

FINAL REPORT

Cut and Capture System Technology for Demilitarization of
Underwater Munitions

ESTCP Project MR18-5116

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Gradient Technology

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ACRONYMS AND ABBREVIATIONS

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
NDSTC	Naval Diving and Salvage Training Center
NEDU	Navy Experimental Diving Unit
NSA	Naval Surface Activity
NSWC-PCD	Naval Surface Warfare Center-Panama City Division
PC	Panama City
RDX	Research Department eXplosive or Royal Demolition eXplosive
RMS	root mean square
TNT	Trinitrotoluene
UXO	unexploded ordnance
WJ	waterjet

NOMENCLATURE

C	confidence level
d_2	orifice diameter
FSW	feet of sea water
gpm	gallons per minute
hp	horsepower
i	number of successes
in	inch
ksi	thousand pounds per square inch
lb	pound
min	minutes
mm	millimeters
n	number of Bernoulli trials
p	probability of success
$p_{1,ga}$	gage pressure
P	power
$Pr(X)$	probability of getting X successes
psi	pounds per square inch
$\dot{Q}$	volumetric flow rate
r	number of failures
R	reliability
RPM	revolutions per minute

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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 project 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.

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

In this project two demonstrations were conducted. During the first demonstration, 48 inert projectiles that included some covered in concrete were processed in a test tank. During this demonstration, all system functions were successfully demonstrated in a controlled environment. After this demonstration, numerous equipment upgrades were identified and implemented before executing the second demonstration.

During the second demonstration, 45 inert projectiles were processed off a pier at Naval Support Activity (NSA) Panama City, Florida. Our goal was to achieve a 80% reliability (success rate) of a given operation during the demonstration. Statistical analysis of the data yielded the following reliability results at 90% confidence: 89% success rate of mating to the projectile, 75% success rate in cutting the access hole, 91% success rate in removing the plug, and 80% success rate in removing the entire fill of the projectile. This analysis assumed each test was identical and independent. In reality, the cutting parameters were changed during the demonstration because initial cut tests yielded an uncut sliver of steel that prevented the plug from being removed. After the cutting parameters were changed, successful cuts were continually achieved and yielded a reliability of 91%.

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

IMPLEMENTATION ISSUES

In this project, 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 project 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 project.

OBJECTIVES

The objective of this project 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 (demonstration #1) and in the ocean off a pier (demonstration #2). 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 16-inch/50-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.

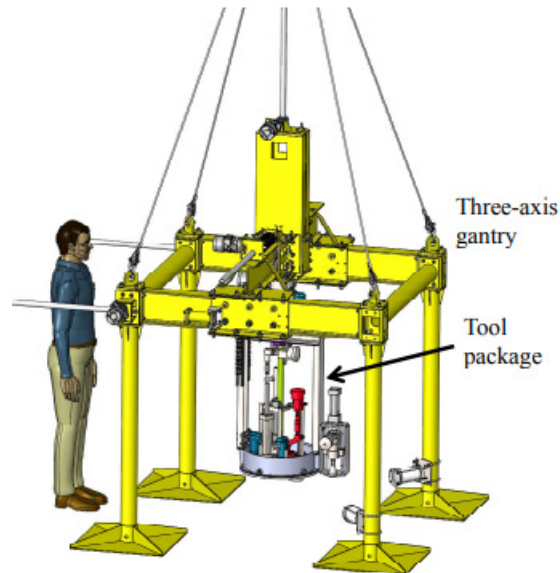


Figure ES-2. Integrated System Consisting of a Three-axis Underwater Gantry and the Tool Package (Computer Model).

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).

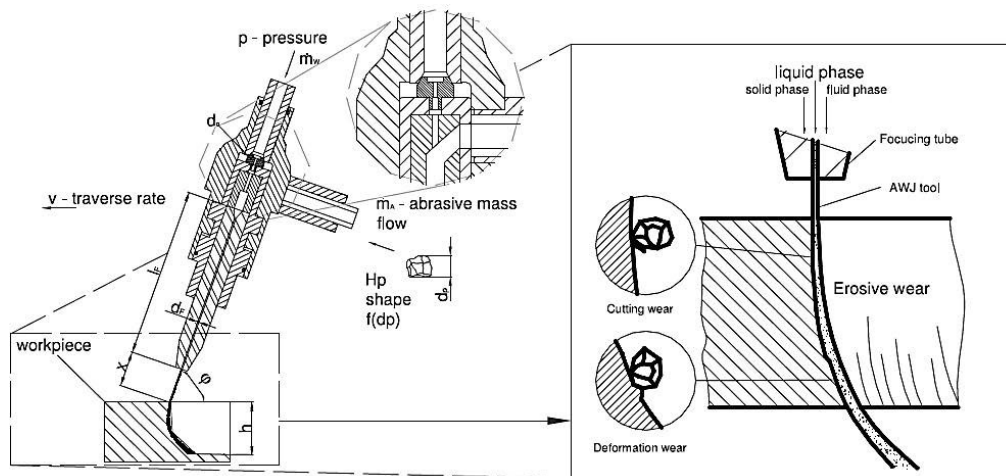


Figure ES-3. The High-pressure Entrainment-style Abrasive Waterjet Cutting Principle.

(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.

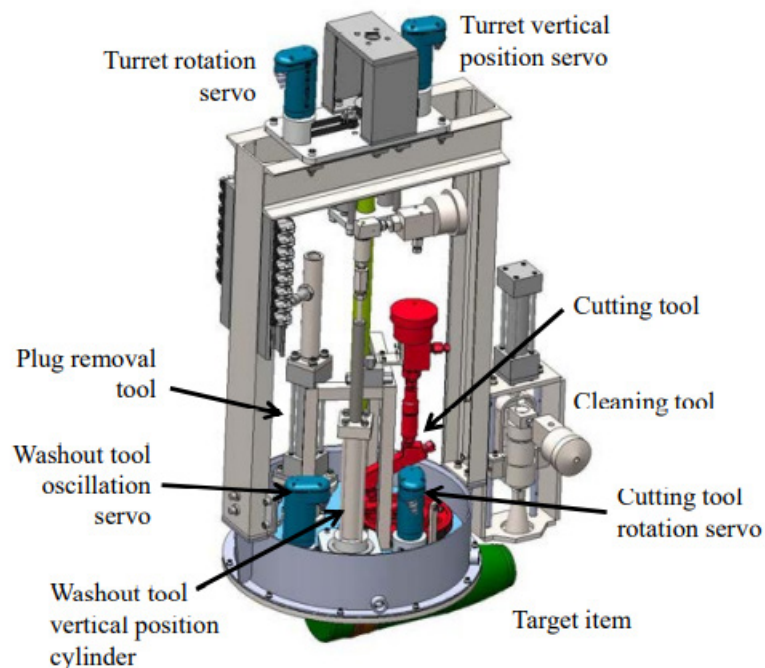


Figure ES 4. The Integrated Underwater Tool Package for *in situ* Demilitarization of Munitions (Computer Model).

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.

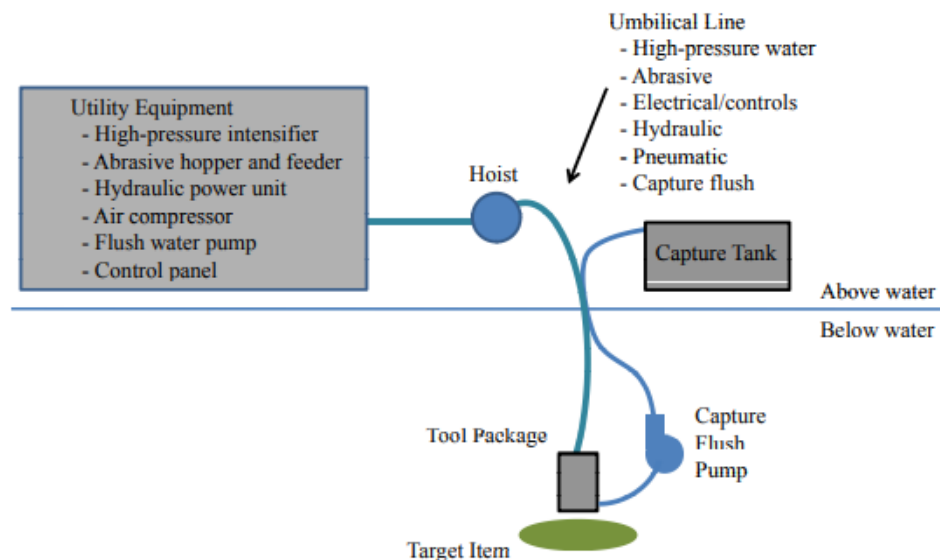


Figure ES-5. Overall Process Schematic of the System Demonstrated in the Test Tank.

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

Demonstration #1

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.

Demonstration #2

A total of 45 inert projectiles were processed during this demonstration. Six of these were also covered with concrete 1 *inch* thick for testing the cleaning tool's effectiveness. The cleaning head again had no issue in removing all of the concrete down to the original pipe surface in one pass. The projectile, however, had to be stabilized so that it did not roll into a hole created on the sea floor by the action of the cleaning head.

The tool operations involving mating, cutting, plug removal, washout, and capture all proceeded reliably. The results of the reliability analysis are as follows for a 90% confidence level:

- Mating $\Rightarrow$ 89%
- Cutting $\Rightarrow$ 91%
- Plug Removal $\Rightarrow$ 91%
- Washout $\Rightarrow$ 80%

Abrasive waterjet cutting was accomplished on all 45 inert projectiles. In addition, 32 inert projectiles, each containing 5.0 *pounds* of microcrystalline cellulose, were used for testing high-pressure waterjet washout. All of the effluent generated during cutting and washout was successfully transferred to a collection tote without leakage to the environment.

Overall, the demonstrations have shown that Gradient Technology's high-pressure waterjet demilitarization technology can be effectively utilized underwater to demilitarize ordnance.

IMPLEMENTATION ISSUES

In this project, 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.

1.0 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 project 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 (demonstration #1) and in the ocean off a pier (demonstration #2). 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.

2.0 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 16-inch/50-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.

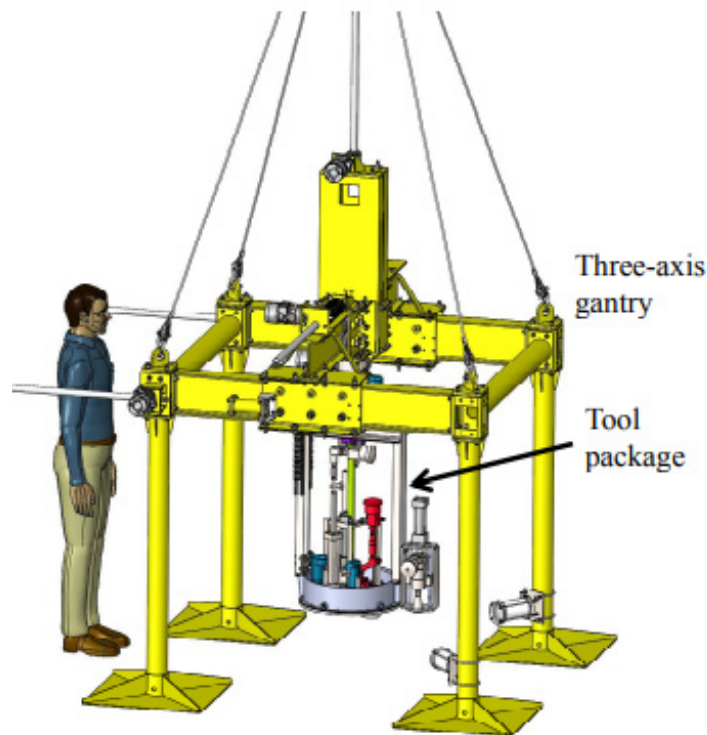


Figure 2. Integrated System Consisting of a Three-axis Underwater Gantry and the Tool Package (Computer Model).



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].

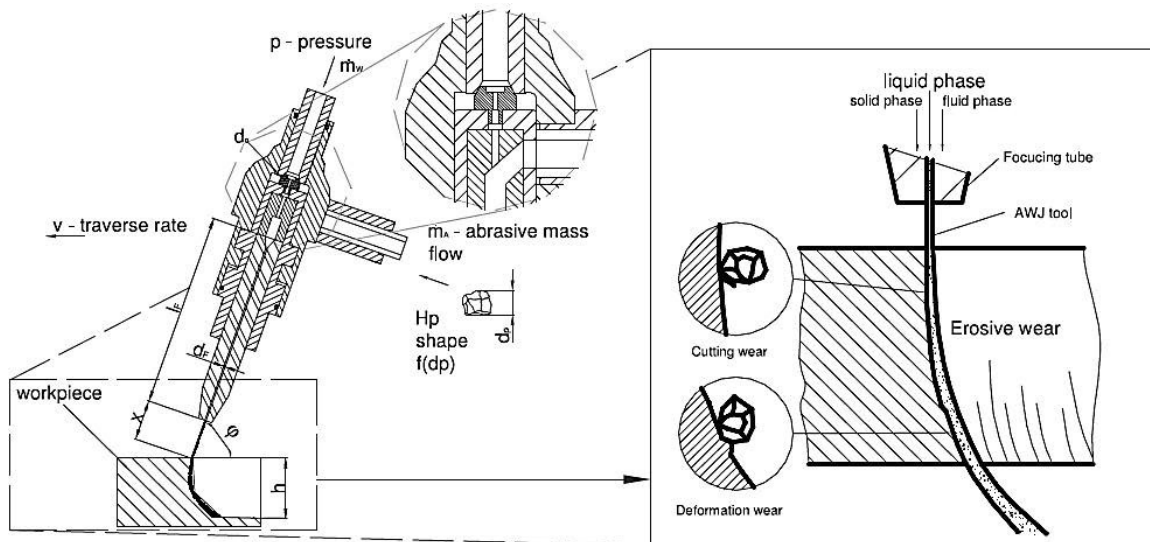


Figure 4. The High-pressure Entrainment-style Abrasive Waterjet Cutting Principle [13].

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.

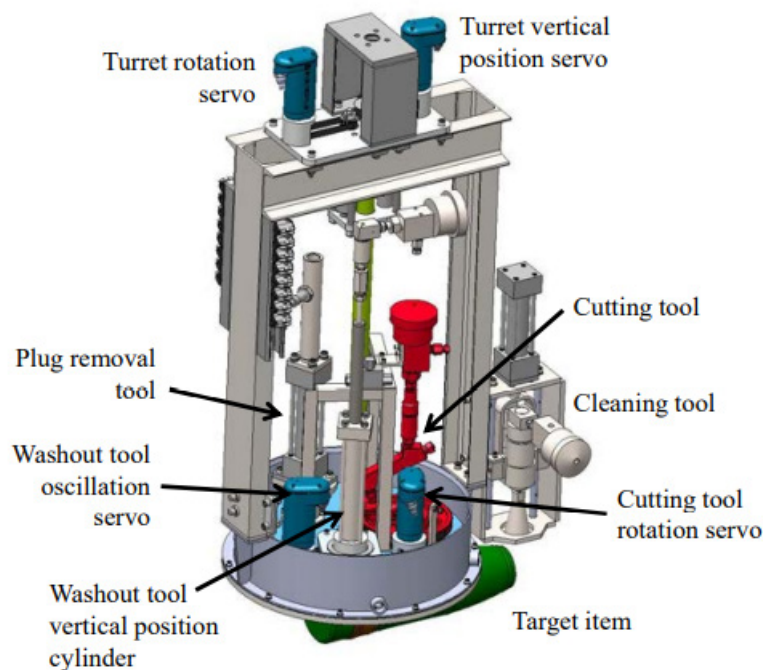


Figure 5. The Integrated Underwater Tool Package for *in situ* Demilitarization of Munitions (Computer Model).

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 first demonstration that highlight the technology and equipment utilized in this demonstration. Figures 11 – 15 contain photographs acquired during the second demonstration off of the pier at NSA PC.

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 project was to validate the integrated tool package in a controlled environment underwater.

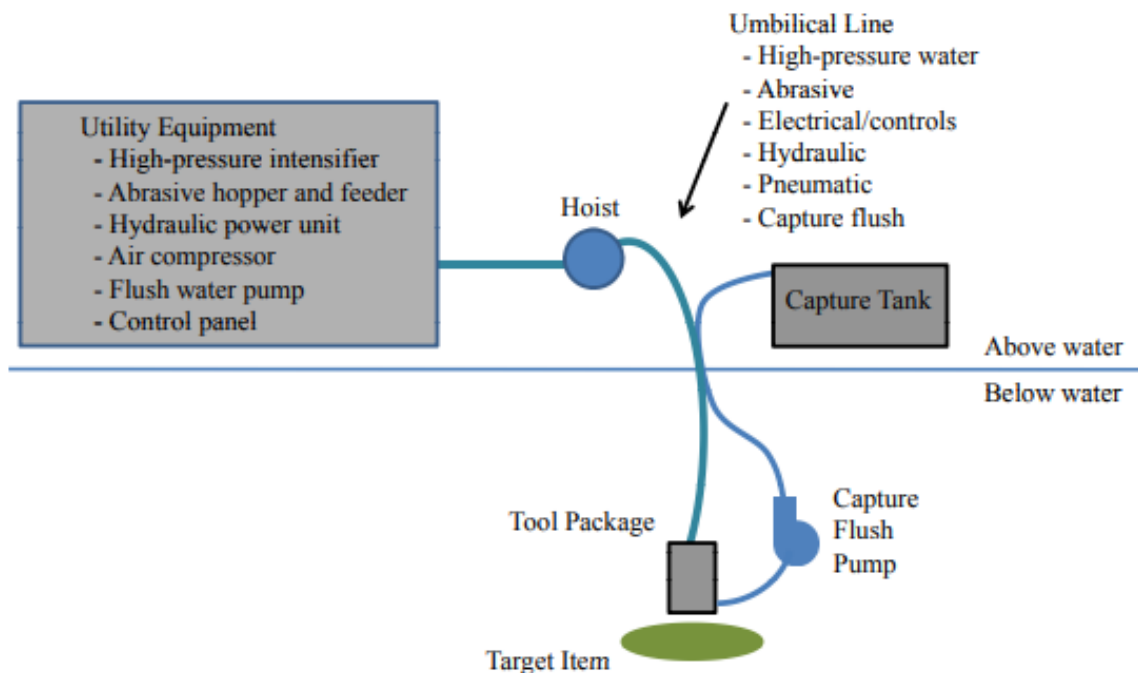


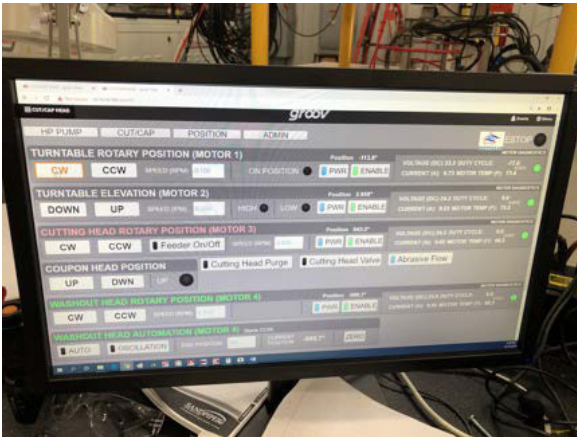
Figure 6. Overall Process Schematic of the System Demonstrated in the Test Tank.



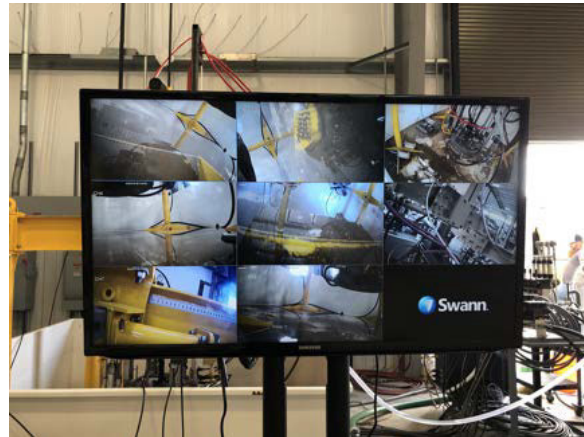
(a) Equipment layout in Delta SubSea's tooling shop.



(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.

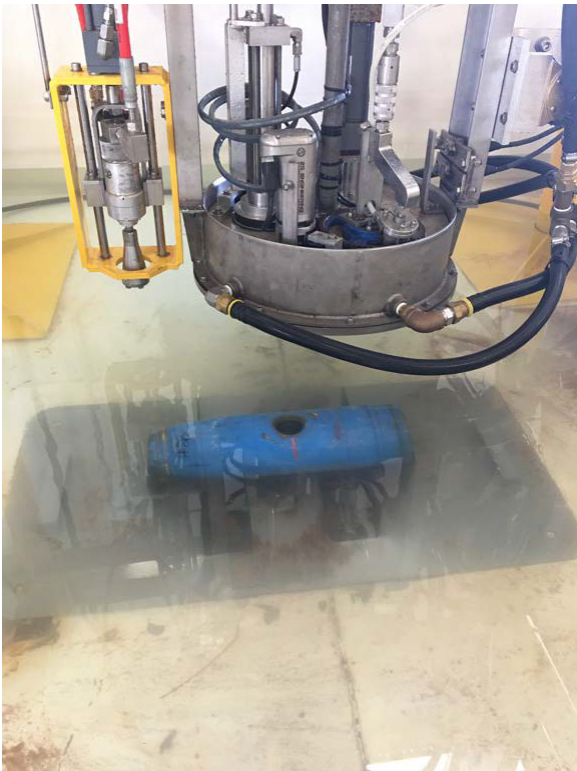
Figure 7. Shop Tank Testing Equipment Layout and Control System.



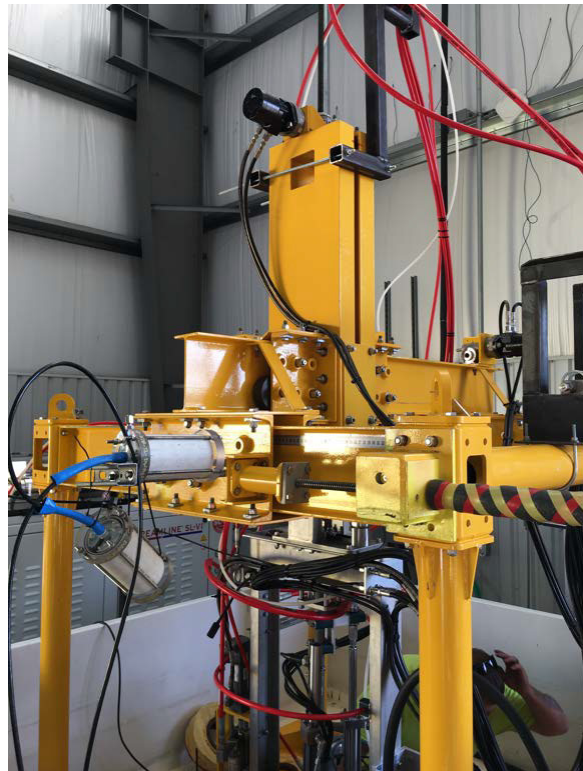
(a) KMT 100 *hp* high-pressure intensifier.



(b) Tool package inside the shop test tank.

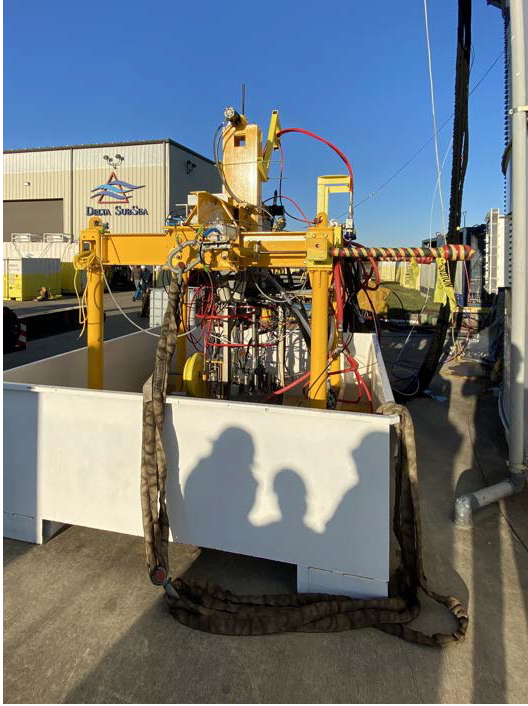


(c) Tool package above an inert projectile after testing.



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

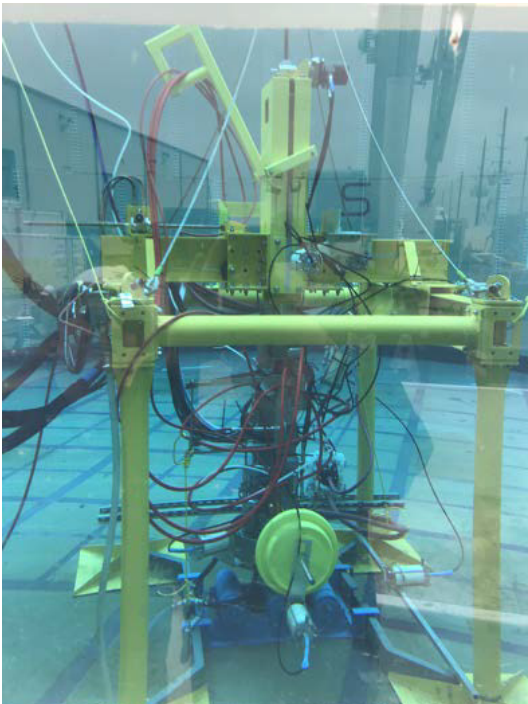
Figure 8. Shop Tank Testing Equipment.



(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.



(a) Site layout at NSA PC.



(b) Diesel-powered generators that provided electrical service to the high-pressure intensifier and other equipment.



(c) Air compressor and dryer that supplied utility air to the capture pumps.



(d) Control room as set up in a mobile trailer.

Figure 11. Site Layout, Utility Equipment, and Control Room at NSA PC



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



(b) High-pressure intensifier feed water system.



(c) Capture tanks located pier side.

Figure 12. Utility and Support Equipment at NSA PC.



(a) Tool package being lowered into the water



(b) Preparation of the tool package prior to deployment.



(c) Tool package as it is submersed into the water

Figure 13. Cut and Capture System Deployment with the Crane.



(a) Item #15 after concrete removal, cutting, and plug removal.



(b) Item #17 after concrete removal, cutting, plug removal, and washout.



(c) Items #1, #21, and #22 in the cradle prior to processing.



(d) Items #27, #47, and #48 after cutting, plug removal, and washout.

Figure 14. Inert Projectiles Processed During the Second Demonstration.



(a) Item #24 after cutting, plug removal, and incomplete washout.



(b) This plug from item #37 is representative of others that contained a sliver of steel after cutting that prevented the plug from being removed with the magnet.



(c) Item #21 after cutting, plug removal, and washout.



(d) Backside of item #21 showing a small hole pierced by the high-pressure waterjet during cutting.

Figure 15. Inert Projectiles After Processing.

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.

3.0 PERFORMANCE OBJECTIVES

There were seven main performance objectives for this project. They contain both qualitative and quantitative metrics as shown in Table 1. The results shown in the table are for the second demonstration conducted at NSA PC. 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	$MTBF_{major} > 3 \text{ hr}$ $MTBF_{minor} > 1 \text{ hr}$	There were two major equipment failures. $MTBF_{major} \approx 7.5 \text{ hr}$
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 in).
Waterjet washout of munition constituents	Percentage of material removed	- Initial mass - Post-washout mass	80% average removal	100% of the fill was removed from 29 of the 32 projectiles; 80% reliability.
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	$P_{attach} > 80\%$	43 of 45 attachments were successful; 89% reliability.
Abrasive waterjet cutting of access hole	Percentage successfully cut	- Items attempted - Items successful	$P_{cut} > 80\%$	38 of 45 of the cuts were successful; 75% reliability, 91% reliability after optimization.
Tool positioning with sonar imaging	Observed utility of sonar imaging for positioning	Observations		Selected sonar was mounted too close to the tool package to be useful.

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 45 inert projectiles were processed during the second demonstration and 2 major failures were observed. Since it takes approximately 20 minutes to process a target item, the mean time between major failures is approximately 7.5 hours. The failure of one of the servo motors accounted for one major failure; it was replaced with a hydraulic motor. The rupture of a high-pressure water line in between the intensifier and the tool package accounted for the other failure. The ruptured line was simply replaced with a spare in about 10 minutes.

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

Six projectiles were covered with concrete 1 *inch* thick for testing the cleaning tool's effectiveness. One of these items was cleaned on the sea floor. However, the cleaning head also pushed away sediment around the projectile which resulted in the projectile rolling down into the resulting hole. Our lesson learned is that we need an apparatus to stabilize items before cleaning if the sea floor is not hard or if the item of interest is not naturally stabilized. As a result, the remaining five projectiles were processed using the cradle to hold items. For these projectiles, the cleaning head had no issue in removing all of the concrete down to the original projectile 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

The washout operation took approximately 8 minutes to complete in which washout occurred as the washout head was slowly traversed down into and back out of the inert projectile. Under these conditions, complete washout regularly occurred. However, for four projectiles, there was some loose material left in the projectile. It is estimated that 95% of the contents were removed in these instances.

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 tote “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

Proper attachment of the tool to the target was quantified during the second demonstration. There were two instances of the 45 projectiles processed in which leakage around the “boot” that seals on the projectile was observed. Therefore, the reliability of this operation was 89% at a 90% confidence level.

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 was 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 demonstration 7 of the 45 projectiles processed resulted in plugs that could not be removed. This resulted from a sliver of steel remaining at the position of the initial pierce of the waterjet; this prohibited the plug from being removed by the magnet. This issue was resolved by cutting in the opposite direction initially for approximately 10° before reversing the cutting direction for a complete revolution. As a result, we were cutting over the initial pierce area three times. If all data is statistically analyzed the reliability of cutting was 75% at a 90% confidence level. When analyzing the data after the change in the cutting profile, the reliability increased to 91% at a 90% confidence. Also, the plug removal data was statistically analyzed and resulted in a 91% reliability at a 90% confidence level.

3.7 OBJECTIVE: TOOL POSITIONING WITH SONAR IMAGING

The utility of sonar imaging in positioning the tool package on the target items will be qualitatively assessed. Two Aris Explorer 3000 sonar imaging systems will be mounted on the tool package and used in conjunction with cameras to position the tool package on the target items. As a result, the utility of sonar imaging can be determined. Sonar imaging could be useful and likely required in low-visibility conditions underwater.

3.7.1 Metric

Qualitatively assess the utility of sonar imaging in positioning the tool package on the target items.

3.7.2 Data Requirements

This is purely observation based.

3.7.3 Success Criteria

The objective will be met if it is determined that this sonar imaging system can supplant visual observation (cameras).

3.7.4 Data and Results

This objective was added for the second demonstration. Two Aris Explorer 3000 sonar imaging systems were mounted to the tool gantry and its performance was assessed during the demonstration. Upon assessment, it was determined that the units were mounted too close to the tool package and target item to provide useful imaging data. As a result, minimal time was spent on optimizing its use in this demonstration.

4.0 SITE DESCRIPTION

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

4.1 SITE SELECTION – DEMONSTRATION #1

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 16. The primary criterion for the test site was that it was 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 5.3 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 17, is used by Delta SubSea to test their own equipment.

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

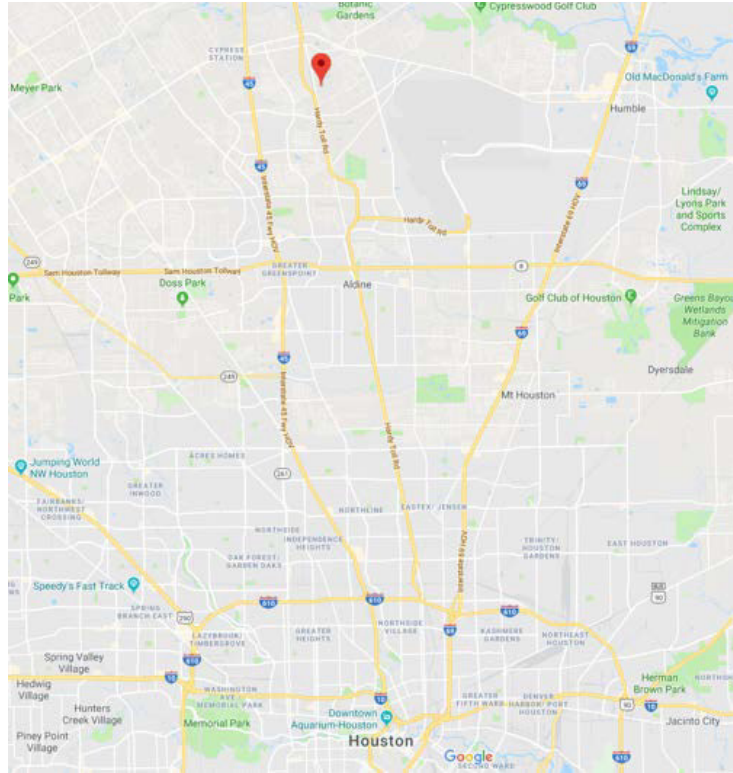


Figure 16. Houston Area Map Showing the Location of Delta SubSea's Test Tank at 1616 Southcreek Lane, Houston, Texas.



Figure 17. 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 SELECTION – DEMONSTRATION #2

The site selected for the second demonstration was Naval Support Activity (NSA) Panama City, Florida. A site map is shown in Figure 18. The test site location on-board NSA Panama City was Alligator Bayou in approximately 10 *FSW* as shown in Figure 19.

This location was selected because of the fairly flat hard sandy bottom, fairly clear water and because it is protected from winds and waves from St. Andrew's Bay. In addition, there was easy access to a fixed gantry crane, fresh water, power, and pier space for lay down of equipment.



Figure 18. NSA Panama City, Alligator Bayou – Location of Second Demonstration.

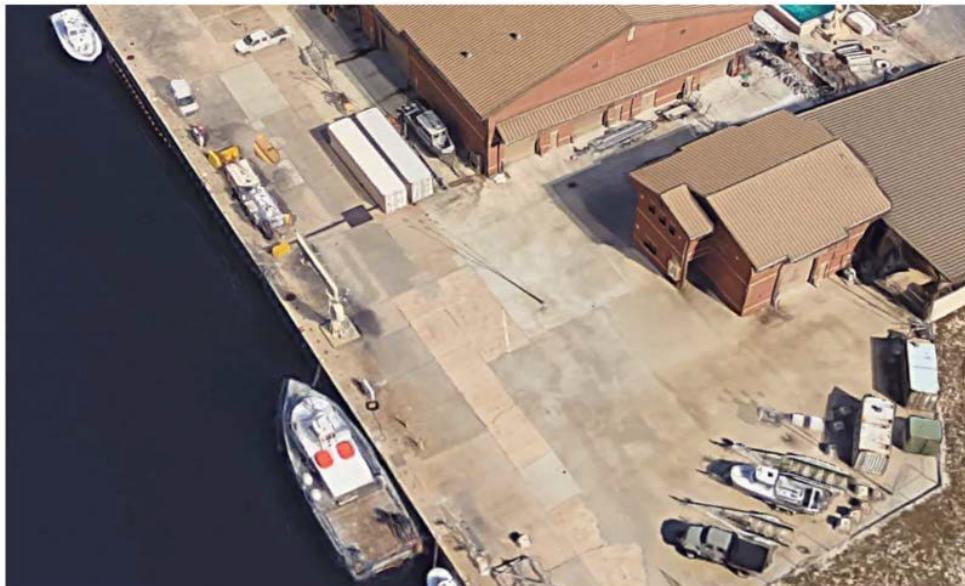


Figure 19. Overhead View of Pier and Gantry Crane Where the Open Water Demonstration Will Occur.

4.3 SITE HISTORY

Naval Support Activity Panama City has its origins in the mine countermeasures research conducted during World War II at the U.S. Naval Mine Warfare Test Station, Solomons, MD. In July 1945, the station was moved from Maryland to Florida to occupy a 373-acre tract along St. Andrew Bay.

Over the ensuing decades the base footprint grew to its current size of more than 650 acres and underwent a myriad of name changes until it reorganized under Commander, Navy Installations Command in October 2003. The base was renamed Naval Support Activity Panama City (NSA PC) reporting to the Commander, Navy Region Southeast, however the mission still remains rooted in its origins of research and development, testing and evaluation, and Navy diving.

The primary mission of NSA PC is to provide, operate, and maintain facilities, provide defense and physical security of critical infrastructure, and provide operational support to the Fleet, Fighter and Family, and supported commands.

Major tenants include Naval Surface Warfare Center-Panama City Division (NSWC- PCD), Naval Diving and Salvage Training Center (NDSTC), Navy Experimental Diving Unit (NEDU), and U.S. Coast Guard Station Panama City. Together, NSA PC employs more than 4,000 civilian and military personnel with an annual payroll of more than \$466 million. Additionally, the base contracts for local goods and services which amounts to more than \$600 million annually in economic impact.

Throughout its existence, NSA Panama City has continued to evolve to meet the demanding requirements of the U.S. Navy – to defend today and to plan for tomorrow in response to national needs.

4.4 SITE GEOLOGY

The area off of the pier at NSA Panama City had a fairly flat hard sandy bottom with fairly clear water.

4.5 MUNITIONS CONTAMINATION

Neither demonstration used live munitions; inert projectiles were utilized.

5.0 TEST DESIGN

The second demonstration commenced in July 2020, after all utility equipment had been installed and confirmed to be operational on the pier. This equipment included the high- pressure intensifier pump, abrasive delivery system, hydraulic power unit, video system, and control system. The first of the 45 projectiles was processed on July 13, 2020, and the last item was completed on July 28, 2020. On July 29, 2020, all equipment was dismantled and shipped out of the site.

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.

The following operational parameters were utilized when processing an inert projectile:

1. Traverse rate of cleaning head = 4 *in/min*.
2. Water pressure for cleaning head, cutting head, and washout head = 50 *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 first phase of testing for the second demonstration occurred in the shop test tank located on the pier as used in the first demonstration. This approach was used to confirm all utilities and the tool package were working properly. Upon confirmation of proper operation, testing commenced in open water off of the pier with the remaining inert target items. The gantry crane was used to deploy the tool package and subsequently retrieve it.

For this demonstration, 48 inert target items were prepared and sent to the site. The preparation of these items is detailed in Section 5.4 and summarized in Table 3. All items had a plate welded on the base and nose to cover pre-existing holes. Of the 48 items, 16 were simply capped without being loaded with the inert fill. These target items were used to conduct cutting, plug removal, and simulate washout. Twenty-six of the items were loaded with inert fill so that cutting, plug removal, and washout could be tested. Lastly, six of the items were partially covered in concrete so all process steps could be tested on each of those items.

For the second demonstration, two approaches were used for placing the inert target items (summarized in table 2). The first approach, as was used in the first demonstration, involved placing three target items in a cradle that is connected to the tool package. This approach is beneficial since the target items can be deployed and retrieved with the tool package. This approach was used first to process a multitude of target items. Figure 20 shows three target items in the cradle from the first demonstration. The second approach utilized independent placement of the target items directly on the floor. Divers were used to place the items directly on their sides on the floor in a region within reach of the tool package; note that the tool package has approximately a 3-foot by 3-foot operating window. As a result, the gantry crane does not have to be able to place the tool package gantry in an exact position. After placement of the tool package over a given target item, the tool gantry was used to attach the tool to the target item. After attachment, the tool package was used to process the item. This approach allowed for testing in a more realistic operational scenario. Note that cameras and lights were attached to the tool package for visualization during processing.



Figure 20. Cradle for Holding Three Target Items.

Table 2. Target Item Placement Summary

Item Numbers	Item Positioning Location	
1, 21, 22	Cradle	Test Tank
2–5, 8–11, 15–20, 23–26	Cradle	Open Water
6–7, 27–48	Floor	Open Water

Overall, the complete demonstration required 4 weeks to complete in which 45 of the 48 target items were processed; only three of the empty projectiles (#12, #13, and #14) were not processed.

At the Naval Support Activity (NSA) Panama City, Florida, four key personnel facilitated the demonstration with Gradient Technology. These individuals were as follows:

- Rick Stynar – Senior Test Director, NSA Panama City
- Jason Tebault – Test Director (alternate), NSA Panama City
- Matthew Warren – Test Director (alternate), NSA Panama City
- Ismael Mendoza-Perez – Test Support, Safety Observer, NSA Panama City

The recent Coronavirus pandemic did not significantly impact the manner in which this demonstration was conducted. All personnel followed NSA-Panama City policies in place at the time of the demonstration.

5.2 STATISTICAL EXPERIMENTAL DESIGN AND DATA ANALYSIS

Many of the objectives of this demonstration were based on success or failure of a given operation. As a result, a set of Bernoulli trials was conducted and it was assumed that the trials were independent from each other and the probability of success didn't change from trial to trial. If this assumption is true, which was the case for our demonstration except for the cutting changes we implemented, then the number of successes in Bernoulli trials has a binomial distribution. There are two important equations that are used to describe the binomial distributions. Equation 1 is the probability mass function:

$$Pr(X = i) = \frac{n!}{i!(n-i)!} \cdot p^i \cdot (1-p)^{n-i} \quad (1)$$

where $Pr(X)$ is the probability of getting $X = i$ successes when n Bernoulli trials are conducted in which each trial has p probability of success. For example, if 10 trials are conducted ($n = 10$) and the probability of success of an individual trial is 50% ($p = 0.5$), then the probability of observing 6 successes ($i = 6$) is 0.205.

Equation 2 is the cumulative distribution function:

$$1 - C = \sum_{i=0}^r \frac{n!}{i!(n-i)!} \cdot R^{n-i} \cdot (1-R)^i \quad (2)$$

where C is the confidence level, r is the number of failures, i and n are again the number of successes and Bernoulli trials respectively, and R is the reliability ($R = p$). From an experimental design perspective, equation 2 can be used to determine the number of allowable failures, r , for n Bernoulli trials with a confidence level C and a reliability of R . For example, if 48 Bernoulli trials are conducted, a confidence level of 95% is desired, and the reliability of the equipment is expected to be at least 80%, then the number of allowable failures, r , can be calculated; the result for this example is four failures. From a data analysis perspective, the reliability is not known.

However, if n Bernoulli trials are conducted and the number of successes, i , are recorded, equation 2 can be used to calculate the reliability for a given confidence level. For example, if 48 Bernoulli trials are conducted and 44 successes are observed, the reliability with a 95% confidence level is 82%. Therefore, equation 2 was used to analyze data collected in the second demonstration. The data is presented in operating characteristic (OC) curves for a particular n and r combination. These curves plot $1 - C$ which is equivalent to $Pr(n - i \leq r)$ or the probability of r or less failures in n samples versus the population failure rate, $1 - p$, i.e. the OC is a plot of equation 2. These curves are useful for understanding the relationship between the probability of r or less failures in n samples versus the population failure rate, $1 - p$, for a given sample size, n , and number of failures, r .

5.3 SITE PREPARATION

The primary activity related to site preparation involved setting up all equipment required to conduct the demonstration. Figure 21 shows the pier where the equipment was located. Figure 22 shows a view where the generator and high-pressure pump were located. Fresh water was available from this building also. A high-pressure water line was run from the high-pressure pump to the tool package. Figure 23 shows the gantry crane that was used to deploy the tool package. Figure 24 shows the area where all other utility equipment was located. Lastly, Figure 25 shows underwater views of a target on the floor where the demonstration occurred. As shown in this figure, the floor was fairly flat and there was decent visibility.

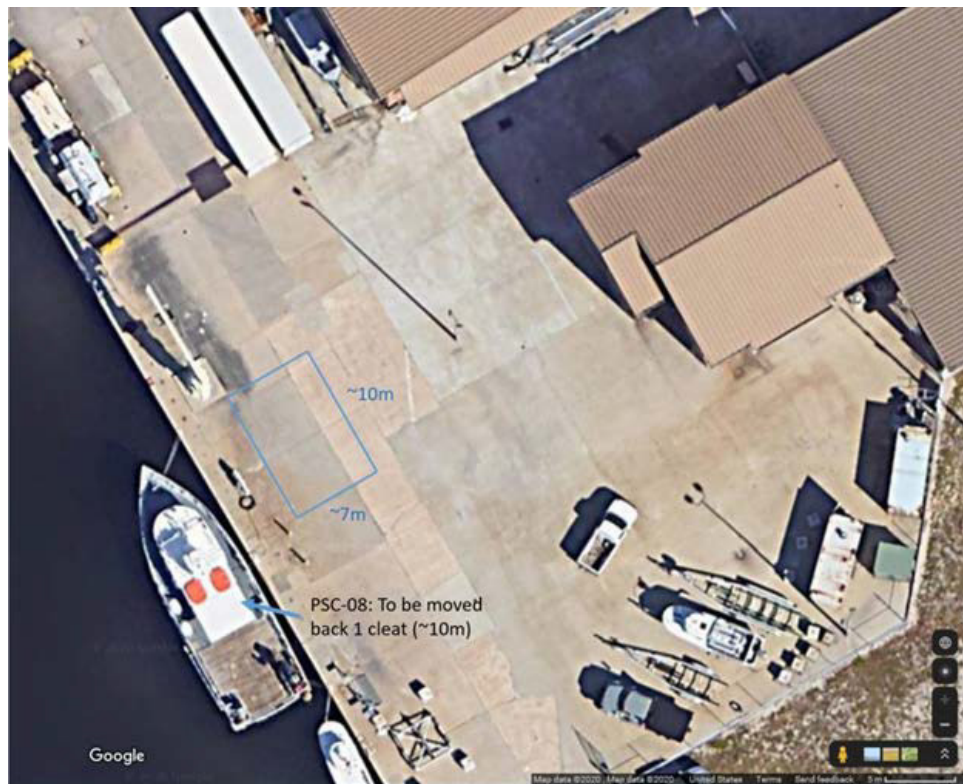


Figure 21. Pier Location Where All Equipment Was Located.



Figure 22. Bayou Is Directly Behind Photographer and the Crane Is to the Left; Building 582 is on the Right and Was Where the Generator and High-pressure Pump Were Located.



Figure 23. Gantry Crane that Was Used to Deploy the Tool Package.



Figure 24. Area Where Utility Equipment Was Located.

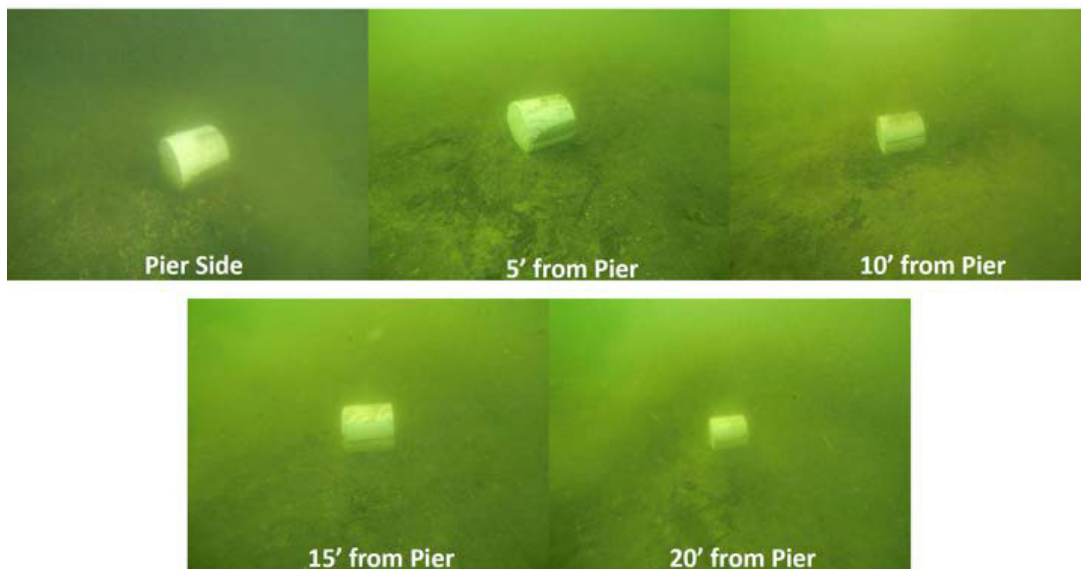


Figure 25. View of a Target Item on the Floor Off of the Pier Where the Demonstration Occurred.

5.4 TEST ITEM PREPARATION

The target items were inert Navy 5-inch/38-caliber projectiles as shown in Figure 26.

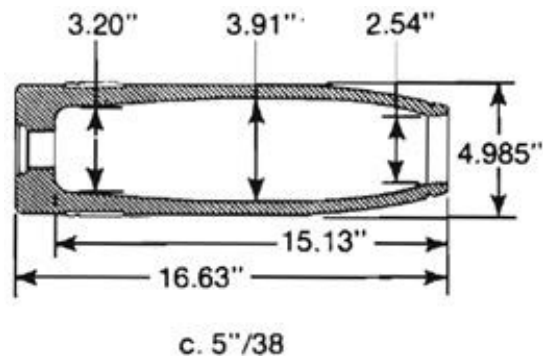


Figure 26. Nominal Dimensions of Navy 5-inch/38-caliber Projectiles.

Figure 27 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 27. Demilitarized Navy 5-inch/38-caliber Projectiles that Were Used for Target Item Creation.

Concrete was cast in a mold around six of the inert projectiles. The concrete was prepared by mixing Type 1 Portland cement, washed plaster sand aggregate (mason sand), and water to achieve a compressive strength of $22 \frac{kN}{m^2}$. The concrete mixture composition was 24.7 wt% cement, 13.6 wt% water, and 61.7 wt% sand.

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 28. 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 29. Figure 30 shows some of the resulting inert projectile bodies. Table 3 summarizes the preparation of the target items.

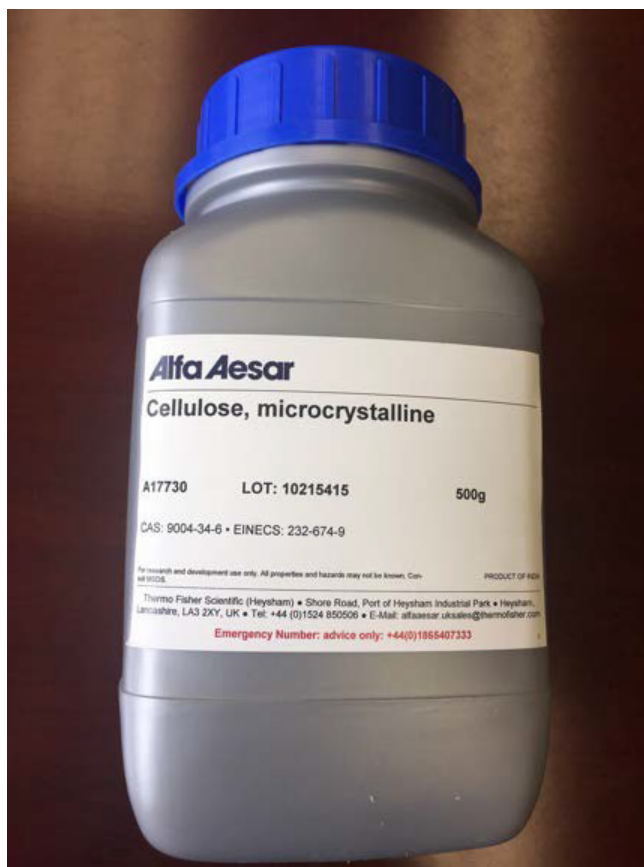


Figure 28. Microcrystalline Cellulose Used as the Inert Fill in the Target Items.



Figure 29. Hydraulic Press for Pressing the Inert Fill into the Target Items.



Figure 30. Inert Projectile Bodies Used for Testing.

Table 3. Target Item Preparation Summary

Item Numbers	Inert Filled	Concrete Covered
1–14	NO	NO
15–16	NO	YES
17–20	YES	YES
21–48	YES	NO

5.5 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:

$$\dot{Q} = 21.3 \cdot d_2^2 \sqrt{p_{1,ga}} \quad (3)$$

$$P = 5.831 \times 10^{-4} \cdot \dot{Q} \cdot p_{1,ga} \quad (4)$$

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 4 and 5 tabulate the flow rate of water and jet power as a function of orifice size and water pressure. Also, Appendix B graphically displays Equations 3 and 4.

Table 4. Water Flow Rate in *gpm* as a Function of Orifice Size and Water Pressure

Orifice Size <i>inches</i>	Pressure in <i>ksi</i>										
	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 5. Waterjet Power in *hp* as a Function of Orifice Size and Water Pressure

Orifice Size <i>inches</i>	Pressure in <i>ksi</i>										
	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.

5.6 CALIBRATION ACTIVITIES

The primary piece of equipment that required calibration was the abrasive feeder. Figure 31 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 ($y = 1.715 \times 10^{-2} \cdot x + 9.09 \times 10^{-5} \cdot x^2$).

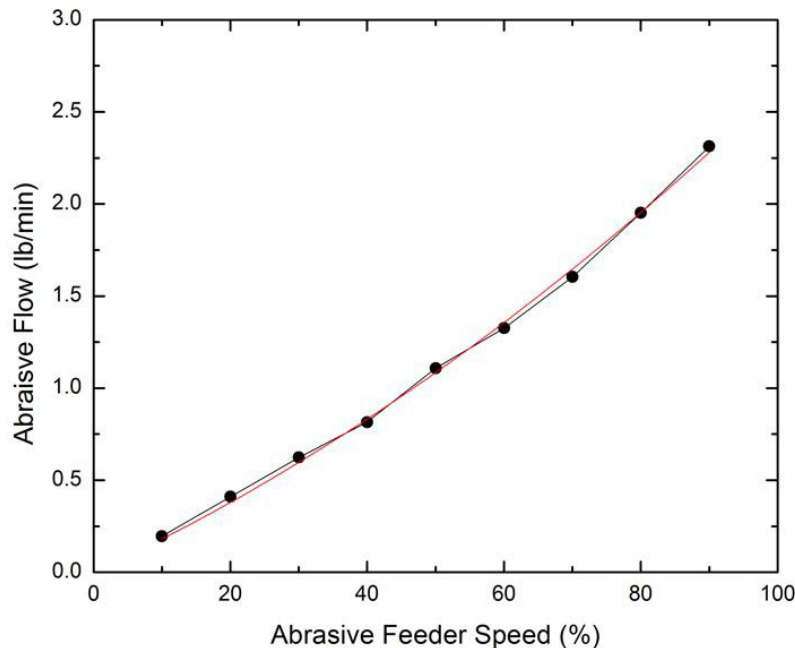


Figure 31. Abrasive Feeder Calibration Curve.

5.7 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.

6.0 DATA ANALYSIS AND PRODUCTS

All data, both quantitative and qualitative, as described in Section 5.7 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 each demonstration. Detection of items was not a part of the scope of this project.

6.3 PARAMETER ESTIMATES

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

6.4 DATA PRODUCTS

Figure 32 shows a completely processed inert projectile in which all of the inert fill was successfully removed and captured. Figure 33 compares a projectile after cutting and plug removal to one that has been completely washed out. Lastly, Figure 34 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.

Figure 35 shows the resulting plugs cut from projectiles 34 and 46. The plug from item 34 shows the small sliver of steel left after cutting; this prevented the plug from being removed. The plug from item 46 is an example of the plugs cut after the cutting profile was modified to initially cut in the opposite direction for approximately 10° before reversing the cutting direction for a complete revolution. As a result, we were cutting over the initial pierce area three times. This change in the cutting profile resulted in successful cuts and plug removal.

The success and failure data collected for the second demonstration is shown in table 6. In this table, successes are denoted ✓ and failures are denoted •. The plug removal data denoted by ‡ indicates plugs that were removed by hand; these were cutting failures prior to cutting optimization. This is the data that was removed from statistical analysis to reassess the cutting reliability.



(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 32. Completely Processed Inert Projectile.



Figure 33. 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 34. Captured Effluent During Cutting and Washout.



Item #34



Item #46

Figure 35. Plugs Cut from Projectiles 34 and 46.

Table 6. Success and Failure Data Collected for the Second Demonstration. Failures Denoted as ●.

	Projectile	Concrete	Fill	Cradle	Tank	Sea Floor	Cleaning	Mating	Cutting	Plug Removal	Washout	Capture	Date
1			✓	✓			✓	✓	✓				7/13/20
2			✓		✓		✓	✓	✓				7/14/20
3			✓		✓		✓	●	†				7/14/20
4			✓		✓		✓	✓	✓				7/28/20
5			✓		✓		✓	✓	✓				7/28/20
6					✓		●	✓	✓				7/17/20
7					✓		✓	✓	✓				7/20/20
8			✓		✓		✓	✓	✓				7/28/20
9			✓		✓		✓	✓	✓				7/28/20
10			✓		✓		✓	✓	✓				7/28/20
11			✓		✓		✓	✓	✓				7/28/20
15	✓		✓		✓	✓	✓	✓	✓				7/13/20
16	✓		✓		✓	✓	✓	✓	✓				7/15/20
17	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		7/27/20
18	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		7/27/20
19	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		7/28/20
20	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		7/28/20
21		✓	✓	✓			✓	✓	✓	✓	✓		7/13/20
22		✓	✓	✓			✓	✓	✓	✓	✓		7/13/20
23		✓	✓		✓		✓	✓	✓	✓	✓		7/14/20
24		✓	✓		✓		✓	●	†	●	✓		7/14/20
25		✓	✓		✓		✓	✓	✓	✓	✓		7/15/20
26		✓	✓		✓		✓	✓	✓	✓	✓		7/15/20
27		✓			✓		✓	✓	✓	✓	✓		7/24/20
28		✓			✓		✓	✓	✓	✓	✓		7/27/20
29		✓			✓		✓	✓	✓	✓	✓		7/27/20
30		✓			✓		✓	✓	✓	✓	✓		7/27/20
31		✓			✓		✓	✓	●	✓	✓		7/17/20
32		✓			✓		●	✓	✓	✓	✓		7/20/20
33		✓			✓		✓	●	†	✓	✓		7/21/20
34		✓			✓		✓	●	†	✓	✓		7/21/20
35		✓			✓		✓	●	†	✓	✓		7/21/20
36		✓			✓		✓	●	†	✓	✓		7/22/20
37		✓			✓		✓	●	†	●	✓		7/22/20
38		✓			✓		✓	✓	✓	✓	✓		7/22/20
39		✓			✓		✓	✓	✓	✓	✓		7/22/20
40		✓			✓		✓	✓	✓	✓	✓		7/22/20
41		✓			✓		✓	✓	✓	●	✓		7/23/20
42		✓			✓		✓	✓	✓	✓	✓		7/23/20
43		✓			✓		✓	✓	✓	✓	✓		7/23/20
44		✓			✓		✓	✓	✓	✓	✓		7/23/20
45		✓			✓		✓	✓	✓	✓	✓		7/23/20
46		✓			✓		✓	✓	✓	✓	✓		7/23/20
47		✓			✓		✓	✓	✓	✓	✓		7/24/20
48		✓			✓		✓	✓	✓	✓	✓		7/24/20

The results of the statistical analysis is shown in table 7 and presented graphically in the operating characteristic curves in figures 36 through 39. A description of the statistical analysis was presented in section 5.2.

Table 7. Statistical Analysis Results

Operation	Trials <i>n</i>	Successes <i>i</i>	Failures <i>r</i>	Confidence <i>C</i>	Reliability <i>R</i>
Mating	45	43	2	90%	89%
Cutting	45	38	7	90%	75%
	25	25	0	90%	91%
Plug Removal Washout	41	40	1	90%	91%
	32	29	3	90%	80%

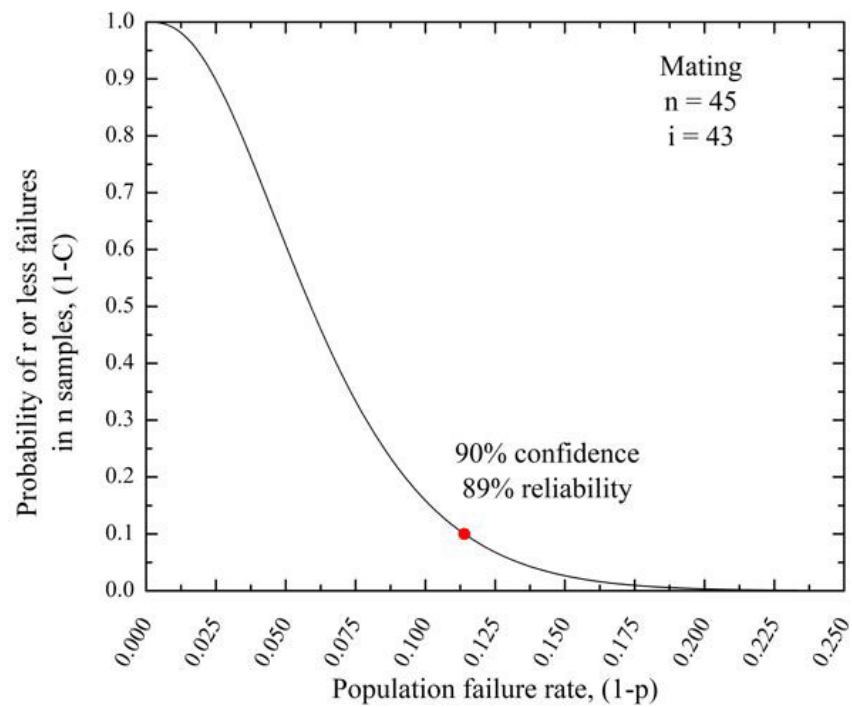


Figure 36. Operating Characteristic Curve for the Mating Operation.

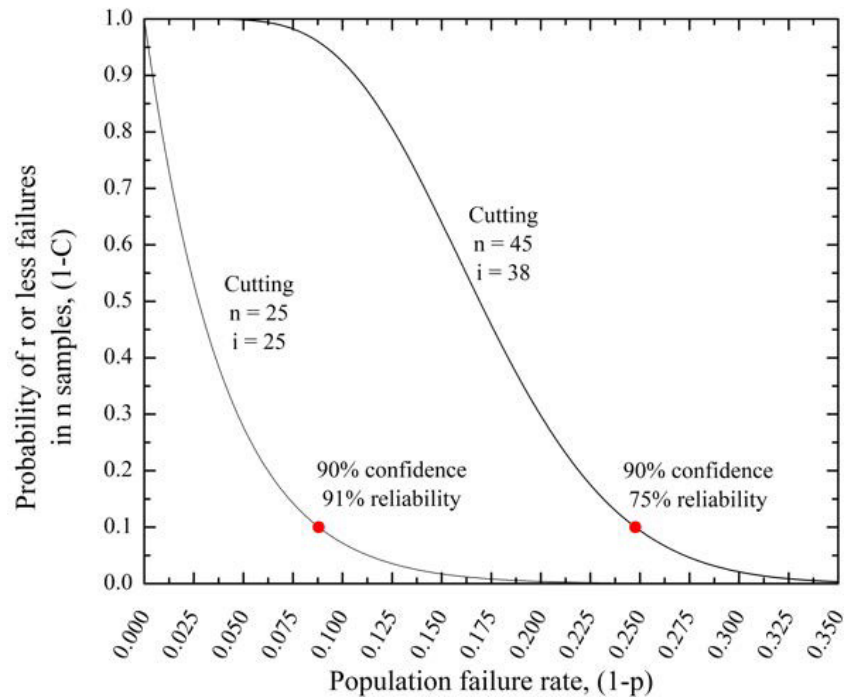


Figure 37. Operating Characteristic Curves for the Cutting Operation.

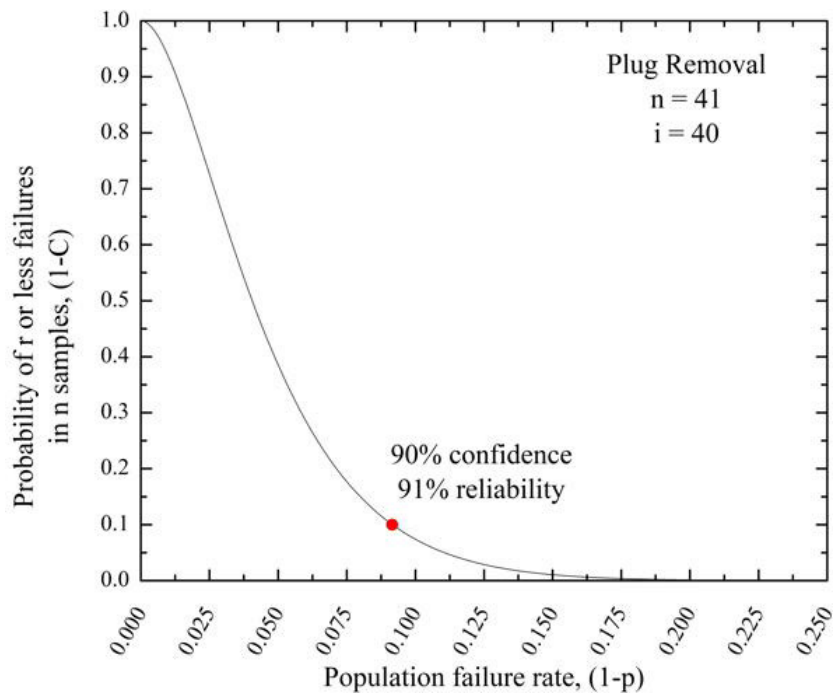


Figure 38. Operating Characteristic Curve for the Plug Removal Operation.

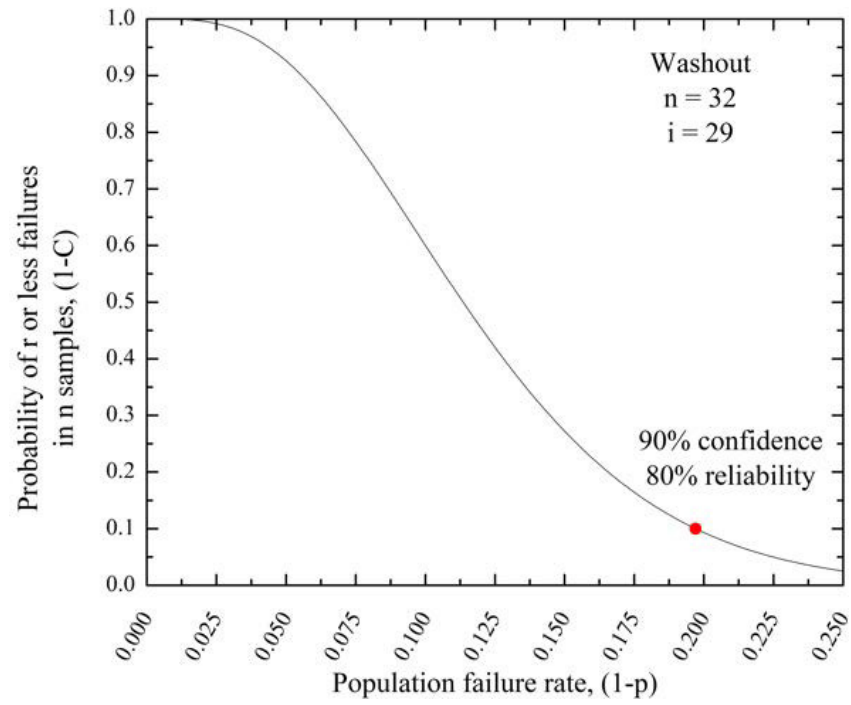


Figure 39. Operating Characteristic Curve for the Washout Operation.

7.0 PERFORMANCE ASSESSMENT

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

7.1 PERFORMANCE ASSESSMENT: EQUIPMENT RELIABILITY

During the second demonstration, two major equipment failures occurred during the processing of the 45 inert projectiles. Since it takes approximately 20 minutes to process a target item, the mean time between major failures is approximately 7.5 hours. The failure of one of the servo motors accounted for one major failure; it was replaced with a hydraulic motor. The rupture of a high-pressure water line in between the intensifier and the tool package accounted for the other failure. The ruptured line was simply replaced with a spare in about 10 minutes.

7.2 PERFORMANCE ASSESSMENT: CLEANING OF THE TARGET

Six projectiles were covered with concrete 1 *inch* thick for testing the cleaning tool's effectiveness. One of these items was cleaned on the sea floor. However, the cleaning head also pushed away sediment around the projectile which resulted in the projectile rolling down into the resulting hole. Our lesson learned is that we need an apparatus to stabilize items before cleaning if the sea floor is not hard or if the item of interest is not naturally stabilized. As a result, the remaining five projectiles were processed using the cradle to hold items. For these projectiles, the cleaning head had no issue in removing all of the concrete down to the original projectile surface in one pass. The surface of the pipe exposed was as smooth as the original pipe. Overall, the cleaning tool was extremely successful in removing hardened concrete for stabilized target items.

7.3 PERFORMANCE ASSESSMENT: WATERJET WASHOUT OF MUNITION CONSTITUENTS

A total of 32 inert projectiles, each containing 5.0 *pounds* of microcrystalline cellulose, were used for testing high-pressure waterjet washout. The washout operation took approximately 8 minutes to complete in which washout occurred as the washout head was slowly traversed down into and back out of the inert projectile. Under these conditions, complete washout regularly occurred. However, for four projectiles, there was some loose material left in the projectile. It is estimated that 95% of the contents were removed in these instances.

7.4 PERFORMANCE ASSESSMENT: CAPTURE OF MUNITION CONSTITUENTS

The capture of munition constituents generated during cutting and washout was accomplished with a pair of diaphragm pump. 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 tote “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

Proper attachment of the tool to the target was quantified during the second demonstration. There were two instances of the 45 projectiles processed in which leakage around the “boot” that seals on the projectile was observed. Therefore, the reliability of this operation was 89% at a 90% confidence level.

7.6 PERFORMANCE ASSESSMENT: ABRASIVE WATERJET CUTTING OF ACCESS HOLE

During the second demonstration 7 of the 45 projectiles processed resulted in plugs that could not be removed. This resulted from a sliver of steel remaining at the position of the initial pierce of the waterjet; this prohibited the plug from being removed by the magnet. This issue was resolved by cutting in the opposite direction initially for approximately 10° before reversing the cutting direction for a complete revolution. As a result, we were cutting over the initial pierce area three times. If all data is statistically analyzed the reliability of cutting was 75% at a 90% confidence level. When analyzing the data after the change in the cutting profile, the reliability increased to 91% at a 90% confidence. Also, the plug removal data was statistically analyzed and resulted in a 91% reliability at a 90% confidence level.

7.7 PERFORMANCE ASSESSMENT: TOOL POSITIONING WITH SONAR IMAGING

This objective was added for the second demonstration. Two Aris Explorer 3000 sonar imaging systems were mounted to the tool gantry and its performance was assessed during the demonstration. Upon assessment, it was determined that the units were mounted too close to the tool package and target item to provide useful imaging data. As a result, minimal time was spent on optimizing its use in this demonstration.

8.0 COST ASSESSMENT

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

9.0 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 project, 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 cannot 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. During the second demonstration, pressure sensors were added to the tool to quantify the force exerted on the item during mating. These measurements indicated a downward force of less than 100 lb_f was required to maintain a seal while not forcing the target item to sink into the sand.

For the demonstrations 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, additional lighting may be required to provide improved visibility. In addition, 3D multibeam scanning sonar technology may be useful in positioning the tool package in low visibility scenarios.

Although an attempt to utilize sonar in the second demonstration failed, the challenges involved do not appear to be insurmountable.

Overall, this project provided validation of the cut and capture technology. Gradient Technology appreciated the support of ESTCP in providing an opportunity to demonstrate the technology. As a result, Gradient Technology is preparing for future demonstrations at sea to further validate the technology offshore while operating on a ship.

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APPENDIX B HIGH-PRESSURE WATERJET ORIFICE SIZE, FLOW RATE, AND POWER DIAGRAM

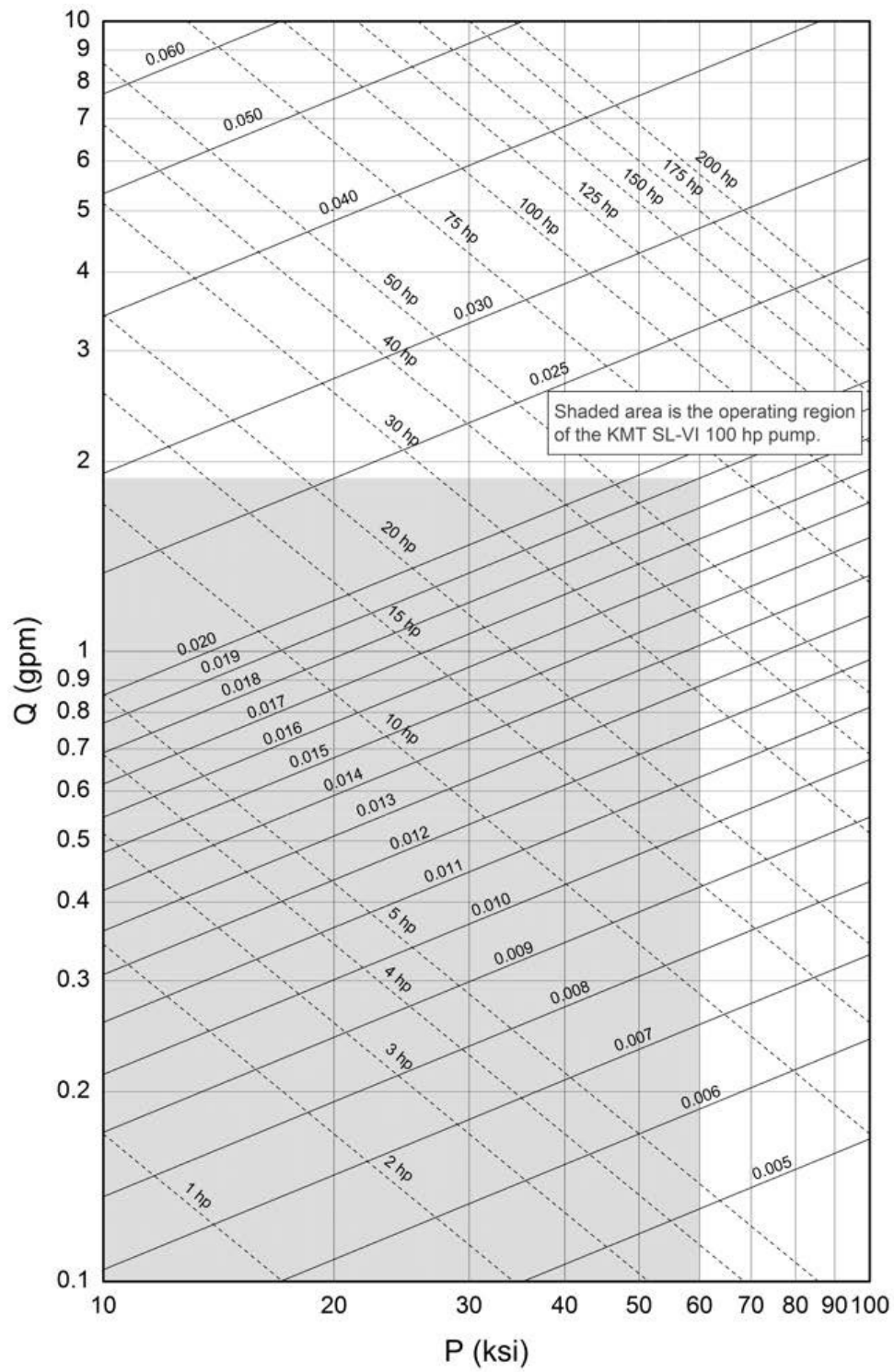


Figure 40. Relationship Between Orifice Size, Water Flow Rate, and Power for High-pressure Waterjets.