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Cut and Capture System Technology for Demilitarization of Underwater Munitions

Steve J. Schmit

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Cut and Capture System Technology for Demilitarization of Underwater Munitions

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Abstract

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 risks to critical infrastructure, recreational divers, and fishermen. The primary goal of the demonstrations was to validate an underwater suite of tools that can be used to render underwater UXO and MEC safe in shallow water (i.e., up to 100 ft). US Navy underwater ranges in the Gulf of Mexico, south of the Naval Support Activity–Panama City, were selected for the first two demonstrations to fully display the integrated system by processing inert munitions, such as the Navy 5 in./38 cal and the Army 105 mm High Explosive (HE) M1 projectile. The third demonstration, however, occurred at the Naval Surface Warfare Center (NSWC), Crane, Lake Glendora Test Facility, in Sullivan, Indiana. Twenty US Army 105 mm HE M1 projectiles filled with TNT were successfully processed. Overall, this project showed that Gradient Technology’s high-pressure waterjet demilitarization technology can be reliably operated underwater at depths less than 100 ft of seawater when the supporting equipment is located on the deck of a vessel or floating pier system.

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Preface

This study was performed under contract by Gradient Technology for the “Demonstration of the Integrated Underwater Cut and Capture System Technology on Submerged Munitions” program for the technical director for Installations and Operational Environments, US Army Engineer Research and Development Center–Environmental Laboratory (ERDC-EL), Program Element Number 0603779A, Project Number E21.

At the time of publication, Dr. Guilherme Lotufo was technical point of contact, Mr. John H. Ballard was program manager, and Dr. Elizabeth A. Ferguson was the technical director for Installations and Operational Environments (all ERDC-EL). The deputy director of ERDC-EL was Dr. Brandon J. Lafferty, and the director was Dr. Edmond J. Russo, Jr.

COL Christian Patterson was commander of ERDC, and Dr. David W. Pittman was the director.

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1 Introduction

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 risks to critical infrastructure, recreational divers, and fishermen. The ordnance can also wash up onshore and place people at serious risk of death or injury from an explosion (Sticht 2013). The purpose of this project was to validate an underwater suite of tools that can be used to demilitarize underwater UXO or MEC.

1.1 Background

Demilitarization of underwater munitions currently requires either (1) in situ remediation using countercharges or jet perforators placed by explosive ordnance disposal (EOD) divers or (2) recovery of the hazardous ordnance for demilitarization on the surface. In situ blow-in-place, when used, 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 (1996) for blast fishing; and can severely injure or deafen marine mammals, such as whales, dolphins, and porpoises, out to 5 km* (Ketten 1995; Klima et al. 1988; Yelverton et al. 1973).

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 (1997). From an explosives safety and environmental protection perspective, it is often preferable to leave munitions in place unless such munitions pose an unacceptable risk to human safety. Even then, it is often preferable to leave the munition casings in place but to remove or reduce the explosive hazard to mitigate the potential risk of damage to the local microbiome, such as coral reefs. The ecotoxic potential for the environmental release of organic chemical fillers (e.g., nitroaromatic and nitramine explosives such as TNT and RDX) from

* For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office, 2016), 248–252, <https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf>.

continuously corroding munitions also must be addressed (Sunahara et al. 2009).

Recovery of live munitions from the subsurface may result in an unintended detonation by 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 it.

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 environmental effects. Such a technology would be highly beneficial to the US DoD as it begins to address underwater munitions in places with sensitive marine environments and high public access, such as Culebra and Vieques, Puerto Rico, and Hawai'i. In this project, Gradient Technology demonstrated its high-pressure waterjet demilitarization technology on inert and TNT-filled projectiles.

1.2 Goals of the Demonstrations

The primary goal of the demonstrations was to validate an underwater suite of tools that can be used to render underwater UXO and MEC safe in shallow water (i.e., up to 100 ft). US Navy underwater ranges in the Gulf of Mexico, south of the Naval Support Activity (NSA)–Panama City (PC), were selected for the first two demonstrations to fully display the integrated system by processing inert munitions, such as the Navy 5 in./38 cal and the Army 105 mm High Explosive (HE) M1 projectile. The third demonstration, however, occurred at the Naval Surface Warfare Center (NSWC), Crane, Lake Glendora Test Facility (LGTF), in Sullivan, Indiana. Twenty US Army 105 mm HE M1 projectiles filled with TNT were successfully processed. The suite of tools tested accomplished the following goals:

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 (AWJ) cutting head and remove the resulting steel plug with a magnetic tool.

4. Wash out the internal contents of the target item using a high-pressure washout head.
5. Capture the effluent generated during high-pressure cutting and washout using a continuous flush and capture tank without leakage to the environment.

The technology demonstrated required the use of support equipment located above water on a vessel or pier to deploy and operate the underwater tool package. Figure 1 shows a simplified overall process schematic for the system that delineates which equipment was above and below water for the first two demonstrations, in which the capture tank was located below water. Figure 2 shows a simplified overall process schematic for the system configuration for a portion of the first demonstration and all of the third demonstration, in which the capture tank was located above water.

Figure 1. Overall process schematic of the system when the capture tank is located on the seafloor.

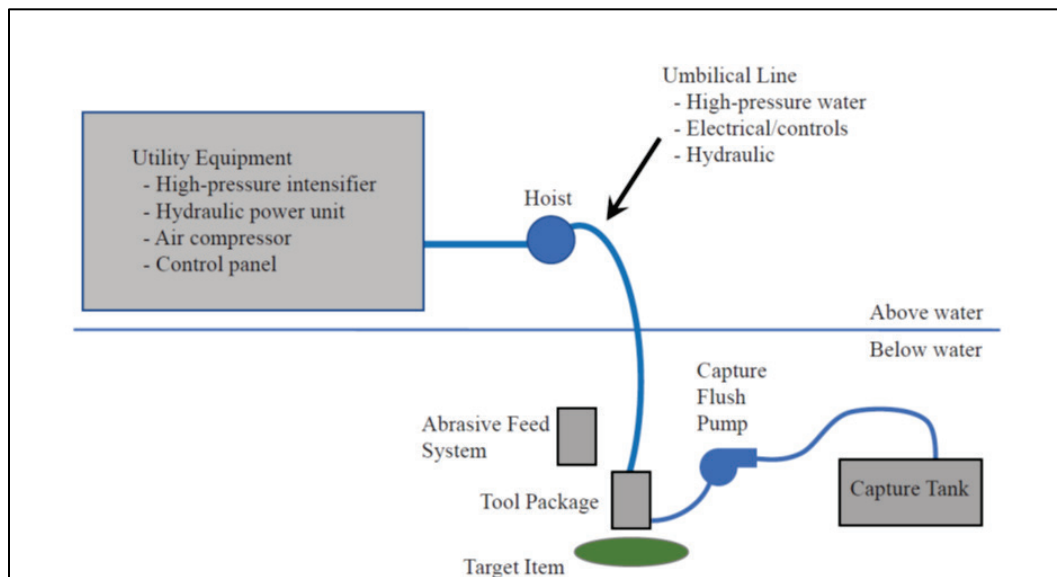
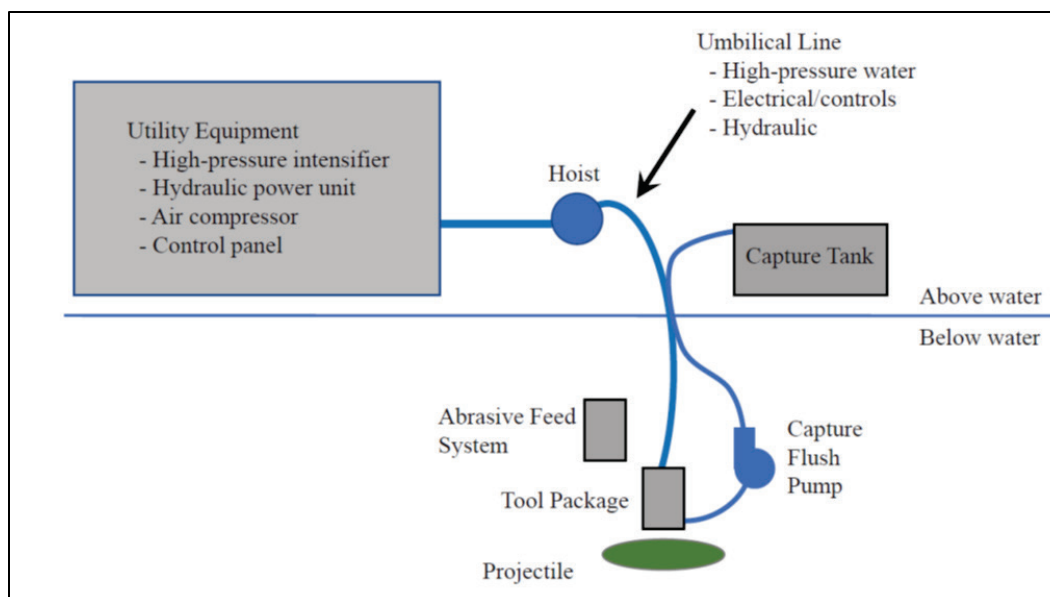


Figure 2. Overall process schematic of the system when the capture tank is located above water.



2 Technology Description

Gradient Technology has extensive experience using high-pressure AWJs to demilitarize munitions on land. The onshore use of AWJs is a proven technology for cutting munitions and washing out their contents. Since 1991, AWJs have been used without incident to safely demilitarize munitions. 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 3, uses high-pressure AWJs with a garnet abrasive to cut out the corroded base fuzes from large-caliber US 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. To date, this one processing line has processed over 300,000 projectiles, ranging in size from US Navy 3 in./50 cal to 16 in./50 cal projectiles, without issue.

Figure 3. Automated abrasive waterjet (AWJ) cutting and washout system processing 8 in./55 cal high capacity (HC) rounds.



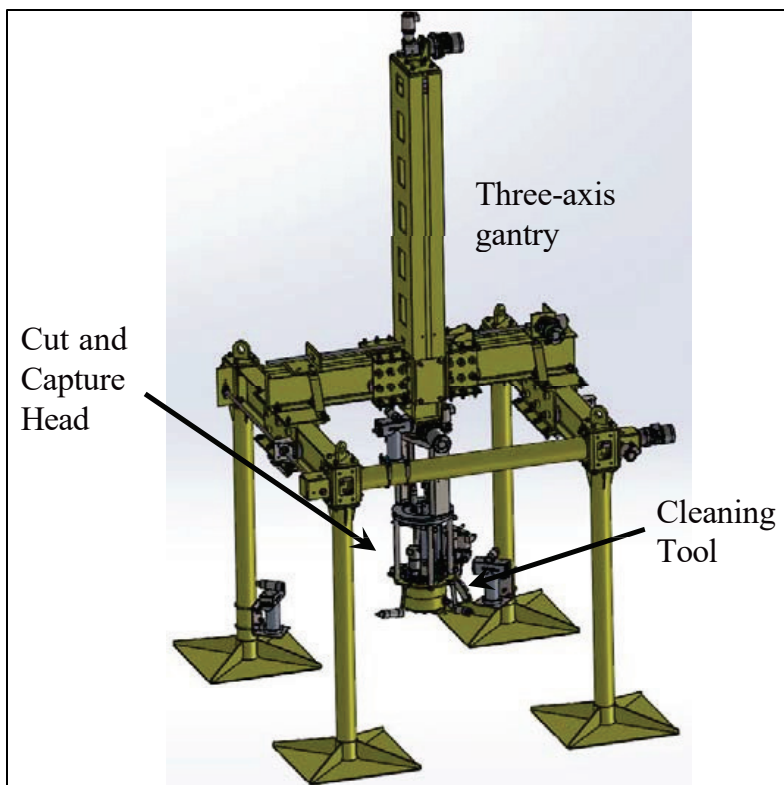
Over the past few years, Gradient Technology has been adapting this AWJ technology for use underwater (Miller et al. 2016, 2017a, 2017b, 2017c). This adaptation has involved integrating a variety of tools into a package that is deployed and operated from the surface to demilitarize munitions in shallow water (i.e., less than 100 ft).

Collectively, the integrated underwater AWJ cut and capture system is called the *Underwater Cut and Capture System*. The proprietary technology incorporated into this system for in situ demilitarization of munitions uses the following tools and technologies:

- Three-axis underwater gantry for positioning the tool package (i.e., the *Cut and Capture Head*) over the munition projectile
- High-pressure waterjet cleaning tool for removing the bioencrustations or debris from the surface of the munition projectile
- High-pressure entrainment-style AWJ cutting head for cutting an access hole in the side of the munition projectile
- Magnet for removing the steel plug that results from cutting
- High-pressure washout head for removing the internal contents of the munition projectile
- A continuous flush, filtration, and storage system for capturing the effluent generated during high-pressure cutting and washout operations
- A high-pressure intensification pump, air compressor, hydraulic power unit, and electrical and control system that are all located above water

A three-axis underwater gantry holds the tool package and allows for positioning it near or over the target item. Figure 4 shows the gantry and tool package. The package contains a variety of tools and control equipment that are collectively called the Cut and Capture Head. The gantry inherently allows for movement of the high-pressure waterjet cleaning tool that is used to remove the bioencrustations or debris from the surface of the item of interest because it is attached external to the Cut and Capture Head. The high-pressure waterjet cleaning tool delivers approximately 2 GPM of 55 ksi water in a plurality of jets directed at the surface to be cleaned.

Figure 4. A computer model of the Underwater Cut and Capture System, which consists of a three-axis underwater gantry and the Cut and Capture Head.



The high-pressure entrainment-style AWJ cutting head used for cutting an access hole in the side of the target item uses approximately 2 GPM 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. The abrasive is subsequently accelerated, impinges on the surface, and erodes the material to be cut.

The high-pressure washout head generates a high velocity water stream similar to that of the cleaning tool. However, the washout head is 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 the demonstrations contained a plurality of orifices used to direct jet energy at the inert fill to remove it.

The Underwater Cut and Capture System shown in Figure 4 is lowered from the surface and placed over the munition projectile. All support

equipment for the system is located above water on a vessel or on a pier. This equipment includes

- a high-pressure waterjet intensifier pump for generating high-pressure water,
- a reel containing an umbilical of lines,
- a hoist-type deployment system for lowering the equipment into the water,
- control panels housing all control hardware for operations, and
- a human–machine interface (HMI) for operating the equipment.

In addition to this equipment, a water source and an electrical power source are needed onboard the vessel, barge, or pier.

3 Performance Objectives

Table 1 lists the six performance objectives for each demonstration.

Table 1. Performance objectives.

Performance Objective	Metric	Data Required	Success Criteria
Equipment reliability	Failure rate per hour Major: Requires repair Minor: Requires reset	- Hours of operation - Number of major failures - Number of minor failures	$MTBF_{\text{major}} > 3 \text{ hr}$ $MTBF_{\text{minor}} > 1 \text{ hr}$
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
Waterjet washout of munition constituents	Percentage of fill material removed	- Initial mass - Postwashout mass	80% average removal
Capture of munition constituents	Percentage of fill material captured	- Initial fill mass - Mass captured	80% average capture
Attachment to target	Percentage successfully attached	- Items attempted - Items successful	$P_{\text{attach}} > 80\%$
AWJ cutting of access hole	Percentage successfully cut	- Items attempted - Items successful	$P_{\text{cut}} > 80\%$

Note: MTBF = mean time between failures, RMS = root mean square, WJ = waterjet.

3.1 Equipment Reliability

The reliability of the equipment used to conduct demilitarization affects rates and operational costs. The Cut and Capture System was engineered to use reliable components to minimize downtime. Because the system used in these demonstrations was highly integrated, one component failure could significantly affect the performance of the entire system. Therefore, redundancy was built into critical areas of the system to avoid the halting of operations. For example, the high-pressure waterjet intensifier pump used to generate high-pressure water for the three downstream tools (i.e., cleaning head, cutting head, and washout head) was 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 fails, 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.

3.2 Cleaning of the Target

Surface roughness, such as that caused by bioencrustations, must be removed from the target item to allow proper attachment of the Cut and Capture Head. Proper attachment is required to prevent the release of fill material to the environment. If the target is not adequately cleaned, (1) a thicker layer 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 properly attach to the target and could allow the munitions constituents to leak into the surrounding environment rather than being captured.

3.3 Waterjet Washout of Munition Constituents

Ideally, all of the fill contained inside a munition should be removed. However, in reality, a portion of the fill may not be easily removed in a timely manner and is expected to remain in the item after washout. The time required for complete removal of the munition energetic fill depends on the size and internal configuration of the target item. This project focused on the common Navy 5 in./38 cal projectile and Army 105 mm HE M1 projectile, neither of which have a base or nose fuze. Other target item configurations may require longer washout times and different washout head orifice configurations to achieve complete washout.

3.4 Capture of Munition Constituents

Another important objective was to collect all the fill removed from the munition. In this project, two capture pumps were evaluated. The first was an air-operated double-diaphragm (AODD) pump, which pulled surrounding seawater through the Cut and Capture Head and discharged it to a capture tank. The second was a duplex hydraulically driven diaphragm pump; this pump eliminated the need for compressed air and instead used hydraulic power that was available on the gantry. For the first two demonstrations, two different inert target item fills were used: microcrystalline cellulose and microcrystalline wax. Both materials are insoluble in water; however, the wax melts at 178°F. Therefore, the capture network was tested using vastly different simulant materials. Last, the capture system

was tested with TNT when TNT-filled projectiles were washed out in the last demonstration.

3.5 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.

3.6 Abrasive Waterjet (AWJ) Cutting of Access Hole

An access hole must 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 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. The tool package can be raised and lowered for inspection when extremely accurate repositioning of the tool package on the target item is not needed. However, accurate repositioning is required for continuing a cut that is not complete.

4 Statistical Data Analysis Summary

Many of the objectives of this project were based on the success or failure of a given operation. As a result, a set of Bernoulli trials was conducted. It was assumed that the trials were independent from each other and that the probability of success did not change from trial to trial. In the theory of probability and statistics, a Bernoulli trial (or binomial trial) is a random experiment with exactly two possible outcomes, “success” and “failure,” in which the probability of success is the same every time the experiment is conducted. If this assumption is true, which was the case for our demonstration (except for the cutting changes we implemented), then the number of success outcomes in Bernoulli trials has a binomial distribution. There are two important equations that are used to describe the binomial distributions. The first important equation is the probability mass function, which is expressed as follows:

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

where $Pr(X)$ is the probability of getting $X = i$ successes when n Bernoulli trials are conducted and 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 six successes ($i = 6$) is 0.205.

The second important equation used to analyze a set of Bernoulli trials is the cumulative distribution function. One form of this distribution function is expressed as follows:

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

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 first two demonstrations. The data are 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 fewer 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 fewer failures in n samples versus the population failure rate, $1 - p$, for a given sample size, n , and number of failures, r .

5 Test Item Preparation

The projectiles used in this project included inert Navy 5 in./38 cal projectiles and inert Army 105 mm HE M1 projectiles. The preparation of the projectiles with an inert fill and the covering of some of the items with concrete is subsequently detailed. The concrete layer covering the projectiles simulated bioencrustation.

5.1 Inert Navy 5 in./38 cal Projectiles

Figure 5 shows the dimensions of Navy 5 in./38 cal projectiles.

Figure 5. Nominal dimensions of Navy 5 in./38 cal projectiles.

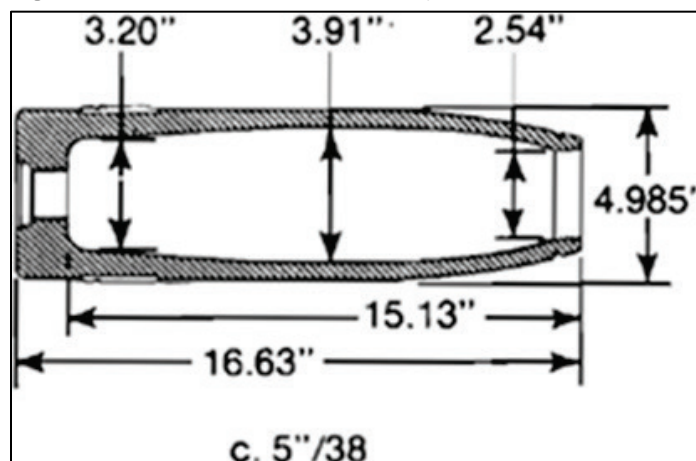


Figure 6 shows the projectile bodies that were used to create the target items. These Navy 5 in./38 cal projectiles were previously demilitarized by Gradient Technology using the high-pressure waterjet projectile accessing and washout system at NSA-Crane. The hole in the bottom of the projectile, where 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 projectile was pressed with inert fill.

Figure 6. Demilitarized Navy 5 in./38 cal projectiles used for target-item creation.



Concrete was cast in a mold around six of the inert projectiles after they were filled with microcrystalline cellulose. The concrete was prepared by mixing Type 1 Portland cement, washed plaster sand aggregate (i.e., mason sand), and water to achieve a compressive strength of 22 kN/m³. The concrete mixture composition was 24.7% cement, 13.6% water, and 61.7% sand by mass. The cast concrete was approximately 1 in. thick.

The energetic simulant pressed into the inert Navy 5 in./38 cal projectiles was microcrystalline cellulose, a biodegradable material that is insoluble in water. Figure 7 shows the microcrystalline cellulose procured from Alfa Aesar (stock number A17730). The inert fill was incrementally poured into the projectile body through the nose and pressed to 20 tons using a hydraulic press. Figure 8 shows the hydraulic press. Table 2 and Table 3 summarize the preparation of the 5 in./38 cal target items for the first and second demonstrations, respectively.

Figure 7. Microcrystalline cellulose used as the inert fill in the target items.



Figure 8. Hydraulic press for pressing the inert fill into the target items.



Table 2. Target item preparation summary for the 5 in./38 cal projectiles in Demonstration 1.

Item Numbers	Inert Filled	Concrete Covered
1-18	YES	NO
19-24	YES	YES
25-48	YES	NO

Table 3. Target item preparation summary for the 5 in./38 cal projectiles in Demonstration 2.

Item Numbers	Inert Filled	Concrete Covered
200, 206, 211, 212	YES	YES
201-205	YES	NO
207-210	YES	NO
213-244	YES	NO

5.2 Inert Army 105 mm High Explosive (HE) M1 Projectiles

Figure 9 shows the dimensions of the Army 105 mm HE M1 projectiles.

Figure 9. Nominal dimensions of the Army 105 mm High Explosive (HE) M1 projectiles.

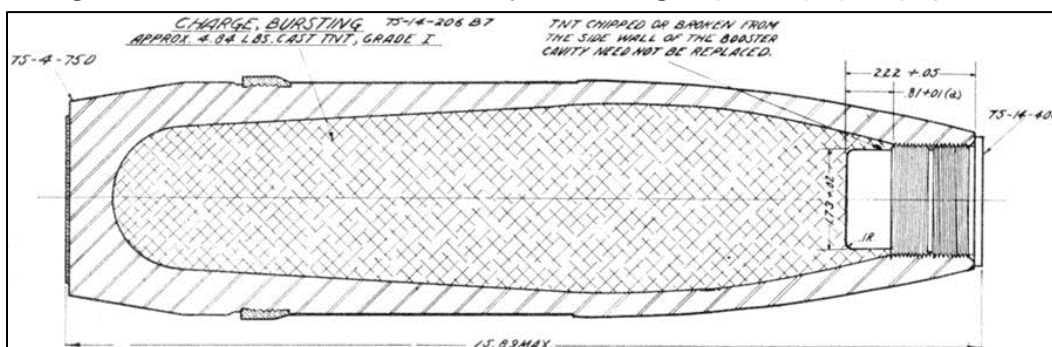


Figure 10 shows the 105 mm projectile bodies that were used to create the target items. These projectiles were demilitarized by the Army at Picatinny Arsenal and sent to Gradient Technology as material documented as safe (MDAS) for use in the demonstration. The fuze well in the nose had a lifting ring installed once the simulant was poured into the item. The simulant used, microcrystalline wax, was selected to simulate TNT. The microcrystalline wax was melted and then poured into the 105 mm projectile to fill the cavity where the TNT would normally be. Figure 11 shows the 105 mm projectile bodies that were filled with 178°F melting point microcrystalline wax. A plug was threaded into the nose after it was filled with wax. Table 4 and Table 5 summarize the preparation of the 105 mm projectile target items for the first and second demonstrations, respectively.

Finally, all inert target items were painted blue and the body was permanently engraved with MDAS followed by the target item number as indicated in Table 2 through Table 5.

Figure 10. Army 105 mm HE M1 projectile body used for testing.



(a) 105 mm projectile bodies



(b) Side view of the body



(c) Nose of the body



(d) Base of the body

Figure 11. Army 105 mm HE M1 projectile bodies (*bottom*) filled with 178°F melting point microcrystalline wax (*top*).



Table 4. Target item preparation summary for the Army 105 mm HE M1 projectiles in Demonstration 1.

Item Numbers	Inert Filled	Concrete Covered
49-66	YES	NO
67-72	YES	YES
73-96	YES	NO

Table 5. Target item preparation summary for the Army 105 mm HE M1 projectiles in Demonstration 2.

Item Numbers	Inert Filled	Concrete Covered
100-195	YES	NO

6 Demonstration Summaries

Gradient Technology conducted three demonstrations at various locations for this project. The demonstrations used inert US Navy 5 in./38 cal projectiles press-loaded with microcrystalline cellulose, inert US Army 105 mm HE M1 projectiles filled with microcrystalline wax, and TNT-filled US Army 105 mm HE M1 projectiles. Table 6 summarizes pertinent information for the three demonstrations.

Table 6. Demonstration information.

	Demo 1	Demo 2	Demo 3
Start date	21/7/21	8/2/22	21/6/22
End date	30/7/21	18/2/22	6/7/22
Location	Gulf of Mexico, PC	Gulf of Mexico, PC	LGTF
Depth	40, 70 FSW	70 FSW	24 FSW
Vessel	HOS <i>Mystique</i>	HOS <i>Bayou</i>	Pier
Inert 5 in./38 cal	29	39	—
Inert 105 mm HE M1	5	4	—
TNT-filled 105 mm HE M1	—	—	20

Each demonstration is summarized in one of the three subsections that follow. A detailed demonstration report was prepared and delivered to the government after each of the demonstrations.

6.1 Demonstration 1

The first demonstration was designed to validate the Underwater Cut and Capture System when deployed from a vessel at sea. The open-ocean demonstration commenced on 21 July 2021, when all equipment was loaded onto the Hornbeck Offshore Services (HOS) *Mystique*. During the transit from Port Fourchon, Louisiana, to NSA-PC on 22 July 2021, all equipment was prepared for operation. The HOS *Mystique* arrived at the pier of NSA-PC on 23 July 2021, when initial testing of the system commenced. The Underwater Cut and Capture System processed inert target items on the deck of the vessel; later that day, the vessel was relocated to 40 ft of seawater (FSW) to proceed with the demonstration. The next two days of the demonstration were spent at that location. On 27 July 2021, the vessel relocated to deeper water, 70 FSW, for additional demonstration work. In the evening of 28 July 2021, the HOS *Mystique* commenced its transit back to Port Fourchon, Louisiana. During the transit, the

equipment was dismantled and prepared for removal from the vessel and storage at Port Fourchon. The HOS *Mystique* arrived in Port Fourchon on 29 July 2021, and all equipment was offloaded from the back deck on 30 July 2021. Figure 12 shows the HOS *Mystique* prior to leaving Port Fourchon. Figures 13 through 16 show various demonstration photographs.

Figure 12. View of the 200-ton crane used to deploy the Underwater Cut and Capture System.

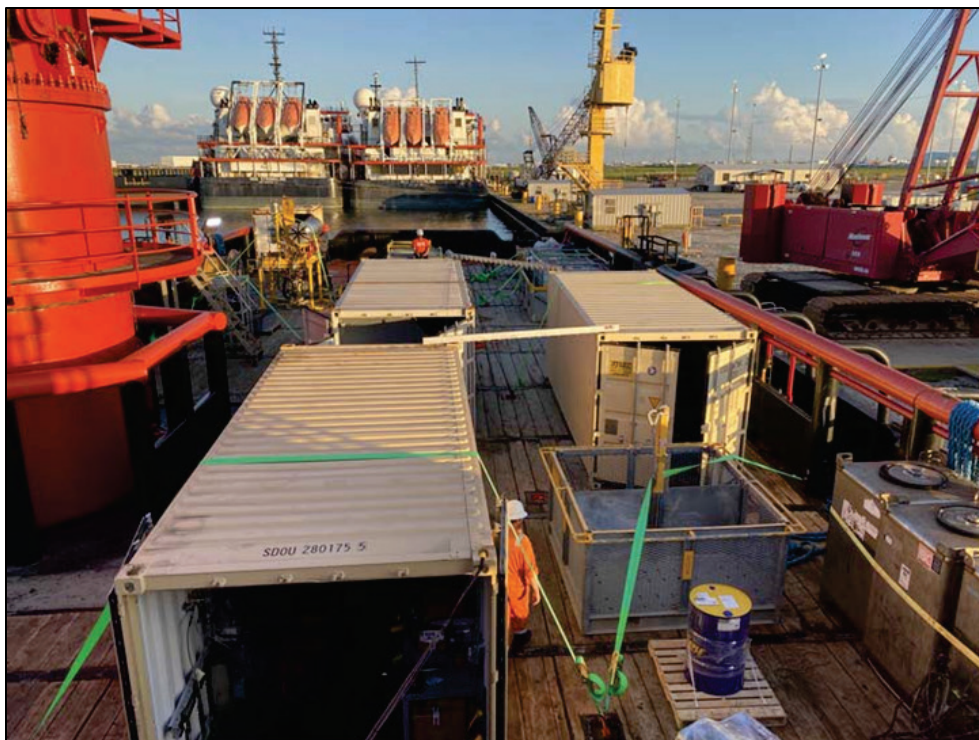


(a) Complete view of the vessel

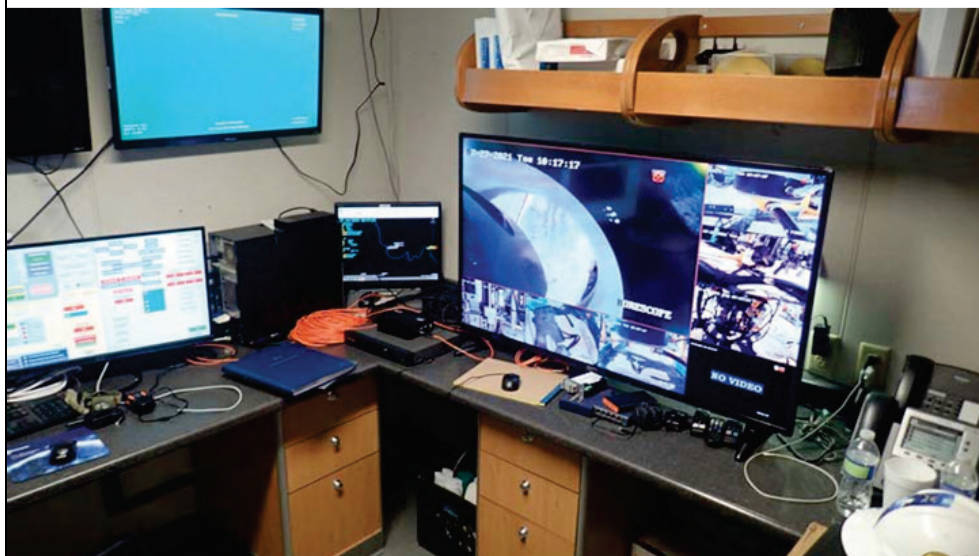


(b) View of the 200 ton crane used to deploy the Underwater Cut and Capture System

Figure 13. Equipment placement on the back deck (*top*) and operations center (*bottom*).



(a) Equipment placement on the back deck



(b) Control room used for demonstration operations

Figure 14. Deployment of the Underwater Cut and Capture System in 40 ft of seawater (FSW).



(a) Underwater Cut and Capture System and the umbilical reel

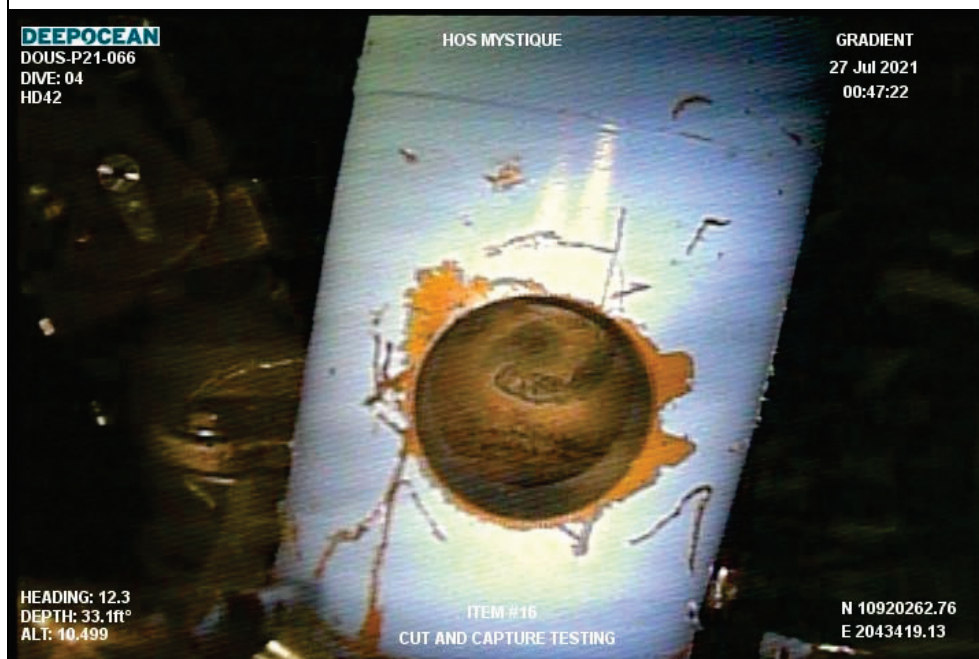


(b) Initial lowering of the system into the water

Figure 15. Inert target item 16.

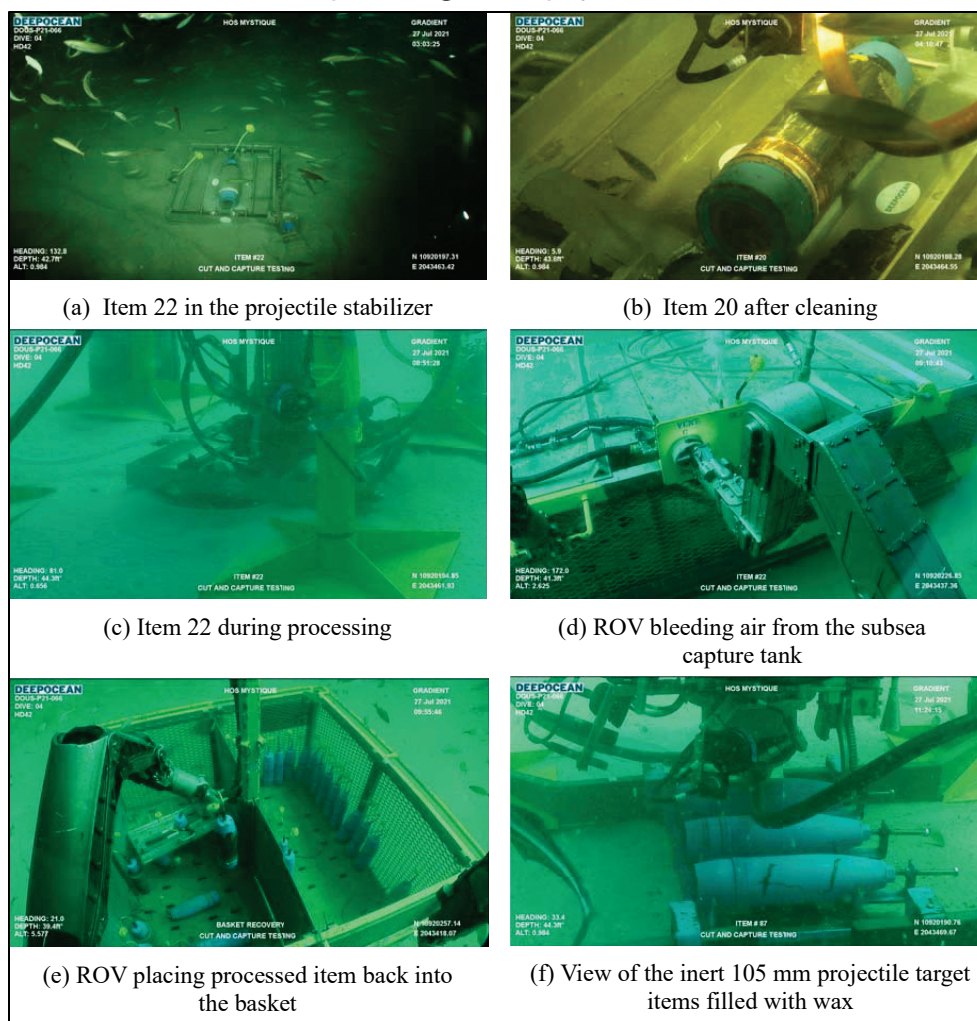


(a) ROV inspection of the processed item



(b) ROV camera showing a view of the internal cavity of the processed item

Figure 16. Subsea photographs from the remotely operated vehicle (ROV) during the processing of inert projectiles.



Initially, the demonstration focused on processing the inert Navy 5 in./38 cal projectiles. After successfully processing these items, the inert Army 105 mm HE M1 projectiles were processed. Although only five of these items were processed, great experience was gained in the capture of the wax fill. Last, an experiment was conducted in which the Underwater Cut and Capture System was deployed, and the vessel was backed away 400 ft from the system to simulate the operations required for processing a live projectile; when processing a live projectile, the vessel will have to back away from the system to maintain a safe operational distance (i.e., an exclusion zone). The required distance was calculated using DoD guidelines.

In this demonstration, all support equipment was located on the deck of *HOS Mystique* and was used to process 34 inert projectiles, including

some covered in concrete. These inert projectiles were processed in a test tank on the deck of the vessel, in water off the pier at NSA-PC, and in both 40 FSW and 70 FSW at an operational area outside of NSA-PC. During this demonstration, all system functions were successfully demonstrated, and there were no observed leaks to the environment while capturing process effluent.

The initial testing of the system occurred in a portable test tank on the deck of the vessel while it was pier side at NSA-PC. Following that effort, the Underwater Cut and Capture System was deployed into 40 FSW and operated. After a few days at this water depth, the vessel moved to 70 FSW, and the demonstration continued. In total, 29 inert Navy 5 in./38 cal projectiles and 5 inert Army 105 mm HE M1 projectiles were processed during the demonstration. Table 7 summarizes the techniques used to process the 34 inert target items.

Table 7. Demonstration 1 target item processing summary.

Item Numbers	Item Type	Item Positioning	Location
6-7, 15, 18	5 in./38 cal	Cradle	Deck
1-2	5 in./38 cal	Cradle	Pier side
3-5	5 in./38 cal	Cradle	40 FSW
8-9	5 in./38 cal	Cradle	40 FSW
12-14, 16-17, 20, 22, 25, 41-42	5 in./38 cal	Floor	40 FSW
10-11, 27-31, 34	5 in./38 cal	Cradle	70 FSW
87-88, 90, 91, 95	105 mm HE M1	Floor	40 FSW

6.2 Demonstration 2

The second demonstration was designed to further validate the Underwater Cut and Capture System when deployed from a vessel at sea. The open-ocean demonstration commenced on 8 February 2022, when all equipment was loaded onto the HOS *Bayou*. During the transit from Port Fourchon, Louisiana, to NSA-PC on 9 February 2022, all equipment was prepared for operation. The HOS *Bayou* arrived at the operational area in 70 FSW on 10 February 2022, when initial testing of the system commenced. The Underwater Cut and Capture System sunk into the sea floor upon deployment on 11 February 2022, and this did not allow for positioning inert target items under it. Recent dredging in the area may have caused sediment to accumulate in this area. Therefore, later that day, the vessel was relocated to another 70 FSW location approximately 4.5 mi away. The next five days of the demonstration were spent at that location

processing inert target items. On 16 February 2022, due to an impending storm, the back deck of the HOS *Bayou* was secured, and the vessel began its journey back to Port Fourchon, Louisiana. During the transit, the equipment was dismantled and prepared for removal from the vessel and storage at Port Fourchon. The HOS *Bayou* arrived in Port Fourchon late on 17 February 2022, and all equipment was offloaded from the back deck on 18 February 2022. Figure 17 shows the HOS *Bayou* prior to leaving Port Fourchon. Figures 18 through 22 show various demonstration photographs. Initially, the demonstration focused on processing the inert Navy 5 in./38 cal projectiles. After successfully processing these items, attention was focused on the inert Army 105 mm HE M1 projectiles. Although only four of these items were processed, great experience was gained in the capture of the microcrystalline wax fill. Due to issues related to the incomplete washout of the inert Army 105 mm HE M1 projectiles, live TNT-filled Army 105 mm HE M1 projectiles were not attempted.

In this demonstration, all support equipment was located on the deck of the HOS *Bayou* and was used to process 43 inert projectiles, including some covered in concrete. These inert projectiles were processed in 70 FSW water at an operational area outside of NSA-PC. During this demonstration, all system functions were successfully demonstrated, and there were no observed leaks to the environment while capturing process effluent. Table 8 summarizes the techniques used to process the 43 inert target items.

Table 8. Demonstration 2 target item processing summary.

Item Numbers	Item Type	Item Positioning	Location
237	5 in./38 cal	Cradle	Deck
200, 202–205	5 in./38 cal	Tray	70 FSW
208–211	5 in./38 cal	Tray	70 FSW
213–214	5 in./38 cal	Tray	70 FSW
216–230	5 in./38 cal	Tray	70 FSW
232–244	5 in./38 cal	Tray	70 FSW
172, 174, 176, 178	105 mm HE M1	Tray	70 FSW

Figure 17. View of the starboard side of the Hornbeck Offshore Services (HOS) *Bayou* in Port Fourchon.



(a) Complete view of the vessel

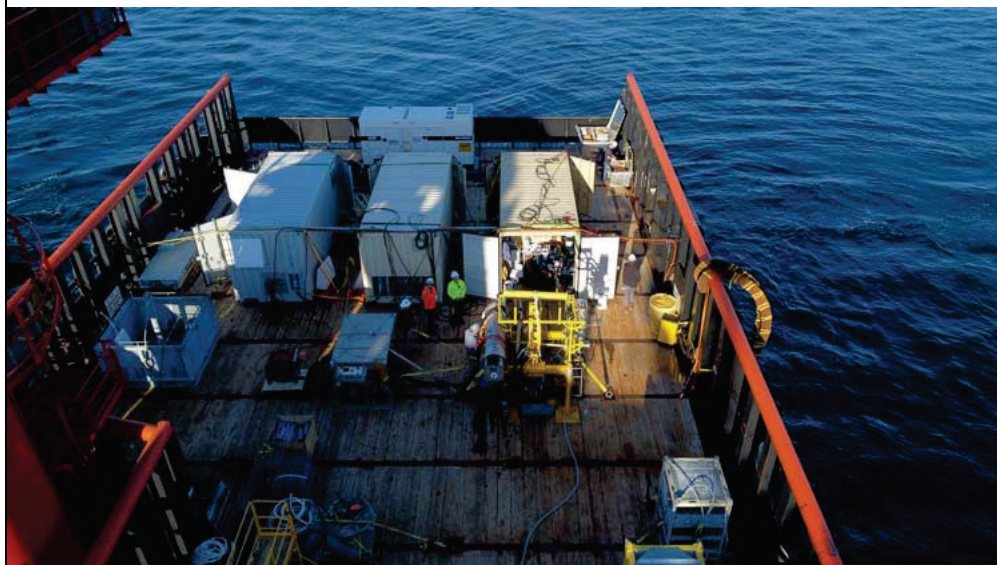


(b) View of the bow and the ROV launch and recovery system (LARS)

Figure 18. HOS *Bayou* on location.



(a) Back deck



(b) Back deck

Figure 19. Operational control rooms.

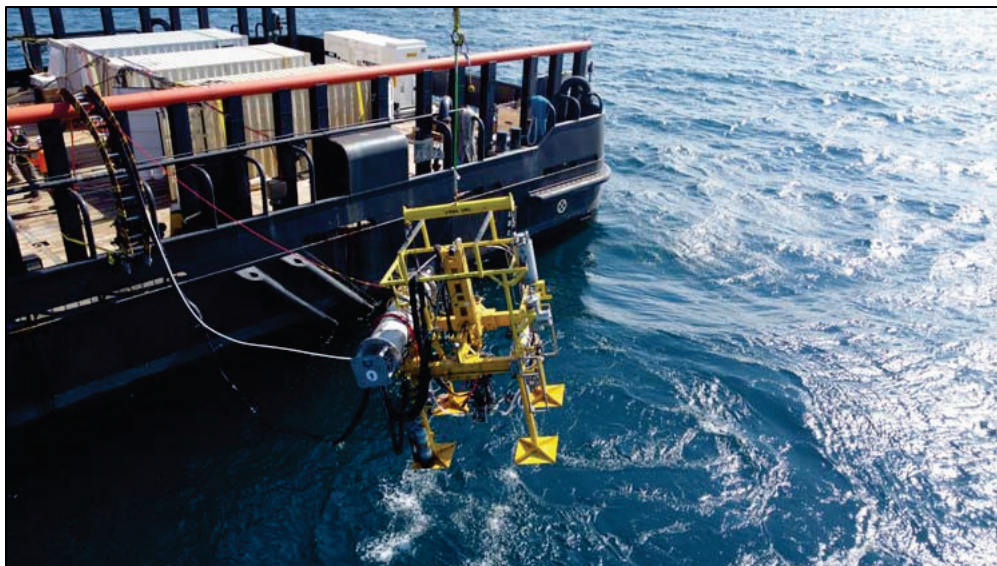


(a) Main operational control room



(b) Control room on the back deck

Figure 20. Deployment of the Underwater Cut and Capture System from the HOS *Bayou*.



(a) Deployment of the Underwater Cut and Capture System

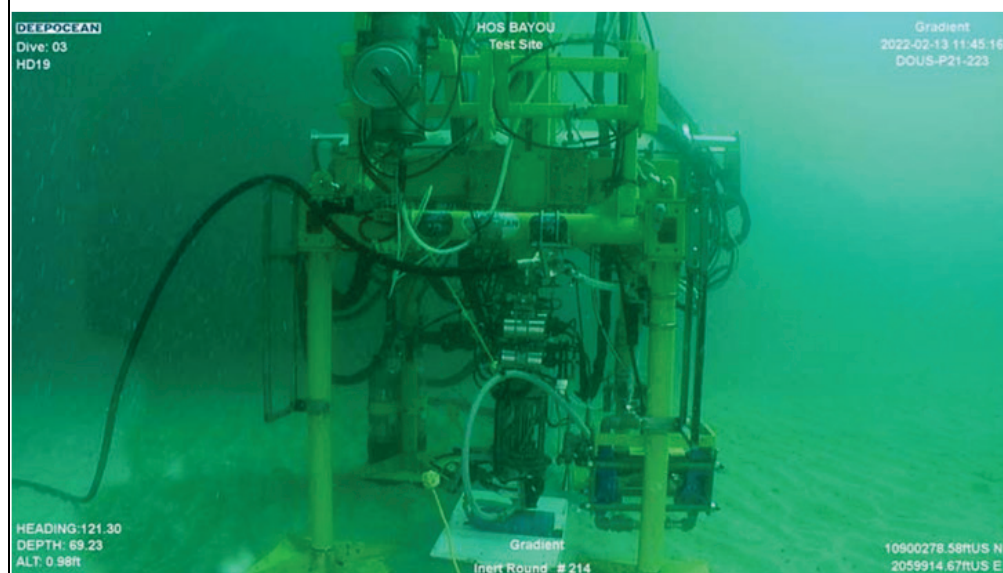


(b) Deployment of the Underwater Cut and Capture System with the ROV nearby

Figure 21. Subsea photographs of the Underwater Cut and Capture System.

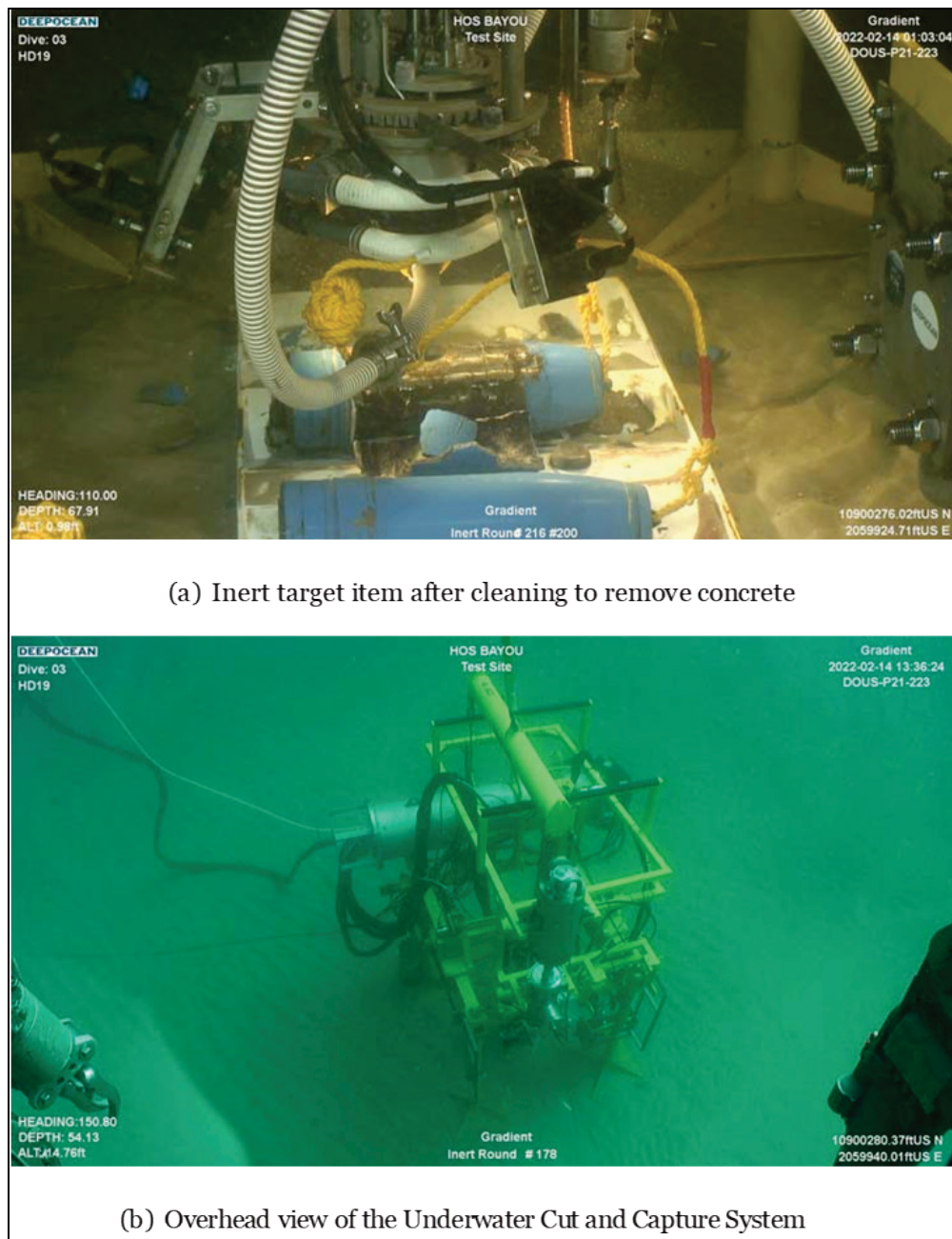


(a) Cut and Capture Head during cutting



(b) Underwater Cut and Capture System during operation

Figure 22. Subsea photographs of the Underwater Cut and Capture System.



6.3 Demonstration 3

The third demonstration occurred at the NSWC Crane, LGTF, in Sullivan, Indiana, 45 mi northwest of the NSA. This 364 acre lake was ideal for this final demonstration because it is an explosive-permitted facility, has the support equipment available or readily accessible, utilizes a floating pier system, has acceptable depths, and is a certified underwater test facility. This is a purpose-built explosive test range for underwater testing and

other acoustic testing. It has been operating since 1991, with explosive testing approved in 1996.

This site was chosen in part because of its geographic proximity to NSWC Crane, where a number of Gradient Technology personnel run a large demilitarization operation. This underwater test facility features three underwater test ranges suitable for work with live ordnance. It also features depths of up to 100 ft throughout the range facility. The floating pier system made this particular range complex very useful.

The third demonstration was designed to validate the Underwater Cut and Capture System when deployed from a floating pier system. The demonstration commenced on 21 June 2022, when all equipment was loaded onto the floating pier system (Figure 23). The next few days were spent setting up and commissioning the system. From 27 June 2022 through 30 June 2022, a total of 20 live TNT-filled Army 105 mm HE M1 projectiles were successfully processed. Beginning 1 July 2022, the system was decontaminated and dismantled prior to demobilization on 6 July 2022. Figures 24 through 27 show various demonstration photographs.

Figure 23. Overhead view of the project site during the demonstration.

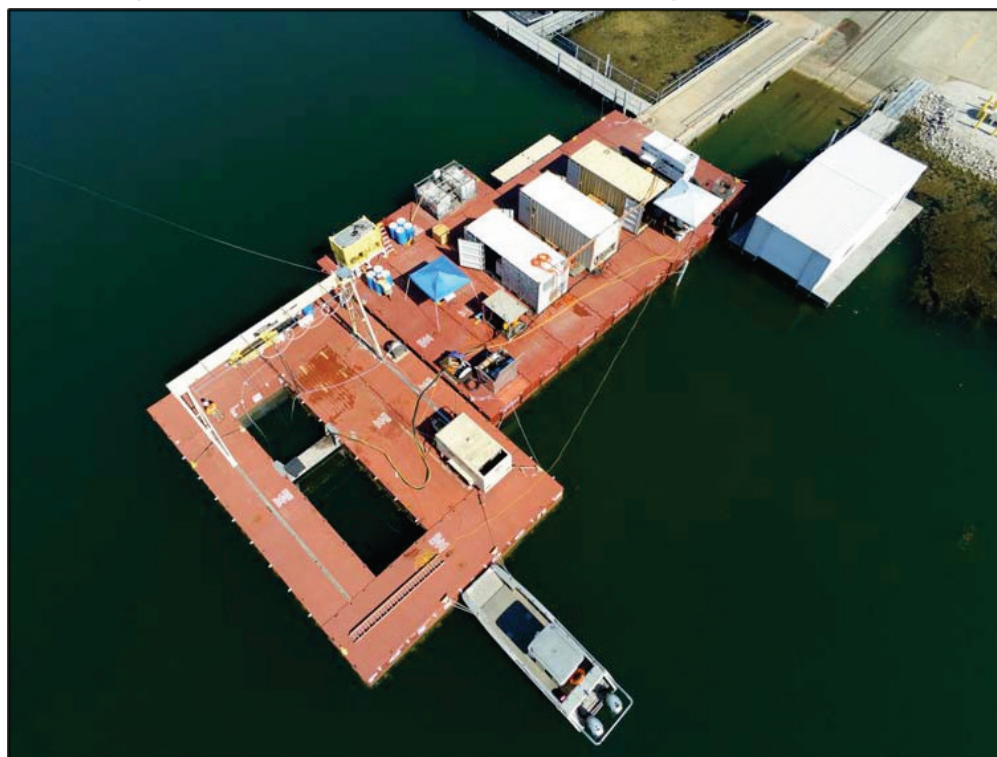


Figure 24. Equipment on the floating pier system after setup.

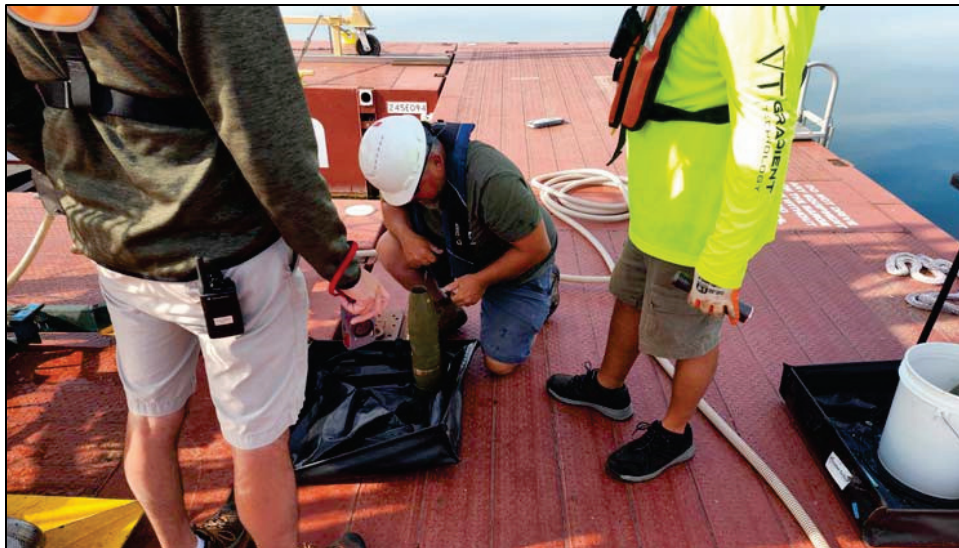


(a) Wide view of the floating pier system



(b) Test deployment of the Underwater Cut and Capture System

Figure 25. Inspection of a processed TNT-filled 105 mm projectile.



(a) Navy EOD Specialist inspecting a processed projectile



(b) Item 2 after processing; nose plug is removed to see that the base is completely clean

Figure 26. Materials collected from a TNT-filled 105 mm projectile.

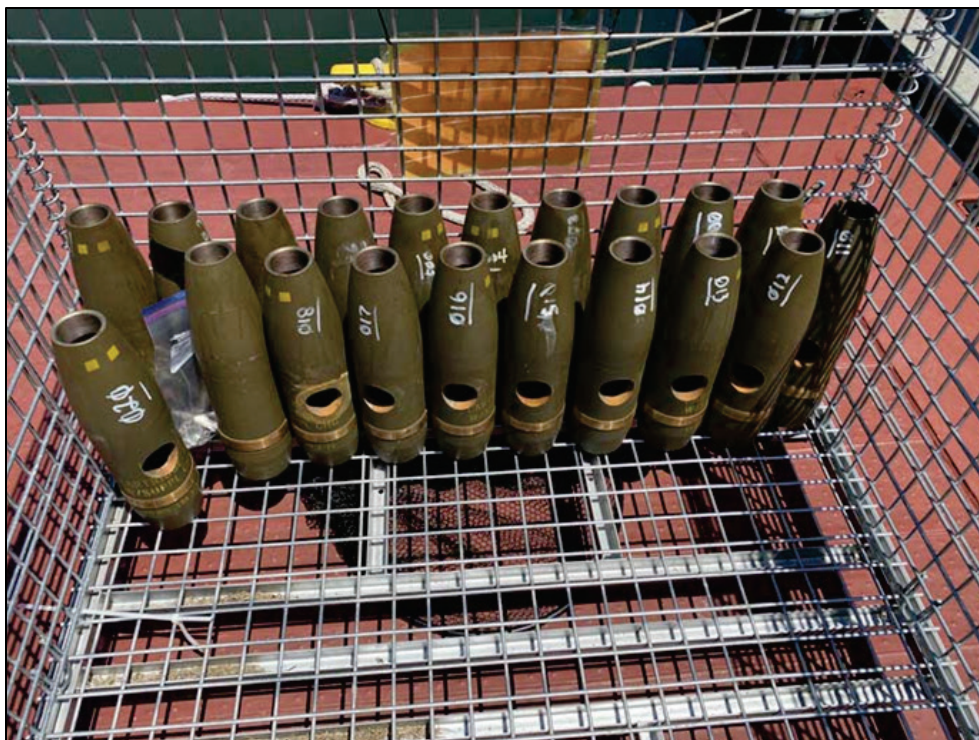


(a) TNT and water mixture collected after processing a TNT-filled 105 mm projectile



(b) Pieces of the aluminum booster cup recovered from the Cut and Capture Head

Figure 27. Twenty processed TNT-filled 105 mm projectiles (*top*) and cut plugs from some of the processed projectiles (*bottom*).



(a) Twenty processed TNT-filled 105 mm projectiles



(b) Cut plugs from some of the processed projectiles

7 Demonstration Results

7.1 Demonstration 1

The success and failure data were analyzed as described in Section 4. Table 9 lists the data for the inert Navy 5 in./38 cal projectiles, and Table 10 lists the data for the inert Army 105 mm HE M1 projectiles. In these tables, successes are denoted 1, and failures are denoted 0. The result of the statistical analysis is shown in Table 11 and is presented graphically in the OC curves in Figures 28 through 31. For this statistical analysis, only the data for the inert Navy 5 in./38 cal projectiles were analyzed because only five inert Army 105 mm HE M1 projectiles were processed.

Table 9. Success and failure data collected for the processing of inert Navy 5 in./38 cal projectiles. Successes denoted as 1, and failures denoted as 0.

Projectile	Concrete	Fill	Cradle	Tank	Seafloor	Cleaning	Mating	Cutting	Plug Removal	Wash-out	Capture	Date
1	—	1	1	—	1	—	1	1	1	1	1	24/7/2021
2	—	1	1	—	1	—	1	1	1	1	1	24/7/2021
3	—	1	1	—	1	—	1	0	—	—	—	25/7/2021
4	—	1	1	—	1	—	1	1	0	—	—	25/7/2021
5	—	1	1	—	1	—	1	1	0	—	—	25/7/2021
6	—	1	—	1	—	—	1	1	0	1	1	25/7/2021
7	—	1	—	1	—	—	1	1	1	1	1	25/7/2021
8	—	1	1	—	1	—	1	0	—	—	—	26/7/2021
9	—	1	1	—	1	—	1	1	1	1	1	26/7/2021
10	—	1	1	—	1	—	1	0	—	—	—	28/7/2021
11	—	1	1	—	1	—	1	1	—	—	—	28/7/2021
12	—	1	—	—	1	—	1	1	1	1	1	26/7/2021
13	—	1	—	—	1	—	1	1	1	1	1	26/7/2021
14	—	1	—	—	1	—	1	1	1	1	1	26/7/2021
15	—	1	—	1	—	—	1	1	1	1	1	24/7/2021
16	—	1	—	—	1	—	1	1	1	1	1	27/7/2021
17	—	1	—	—	1	—	1	1	1	1	1	26/7/2021
18	—	1	—	1	—	—	1	1	—	—	—	24/7/2021
20	1	1	—	—	1	1	1	1	1	1	1	27/7/2021
22	1	1	—	—	1	1	1	1	1	1	1	27/7/2021
25	—	1	—	—	1	—	1	1	1	1	1	27/7/2021
27	—	1	1	—	1	—	1	1	1	1	1	28/7/2021
28	—	1	1	—	1	—	1	1	—	—	—	28/7/2021
29	—	1	1	—	1	—	1	0	—	—	—	28/7/2021
30	—	1	1	—	1	—	1	1	1	1	1	28/7/2021
31	—	1	1	—	1	—	1	1	1	1	1	28/7/2021
34	—	1	1	—	1	—	1	1	1	1	1	28/7/2021
41	—	1	—	—	1	—	1	1	1	1	1	27/7/2021
42	—	1	—	—	1	—	1	1	1	1	1	27/7/2021

Table 10. Success and failure data collected for the processing of inert Army 105 mm HE M1 projectiles. Successes denoted as 1, and failures denoted as 0.

Projectile	Concrete	Fill	Cradle	Tank	Seafloor	Cleaning	Mating	Cutting	Plug Removal	Washout	Capture	Date
087	—	1	1	—	1	—	1	1	1	1	1	27/7/2021
088	—	1	1	—	1	—	1	0	—	—	—	27/7/2021
090	—	1	1	—	1	—	1	1	1	1	1	27/7/2021
091	—	1	1	—	1	—	1	1	1	1	1	27/7/2021
095	—	1	1	—	1	—	1	0	—	—	—	27/7/2021

Table 11. Statistical analysis results for the processing of inert Navy 5 in./38 cal projectiles.

Operation	Trials n	Successes i	Failures r	Confidence C	Reliability R
Mating	29	29	0	90%	92%
Cutting	29	25	4	90%	74%
Plug Removal	25	22	3	90%	75%
Washout	20	20	0	90%	89%

Figure 28. Operating characteristic (OC) curve for the mating operation.

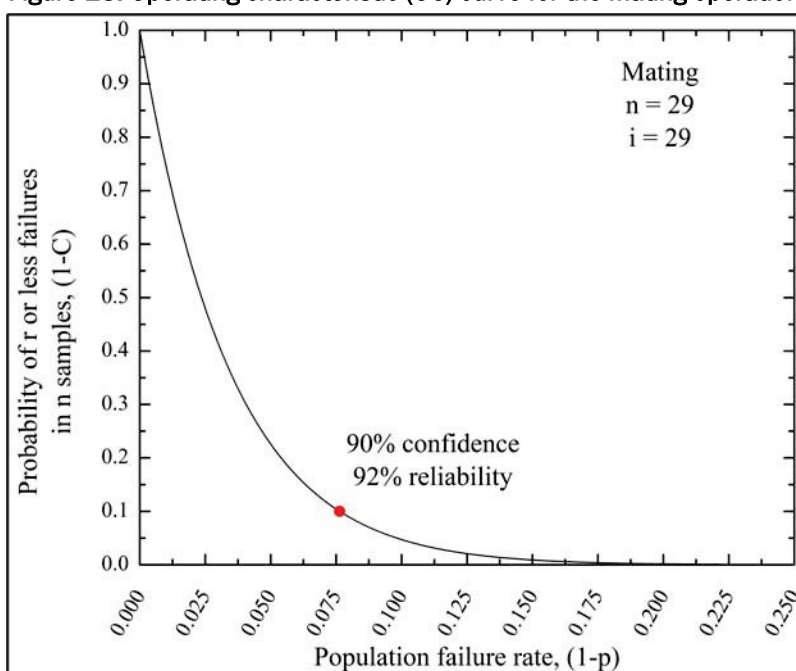


Figure 29. OC curve for the cutting operation.

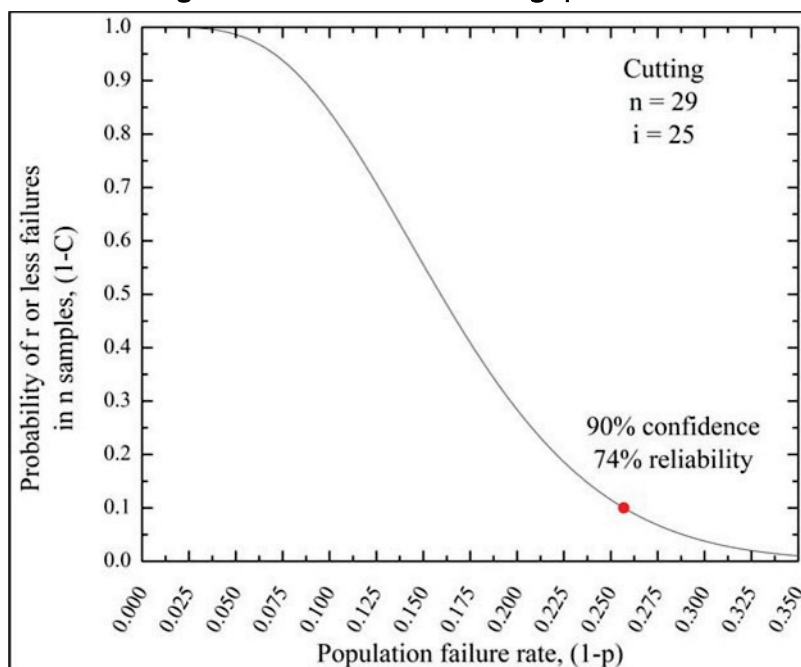


Figure 30. OC curve for the plug removal operation.

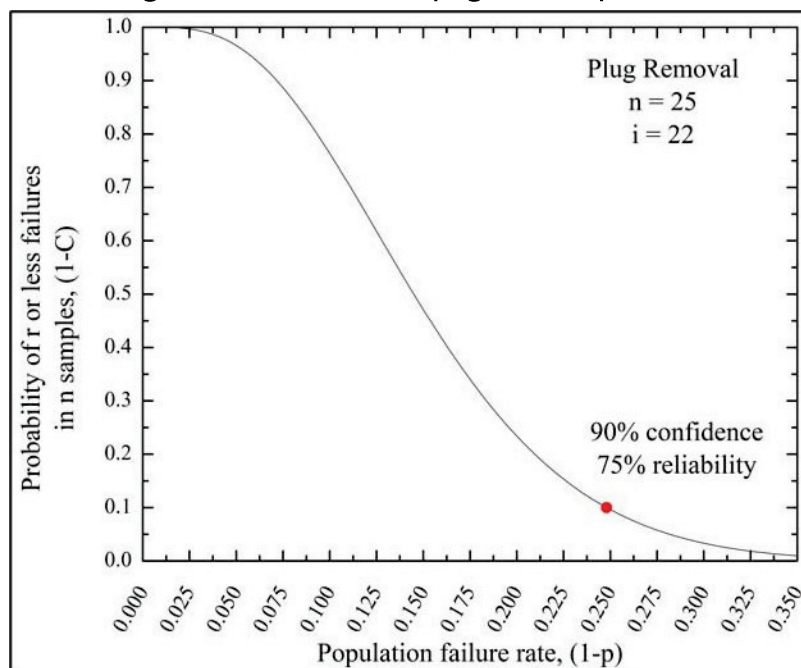
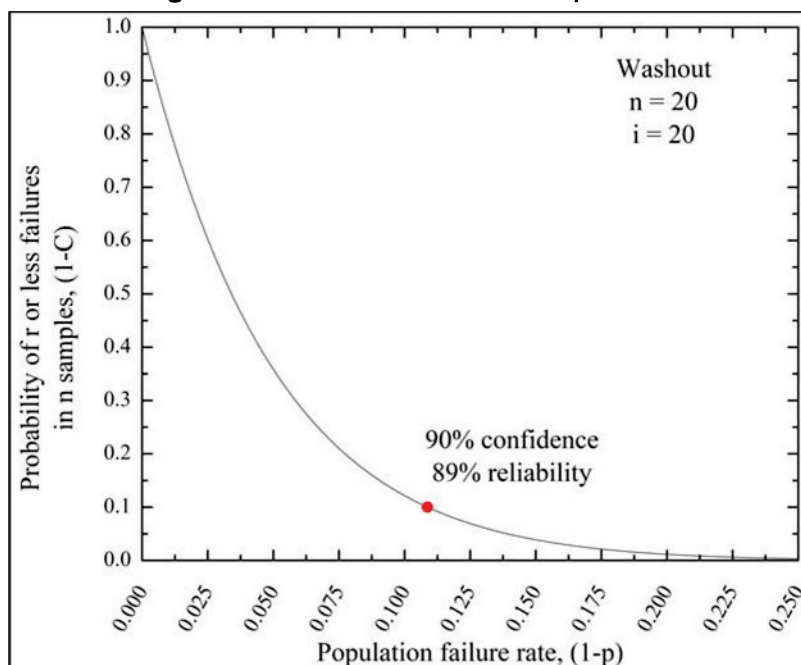


Figure 31. OC curve for the washout operation.



The previous statistical analysis included all items processed during the demonstration, including the items processed during the initial commissioning and testing of the system on the vessel. As such, it was expected that issues would be experienced during this startup effort. If the failures observed during the first few days of the demonstration, as issues were being rectified, are eliminated from the statistical analysis, the reliability results for both the cutting and plug removal operations vastly improve. In fact, the reliability result for cutting increases from a 74% to an 83% success rate; the reliability result for plug removal increases from a 75% to a 91% success rate. The results of the statistical analysis are shown in Table 12 and are presented graphically in the OC curves in Figures 32 and 33.

Table 12. Statistical analysis results for the cutting and plug removal operations when eliminating commissioning data.

Operation	Trials n	Successes i	Failures r	Confidence C	Reliability R
Cutting	29	27	2	90%	83%
Plug Removal	25	25	0	90%	91%

Figure 32. OC curve for the cutting operation after removing commissioning data.

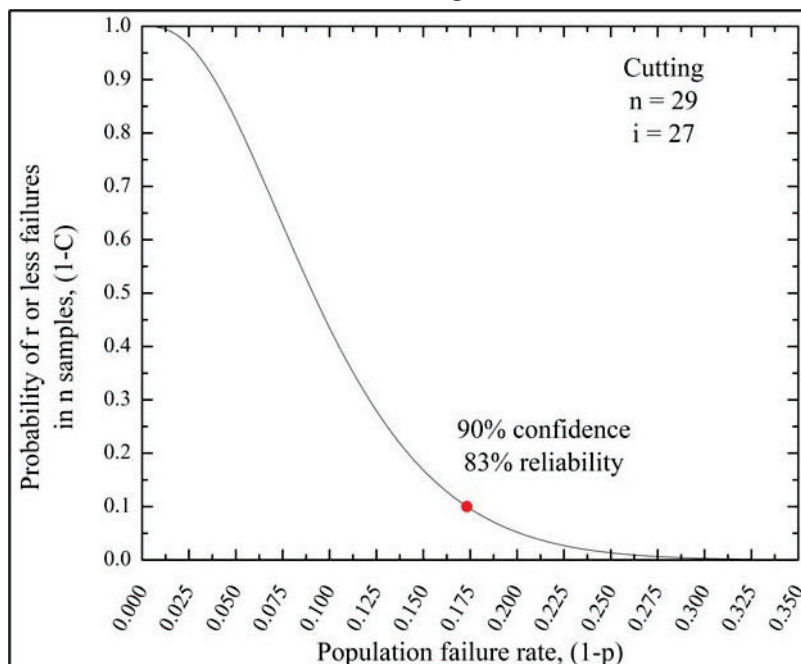
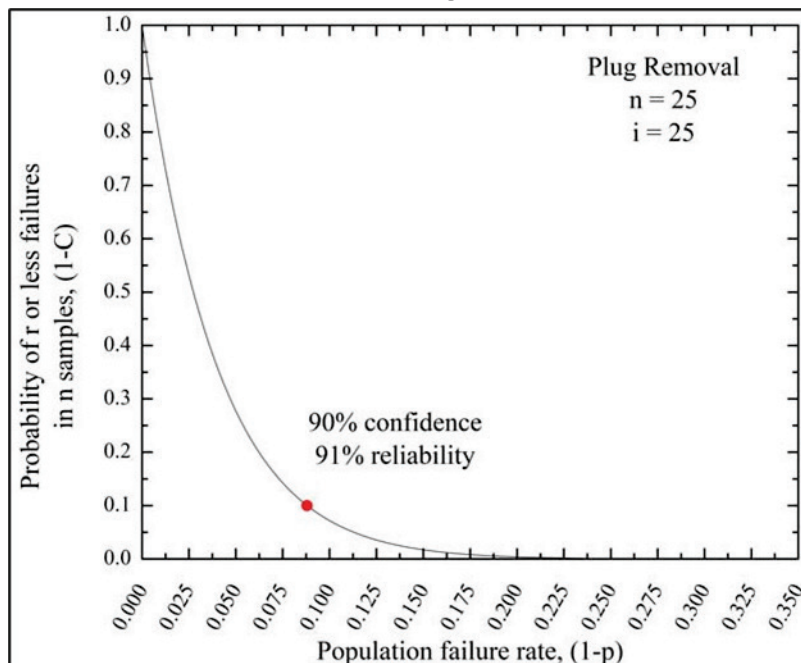


Figure 33. OC curve for the plug removal operation after removing commissioning data.



7.1.1 Performance Results

The performance results for this demonstration are detailed in this section and summarized in Table 13.

7.1.1.1 Equipment Reliability

During the initial phase of the demonstration, numerous major equipment failures were experienced. These included a faulty communication line, water intrusion into the subsea electronic and hydraulic module (SEHM), water intrusion into the underwater abrasive feed system, and the unintentional disconnecting of capture network plumbing lines subsea. These failures were all successfully repaired. As the demonstration proceeded, the frequency of major equipment failures lessened substantially. Therefore, over the course of the entire demonstration, it is estimated there were 8 hr in between failures. All of the support equipment on the deck of the vessel performed flawlessly. The equipment failures experienced during the demonstration guided system improvements that were implemented prior to the second demonstration.

7.1.1.2 Cleaning of the Target

Two inert projectiles covered with 1 in. thick concrete were processed to test the cleaning tool's effectiveness. Both of these items were cleaned on the seafloor using the projectile stabilization device. During previous demonstrations, the cleaning head also pushed away sediment around the projectile, which caused the projectile to roll down into the resulting hole. The projectile stabilization device proved useful in preventing this from occurring, and both items were successfully cleaned; the cleaning head had no issue removing all of the concrete, down to the original projectile surface, in one pass. The surface of the pipe that was 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 fully successful in removing concrete.

7.1.1.3 Waterjet Washout of Munition Constituents

The washout operation took approximately 8 min to complete; washout occurred as the washout head was slowly traversed down into and back out of the inert projectile. Under these conditions, complete washout always occurred. Because 20 items were washed successfully, the reliability of complete washout was 89% at a 90% confidence level.

7.1.1.4 Capture of Munition Constituents

When using the capture tank located on the deck of the vessel and cutting an inert Navy 5 in./38 cal projectile filled with microcrystalline cellulose,

the stream entering the capture tank became dark and cloudy during cutting; this was caused by the garnet abrasive and inert fill being removed by the capture network. Most important, 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 previous testing in Gradient Technology's shop. During washout, the stream entering the capture tank became a 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, the capture fluid entering the collection tote cleared up as the last of the microcrystalline cellulose was removed and collected. Because there was no visible evidence of leakage to the surroundings, >95% of the inert fill was captured; some material can remain inside the annulus created by the turret. A borescope inserted into this area showed evidence of a small amount of material remaining in the area.

Next, the technique by which the capture tank was placed on the seafloor was tested. This technique performed effectively and in the same fashion as if it were located on the deck of the vessel.

7.1.1.5 Attachment to Target

Proper attachment of the tool to the target was verified during the demonstration by qualitatively observing for leaks around the attachment boot that seals on the projectile. For the processing of the inert Navy 5 in./38 cal projectiles, 29 of 29 matings were successful. Therefore, the reliability of this operation was 92% at a 90% confidence level. During the demonstration, the attachment boot could rotate. Because we used a fan laser mounted independent of the attachment boot to guide the mating operation, rotation of the boot led to misalignments of the fan laser. Prior to the second demonstration, the attachment boot was rigidly fixed so that it could not rotate independent of the fan laser.

7.1.1.6 AWJ Cutting of Access Hole

During the demonstration, 4 of the 29 inert Navy 5 in./38 cal 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 water-jet; this prohibited the plug from being removed by the magnet. This issue was resolved by increasing the high-pressure water pressure and

increasing the overlap for cutting to about 200°. The cutting data were statistically analyzed and resulted in an 83% reliability at a 90% confidence level. Table 13 summarizes the results of this demonstration.

Table 13. Performance results for Demonstration 1.

Performance Objective	Metric	Data Required	Success Criteria	Results
Equipment reliability	Failure rate per hour Major: Requires repair Minor: Requires reset	- Hours of operation - Number of major failures - Number of minor failures	$MTBF_{major} > 3 \text{ hr}$ $MTBF_{minor} > 1 \text{ hr}$	There were numerous major equipment failures. However, when averaged over the duration, the $MTBF_{major} \approx 8 \text{ hr}$.
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.
Waterjet washout of munition constituents	Percentage of material removed	- Initial mass - Postwashout mass	80% average removal	All (100%) of the fill was removed from 20 of the 20 projectiles; 89% reliability. Based on observations.
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 (29 of 29) attachments were successful; 92% reliability.
Abrasive waterjet cutting of access hole	Percentage successfully cut	- Items attempted - Items successful	$P_{cut} > 80\%$	Nearly all (27 of 29) of the cuts were successful; 83% reliability.

Note: MTBF = mean time between failures, RMS = root mean square, WJ = waterjet.

7.1.2 Results Summary

In total, 29 inert Navy 5 in./38 cal projectiles and five inert Army 105 mm HE M1 projectiles were processed. Our goal was to achieve an 80% reliability (success rate) in a given operation during the demonstration. Statistical analysis of the data yielded the following reliability results at 90% confidence for the 29 inert Navy 5 in./38 cal projectiles:

- Mating: 92%
- Cutting: 83%

- Plug removal: 91%
- Washout: 89%

Overall, this demonstration showed that Gradient Technology's high-pressure waterjet demilitarization technology can be reliably (>80%) operated underwater in 40 FSW to 70 FSW when the supporting equipment is located on the deck of a vessel. In addition, the following aspects of the Underwater Cut and Capture System were successfully demonstrated for the first time:

1. Deployment of the system off the deck of a vessel and onto the ocean floor using a crane
2. Use of a remotely operated vehicle (ROV) to disconnect the crane rigging from the system subsea
3. Use of an ROV to reconnect the crane rigging to the system subsea
4. Retrieval of the system from the ocean floor and onto the deck of a vessel using a crane
5. Use of a subsea capture tank to collect all effluent generated during inert target item processing
6. Use of an ROV to connect the discharge of the subsea capture pump to the subsea capture tank
7. Use of an ROV's camera to inspect the internal cavity of projectile bodies
8. Movement of the vessel over 400 ft away from the system while laying the umbilical on the ocean floor
9. Movement of the vessel back to the system while retrieving the umbilical

After the demonstration, three equipment upgrades were identified and were addressed prior to executing the second demonstration. These three primary equipment upgrades were as follows:

1. Improve the magnet used to remove the cut plug.
2. Install a subsea-rated fiber optic communication line to the SEHM.
3. Improve the transfer of the wax simulant from the Cut and Capture Head to the subsea capture tank.

7.2 Demonstration 2

The success and failure data for the second demonstration were analyzed as described in Section 4. Table 14 shows the data for the inert Navy 5 in./38 cal projectiles, and Table 15 shows the data for the inert Army 105 mm HE M1 projectiles. In these tables, successes are denoted 1, and

The previous statistical analysis included all Navy 5 in./38 cal projectiles processed during the demonstration. However, when processing two of the inert Navy 5 in./38 cal projectiles (i.e., 204 and 233), a momentary system communication error during cutting halted its operation. If these two failures are eliminated from the data set, the cutting reliability increases from 81% to 86% at 90% confidence. The results of the statistical analysis are shown in Table 17 and presented graphically in the operating characteristic curves in Figure 38.

[illegible]

Table 14 (cont.). Success and failure data collected for the processing of inert Navy 5 in./38 cal projectiles. Successes denoted as 1, failures denoted as 0, and plugs not removed with the magnet denoted with a symbol ($\neq$).

Projectile	Concrete	Tray	Seafloor	Cleaning	Mating	Cutting	Plug Removal	Washout	Capture	Date
224	—	1	1	1	1	1	1	1	1	15/2/2022
225	—	1	1	1	1	1	1	1	1	15/2/2022
226	—	1	1	1	1	1	1	1	1	15/2/2022
227	—	1	1	1	1	1	$\neq$	1	1	15/2/2022
228	—	1	1	1	1	1	$\neq$	1	1	16/2/2022
229	—	1	1	1	1	1	1	1	1	15/2/2022
230	—	1	1	1	1	1	1	1	1	15/2/2022
232	—	1	1	1	1	1	1	1	1	14/2/2022
233	—	1	1	1	1	0	—	—	—	15/2/2022
234	—	1	1	1	1	1	$\neq$	1	1	16/2/2022
235	—	1	1	1	1	1	0	—	—	12/2/2022
236	—	1	1	1	1	1	$\neq$	1	1	12/2/2022
237	—	—	—	—	1	1	1	1	1	11/2/2022
238	—	1	1	—	1	1	0	—	—	11/2/2022
239	—	1	1	1	1	1	1	1	1	12/2/2022
240	—	1	1	1	1	1	$\neq$	1	1	13/2/2022
241	—	1	1	1	1	1	$\neq$	1	1	12/2/2022
242	—	1	1	1	1	1	1	1	1	14/2/2022
243	—	1	1	1	1	0	—	—	—	12/2/2022
244	—	1	1	1	1	1	1	1	1	13/2/2022

Table 15. Success and failure data collected for the processing of inert Army 105 mm HE M1 projectiles. Successes denoted as 1, and failures denoted as 0.

Projectile	Concrete	Tray	Seafloor	Cleaning	Mating	Cutting	Plug Removal	Washout	Capture	Date
172	—	1	1	1	1	0	—	—	—	16/2/2022
174	—	1	1	1	1	1	—	—	—	16/2/2022
176	—	1	1	1	1	1	—	—	—	16/2/2022
178	—	1	1	1	1	1	1	1	1	14/2/2022

Table 16. Statistical analysis results for the processing of inert Navy 5 in./38 cal projectiles.

Operation	Trials, n	Successes, i	Failures, r	Confidence, C	Reliability, R
Mating	39	39	0	90%	94%
Cutting	39	35	4	90%	81%
Plug Removal	35	33	2	90%	86%
Washout	35	35	0	90%	94%

Table 17. Statistical analysis results for the cutting operation when eliminating two failures due to system communication errors.

Operation	Trials, n	Successes, i	Failures, r	Confidence, C	Reliability, R
Cutting	37	35	2	90%	86%

Figure 34. OC curve for the mating operation.

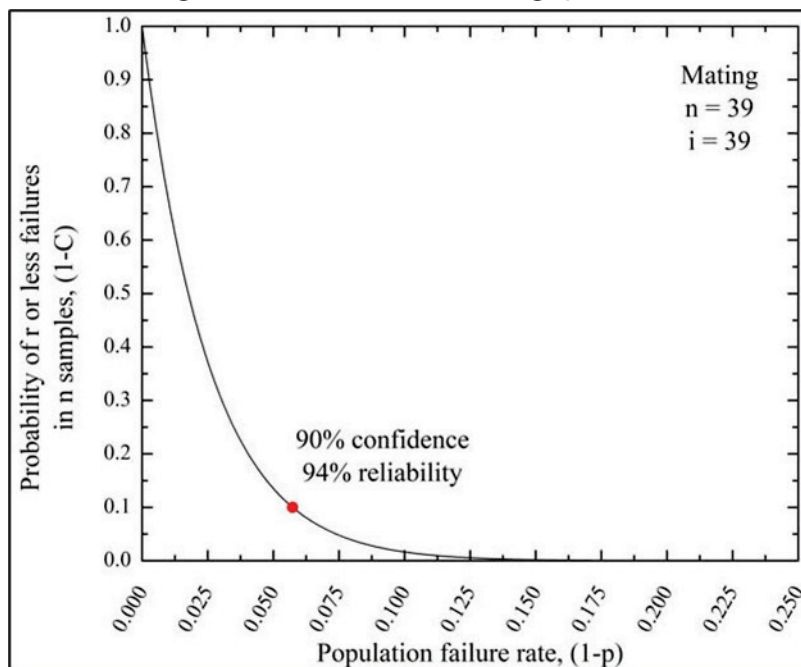


Figure 35. OC curve for the cutting operation.

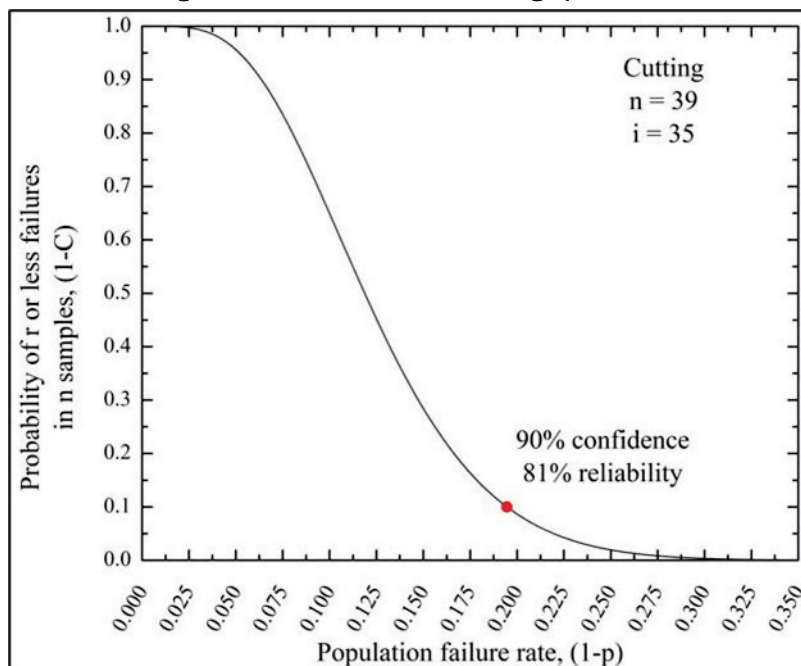


Figure 36. OC curve for the plug removal operation.

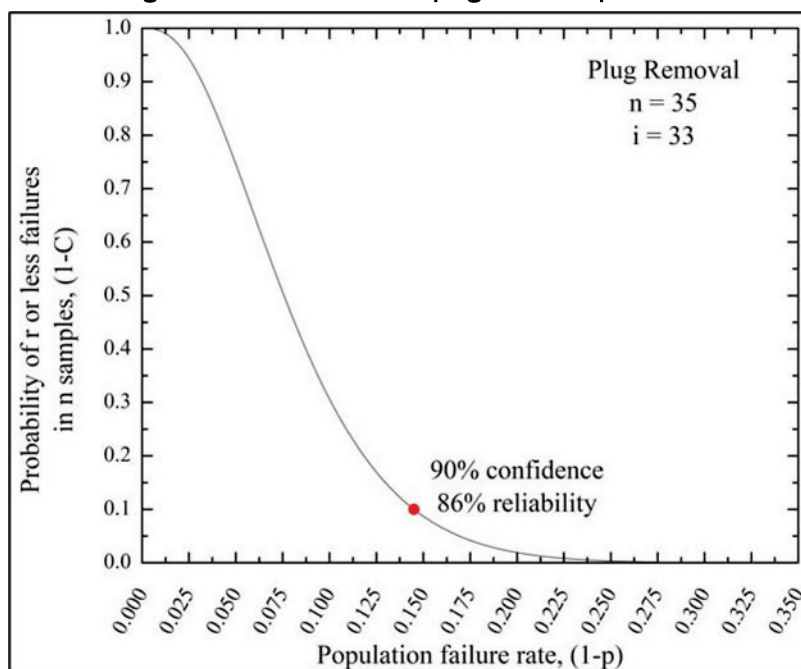


Figure 37. OC curve for the washout operation.

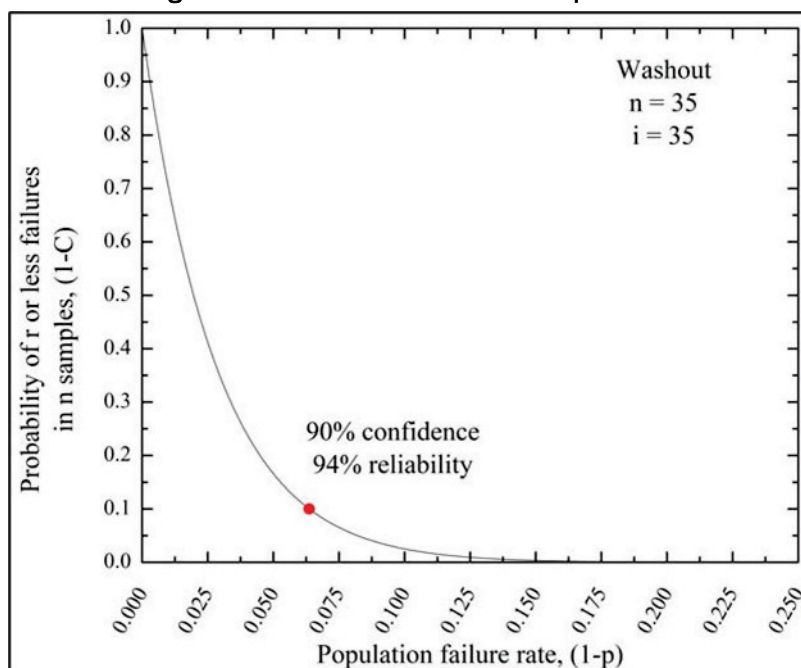
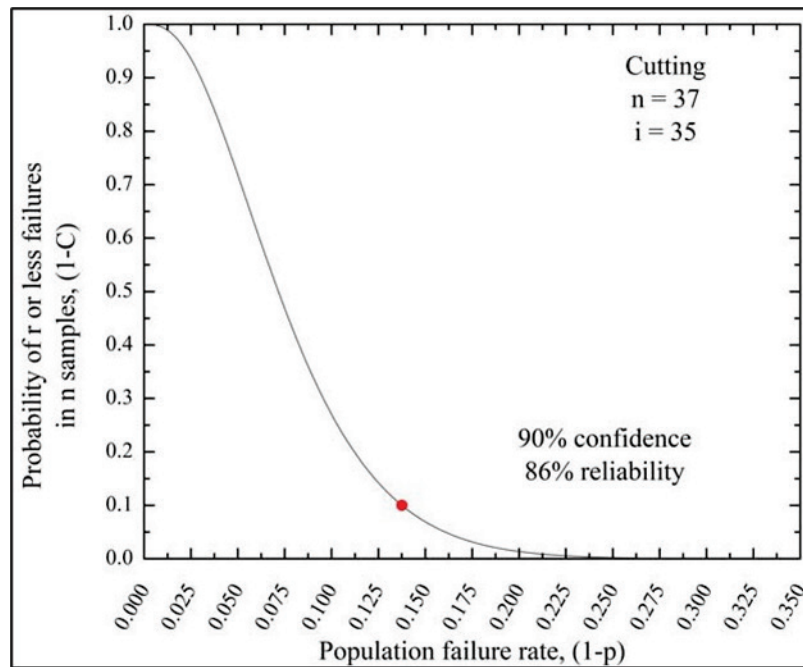


Figure 38. OC curve for the cutting operation after eliminating two failures due to system communication errors.



7.2.1 Performance Results

The performance results for this demonstration are detailed in this section and summarized in Table 18.

7.2.1.1 Equipment Reliability

During the initial phase of the demonstration, one major equipment failure was experienced when the pressure-regulating valve on the abrasive delivery system failed. This failure was remedied by adding a tube to the umbilical to allow the abrasive delivery system to draw air into it from the surface via the tube. Another major equipment failure occurred when wax-filled target items were processed; the wax accumulated inside the capture pump, resulting in plugging and ultimately pump damage. The pump was replaced with a spare one. Over the course of the entire demonstration, there were approximately 12 hr in between failures; this is an estimated combined time. All of the support equipment on the deck of the vessel again performed flawlessly. The equipment failures experienced during the demonstration guided the system improvements undertaken prior to the last demonstration.

7.2.1.2 Cleaning of the Target

Two inert projectiles covered with 1 in. thick concrete were processed to test the cleaning tool's effectiveness. Both of these items were cleaned on the seafloor using the projectile tray. During previous demonstrations, the cleaning head also pushed away sediment around the projectile, which caused the projectile to roll down into the resulting hole. The projectile tray proved useful in preventing this from occurring, and both items were successfully cleaned; the cleaning head had no issue removing all of the concrete, down to the original projectile surface, in one pass. The surface of the pipe that was exposed was as smooth as the original pipe.

The cleaning head was also used to remove the paint from all the other nonconcrete-covered inert projectiles to improve the performance of the magnet when removing the cut plug. This operation was carried out as expected.

7.2.1.3 Waterjet Washout of Munition Constituents

When processing inert Navy 5 in./38 cal projectiles filled with microcrystalline cellulose, the washout operation proceeded swiftly; the washout operation took approximately 8 min to complete. Washout occurred as the washout head was slowly traversed down into and back out of the inert projectile. Under these conditions, complete washout always occurred. Because 35 items were washed successfully, the reliability of complete washout was 94% at a 90% confidence level.

The washout of the inert 105 mm HE M1 projectiles filled with microcrystalline wax was much more challenging. The wax was extremely difficult to remove after the plug was removed. This difficulty arose from the nature of the microcrystalline wax in the cold ocean and the lack of a powerful leading jet in the washout nozzle. As a result, a hole could not be easily bored into the wax to allow for insertion of the washout nozzle. Reconfiguration of the washout nozzle and modification of the washout recipe were investigated prior to the last demonstration.

7.2.1.4 Capture of Munition Constituents

The capture network performed flawlessly when processing inert Navy 5 in./38 cal projectiles filled with microcrystalline cellulose. The new duplex hydraulically driven diaphragm pump easily transferred the effluent

to the subsea capture bladder. Also, 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 previous demonstration work.

The capture of effluent generated during the processing of the inert 105 mm HE M1 projectiles filled with microcrystalline wax proved to be more challenging than expected. The microcrystalline wax softened during cutting and washout due to the heat generated by the high-velocity waterjet. The wax subsequently solidified due to its insolubility in water and thus was trapped in different areas of the capture network, including in the flap-check valves of the duplex hydraulically driven diaphragm pump and in the constriction of the hot stab connection on the subsea bladder. Once the hot stab connection at the bladder was plugged, the duplex hydraulically driven diaphragm pump was deadheaded and destroyed itself. In the future, all hot stab connections need to be increased in size to prevent plugging. As a result of the issues related to washout and capture of the microcrystalline wax, only four of the inert 105 mm HE M1 projectiles filled with microcrystalline wax were processed. The capture network issues experienced during the processing of the wax guided the system improvements undertaken prior to the last demonstration.

7.2.1.5 Attachment to Target

Proper attachment of the tool to the target was verified during the demonstration by qualitatively observing for leaks around the attachment boot that seals on the projectile. For the processing of the inert Navy 5 in./38 cal projectiles, 39 of 39 matings were successful. Therefore, the reliability of this operation was 94% at a 90% confidence level.

7.2.1.6 AWJ Cutting of Access Hole

During the demonstration, 2 of the 35 inert Navy 5 in./38 cal projectiles processed had 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. Statistical analysis of the cutting data resulted in an 86% reliability at a 90% confidence level.

7.2.1.7 Magnetic Removal of the Cut Plug

During the first two demonstrations, an electromagnet was used to remove the cut plug from the target items. Initially, the electromagnet worked well, but it degraded over time due to the ingress of seawater into the electrical connection on the electromagnet. Because subsea electromagnets are not commercially available in the size and profile required, off-the-shelf electromagnets were retrofitted for use in our application. Prior to the third demonstration, alternative magnet configurations were investigated and tested in our shop. These alternatives included a cleanable permanent magnet and electromagnets with more robustly prepared electrical connections. Table 18 summarizes the performance results.

Table 18. Performance results for Demonstration 2.

Performance Objective	Metric	Data Required	Success Criteria	Results
Equipment reliability	Failure rate per hour Major: Requires repair Minor: Requires reset	- Hours of operations - Number of major failures - Number of minor failures	$MTBF_{\text{major}} > 3 \text{ hr}$ $MTBF_{\text{minor}} > 1 \text{ hr}$	There were numerous major equipment failures. However, when averaged over the duration, the $MTBF_{\text{major}} \approx 12 \text{ hr}$.
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.
Waterjet washout of munition constituents	Percentage of material removed	- Initial mass - Post-washout mass	80% average removal	All (100%) of the fill was removed from 35 of the 35 projectiles; 94% reliability.
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	$P_{\text{attach}} > 80\%$	All (39 of 39) attachments were successful; 94% reliability.
Abrasive waterjet cutting of access hole	Percentage successfully cut	- Items attempted - Items successful	$P_{\text{cut}} > 80\%$	Nearly all (35 of 37) cuts were successful; 87% reliability.

Note: MTBF = mean time between failures, RMS = root mean square, WJ = waterjet.

7.2.2 Results Summary

Specifically, 39 inert Navy 5 in./38 cal projectiles and four inert Army 105 mm HE M1 projectiles were processed. Our goal was to achieve 80% reliability (i.e., success rate) in a given operation during the demonstration. Statistical analysis of the data yielded the following reliability results at 90% confidence for the 39 inert Navy 5 in./38 cal projectiles:

- Mating: 94%
- Cutting: 86%
- Plug removal: 86%
- Washout: 94%

Overall, this demonstration showed that Gradient Technology's high-pressure waterjet demilitarization technology can be reliably (>80%) operated underwater in 70 FSW when the supporting equipment is located on the deck of a vessel. In addition, the following aspects of the Underwater Cut and Capture System were successfully demonstrated for the second time:

1. Deployment of the system off the deck of a vessel and onto the ocean floor using a crane
2. Use of an ROV to disconnect the crane rigging from the system subsea
3. Use of an ROV to reconnect the crane rigging to the system subsea
4. Retrieval of the system from the ocean floor and onto the deck of a vessel using a crane
5. Use of a subsea capture tank to collect all effluent generated during inert target item processing
6. Use of an ROV to connect the discharge of the subsea capture pump to the subsea capture tank
7. Use of an ROV's camera to inspect the internal cavity of projectile bodies
8. Use of a 600 ft umbilical from the deck of the ship to the system.

After the demonstration, two equipment upgrades were identified and addressed prior to executing the third demonstration. These primary equipment upgrades were as follows:

1. Improve the magnet used to remove the cut plug.
2. Improve the washout capability of the leading orifice of the washout nozzle.

7.3 Demonstration 3

Table 19 shows the success and failure data for processing the 20 TNT-filled Army 105 mm HE M1 projectiles. In this table, successes are denoted 1, and failures are denoted 0. The washout data denoted by 0 indicate the projectile had to be rewashed to remove residual TNT from the base.

Table 19. Success and failure data collected for the processing of Army 105 mm HE M1 projectiles. Successes denoted as 1, failures denoted as 0, and washout requiring rewashing denoted as 0.

Projectile	Mating	Cutting	Plug Removal	Washout	Capture	Date	Time
001	1	1	0	0	1	27/6/2022	1115
002	1	1	1	1	1	28/6/2022	0832
003	1	1	1	0	1	28/6/2022	0932
004	1	1	0	0	1	28/6/2022	1123
005	1	1	1	0	1	28/6/2022	1310
006	1	1	1	0	1	28/6/2022	1416
007	1	1	1	0	1	28/6/2022	1614
008	1	1	0	1	1	29/6/2022	1034
008	1	1	1	1	1	29/6/2022	1225
010	1	1	1	1	1	29/6/2022	1302
011	1	1	1	1	1	29/6/2022	1408
012	1	1	1	1	1	29/6/2022	1437
013	1	1	1	1	1	29/6/2022	1513
014	1	1	1	1	1	29/6/2022	1541
015	1	1	0	0	1	29/6/2022	1612
016	1	1	1	1	1	30/6/2022	0815
017	1	1	1	1	1	30/6/2022	0844
018	1	1	1	1	1	30/6/2022	0912
019	1	1	1	0	0	30/6/2022	0959
020	1	1	1	1	1	30/6/2022	1119

7.3.1 Performance Results

The performance results for this demonstration are detailed in this section and summarized in Table 20.

7.3.1.1 Equipment Reliability

During the demonstration, three major equipment failures were experienced. First, the hard stop on a hydraulically actuated valve on the

abrasive feed line to the cutting head broke. This resulted in the valve remaining open, which subsequently allowed water to flow back to the abrasive feeder housing. The hard stop was rewelded, and the system was dried prior to proceeding with the demonstration. The second equipment failure involved the hydraulic motor that rotates the tool during cutting. A shaft seal on this hydraulic motor failed, which allowed hydraulic fluid to leak. When this leak was identified, the hydraulic motor was replaced. The last equipment failure involved the hydraulically driven diaphragm pump on the capture network. During washout, the aluminum booster cup was typically shredded into small pieces. Most of these pieces flowed through the capture network and ended up in the 500 gal. capture tank. However, one of these pieces must have been sharp and punctured a hole in one of the rubber diaphragms of the capture pump. As a result, it is estimated that less than 100 mL of capture fluid leaked out of the diaphragm pump; this occurred on the last day of the projectile processing. The rubber diaphragm was replaced, and operations continued.

7.3.1.2 Cleaning of the Target

No cleaning of the target was conducted during this demonstration.

7.3.1.3 Waterjet Washout of Munition Constituents

Initially in this demonstration, it was difficult to remove TNT from the base of three of the first four projectiles. Approximately 1 in. of hard crystalline TNT remained at the base. As a result, the team changed the orifice configuration in the washout head to determine the configuration that effectively removed all of the material from the body. Because the team had not previously attempted to process TNT, this effort was not unexpected. After testing different configurations with projectiles 5 through 7, we determined that a single orifice at the side position was required to remove all of the TNT from the projectiles in approximately 10 min. This configuration thus focused all of the available jet power into a single jet. After arriving at this configuration, the processing of the remaining items (i.e., 8–20) went smoothly, with one exception. The magnet was unsuccessful in removing the plug from projectile 15, which had to be rewashed as a small amount of TNT remained at the base.

7.3.1.4 Capture of Munition Constituents

The capture network effectively moved the effluent generated during cutting and washout to the 500 gal. capture tank. Because this was the first time the capture network was used to move TNT from a projectile, the team was not exactly sure how the system would behave. However, we quickly realized that if capture flow is maintained, the TNT slurry can be readily pumped all the way to the capture tank.

As previously mentioned, there was one failure when a rubber diaphragm was punctured. Aside from that failure, the team was proactive in monitoring and routinely replacing the four check valves on the capture pump. When flow from the pump appeared to slow down, the check valves were inspected and replaced. Check-valve failure occurred three times during washout (with projectiles 6, 10, and 18); when this occurred, a small leak around the boot was observed. Refer to Section 7.3.2 for water sampling results. The design of the check valves will require further assessment, and alternatives will be explored in the future because they are critical components in maintaining capture network integrity.

7.3.1.5 Attachment to Target

During the demonstration, the effectiveness of the attachment of the boot to the projectile was assessed by observing for leaks and denoting it as a pass or fail. It is common to observe a momentary leak around the boot when the cutting head is first started due to a pressure spike generated from the high-pressure water. After a brief time, however, the pressure spike subsides. A munition holder was used in this demonstration so that the projectile processed could be deployed and retrieved with the Underwater Cut and Capture System; this process naturally facilitated effective attachment of the Cut and Capture Head to the projectile body.

7.3.1.6 AWJ Cutting of Access Hole

During the demonstration, there were no issues with effectively cutting the plug in the side of the projectile. Table 20 lists the performance results for this demonstration.

Table 20. Performance results for Demonstration 3.

Performance Objective	Metric	Data Required	Success Criteria	Results
Equipment reliability	Failure rate per hour Major: Requires repair Minor: Requires reset	- Hours of operations - Number of major failures - Number of minor failures	$MTBF_{major} > 3 \text{ hr}$ $MTBF_{minor} > 1 \text{ hr}$	There were three major equipment failures.
Waterjet washout of munition constituents	Percentage of material removed	- Initial mass - Postwashout mass	80% average removal	All (100%) of the fill was ultimately removed from all projectiles: 35% of projectiles (7 of 20) required rewash.
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 20 initial attachments were successful; leakage observed 3 times when capture pump check valves failed (Projectiles 6, 10, and 18).
Abrasive waterjet cutting of access hole	Percentage successfully cut	- Items attempted - Items successful	$P_{cut} > 80\%$	All 20 cuts were successful; however, due to magnetic plug removal failure, 20% (4 or 20) of plugs required manual removal.

Note: MTBF = mean time between failures.

7.3.2 Water Sampling Conducted during the Demonstration

During the demonstration, US Army Engineer Research and Development Center (ERDC) personnel collected water samples during waterjet cutting of the access hole and waterjet washout of munition constituents for projectiles 1 to 15. The sampling methodology and results are presented in Lo-tufo et al. (2023).

7.3.3 Results Summary

Overall, this demonstration showed that Gradient Technology's high-pressure waterjet demilitarization technology can effectively process live TNT-filled Army 105 mm HE M1 projectiles without fuzing when the supporting equipment is located on a floating pier system. This demonstration was the first time live projectiles were processed. In addition, the following aspects of the Underwater Cut and Capture System were successfully demonstrated:

1. Deployment of the system off the deck of a floating pier system using a gantry crane
2. Capture of TNT from live items
3. Washout of live items containing an internal booster cup
4. Complete washout of an item with a single orifice in the washout head

After the demonstration, however, two equipment upgrades were identified. First, further improvements to the magnet for removing the cut plug are required. Accurate positioning of the permanent magnet is required for reliable operation. As a result, the positioning and movement of this magnet will require robust and more accurate equipment, such as an encoder and drive train, to improve reliability. In addition, nonmagnetic approaches to plug removal should be explored for cases in which the cut plug is not ferrous.

The second upgrade identified pertains to the capture network. Although significant strides were made in improving the capture network over the course of the three demonstrations conducted for this project, further improvements related to the integrity of the equipment used are required. The current capture pump is a hydraulically driven duplex diaphragm pump that utilizes rubber diaphragms and rubber flap check valves. This pump configuration is relatively inexpensive, and spare parts are readily available. Repair is also rather simple. However, when the Underwater Cut and Capture System is deployed, it is not desirable to retrieve the system for repairs. These repairs were relatively easy in the environment and water depths explored during the course of this demonstration, but they would be time consuming if required when operating from a vessel in a deep-water marine environment. Therefore, alternative capture pumps and improved diaphragms and check valves will be investigated.

The team was able to completely demilitarize the 20 live TNT-filled Army 105 mm HE M1 projectiles available for this demonstration in four days. Numerous challenges were quickly overcome, especially when it came to the removal of residual TNT left at the base of items. On-site engineering decisions were effectively made to arrive at a single-orifice configuration for washout so that the projectiles could be completely cleaned.

8 Lessons Learned

During the course of this project, numerous lessons were learned that provided the basis for continuous improvement of the technology as we proceeded through the three demonstrations. Because the core of the technology involves waterjet cleaning of the target item, attachment of the Cut and Capture Head, AWJ cutting, removal of the cut plug, washout of the internal fill, and capture of the effluent generated during cutting and washout, the discussion in this section focuses on these six operations.

8.1 Waterjet Cleaning

During the first two demonstrations, four inert Navy 5 in./38 cal projectiles covered in concrete were successfully cleaned prior to attaching the Cut and Capture Head to the projectile. The multi-orifice cleaning head proved to be very efficient in removing hard material from the projectile bodies. Positioning and moving the cleaning head were also readily achieved with the gantry.

8.2 Attachment of the Cut and Capture Head

Attachment of the Cut and Capture Head to the projectile is critical for achieving the strong seal that is required for subsequent capture efforts. A 3D-printed attachment boot located on the bottom of the Cut and Capture Head is used to achieve this seal. The thermoplastic polyurethane (TPU) material used for construction of the attachment boot proved to be an effective, pliable material for this application and was used throughout the demonstrations.

8.3 AWJ Cutting

A high-pressure entrainment-style AWJ cutting head is used in the Underwater Cut and Capture System to cut a circular plug out of the side of the target item. In the first and second demonstrations, numerous failed cuts occurred and were primarily due to a small sliver of steel remaining where the cut started (i.e., the initial pierce). To address that issue, the cut profile was changed from a single revolution with a few degrees of overlap (i.e., rotation of the cutting head after the initial pierce was only a few degrees beyond a full 360°) to approximately 200°. This allowed the cutting head to pass over the initial pierce. This change improved our success rate for cutting. However, numerous other variables can affect cutting

performance. These variables include the cutting head rotation rate, the water pressure, and the abrasive flow rate. Because the goal was to cut a plug free without cutting through the back side of the target item, a variety of additional changes were tested to improve the reliability of obtaining a freely cut plug. Ultimately, the team determined a cutting head rotation rate, water pressure, abrasive flow rate, and cutting profile (i.e., degree of cutting overlap) that successfully cut all 20 live TNT-filled projectiles in the last demonstration.

8.4 Plug Removal

After a plug is cut free from the side of a target item, it must be removed. A magnet is used in the Cut and Capture Head to retrieve the cut plug. Because the steel being cut is magnetic and the abrasive used (garnet) can become magnetized after impinging steel, the magnet can become coated with this magnetic material. As a result, an electromagnet was initially used because it could be de-energized when not used for removing a plug, thereby reducing its chance of becoming coated with magnetic material.

Because we were not able to procure small subsea-rated electromagnets, commercially available electromagnets were modified for use in the Cut and Capture Head. Modification efforts focused on sealing the electrical wiring leaving the magnet assembly to prevent water from intruding into the wire and core assembly. During the demonstrations, the electromagnets slowly lost strength over time when subsea. Water migrated past our seal material and slowly degraded the performance of the electromagnet. As a result, the electromagnet required periodic replacement.

To avoid periodic replacement of the electromagnet, a new permanent magnet assembly was tested in the third demonstration. In this assembly, a permanent magnet was installed inside of a thin protective stainless steel (nonferrous) housing that allowed for the magnetic particles to be mechanically removed from the assembly by springs internally connecting the magnet to the housing.

The permanent magnet concept tested during the third demonstration was very effective. This technique, however, requires precise control and positioning of the assembly. This is achieved with the use of a subsea-rated encoder that measures the position of the assembly. There are numerous encoders on the Underwater Cut and Capture System, and a few of these

failed during operation. As a result, alternative subsea-rated encoders are being investigated for use in the future.

8.5 Washout

The washout head used in the demonstrations allows three orifices to be used and arranged at specific angles 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; the maximum pump capacity is approximately 2 GPM. Three orifices were very effective when washing out the inert Navy 5 in./38 cal projectiles that were press-loaded with microcrystalline cellulose. The same orifice configuration was not as effective when washing out the inert Army 105 mm HE M1 projectiles filled with cast microcrystalline wax.

Prior to the third demonstration, a variety of washout experiments were conducted to improve the wax washout. These experiments included not only changing the size of the orifices but also varying the washout head insertion rate and rotational speed when conducting a washout cycle. The purpose of using wax was to simulate TNT; this was why 178°F melting point microcrystalline wax was chosen as the inert simulant. Experimentation resulted in improved washout of the target items filled with wax. Nonetheless, the true test of the washout recipe did not occur until processing the live TNT-filled Army 105 mm HE M1 projectiles.

During the processing of the live TNT-filled projectiles, it was discovered that our three-orifice configuration did not adequately remove all the TNT located at the base of the projectile. Extended washout periods did not resolve the issue and only generated large quantities of captured water. During the demonstration, the team increased the water flow issuing from the side orifices and eliminated the downward facing jet. This change did not appreciably affect the removal of the TNT from the base. Finally, a single side-facing jet was used that directed all the available pump capacity into one powerful jet. This change effectively removed all the TNT from the base of the projectile. A single-orifice configuration was used for the remainder of the demonstration and was able to effectively wash out all the TNT from the projectiles.

8.6 Capture

The capture of the effluent generated during the cutting and washout of target items is a vital aspect of the demonstrated technology. Capture is achieved by pulling surrounding water through the Cut and Capture Head during cutting and washout and pumping it to a capture tank. Because cutting and washout operations yield solid materials, the capture network must be able to pump a solid and liquid slurry. In addition, during the cutting operation, air is entrained with the abrasive as it enters the cutting head. This air leaves the Cut and Capture Head via the capture network, and hence, the capture network must handle a three-phase stream (i.e., air, water, and abrasive).

As the team progressed through the three demonstrations, two capture network configurations and pumps were tested. During the first demonstration, an AODD capture pump was used to pull surrounding water into and out of the Cut and Capture Head to remove the cutting and washout effluent. This pump worked well for moving the microcrystalline cellulose but experienced plugging when handling wax. The wax plugging issue primarily arose from our initial use of lower-melting-point paraffin wax that melted during washout and then resolidified during capture. This issue was partially resolved using higher-melting-point microcrystalline wax.

One disadvantage of the AODD capture pump is its inherent use of compressed air for driving it. As a result, compressed air must be either taken down with the system or supplied from the surface. Because the AODD pump consumes large quantities of air, it is impractical to carry that air with the Underwater Cut and Capture System. Supplying the compressed air from the surface is only practical when operating in shallow water, where the compressed air line length is short; the air pressure drop becomes significant when the line length exceeds 100 ft. Because our umbilical was approximately 600 ft long, the AODD pump was rendered impractical.

Prior to the second demonstration, the team replaced the AODD pump with a duplex hydraulically driven diaphragm pump. This new pump eliminated the need for compressed air and, instead, utilized hydraulic power available from the hydraulic manifold inside the SEHM. The hydraulically driven diaphragm pump worked well for moving the microcrystalline cellulose to the capture tank. Once again, however, the pump experienced

some plugging when processing the microcrystalline wax. Aside from the pump plugging issues, there were plugging issues related to the plumbing from the discharge of the pump to the capture tank. Specifically, the hot-stab connection used to connect the discharge line to the capture tank had a port size approximately half the diameter of the plumbing line size. As a result, larger particles transported in the plumbing line plugged the hot stab. The size of the discharge plumbing and fittings should never decrease but, instead, should increase.

Thus far, capture-related issues have all involved the transport of wax. Because TNT had not been processed prior to the third demonstration, the team may have addressed issues that would not be present when processing TNT-filled projectiles. In fact, during the third demonstration, the capture of TNT proved to be easier than the capture of wax. The primary issue with the capture network during the third demonstration, in which 20 TNT-filled 105 mm projectiles were processed, was the short lifetime of the flap check valves integrated within the duplex hydraulically driven diaphragm pump. The failure of these check valves can likely be attributed to the presence of small pieces of aluminum that were generated from the destruction of the aluminum booster cup in the nose of the projectiles. Although the check valves required periodic replacement, the system was able to properly capture the effluent and move it to the capture tank without leakage. Nonetheless, alternative capture pumps and improved diaphragms and check valves will be investigated to improve the performance of the capture network.

9 Conclusions and Recommendations

Overall, this project showed that Gradient Technology's high-pressure waterjet demilitarization technology can be reliably operated underwater at depths less than 100 FSW when the supporting equipment is located on the deck of a vessel or floating pier system. In addition, the following aspects of the Underwater Cut and Capture System were successfully demonstrated for the first time:

1. Deployment of the system off the deck of a vessel and onto the ocean floor using a crane
2. Deployment of the system off the deck of a floating pier system using a gantry crane and moon pool
3. Use of an ROV to disconnect the crane rigging from the system subsea
4. Use of an ROV to reconnect the crane rigging to the system subsea
5. Retrieval of the system from the ocean floor and onto the deck of a vessel using a crane
6. Use of a subsea capture tank to collect all effluent generated during inert target item processing
7. Use of an ROV to connect the discharge of the subsea capture pump to the subsea capture tank
8. Use of an ROV's camera to inspect the internal cavity of projectile bodies
9. Movement of the vessel over 400 ft away from the Underwater Cut and Capture System while laying the umbilical on the ocean floor
10. Movement of the vessel back to the system while retrieving the umbilical
11. Capture of TNT from live items
12. Washout of live items containing an internal booster cup
13. Complete washout of an item with a single orifice in the washout head

During the course of the three demonstrations conducted for this project, 68 inert US Navy 5 in./38 cal projectiles press-loaded with microcrystalline cellulose, 9 inert US Army 105 mm HE M1 projectiles filled with microcrystalline wax, and 20 live US Army 105 mm HE M1 projectiles filled with TNT were processed. All of the items, aside from the TNT-filled projectiles, were processed in an open-ocean environment. The team gained invaluable experience operating in that environment and leveraged experience gained from one demonstration to improve the next demonstration. In addition, the team was able to completely demilitarize the 20 live TNT-filled projectiles in just four days.

The technology demonstrated in this project, nonetheless, must continue to evolve. Currently, the system can only readily process target items that are lying on their sides on relatively hard seafloor. The next version of this technology package should address munitions that rest in varying positions on seafloors with varying properties. The removal of cut plugs can also improve, and a new technique will be required to remove cut plugs that are not magnetic. The capture network can also improve from both a reliability perspective and also a waste-volume perspective; minimization of the wastewater captured will reduce operational costs.

The goal of the technology is to provide a solution for safely demilitarizing UXO and MEC in a variety of underwater environments. This project provided Gradient Technology with the opportunity to demonstrate the first version of an equipment and technology package that can begin to address underwater ordnance issues around the globe. Our technology is continuing to evolve and improve, and we look forward to a future demonstration with the next version of the Underwater Cut and Capture System.

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Abbreviations

AODD	Air-operated double-diaphragm
AWJ	Abrasive waterjet
EOD	Explosive ordnance disposal
ERDC	US Army Engineer Research and Development Center
FSW	Feet of seawater
HC	High capacity
HE	High Explosive
HMI	Human–machine interface
HOS	Hornbeck Offshore Services
LARS	Launch and recovery system
LGTF	Lake Glendora Test Facility
MDAS	Material documented as safe
MEC	Munitions and explosives of concern
MTBF	Mean time between failures
NSA	Naval Support Activity
NSWC	Naval Surface Warfare Center
OC	Operating characteristic
PC	Panama City
RMS	Root mean square
ROV	Remotely operated vehicle
SEHM	Subsea electronic and hydraulic module
TPU	Thermoplastic polyurethane
UXO	Unexploded ordnance
WJ	Waterjet

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13. SUPPLEMENTARY NOTES This study was performed under contract by Gradient Technology for the "Demonstration of the Integrated Underwater Cut and Capture System Technology on Submerged Munitions" program.					
14. ABSTRACT 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 risks to critical infrastructure, recreational divers, and fishermen. The primary goal of the demonstrations was to validate an underwater suite of tools that can be used to render underwater UXO and MEC safe in shallow water (i.e., up to 100 ft). US Navy underwater ranges in the Gulf of Mexico, south of the Naval Support Activity–Panama City, were selected for the first two demonstrations to fully display the integrated system by processing inert munitions, such as the Navy 5 in./38 cal and the Army 105 mm High Explosive (HE) M1 projectile. The third demonstration, however, occurred at the Naval Surface Warfare Center (NSWC), Crane, Lake Glendora Test Facility, in Sullivan, Indiana. Twenty US Army 105 mm HE M1 projectiles filled with TNT were successfully processed. Overall, this project showed that Gradient Technology's high-pressure waterjet demilitarization technology can be reliably operated underwater at depths less than 100 ft of seawater when the supporting equipment is located on the deck of a vessel or floating pier system.					
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