was captured.
Attachment to target	Percentage successfully attached	• Items attempted • Items successful	$P_{attach} > 80\%$	All attachments were successful.
Abrasive waterjet cutting of access hole	Percentage successfully cut	• Items attempted • Items successful	$P_{cut} > 80\%$	83% of the cuts were successful.
Abbreviations: $MTBF$ = meant time between failures RMS = root mean square				

3.1 Objective: Equipment Reliability

The reliability of the equipment used to conduct demilitarization will affect rates and operational cost. The system has been engineered to utilize reliable components to minimize downtime. Since the system used in this demonstration is highly integrated, one component failure can significantly impact the performance of the entire system. Therefore, redundancy has been built into critical areas of the system to alleviate the halting of operations. For example, the high-pressure waterjet intensifier pump used to generate high-pressure water for the three downstream tools (cleaning head, cutting head, and washout head) has been fitted with a redundant intensifier. The intensifier contains components such as seals that periodically fail and their replacement can take a few hours by a trained technician. If a redundant intensifier is incorporated into the system and the in-use intensifier does fail, changing over to the redundant intensifier can be accomplished in minutes by turning a few manual valves. Operations are thus only interrupted briefly and maintenance on the failed intensifier can commence.

3.1.1 Metric

The number and type of major and minor failures are used to quantify a mean time between failures. A major failure is one requiring repair whereas a minor failure is one requiring a reset.

3.1.2 Data Requirements

The number and type of major and minor failures will be recorded for all tests.

3.1.3 Success Criteria

The objective will be met if the mean time between major failures is greater than 3 $hours$ and the mean time between minor failures is greater than 1 $hour$.

3.1.4 Data and Results

A total of 48 inert projectiles were processed during the demonstration and 4 major failures were observed. Since it takes approximately 20 minutes to process a target item, the mean time between major failures is approximately 4 hours. There were no failures observed during the second phase of the demonstration in which 6 inert projectiles were processed in the large test tank.

3.2 Objective: Cleaning of the Target

Target item surface roughness such as bioencrustations require removal to allow proper attachment of the tool package. Proper attachment is required to increase the amount of material collected in the capture system. Successful execution of this objective is operationally important because the results impact the ability of the system to meet the subsequent objectives. If the target is not adequately cleaned, (1) a thicker amount of material must be cut resulting in longer cut times, (2) the magnet used to remove the cut plug may not be strong enough to hold it, and (3) the tool may not be properly attached to the target and could allow the munitions constituents to leak into the surrounding environment as opposed to being captured.

3.2.1 Metric

The surface roughness is quantified with an instrument such as a depth gauge or an optical stereo microscope.

3.2.2 Data Requirements

The surface roughness data collected is a direct measurement of the required information.

3.2.3 Success Criteria

The objective will be met if 90% of the cleaned area has a surface roughness of less than 6.35 *mm*.

3.2.4 Data and Results

Three pipes were covered with concrete 1.5 *inches* thick for testing the cleaning tool's effectiveness. These items were cleaned in the shop test tank and the cleaning head had no issue in removing all of the concrete down to the original pipe surface in one pass. The surface of the pipe exposed was as smooth as the original pipe. Therefore, surface roughness measurements were not taken but were visually observed to be significantly less than 6.35 *mm*. The cleaning tool was extremely successful in removing concrete.

3.3 Objective: Waterjet Washout of Munition Constituents

Ideally, it is desired to remove all of the fill contained inside a munition. However, in reality, a portion of the fill may not be easily removed in a timely manner and it is expected some material will remain in the item after washout. The time required for complete removal of the munition energetic fill will depend upon the size and internal configuration of the target item. This demonstration focuses on the common Navy 5-inch/38-caliber projectile that has no base or nose fuze. In addition, a three-orifice washout head has been selected so that the entire cavity can be washed when entering the item from the side; this will be verified in this demonstration. Other target item configurations may require longer washout times coupled with different washout head orifice configurations to achieve complete washout. Lastly, there could be situations in which complete washout is not required to render the target item safe. Operationally, Gradient Technology's goal is to achieve complete washout, however, this comes at the potential expense of washout time. Although difficult to quantify during the demonstration, the relationship between washout rate and the amount of material remaining in the target item will be assessed.

3.3.1 Metric

The mass of material removed is quantified by difference between the initial and final weight of the target item.

3.3.2 Data Requirements

The mass of the target item before and after washout is measured and the difference represents the mass removed. Since the initial mass is recorded, the fraction removed can be determined.

3.3.3 Success Criteria

The objective will be met if more than 80% of the munition constituents are removed.

3.3.4 Data and Results

Initially, the washout operation was set at approximately 5 minutes in which washout occurred only as the washout head was slowly traversed down into the inert projectile. Under these conditions, complete washout regularly occurred. However, on occasion, there was some loose material (approximated to be tens of grams) left in the projectile. It is estimated that 95% of the contents were removed in these instances. When the washout operation was set at approximately 10 minutes in which washout occurred as the washout head was slowly traversed down and back up out of the inert projectile, all material was removed. Therefore, under the conditions of this demonstration, 10 minutes of washout were required to remove all of the material.

3.4 Objective: Capture of Munition Constituents

Ideally, it is desired to collect all of the fill removed from the munition. However, in reality, a portion of the fill may leak from seals and, as a result, will not be collected in the capture system. Operationally, there are two techniques that can be used to collect the washed out material. Both techniques utilize a pump to pull slurry from the tool package chamber; it is desired to pull the slurry from the chamber as opposed to pumping water through the chamber so that the chamber experiences negative relative pressure (across the seal) as opposed to a positive relative pressure. The difference between the two techniques arises at the discharge of the pump. For one technique, the discharge of the pump is plumbed to a surface tank to hold the slurry. In the second technique, the pump discharge is connected to an underwater bladder located near the tool package. This technique is more applicable for deep water operations when the transfer of the slurry long distances to the surface becomes less efficient. This demonstration will utilize a surface tank to collect the washed out material.

3.4.1 Metric

Qualitatively observe the amount of inert fill floating at the top of the test tank as this is the material lost to the environment. Since the microcrystalline cellulose is less dense than water, it will float to the surface. Attempts will be made to collect this material by skimming the surface of the test tank for quantification.

3.4.2 Data Requirements

This is a purely qualitative observation. However, if wet solids are collected from the surface of the test tank, they will be dried and weighed. Since the mass of inert fill removed during washout is known (see Objective 3.3), the fraction of washed out material actually collected can be estimated.

3.4.3 Success Criteria

The objective will be met if more than 80% of the munition constituents removed are collected.

3.4.4 Data and Results

During cutting, one would observe the stream entering the collection tote becoming dark and cloudy; this was caused by the garnet abrasive and inert fill being removed by the capture network. Most importantly, there was no visible evidence of any leakage to the surroundings; small leaks in the capture network to the surroundings were confirmed to be readily visible via the system of cameras positioned around the tool. During washout, one would observe the stream entering the collection tote becoming cloudy white; this was caused by the inert fill being removed by the capture network. Again, there was no visible evidence of any leakage to the surroundings. Toward the end of the washout operation, it should be noted that one could observe the capture fluid entering the collection note "clearing up" as the last of the microcrystalline cellulose was removed and collected. Since there was no visible evidence of leakage to the surroundings, $> 95\%$ of the inert fill was captured since some material can remain inside the annulus created by the turret. A borescope inserted into this area did show evidence of a small amount of material remaining in this area.

3.5 Objective: Attachment to Target

Proper attachment of the tool package to the target is important for two reasons. First, proper attachment is required so that proper positioning of the individual tools is achieved. Second, proper attachment is required so that efficient capture is achieved. Proper cleaning of the target item is critical for achieving this objective. In addition, the performance of the positioning system is critical so that the tool package can be placed at the desired point on the target item. Therefore, successful operation of both the cleaning head and positioning system will lead to achievement of this objective.

3.5.1 Metric

Qualitatively observe attachment as well as capture during cutting to determine if there is significant observable leakage.

3.5.2 Data Requirements

This is a purely qualitative observation.

3.5.3 Success Criteria

The objective will be met if more than 80% of the attachments are deemed sufficient.

3.5.4 Data and Results

After the design of an appropriate "boot" to mate to the target item, all matings to the items were deemed successful since no visible leakage could be detected.

3.6 Objective: Abrasive Waterjet Cutting of Access Hole

An access hole is required to be cut into the target item so that the fill can be removed. The access hole is cut using an entrainment-style abrasive cutting head. The cutting head is integrated into the tool package such that a fixed-diameter hole is cut. The cutting head is also mounted at an angle so that the resulting plug does not drop into the cavity of the target item; this allows for the magnet to remove the steel plug. If there is a place on the circumference of the cutting path that is not completely cut, the magnet will not remove the plug. Raising and lowering the tool package for inspection can be utilized where extremely accurate repositioning of the tool package on the target item is not needed. However, accurate repositioning is required for continuing a cut that may not have been complete. Therefore, a small inspection camera may be implemented in the tool package chamber for confirming the magnet has removed the cut plug.

3.6.1 Metric

Qualitatively observe that a hole was properly cut in the target.

3.6.2 Data Requirements

After a cut is complete and the magnet has been used to remove the cut plug, the tool package can be readily raised to observe the resulting access hole.

3.6.3 Success Criteria

The objective will be met if more than 80% of the cuts yield a usable access hole.

3.6.4 Data and Results

During the second phase of testing in the large test tank, six inert projectiles were processed. Of these six cuts, five resulted in plugs that were successfully removed by the magnet. The unsuccessful cut likely resulted from a momentary loss of abrasive from the abrasive feeder to the cutting head. As a result, there was a sliver of steel not cut; this prohibited the plug from being removed by the magnet. Since five of six cuts were successful, the success rate was 83%.

4 Site Description

Test sites with a controlled environment were used to execute this demonstration. The pertinent details of this site are subsequently documented. Project points of contact are included in Appendix A.

4.1 Site Selection

The site selected for this demonstration was Delta SubSea's tooling shop and $200,000$ *gallon* test tank located in Houston, Texas; a site location map is shown in Figure 11. The primary criterion for the test site was that it is equipped with tanks of water large enough to contain the equipment to be tested.

This demonstration occurred in two phases. In the first phase, the various tool and components that comprise the technology were tested in a smaller test tank. This "shop test tank" holds approximately 500 *gallons* of water and was located in Delta SubSea's tooling shop next to the high-pressure intensifier pump (see Section 5.2 for more details).

The purpose of the shop test tank was to facilitate testing by allowing for testing and experimentation to occur more quickly since the gantry and tool package could be placed into and removed out of this smaller tank easily with a forklift. Therefore, a significant amount of experimentation was conducted in this smaller tank. This phase of testing proved the principles of the technology in a minimal amount of water prior to subsequent testing in the much larger and deeper tank.

The second phase of the demonstration involved testing the completely integrated gantry and tool package in deeper water, 20 $feet$ as opposed to the 2 $feet$ in the shop test tank. This test tank, shown in Figure 12, is used by Delta SubSea to test their own equipment.

Lastly, these test tanks provided an underwater environment with controlled conditions that include a solid floor and minimal currents. This environment does not accurately simulate a lake or ocean environment but is not required nor desired for this demonstration. The purpose of this demonstration was to test the equipment in a controlled underwater environment.

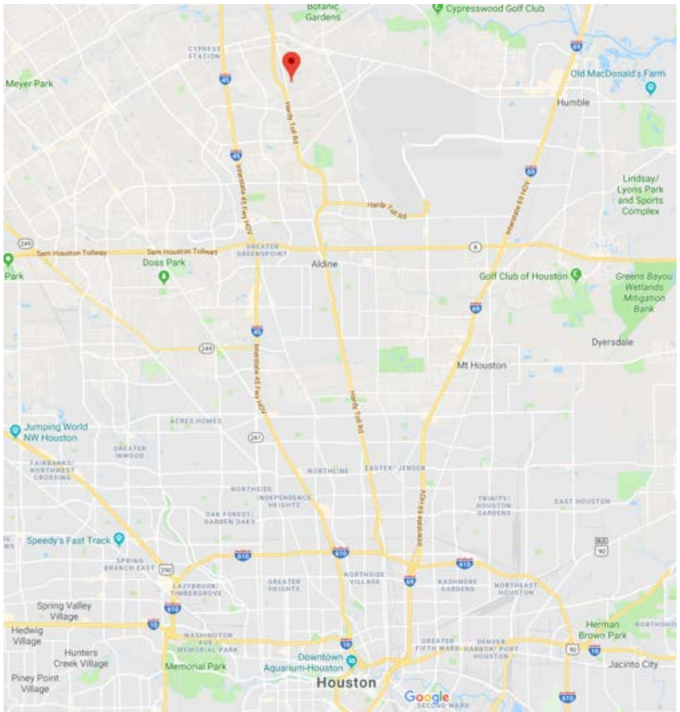


Figure 11: Houston area map showing the location of Delta SubSea's test tank at 1616 Southcreek Lane, Houston, Texas.

Figure 12: Delta SubSea's tooling test tank that is 38.3 *feet* in diameter and 23.4 *feet* deep holding 200,567 *gallons* of water.

4.2 Site History

The 200,000 *gallon* test tank is owned by Delta SubSea and has historically been used to test their proprietary equipment. The shop test tank was fabricated by Gradient Technology specifically for the first phase of the demonstration.

4.3 Site Geology

The 200,000 *gallon* test tank is located on an appropriate concrete foundation.

4.4 Munitions Contamination

Both test tanks were not being used in conjunction with any live munitions.

5 Test Design

The first phase of the demonstration in the shop test tank commenced in October 2019, after all utility equipment had been installed and confirmed to be operational. This equipment included the high-pressure intensifier pump, abrasive delivery system, hydraulic power unit, video system, and control system. This first phase of testing continued through December 2019. On December 18, 2019, Dr. Mike Richardson attended a day of testing in the shop test tank. At the conclusion of this test, plans were made to prepare the system for demonstration in the large test tank (the second phase of the demonstration). The utilities and tool package were subsequently relocated outside in January 2020. Testing in the large test tank commenced in February and a formal demonstration was conducted on February 27, 2020.

5.1 Conceptual Experimental Design

The successful demilitarization of an item requires the successful execution of the following five steps:

1. **Clean** an inert munition of external bioencrustations using a high-pressure waterjet cleaning tool and the three-axis underwater gantry,
2. **Position and attach** the tool package on the target item using a three-axis underwater gantry,
3. **Cut** an access hole in the side of the target item using a high-pressure entrainment-style abrasive waterjet cutting head and remove the resulting steel plug with a magnetic head,
4. **Wash out** the internal contents of the target item using a high-pressure washout head, and
5. **Capture** the effluent generated during high-pressure cutting and washout using a continuous flush to a capture tank.

During the first phase of the demonstration in the shop test tank, each process step was thoroughly tested. This testing occurred over a period of two months and required various tooling upgrades and changes. During this testing, the following operational parameters were arrived upon:

1. Traverse rate of cleaning head = 4 in/min.
2. Water pressure for cleaning head, cutting head, and washout head = 60 ksi.
3. Abrasive feed rate for cutting = 1.25 lb/min.
4. Cutting head rotational rate = 0.6 RPM.
5. Washout head rotational rate = 1 RPM.
6. Washout head traverse rate = 1 in/min.

The cleaning head was tested strictly in the shop test tank where pipes covered in concrete were utilized to determine its effectiveness in removing bioencrustations. For this experimentation, the items prepared with bioencrustations as detailed in Section 5.3 were cleaned underwater in the shop test tank. No further testing of the cleaning head was conducted after the pipes were processed.

The next testing activity in the shop test tank involved testing the attachment of the tool package on the target item, cutting of the access hole, and removal of the resulting plug while capturing the effluent generated during high-pressure cutting. Both empty pipes and inert projectiles were used for this series of tests. Each experiment began by attaching the tool package to the target item and conducting a cut while the capture network was operational. After cutting was completed, the plug removal tool was used to retrieve the plug. Next, the tool package was raised so that a pre-positioned video camera could be used to determine if the cutting and plug removal steps were successful. Later, a borescope was installed in the tool so the magnet could be viewed retrieving a cut plug.

Following the testing of the cutting and plug removal operations, the washout head and associated capture network was tested. Both empty pipes and inert projectiles were used for this series of tests. These target items were pressed with microcrystalline cellulose and contained a precut hole in the side of the item so washout could be tested without cutting.

At this point, after all individual operations were tested, inert projectiles were used to test all operations in series. On December 18, 2019, Dr. Mike Richardson attended a day of testing in the shop test tank. A few mechanical issues were noted during this day of testing and were addressed during the following few weeks. After the modifications were implemented and tested, the team had a high level of confidence to proceed to the second phase of testing in the large test tank. As a result, all equipment was relocated outside and prepared for a final demonstration. The final demonstration occurred on February 27, 2020, in which six inert projectiles were completely processed.

5.2 Site Preparation

The primary activity related to site preparation involved the set up of all equipment required to conduct the demonstration. Figure 13 shows the equipment layout in Delta SubSea's tooling shop where the first phase of testing occurred in the shop test tank. Figure 14 shows the same equipment relocated to the $200,000$ *gallon* test tank for the second phase of testing. Note that the high-pressure intensifier was left inside Delta SubSea's tooling shop and a high-pressure water line was run from the high-pressure pump to the tool.

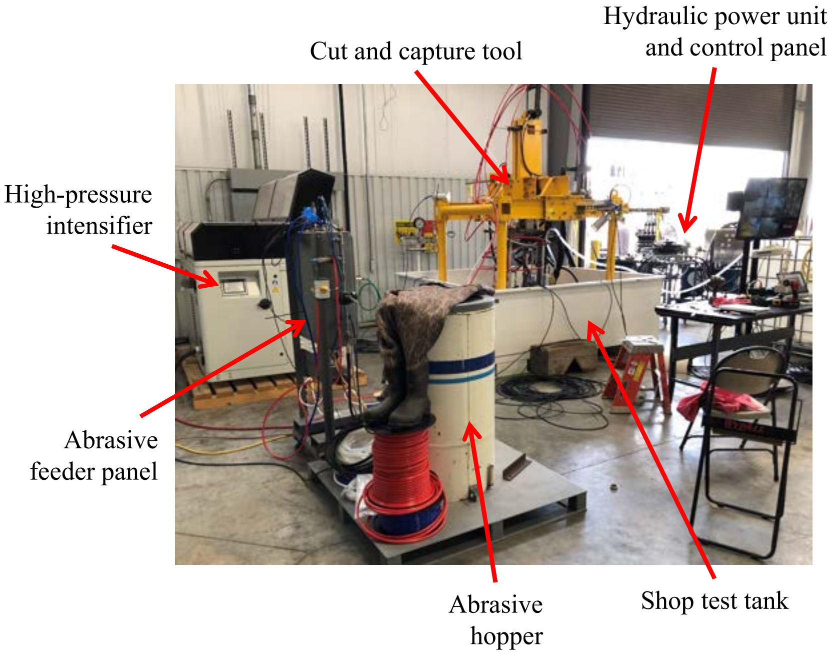


Figure 13: Equipment layout for the shop test tank demonstration.

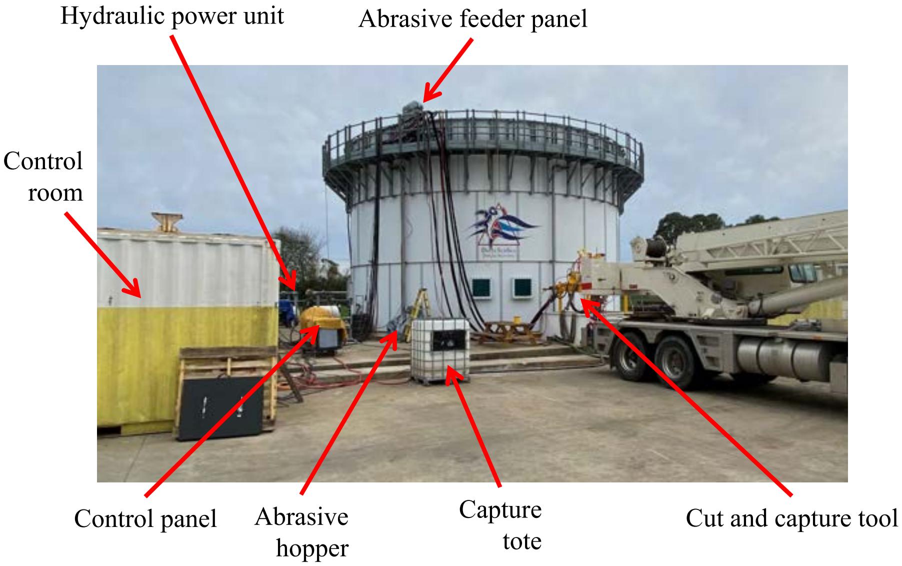


Figure 14: Equipment layout for the large test tank demonstration.

5.3 Test Item Preparation

The target items were primarily inert Navy 5-inch/38-caliber projectiles as shown in Figure 15.

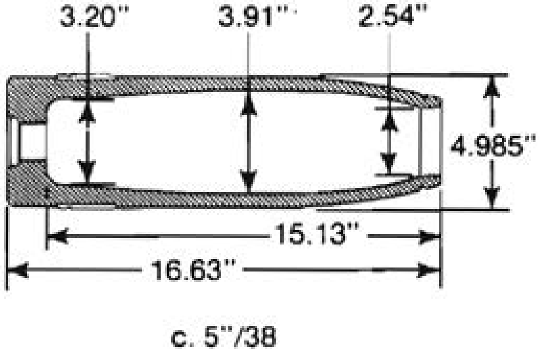


Figure 15: Nominal dimensions of Navy 5-inch/38-caliber projectiles.

Figure 16 shows the projectile bodies that were used to create the target items. These Navy 5-inch/38-caliber projectiles had already been demilitarized by Gradient Technology using the high-pressure waterjet projectile accessing and washout system at NSA-Crane and certified as Material Documented as Safe (MDAS). The hole in the bottom of the projectile where the base fuze was located was plugged by welding in a piece of steel. The nose opening was welded shut with a circular plate after the item was pressed with inert fill.

Figure 16: Demilitarized Navy 5-inch/38-caliber projectiles that were used for target item creation.

Sections of 4 *inch* pipe were used to prepare target items for testing the cleaning head. Concrete was cast around pipe that was previously coated with an epoxy adhesive to ensure the concrete adhered to the pipe. The concrete was prepared by mixing Type 1 Portland cement, washed plaster sand aggregate (mason sand), and water to achieve a compressive strength of 22 $\frac{kN}{m^3}$. The concrete mixture composition is 24.7 $wt\%$ cement, 13.6 $wt\%$ water, and 61.7 $wt\%$ sand. A plastic sleeve with an internal diameter of approximately 7 *inches* was centered over the 4 *inch* pipe and concrete was poured into the annulus. After the concrete cured, the outer plastic sleeve was removed. Figure 17 shows the resulting concrete covered pipe.

Figure 17: Concrete covered pipe for cleaning head testing.

The energetic simulant pressed into the inert Navy 5-inch/38-caliber projectiles consisted of microcrystalline cellulose. This material is insoluble in water. The microcrystalline cellulose was procured from Alfa Aesar (stock number A17730) and is shown in Figure 18. The inert fill was incrementally poured into the projectile body through the nose and pressed to 20 *tons* using a hydraulic press. The hydraulic press is shown in Figure 19. Figure 20 shows some of the resulting inert projectile bodies. Sections of 5 *inch* Schedule 120 pipe were also pressed with microcrystalline cellulose for testing. The wall thickness of this pipe is 0.5 *inch* and is thus similar to the Navy 5-inch/38-caliber projectiles. Figure 21 shows four of these pipes with precut holes in the side.

Figure 18: Microcrystalline cellulose used as the inert fill in the target items.

Figure 19: Hydraulic press for pressing the inert fill into the target items.

Figure 20: Inert projectile bodies used for testing.

Figure 21: Filled pipe with precut holes used for testing.

5.4 System Specification

The core of the technology demonstrated involved the tool package as previously shown in Figure 5. The first tool tested was the cleaning head. The purpose of this tool was to remove bioencrustations from the target item surface so that the turret containing the other tools could be adequately sealed on the target item.

The high-pressure water fed to the cleaning head was at maximum pressure. The KMT Streamline SL-VI 100 *hp* waterjet intensifier pump used for this demonstration has a maximum operating pressure of $60,000$ *psi* and a maximum water flow rate of 1.88 *gpm*. Since the size of the orifices used sets the flow rate of water at a given pressure, the five orifices used in the cleaning head had to be carefully selected. In addition, it is generally desired to have maximum jet power, i.e., use the maximum water flow rate available at the highest pressure available. There are two basic equations that are used to determine water flow rate and jet power:

$$\boxed{\dot{Q} = 21.3 \cdot d_2^2 \sqrt{p_{1,ga}}} \tag{1}$$

$$\boxed{P = 5.831 \times 10^{-4} \cdot \dot{Q} \cdot p_{1,ga}} \tag{2}$$

where $\dot{Q}$ is volumetric flow rate of water in *gpm*, d_2 is orifice diameter in *inches*, $p_{1,ga}$ is the water pressure immediately upstream of the orifice, and P is the power in *hp*. Tables 2 and 3 tabulate the flow rate of water and jet power as a function of orifice size and water pressure. Also, Appendix B graphically displays Equations 1 and 2.

Table 2: Water Flow Rate in *gpm* as a Function of Orifice Size and Water Pressure

Orifice Size *inches*	Pressure in *ksi*										
	40	42	44	46	48	50	52	54	56	58	60
0.003	0.038	0.039	0.040	0.041	0.042	0.043	0.044	0.045	0.045	0.046	0.047
0.004	0.068	0.070	0.071	0.073	0.075	0.076	0.078	0.079	0.081	0.082	0.083
0.005	0.107	0.109	0.112	0.114	0.117	0.119	0.121	0.124	0.126	0.128	0.130
0.006	0.153	0.157	0.161	0.164	0.168	0.171	0.175	0.178	0.181	0.185	0.188
0.007	0.209	0.214	0.219	0.224	0.229	0.233	0.238	0.243	0.247	0.251	0.256
0.008	0.273	0.279	0.286	0.292	0.299	0.305	0.311	0.317	0.323	0.328	0.334
0.009	0.345	0.354	0.362	0.370	0.378	0.386	0.393	0.401	0.408	0.416	0.423
0.010	0.426	0.437	0.447	0.457	0.467	0.476	0.486	0.495	0.504	0.513	0.522
0.011	0.515	0.528	0.541	0.553	0.565	0.576	0.588	0.599	0.610	0.621	0.631
0.012	0.613	0.629	0.643	0.658	0.672	0.686	0.699	0.713	0.726	0.739	0.751
0.013	0.720	0.738	0.755	0.772	0.789	0.805	0.821	0.836	0.852	0.867	0.882
0.014	0.835	0.856	0.876	0.895	0.915	0.934	0.952	0.970	0.988	1.005	1.023
0.015	0.959	0.982	1.005	1.028	1.050	1.072	1.093	1.114	1.134	1.154	1.174
0.016	1.091	1.117	1.144	1.169	1.195	1.219	1.243	1.267	1.290	1.313	1.336
0.017	1.231	1.262	1.291	1.320	1.349	1.376	1.404	1.430	1.457	1.482	1.508
0.018	1.380	1.414	1.448	1.480	1.512	1.543	1.574	1.604	1.633	1.662	1.690
0.019	1.538	1.576	1.613	1.649	1.685	1.719	1.753	1.787	1.820	1.852	1.883
0.020	1.704	1.746	1.787	1.827	1.867	1.905	1.943	1.980	2.016	2.052	2.087

Table 3: Waterjet Power in *hp* as a Function of Orifice Size and Water Pressure

Orifice Size *inches*	Pressure in *ksi*										
	40	42	44	46	48	50	52	54	56	58	60
0.003	0.9	1.0	1.0	1.1	1.2	1.2	1.3	1.4	1.5	1.6	1.6
0.004	1.6	1.7	1.8	2.0	2.1	2.2	2.4	2.5	2.6	2.8	2.9
0.005	2.5	2.7	2.9	3.1	3.3	3.5	3.7	3.9	4.1	4.3	4.6
0.006	3.6	3.8	4.1	4.4	4.7	5.0	5.3	5.6	5.9	6.2	6.6
0.007	4.9	5.2	5.6	6.0	6.4	6.8	7.2	7.6	8.1	8.5	8.9
0.008	6.4	6.8	7.3	7.8	8.4	8.9	9.4	10.0	10.5	11.1	11.7
0.009	8.0	8.7	9.3	9.9	10.6	11.2	11.9	12.6	13.3	14.1	14.8
0.010	9.9	10.7	11.5	12.3	13.1	13.9	14.7	15.6	16.5	17.3	18.3
0.011	12.0	12.9	13.9	14.8	15.8	16.8	17.8	18.9	19.9	21.0	22.1
0.012	14.3	15.4	16.5	17.6	18.8	20.0	21.2	22.4	23.7	25.0	26.3
0.013	16.8	18.1	19.4	20.7	22.1	23.5	24.9	26.3	27.8	29.3	30.8
0.014	19.5	21.0	22.5	24.0	25.6	27.2	28.9	30.5	32.3	34.0	35.8
0.015	22.4	24.1	25.8	27.6	29.4	31.2	33.1	35.1	37.0	39.0	41.1
0.016	25.4	27.4	29.3	31.4	33.4	35.5	37.7	39.9	42.1	44.4	46.7
0.017	28.7	30.9	33.1	35.4	37.7	40.1	42.6	45.0	47.6	50.1	52.8
0.018	32.2	34.6	37.1	39.7	42.3	45.0	47.7	50.5	53.3	56.2	59.1
0.019	35.9	38.6	41.4	44.2	47.2	50.1	53.2	56.3	59.4	62.6	65.9
0.020	39.7	42.8	45.9	49.0	52.2	55.5	58.9	62.3	65.8	69.4	73.0

Although the waterjet intensifier pump has a maximum operating pressure of $60,000$ *psi*, there is significant pressure drop through the piping that leads to the cleaning head (or similarly to the cutting head and washout head). Efforts are made to minimize the observed pressure drop but nonetheless the pressure drop must be accounted for when selecting an orifice.

Next, the cutting head can utilize up to a 0.020 *in* orifice which corresponds to a water flow rate of 1.81 *gpm* and 47.4 *hp* for water at $45,000$ *psi*. The washout head allows for three orifices to be used and are arranged at specific angles so as to maximize jet coverage within the target item cavity. A variety of orifice sizes can be used as long as the total flow rate of water does not exceed the waterjet intensifier pump capacity. If the maximum pump capacity (1.88 *gpm*) is utilized and the pressure at the washout head is assumed to be $45,000$ *psi*, then the sets of orifices that don't exceed the maximum pump flow rate at the specified pressure can be used.

5.5 Calibration Activities

The primary piece of equipment that required calibration was the abrasive feeder. Figure 22 shows the calibration curve for the abrasive feeder in which the delivered abrasive mass flow rate is plotted versus the abrasive feeder speed setpoint and fit to a second-degree polynomial ($y = 1.715 \times 10^{-2} \cdot x + 9.09 \times 10^{-5} \cdot x^2$).

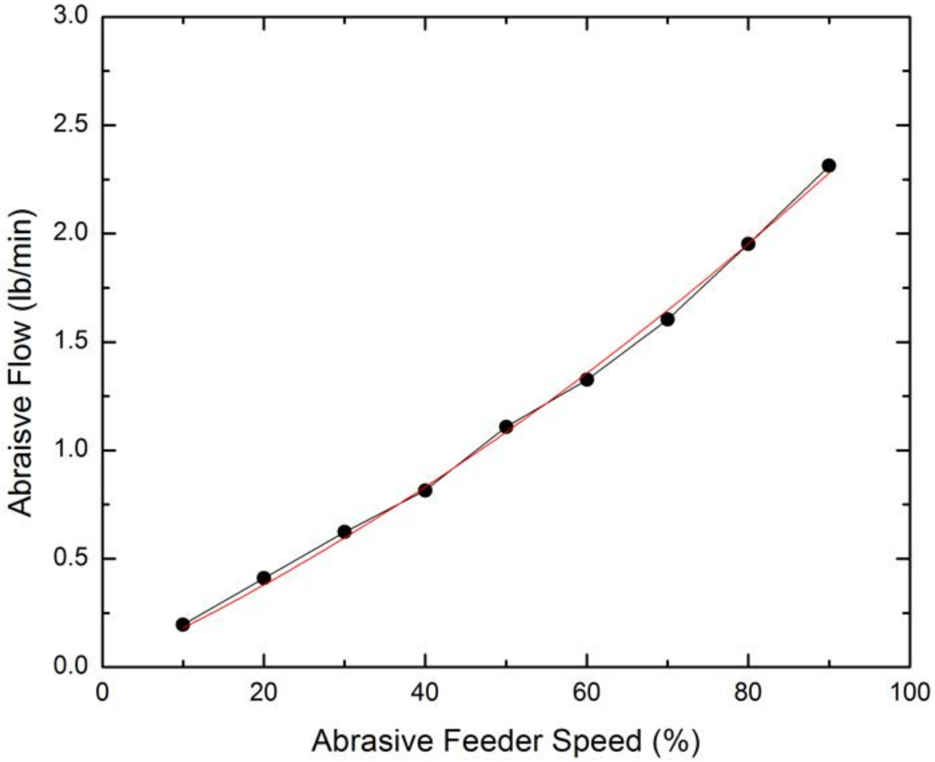


Figure 22: Abrasive feeder calibration curve.

5.6 Data Collection

The primary method of data collection was via observation. All operations were recorded with eight external cameras and two borescopes attached to a digital video recorder (DVR). These recordings were used to determine or verify translational and rotational rates of equipment. All observations, equipment setpoints, and other pertinent data and observations were recorded in a project laboratory notebook.

6 Data Analysis and Products

All data, both quantitative and qualitative, as described in Section 5.6 were analyzed during or immediately after a given test so that proper changes or adjustments could be implemented.

6.1 Preprocessing

The data collected during this demonstration did not require any preprocessing.

6.2 Target Selection For Detection

All targets were inert and prepared prior to the demonstration. Detection of items is not a part of the scope of this demonstration.

6.3 Parameter Estimates

The primary parameters required in the demonstration have been summarized in Section 5.1.

6.4 Data Products

Figure 23 shows the concrete covered pipe before and after cleaning with the high-pressure cleaning head. This figure shows the effectiveness the cleaning head has on concrete. Figure 24 shows proper and improper cuts observed during cut testing. Figure 25 shows a completely processed inert projectile in which all of the inert fill was successfully removed and captured. Figure 26 compares a projectile after cutting and plug removal to one that has been completely washed out. Lastly, Figure 27 compares the effluent captured during cutting to the effluent captured during washout. In this figure, the darker color of the effluent collected during cutting is the result of the abrasive used for cutting the steel projectile body. During washout of the inert fill, abrasive is not used. Therefore, the effluent collected during washout is the result of the white microcrystalline cellulose being washed out of the body with only high-pressure water.

(a) Concrete covered pipe in cradle for processing.

(b) Concrete covered pipe after cleaning underwater.

(c) Close view of the surface generated from the cleaning head.

Figure 23: Concrete covered pipe results after testing the high-pressure cleaning head.

(a) Spiral cut resulting from motion of the cutting head relative to the projectile during testing.

(b) Properly cut inert projectiles.

Figure 24: Proper and improper cuts observed during cut testing.

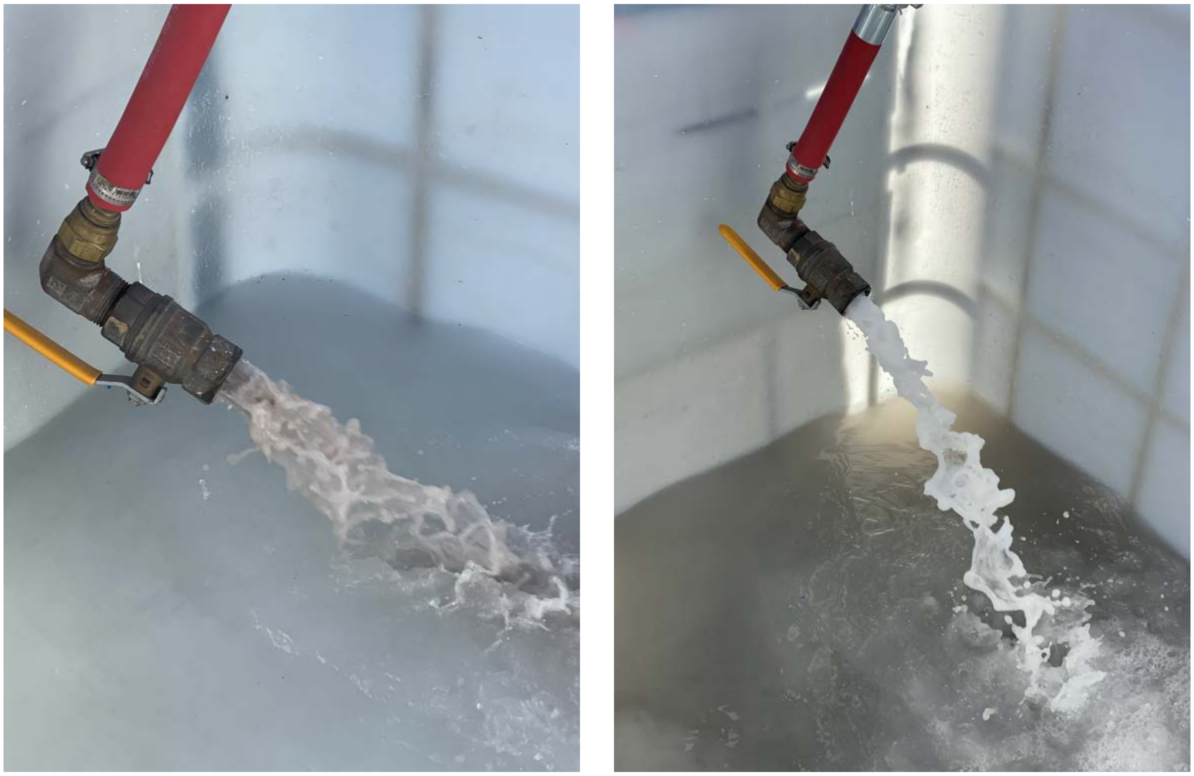
(a) Successfully washed projectile.

(b) Close view of the backside of the projectile after washout; notice some cutting of the backside material occurred.

(c) Plug cut from a projectile.

Figure 25: Completely processed inert projectile.

Figure 26: Inert filled projectiles after cutting/plug removal and washout.



(a) Captured effluent during cutting exhibiting a darker color due to the abrasive.

(b) Captured effluent during washout exhibiting a white color due to the cellulose.

Figure 27: Captured effluent during cutting and washout.

7 Performance Assessment

In this section, the performance objectives identified in Section 3 are assessed.

7.1 Performance Assessment: Equipment Reliability

During the large test tank demonstration, no major or minor equipment failures occurred. However, during shop tank testing, a few major failures were observed. The first failure involved one of the axes of the gantry; the drive screw attached to a hydraulic motor had to be replaced after it bent when the tool was traversed beyond its end of stroke. The second failure involved high-pressure swivel fittings. The cutting and washout heads both utilize a high-pressure swivel fitting to allow for rotation during operation. Both of these fittings failed and resulted in the swivels' inability to rotate. Spare parts were on hand and the fittings were rebuilt. These failures are expected. However, they occurred early in their life expectancy likely due to improper alignment during tool assembly. The last major failure involved the high-pressure waterjet intensifier pump. Before the large test tank demonstration, it was discovered that the 100 *hp* electric motor became decoupled from the hydraulic pump. This failure came as a surprise considering the pump had less than 25 hours of operation on it. The failure resulted from an inadequate motor-pump coupling. KMT provided a new coupling the next day. It was successfully installed and operations proceeded.

A total of 48 inert projectiles were processed during the demonstration and 4 major failures were observed. Since it takes approximately 20 minutes to process a target item, the mean time between major failures is approximately 4 hours.

7.2 Performance Assessment: Cleaning of the Target

Three pipes were covered with concrete 1.5 *inches* thick for testing the cleaning tool's effectiveness. These items were cleaned in the shop test tank as opposed to the large test tank so that the removed material could be isolated to a smaller volume of water. The cleaning head had no issue in removing all of the concrete down to the original pipe surface in one pass. The surface of the pipe exposed was as smooth as the original pipe. Therefore, surface roughness measurements were not taken. The cleaning tool was extremely successful in removing hardened concrete.

7.3 Performance Assessment: Waterjet Washout of Munition Constituents

A total of 19 inert projectiles, each containing 5.0 *pounds* of microcrystalline cellulose, were used for testing high-pressure waterjet washout. The first 15 of these items were processed in the shop test tank. The remaining 4 were processed in the large test tank for the second phase of the demonstration. Initially, the washout operation was set at approximately 5 minutes in which washout occurred only as the washout head was slowly traversed down into the inert projectile. Under these conditions, complete washout regularly occurred. However, on occasion, there was some loose material (approximated to be tens of grams) left in the projectile. It is estimated that 95% of the contents were removed in these instances. When the washout operation was set at approximately 10 minutes in which washout occurred as the washout head was slowly traversed down and back up out of the inert projectile, all material was removed. Therefore, under the conditions of this demonstration, 10 minutes of washout were required to remove all of the material. Note that the washout time was not optimized and could potentially take less than 10 minutes.

7.4 Performance Assessment: Capture of Munition Constituents

During the first phase of testing in the shop test tank, the capture of the effluent during cutting as well as during washout was tested and modified numerous times to arrive at a repeatable and successful technique. In the end, two diaphragm pumps were utilized. One pump was dedicated to pulling water in from the environment and through the sealing volume created when the “boot” on the bottom of the turret is mated to the target item. This volume was flushed continuously during cutting and washout with approximately 10 *gpm* of water. The discharge of the diaphragm pump was plumbed to a collection tote above water. The second pump was dedicated to pulling water in from the environment and through the volume under the turret and above the bottom of the tool. This volume was also flushed continuously during cutting and washout with approximately 10 *gpm* of water. The discharge of this diaphragm pump was similarly plumbed to the collection tote. During cutting, one would observe the stream entering the collection tote becoming dark and cloudy; this was caused by the garnet abrasive and inert fill being removed by the capture network. Most importantly, there was no visible evidence of any leakage to the surroundings; small leaks in the capture network to the surroundings were confirmed to be readily visible via the system of cameras positioned around the tool. During washout, one would observe the stream entering the collection tote becoming cloudy white; this was caused by the inert fill being removed by the capture network. Again, there was no visible evidence of any leakage to the surroundings. Toward the end of the washout operation, it should be noted that one could observe the capture fluid entering the collection note “clearing up” as the last of the microcrystalline cellulose was removed and collected. Since there was no visible evidence of leakage to the surroundings, $> 95\%$ of the inert fill was captured since some material can remain inside the annulus created by the turret. A borescope inserted into this area did show evidence of a small amount of material remaining in this area.

7.5 Performance Assessment: Attachment to Target

During the first phase of testing in the shop test tank, a few different designs of the “boot” that mates the tool to the target item were tested. In the end, a 3D-printed boot provided a tight seal against the target item and prevented leakage to the surroundings. After use of this design, all matings to the target item were deemed successful since no visible leakage could be detected.

7.6 Performance Assessment: Abrasive Waterjet Cutting of Access Hole

During the first phase of testing in the shop test tank, it was observed that the target items would, on occasion, move relative to the cutting head during the cutting operation. This movement led to a spiral cut path as opposed to the desired circle. There were likely several contributors to this phenomena occurring. Initially a thin gasket was used on the boot that mated to the target item. It was observed that this gasket separated from the boot and could have allowed for relative motion of the target item to occur. In addition, initially the force applied to the boot was central to the tool package, however, the boot is not central to the tool package. Therefore, the load applied to the boot was not central to it and likely resulted in forcing the tool to slide relative to the target item. This issue was resolved by placing an offset plate at the top of the tool to redirect the downward applied force to be central to the boot. In addition, counterweights were added to the tool package to keep it vertical; when the tool package freely hung it would lean in one direction due to backlash in its positioning system. Keeping the system vertical is important in that the force applied during mating will remain perpendicular to the target item. After incorporating these changes, circular cuts resulting in plugs that could be removed by the magnet were routinely achieved.

During the second phase of testing in the large test tank, six inert projectiles were processed. Of these six cuts, five resulted in plugs that were successfully removed by the magnet. The unsuccessful cut likely resulted from a momentary loss of abrasive from the abrasive feeder to the cutting head. As a result, there was a sliver of steel not cut; this prohibited the plug from being removed by the magnet. Since five of six cuts were successful, the success rate was 83%.

8 Cost Assessment

This is not applicable as the Government will not be acquiring this technology.

9 Implementation Issues

The demonstration of Gradient Technology's high-pressure waterjet demilitarization technology in an underwater environment has resulted in a system that can effectively demilitarize Navy 5-inch/38-caliber projectiles. In this demonstration, the projectiles were positioned horizontally and were processed in that specific orientation relative to the tool. The equipment, as currently configured, is thus only capable of demilitarizing items that rest on their sides. This limitation was recognized but accepted so that the core of the technology could be validated. In other words, the goal of this demonstration was to prove that ordnance could be first cleaned so that the tool package could be attached to the target. Following attachment, it has been shown that high-pressure waterjets can be used effectively to cut an access hole in the side of the target, the resulting plug can be removed, and the contents can be completely washed out. In the meantime, all cutting and washout effluent can be collected without leakage to the environment. Therefore, the core technology has been successfully demonstrated. As a result, additional efforts can now be focused on manipulating the tool underwater to demilitarize ordnance in varying positions. In order to accomplish this, the gantry used to manipulate the tool package can be modified or replaced with a more flexible positioning system. This aspect of tool positioning has been and will continue to be advanced by Gradient Technology.

Next, the boot used to attach to the Navy 5-inch/38-caliber projectiles was fabricated to fit the contour of this projectile. As a result, the tool could not be immediately mated to a larger diameter projectile. Either diameter-specific attachment boots or a more universal flexible attachment boot would be needed to demilitarize other diameter items. This implementation issue is also being addressed by Gradient Technology.

Another potential issue that is related to the attachment of the tool to the item being demilitarized pertains to the downward force required to maintain an appropriate seal on the item. The force required to maintain a seal and prevent leakage is dependent upon the properties of the attachment boot. Fortunately, the capture network is configured to pull liquid into the boot from the surroundings. This configuration was intentionally designed so that if leakage occurred it would occur from the outside to the inside. The disadvantage of leakage is that more captured liquid volume is generated for disposal. In addition, if too much force is applied to the item, it may be pushed into the material the item is resting on. For example, if the demonstration were conducted using projectiles lying on sand, there is a chance the projectiles would have been pushed down too far before an adequate seal was obtained. These potential issues will be further addressed in the second proposed demonstration in which inert projectiles will be positioned on the ocean floor off of a pier instead of on a solid floor.

Gradient Technology's second demonstration is likely to occur in Panama City, Florida off of a pier at NAVSURFWARCEN PNC FL. The water depth is approximately 10 $feet$ and has a mud/silt floor. Gradient Technology is intending to washout inert Navy 5-inch/38-caliber projectiles as in this demonstration. The items will be processed in a cradle as accomplished in this demonstration, however, we will also attempt to process them on the mud/silt floor. Deployment of the tool is expected to be somewhat simpler than the deployment in this demonstration. For the demonstration documented herein, the tool package had to be hoisted up 30 $feet$ and then lowered back down 30 $feet$ inside the larger test tank. This deployment required extensive cable management during deployment.

For the demonstration documented herein, excellent visibility allowed for operations to be easily captured with underwater cameras. In real world conditions, visibility will likely be limited. As a result, lights will be attached to the tool package to provide improved visibility. In addition, 3D multibeam scanning sonar technology may be used to assess its utility in positioning the tool package in low visibility scenarios. Overall, Gradient Technology looks forward to challenging the technology and improving it as it is subjected to more realistic operating conditions.

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Appendix A

Points of Contact

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Appendix B

High-pressure Waterjet Orifice Size, Flow Rate, and Power Diagram

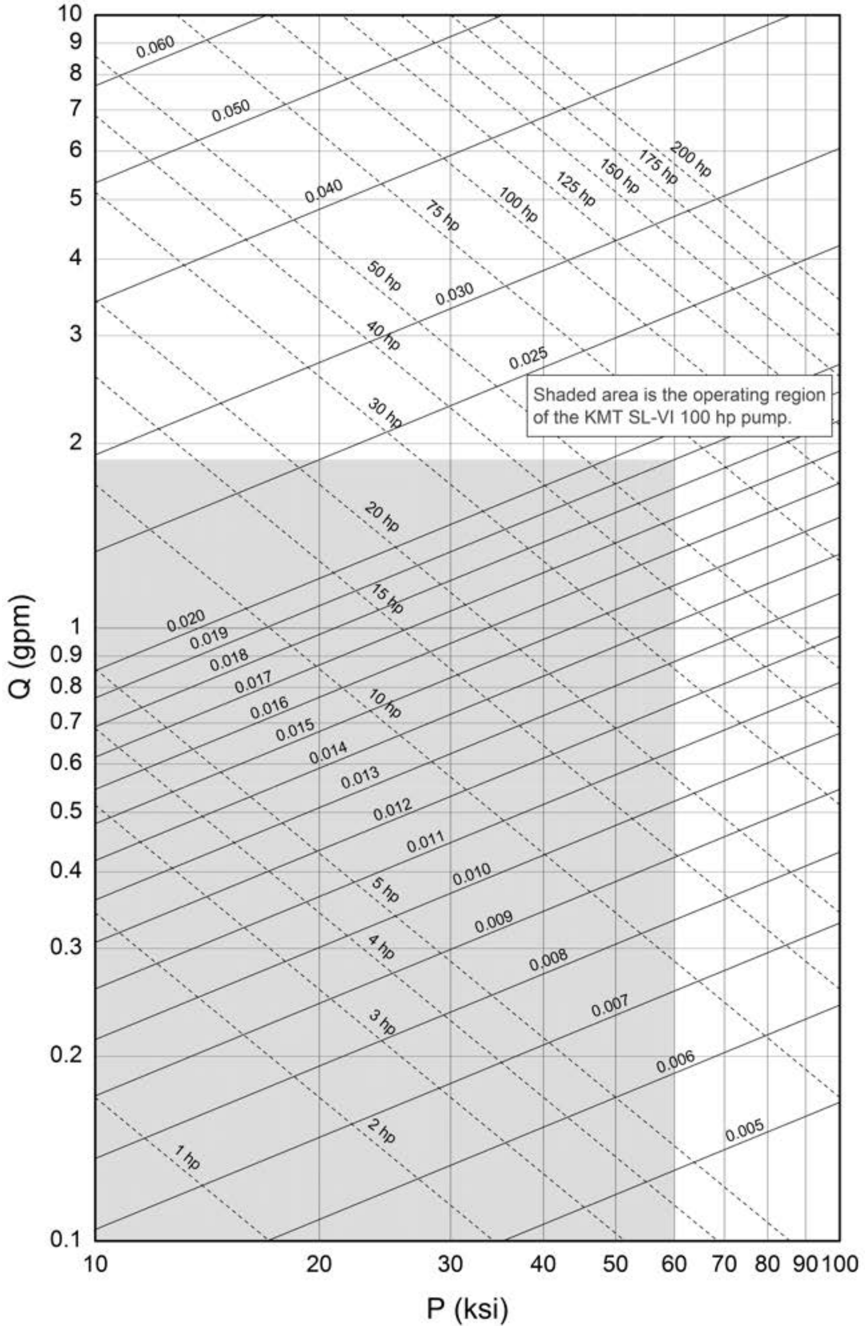

Figure 28: Relationship between orifice size, water flow rate, and power for high-pressure waterjets.