EGP Test Report and Proposal: MR-201611 - Underwater UXO Neutralization by Explosively Generated Plasma

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14. ABSTRACT
Navy explosive ordnance disposal (EOD) technicians require environmentally acceptable remediation techniques for underwater ordnance disposal where unexploded ordnance (UXO) cannot be moved to the surface and rendered safe. The current protocol calls for a blow-in-place (BIP) procedure where an explosive charge is utilized to detonate the UXO in place, adding to the net explosive weight of the UXO. During a typical BIP procedure, the resulting shockwave and bubble formation/collapse from the detonation of the UXO and BIP charge introduces pressures and acoustic noise that is detrimental to marine life. Therefore, a method is needed that serves to neutralize the UXO with minimal environmental impact (no detonation). This effort demonstrated the phenomena of explosively-generated plasma (EGP) technology for the remediation of underwater UXOs. It was shown that a drastically smaller explosive charge could be used to initiate a “low order” response for the UXO and significantly reduce the pressure and impulse seen by marine life.

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Underwater UXO Neutralization, Explosively Generated Plasma, Unexploded Ordnance, UXO, EGP

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

Navy explosive ordnance disposal (EOD) technicians require environmentally acceptable remediation techniques for underwater ordnance disposal where unexploded ordnance (UXO) cannot be moved to the surface and rendered safe. The current protocol calls for a blow-in-place (BIP) procedure where an explosive charge is utilized to detonate the UXO in place, adding to the net explosive weight of the UXO. During a typical BIP procedure, the resulting shockwave and bubble formation/collapse from the detonation of the UXO and BIP charge introduces pressures and acoustic noise that is detrimental to marine life. Therefore, a method is needed that serves to neutralize the UXO with minimal environmental impact (no detonation). This effort demonstrated the phenomena of explosively-generated plasma (EGP) technology for the remediation of underwater UXOs. It was shown that a drastically smaller explosive charge could be used to initiate a “low order” response for the UXO and significantly reduce the pressure and impulse seen by marine life.

1.1 Background

EGPs are created by the focusing of a shock produced from an explosive donor via a conical waveguide. In the waveguide, the gases from the explosive, along with the trapped air, are accelerated and compressed (by Mach stemming) to such an extent that plasma is produced. These EGPs have been measured in controlled experiments to travel at velocities as high as 21,000 kilometers per second, with temperatures in the range of 10,000 – 20,000 Kelvin. Previous work at the Naval Surface Warfare Center Indian Head Explosive Ordnance Disposal Technology Division (NSWC IHEODTD) has demonstrated that EGPs impact on steel-cased explosive test items rapidly penetrate through the casing without fragmenting or deforming the case via a plasma ablation process (Reference 1). After penetration through the casing, the EGP couples with the high-explosive (HE) fill resulting in a high-temperature chemical decomposition along non-traditional kinetic pathways that results in rapid deflagration without detonation. Any remaining explosive is subject to non-reactive dispersion (pulverization) into a fine sand-like state. The introduction of an EGP-based technology with a sealed waveguide for the remediation of underwater UXOs would provide an innovative alternative to existing BIP operations with far less environmental impact. This technology provides the potential for rapid and near-complete consumption of the energetic fill without the associated shock and bubble formation/collapse from a detonating UXO. In addition, this technology has the potential to reduce the amount of donor charge by > 90% compared to shaped charges employed by standard BIP operations. Previous efforts have shown that the use of shaped charges to induce low order detonation events in underwater UXOs such as TNT-filled 155-millimeter projectiles and tritonal-filled MK 82 bombs can lead to a 99% reduction of explosive yield from the UXO (Reference 2). To validate the performance of EGPs as a remediation tool for underwater UXOs, testing and evaluation of donor size, waveguide configuration, and mounting location of typical underwater UXOs (i.e., 5-inch/38 caliber Naval gun rounds) must be conducted.

As an alternative to BIP operations, EGP technology proposes the following benefits to the Department of Defense (DoD): a deflagration-only response (“low order”) from the remediation of underwater UXOs including a significant reduction in donor charge compared to standard BIP operations; near complete consumption of the energetic fill; and reduced costs in the purchase of explosives and waste removal. EGP waveguides could be a print-on-demand addition to existing remediation demolition procedures that do not require new donor explosives to be employed.

The estimated cost of the waveguides is approximately $10 per item for 3-D printed items, and the anticipated reduction in cost of the explosive in the donor is 90% over that for explosive charges used in BIP procedures (by cost of C-4 per pound). The EGP process also has the potential to reduce permitting costs through the reduction in hazard level and safety arcs as well as associated environmental analysis and impact studies by removing the UXO detonation event.

1.2 Objective of the Demonstration

The experiment objective is to demonstrate the underwater EGP tool performance when fired against a Comp-A3 filled, WWII-era 5-inch/38 round in an underwater test area prior to transitioning to Joint Explosive Ordnance Disposal (JEOD) forces and civilian/humanitarian disposal groups.

1.3 Regulatory Drivers

- Operational Risk Management (ORM). OPNAVINST 3500.39C. Department of the Navy, Office of the Chief of Naval Operations. July 30, 2010. Available online at: http://safetycenter.navy.mil/instructions/ORM/3500_39B.pdf.
- Military Munitions Response Program Oversight. NOSSAINST 9 8020.15.D. April 18, 2013.
- Ammunition and Explosives Ashore: Safety Regulations for Handling, Storing, Production, Renovation, and Shipping. NAVSEA OP 5, Volume 1. Seventh Revision Change 13. April 15, 2014.

2.0 TECHNOLOGY

2.1 Technology Description

EGP devices direct and amplify explosive shock through a conical, converging transmission shock tube onto a target. Amplification of the shock pressure is accomplished by manipulating, through device design, a Mach stemming process that occurs naturally in the converging channel. By designing the appropriate geometry of the hot detonation gases interact with the Mach stems to increase pressure and temperature of the gases to the point where electrons are stripped from molecules and plasma is formed allowing temperatures to exceed 20,000 Kelvin (~2 eV) and gas/plasma transit velocity to approach 25 km/s. The EGP devices used in this effort were constructed of a 3-D printed ABS plastic. A C-4 donor charge was used to create the shock and detonation gases that translate the transmission tube and interrogate the target. The donor charge was initiated using a Risi RP-83 Exploding Bridgewire (EBW) detonator. Efforts in years 1 and 2 of this program determined the working range of donor charge sizes and EGP system dimensions through a combination of modeling and testing. In year 2, that design was optimized for the 5-inch/38 caliber round through surface testing and aquarium tank testing. Figure 1 is a drawing of the finalized EGP device that was employed.

Figure 1. EGP Underwater Design (Exploded View)

2.2 Advantages and Limitations of the Technology

This technology is a low-pressure, reduced-driver explosive means of burning-out to low ordering UXO. Alternative technologies employ shaped charges which either low-order or high-order the target or employ reactive material jets which often are limited in their casing penetration power. There are no other options which employ plasma as a means to both penetrate and burn-out UXO.

3.0 PERFORMANCE OBJECTIVES

Performance objectives are shown in Table 1.

Table 1. Performance Objectives

Performance Objective	Metric	Data Required	Success Criteria
Quantitative Performance Objectives			
Disrupt/remediate underwater 5”/38 cal. naval gun round	Reduced shock to water (Peak Pressure/Peak Impulse)	• Pressure (key data) • Acoustic noise (supporting data)	Reduction in Peak Pressure of at least 50% and Peak Impulse of at least 40% in water measured at gauges
Qualitative Performance Objectives			
Disrupt/remediate underwater 5”/38 cal. naval gun round	Reaction violence	• Videography	Cavitation-only response at surface, minimal plume
	Explosive consumption	• Post-event analysis	Intact casing, collectable large fragments, and/or minimal explosive in or around casing

Performance Objective	Metric	Data Required	Success Criteria
Ease of use		• Feedback from onsite EOD forces, retired EOD civilians, and UXO subject matter experts (SMEs) on usability of technology and time required	

3.1 Objective: Disrupt / Remediate Underwater 5-Inch / 38 Caliber Round

The effectiveness of the EGP technology will be determined by the live demonstration of the disruption/remediation of an underwater, 5-inch / 38 caliber naval gun round at various depths.

3.1.1. Metric

The EGP tool, when employed to disrupt/remediate an underwater UXO, must reduce the pressure input into the surrounding environment. Peak pressure and peak impulse are strong metrics of aquatic mammal, fish, and invertebrate "safety". Many experts accept that larger marine life has a safe peak pressure threshold of 20-25 psi and smaller marine life has a safe peak pressure threshold of 10-12 psi (Reference 3). Larger marine life (mammals) has a safe peak impulse threshold of 5 psi-ms, while smaller marine life (fish) has a peak impulse threshold range of 20-50 psi-ms (Reference 4). Reductions in peak pressure/peak impulse reduce the zone of influence in which marine life is affected by an energetic event, therefore, they are sufficient quantitative metrics.

3.1.2. Data Requirements

Pressure gauge data and hydrophone data at relevant depths to capture shock and shock noise at a distance from the event. In total, 20 – Comp-A3 filled 5-inch/38 rounds will be employed, with the initial three rounds being shot unfused underwater with C-4 packed fuse wells to established a blast pressure baseline. The remaining 17 will be tested with unarmed MK 403 Mechanical Time/Point-Detonating (MT/PD) fuses.

3.1.3. Success Criteria

Estimates using similitude relationships for explosives under water, which are good for a range of depths and salinities, predict that a high-order detonation of the 5-inch / 38 round at 100 feet and 200 feet will be ~236 psi / ~78 psi-ms and ~103 psi / ~41 psi-ms respectively. The EGP driver, under water (250g C-4) at 100 feet and 200 feet will be ~82 psi / ~34 psi-ms and ~36 psi / ~18 psi-ms respectively. This is an average reduction in peak pressure of 65% and peak impulse of 56%. As this is a prediction only and does not include any contribution from deflagration/low-order of the round, a conservative metric of 50% reduction in peak pressure, and 40% reduction in peak impulse was chosen. As a note, in air (above water) at 10 feet, the reduction in peak pressure was ~77%.

4.0 SITE DESCRIPTION

4.1 Site Selection

The site chosen for the EGP demonstration was the Lake Glendora Test Facility (Figure 2). It features three underwater test ranges suitable to test live 5-inch/38 caliber rounds at an array of depths. It is the optimum place to test smaller UXO remediation tools due to the explosive limits, onsite test support equipment, and cost to the project.

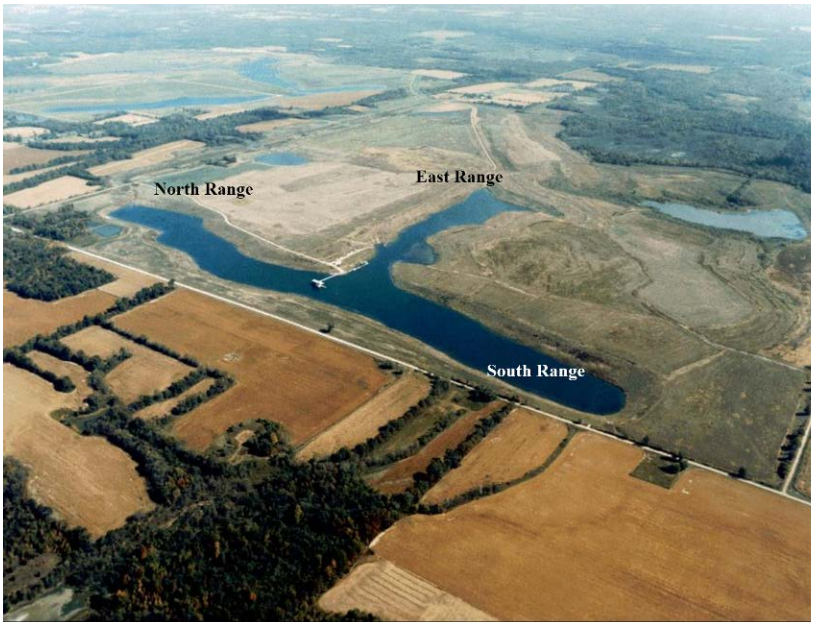

Figure 2. Lake Glendora Test Facility

4.2 Site History

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.

4.3 Site Geology

The relevant information is that the depth profile is such that testing can be undertaken down to 100 feet on the North Range, and can test up to 100 pounds' net explosive weight of hazard class 1.1 cased explosives underwater.

5.0 TEST DESIGN

5.1 Conceptual Experimental Design

The purpose of this experimental demonstration of the EGP tool was to collect performance data (underwater pressure results) and qualitative data (casing damage, effect on fuze/booster, and explosive fill remaining after EGP attack, etc.). The singular element of this demonstration was to determine if the EGP tool can reliably deflagrate/low-order a common underwater UXO, the 5-inch/38 caliber gun round.

The demonstration was conducted during 1 week of onsite testing at the Lake Glendora Test Facility near Crane, Indiana. There were no planned programmatic or technical decisions points that occurred during the testing.

Lake Glendora Testing GANTT Chart	FY19 – Q3 – APR 22-26	
	Mon	Tues - Friday
Baseline Shots		
EGP Device - Live Round Shots		

5.2 Site Preparation

A catch net was installed order to collect remnants of the tested UXO including pieces of the steel casing and any large chunks of explosive material. The net was designed to be lowered to depth using electric hoists. During the test series, the net was lowered 20 feet below the test item in all tests. Figure 3 shows a picture of the catch net and electric hoists at the four corners of the net.

Figure 3. Catch Net and Electric Hoists

5.3 System Specification: EGP 5-Inch / 38 Caliber Remediation Device Prototype

The dimensions of the EGP tool to be used in this assessment are listed in Table 2. Small scale testing showed this configuration to be capable of remediating 5-inch/38 caliber rounds at the surface and underwater in aquarium tanks. Three charge masses are described (188, 219, and 250 grams) as modeling and test results from year 2 effort have demonstrated a range of explosive driver weight that could remediate the 5-inch/38 caliber round.

Table 2. EGP Tool Configuration

Device	Description	Image
ESTCP - EGP Cone for 5”/38s	Charge Mass: 188 grams Charge Diameter: 1.82 inches Charge Height: 2.73 inches Cone Height: 2.60 inches Cone Angle: 16.25˚ Charge to Tip Diameter Ratio: 6 Charge Mass: 219 grams Charge Diameter: 1.91 inches Charge Height: 2.87 inches Cone Height: 2.74 inches Cone Angle: 16.25˚ Charge to Tip Diameter Ratio: 6 Charge Mass: 250 grams Charge Diameter: 2.00 inches Charge Height: 3.00 inches Cone Height: 2.86 inches Cone Angle: 16.25˚ Charge to Tip Diameter Ratio: 6	

5.4 UXO Test Target: Comp A-3 Filled MK 51, 5-Inch/38 Caliber HE (MT/PD)

The MK 51, 5-inch/38 projectile (Figure 4) consists of a 45.3 pound steel casing filled with 7.7 pounds of Comp-A3 (91% RDX, 9% wax). The projectile uses the MK 403 MT/PD fuse, which contains Tetryl in the primer and booster charges. The projectile uses a MK 51 steel body.

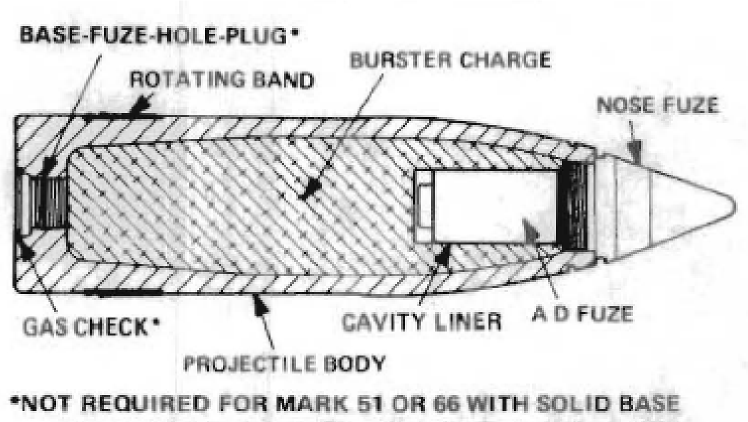

Figure 4. MK 51, 5-Inch/38 Round

The MT/PD configuration uses the MK 51 body and therefore has a solid base.

5.5 Sampling Procedures and Run Order

A total of 24 tests were conducted underwater against 5-inch/38 caliber rounds. In all tests, the EGP device was placed at the thinnest point on the casing, centered approximately 8 inches from the base.

5.6 INSTRUMENTATION

The following instrumentation was used during this assessment

- “Go Pro” Digital Camera
- Submersible Pressure Probes
- Hydro Phones
- Tape Measure

Pressure sensors were arranged using the configuration in Figure 5 for each of the EGP tests.

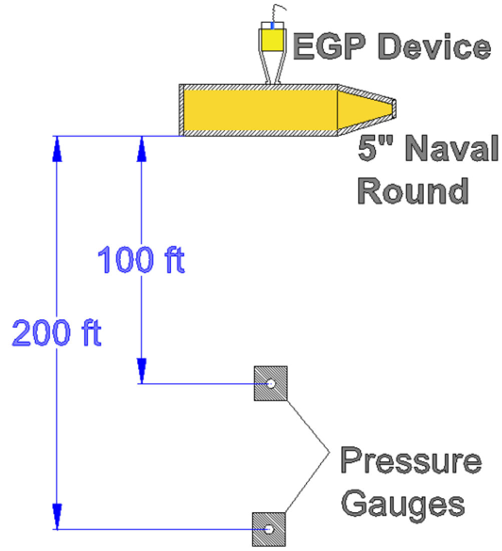

Figure 5. Pressure Probe Configuration for EGP Tests

The critical instrumentation used in this series was the underwater PCB Piezotronics pressure probes. Details of the probes are included in Appendix D, to include their National Institute of Standards & Technology (NIST) traceable calibration details to both International Organization for Standardization (ISO) and American National Standards Institute (ANSI) standards. They were chosen because of their prior use in underwater testing at NSWC Crane, and because they are able to respond to large pressure changes (1000 psi and 5000 psi) favorably (< 1.5 microsecond rise time) with excellent uncertainty (+/- 3% for both probes) and linearity (0.7% FS via least squared fitting for 1000 psi probe) in measurement.

A hydrophone at 200 feet was also fielded in order to compare the recorded data to that taken by the PCB underwater pressure gauges. Details on the hydrophone are also included in Appendix D.

5.7 Experimental Procedures

General safety precautions and procedures are covered in the Lake Glendora Stand Operating Procedure (SOP). The 5-inch/38 caliber rounds were delivered and tested fused. The test day procedures followed in this series are shown in Table 3.

Table 3. Test Day Procedures

Configuration	Description
5-inch/38 MT/PD (Baseline)	• Pack fuse well of unfused test rounds with C-4 • Transport the round to the test area • Attach lowering bridle • Insert blasting cap/detonator/det cord • Ensure blast pressure probes lowered to appropriate depth • Lower test round with divers ensuring test round is lowered to appropriate depth orientating charge to a 12 o'clock position • Recover divers and return to a safe area and fire per the Lake Glendora SOP • Download and catalog blast pressure and acoustic results
5-inch/38 MT/PD (EGP)	• Weigh C-4, pack the charge cylinder with C-4. Poke a ¼ inch deep cap well through the small hole on the back side of the charge • Weigh the charge • Waterproof charge using flex seal tape around charge cylinder and waveguide junction • Place a mark on the target body, centered 8 inches from the base *Note: If mounting with tape, place the assembly over the marking and tightly tape around the edges of the mounting* • Transport the round to the test area • Attach lowering bridle • If mounting with epoxy underwater, have divers descend to 10 feet underwater with test round and EGP charge. Apply a layer of epoxy to the bottom of the mount and then firmly press the assembly over the marking, holding for ~30 seconds • Insert blasting cap/detonator/det cord • Divers will ensure catch frame lowered to 5 feet below test depth • Divers will ensure blast pressure probes lowered to appropriate depth • Lower test round with divers ensuring test round is lowered to appropriate depth orientating charge to a 12 o'clock position

Configuration	Description
	• Recover divers and return to a safe area and fire per the Lake Glendora SOP • Retrieve catch frame • Collect, catalog, and photograph results

6.0 RESULTS

6.1 Baseline Tests

Calibration tests were conducted to establish a baseline for tests involving the EGP remediation tool (Figure 6). In the calibration tests, the Naval 5-inch/38 round was intentionally detonated by placing a detonator directly on the booster. Three baseline tests were conducted at a depth of 20 feet. The 20 foot depth was chosen as a common depth for UXO remediation efforts at military training grounds. A 140g charge of C-4 was used to initiate the booster in the 5-inch round. Figure 6 is a picture of the charge prior to lowering it to depth.

Figure 6. Naval 5-Inch/38 Round Prior to Baseline Testing

Pressure was measured at the same depth as the charge at a distance of 150 feet and 200 feet. The test range required an increased standoff for the baseline (high order) tests between the test round and the test structure (barge). Pressure gauges in the baseline tests were positioned at 150ft and 250ft. Underwater scaling relations were calibrated to the baseline data and used to calculate the peak pressure and impulse at the gauge standoffs used in the EGP tests (100ft and 200ft from the charge). In Figure 7, the 150 foot data is presented, and provides a better estimate of released energy due to less rarefaction occurring. Due to rarefactions from the surface of the water, the pressure and impulse drops off about 1.2 ms after the initial shock front reaches the gauge. For this reason, an estimated total impulse, assuming no surface effects, for the waveform is calculated using scaling relations and shown in Table 4; discussed in greater detail later in the report. A measured peak pressure of approximately 130 psi and 0.045 psi-s was recorded in the baseline tests.

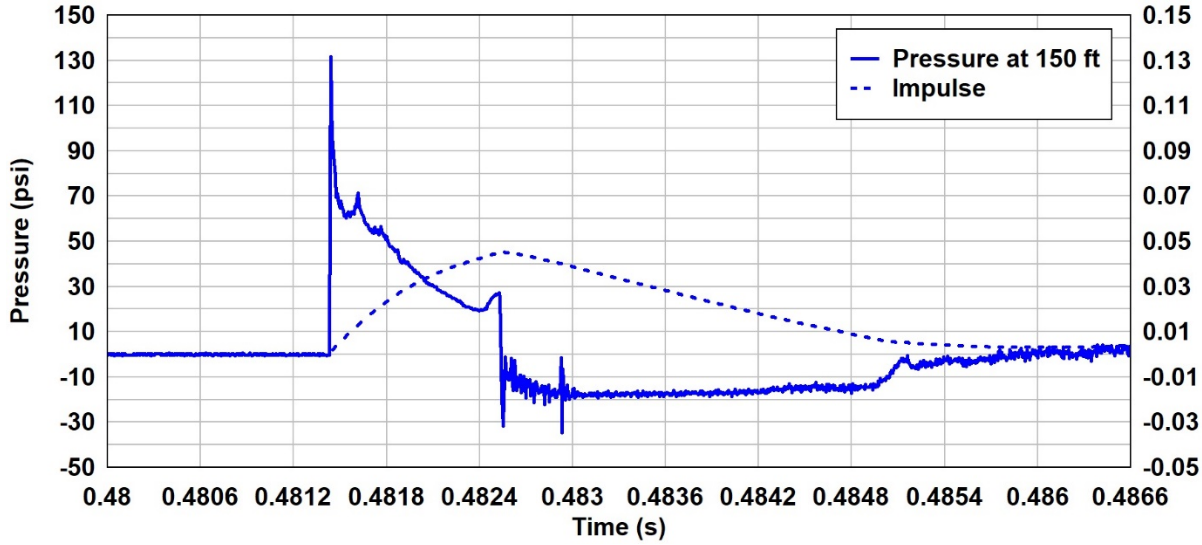

Figure 7. Baseline Pressure and Impulse Recorded at 150 Foot Standoff and 20 Foot Depth

The energy spectral density of the baseline shots was numerically derived from pressure-time data using a method described in Appendix E. Peak energy flux and the frequency of the peak are summarized later in the report in Table 6. Since the hydrophones saturated during the baselines, only the tourmaline gauge (underwater pressure gauge) data was analyzed. Figure 8 presents one of the baseline shots. As a point of comparison, energy spectral density was calculated using an analytical method (also described in Appendix E) from (Reference 5) combined with similitude relations from (Reference 6). Pulse energy was found to have a broadband distribution, with approximately 90% of the energy contained in the 100-1000 Hz band. Contrary to theory (Reference 5) and old experimental data (Reference 6), peak energy flux did not occur at the bubble pulse frequency (i.e., the inverse of the first bubble period), suggesting it was shifted forward by surface cut-off. The analytical method was found to agree qualitatively with the data, matching especially well in the 100-1000 Hz band. Divergence was observed at both very low frequencies and very high frequencies. Attempts to address to address these divergences are discussed in Appendix E.

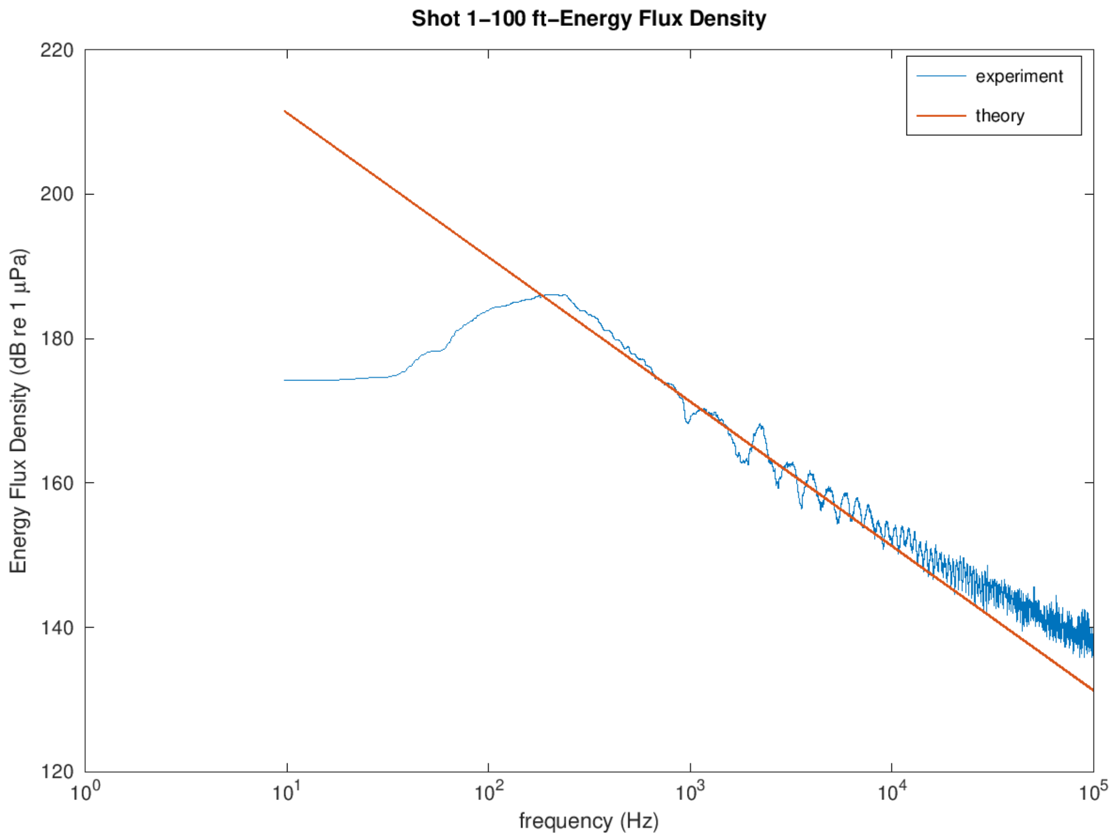

Figure 8. Energy Flux Density Spectra for Baseline Shot

6.2 EGP Tests

The majority of the tests conducted with EGP tools resulted in missed data points due to water leaking into the conical section of the EGP device. Although efforts were taken to pressure test these devices prior to this demonstration series, water seal failures quickly became a major issue at the Lake Glendora Test Range. These are discussed in Sections 6.3 and 6.4.

The typical EGP tests setup used a single EGP device attached to the side of the Naval 5-inch/38 caliber round, 8 inches from the base of the round. The EGP tool is attached using both 5-minute epoxy and tape. The device can be attached using any method that maintains intimate contact between the tip of the cone and the target UXO. Figure 9 shows the EGP device attached to the round prior to being lowered to depth.

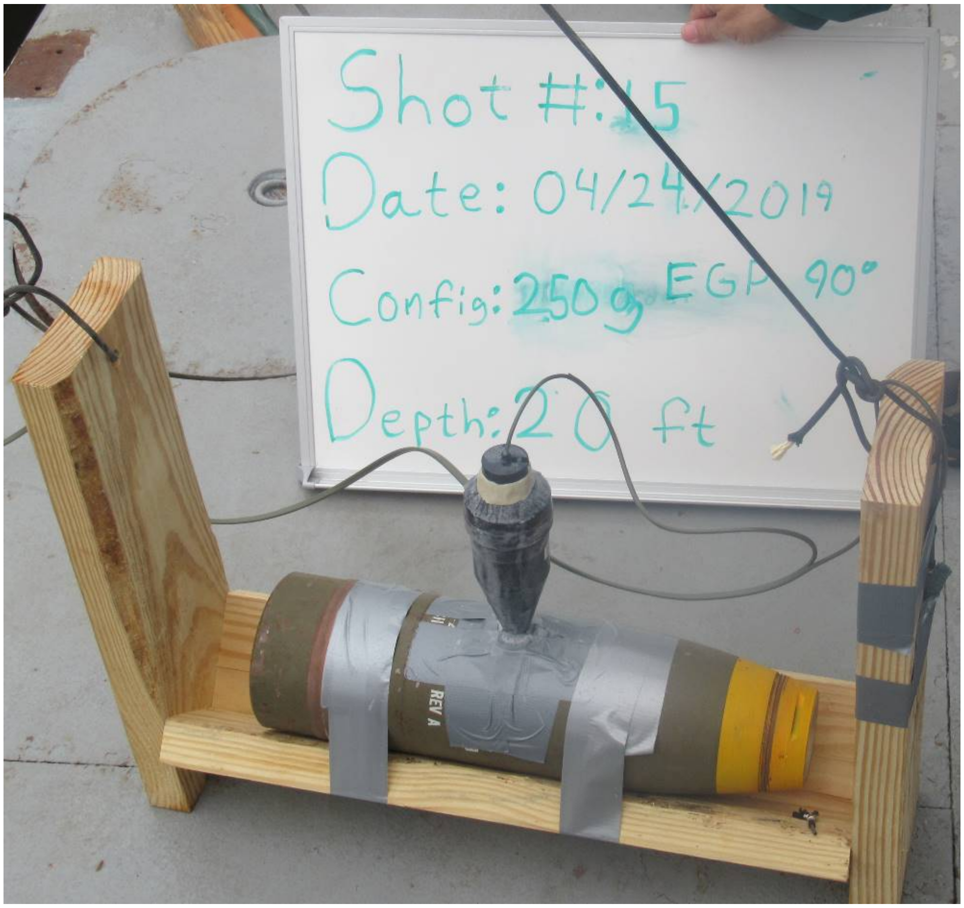

Figure 9. EGP Device Attached to Naval 5-Inch Round

In some of the tests, we were able to successfully able to keep water out of the EGP tools by incorporating many layers of glues, putty's, tape, and spray sealants. These tests resulted in either a "low-order" response or a response in which the fuse was ejected from the round. It is assumed that an ejected fuse scenario (instead of a "low-order" response) is a result of decreased performance due to a small amount of water seepage into the cone of the tool. Figure 10 shows an ejected fuse and the 1-inch diameter hole in the munition generated by the EGP device. The diameter of the hole generated by the EGP tool is consistent between tests and allows for venting is certain slow burn scenarios on land.

Figure 10. Ejected Fuze and Naval 5-Inch Round

Low order responses were obtained using the 250-gram EGP variant. Here the test item was broken into many pieces. The explosive fill was partially consumed by the EGP device. Approximately 50% of the explosive fill was recovered using the catch net below the charge. The steel casing was broken into large strips denoting a low order reaction. The booster material appears to have been completely consumed and all components of the UXO are readily accessible following this type of response. Figure 11 shows the pieces of the Naval 5-inch/38 caliber round following testing.

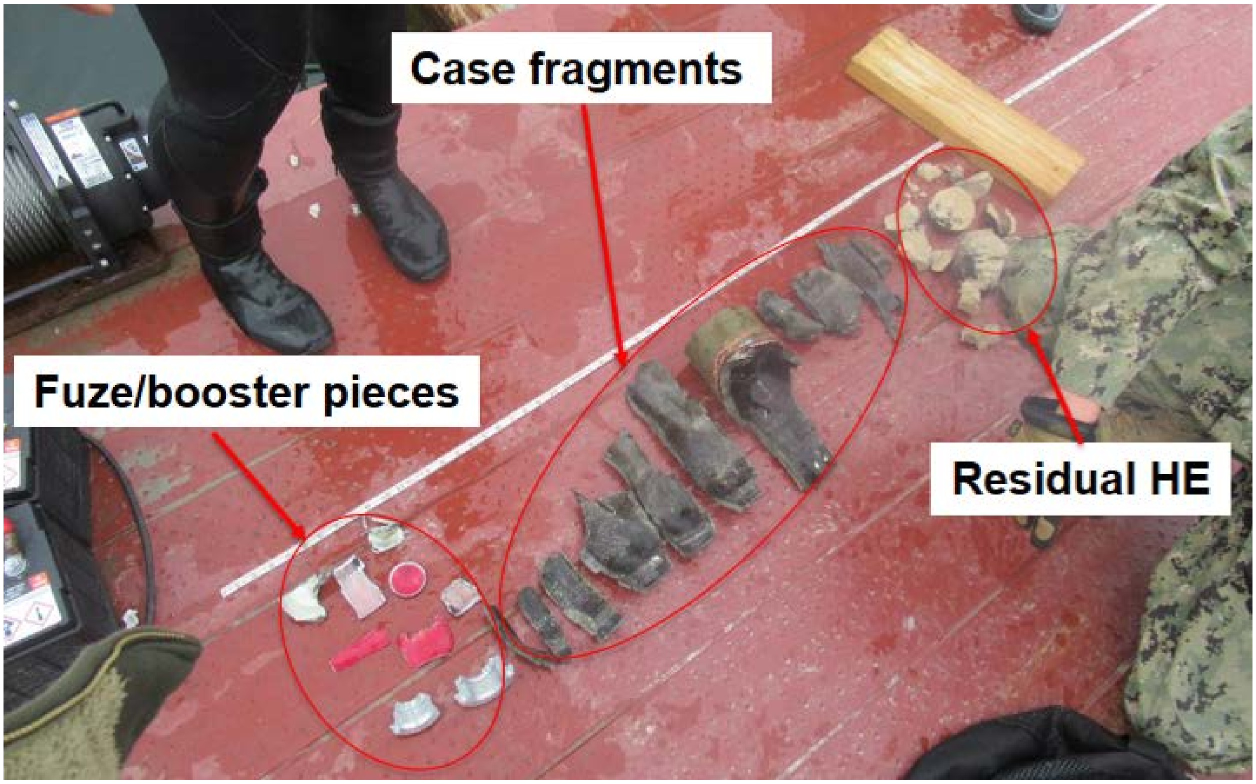

Figure 11. UXO Components Following Low Order Reaction

For the above low order test, the measured pressure at the 100-foot gauge location was reduced by 72% when compared to the baseline experiments. The calculated impulse (assuming no surface reflection) is reduced by 78%. Figure 12 shows the recorded pressure and impulse from the EGP test. Table 4 shows some important measured peak pressures and calculated impulses at 100 feet and 200 feet from the charge.

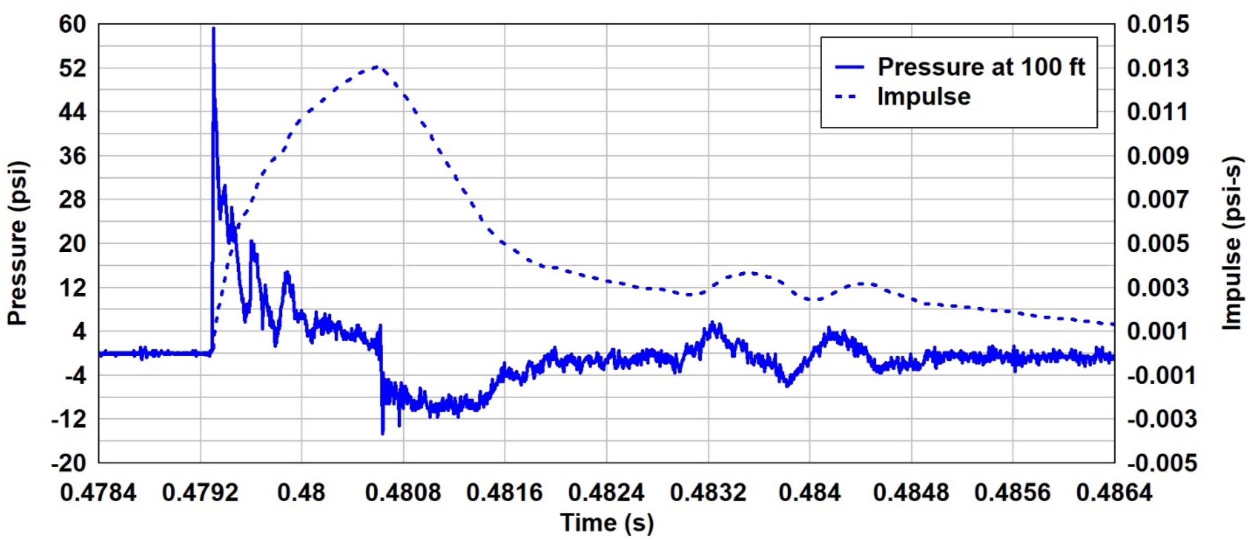

Figure 12. Recorded Pressure and Impulse in EGP Low Order Event

Table 4. Peak Pressure and Impulse from Shots

Experiment	Depth (ft)	Observed Result	Measured Peak Pressure at 100 ft (psi)	Calculated Impulse at 100 ft (psi-s)	Measured Peak Pressure at 200 ft (psi)	Calculated Impulse at 200 ft (psi-s)
Baseline	20	High Order Response	213.99	0.076	93.4	0.04
250g EGP	50	Ejected Fuse	80.67	0.0158	47.33	0.0134
250g EGP	20	Low Order Response	59.32	0.0096	22.07	0.0039
Percentage Reduction*			72.3%	87.4%	76.4%	90.3%
Criteria Success – Section 3.1.3			✓	✓	✓	✓

*Reduction percentages are a comparison of the 20ft depth high order baseline experiment to the 20ft depth low order EGP experiment.

Animal impact assessments were performed using data collected in the SEAWOLF (Reference 9) and Kilma et al (Reference 10) assessments. The assessments outline the impact reduction for 12.2kg dolphin calves and both “small” and “large” sea turtles. Figures 12 and 13 provide a visual arc for the Animal impact assessments were performed using data collected in the SEAWOLF FEIS (Reference 9) and Kilma et al (Reference 10) assessments. The assessments outline the impact reduction for 12.2kg dolphin calves and both “small” and “large” sea turtles. The assessments were generated by scaling the data from the high order baseline experiment and the low order EGP experiments and calculating the standoff distances at which the thresholds occur for dolphin calves and sea turtles. shows the Radial Arcs for projected impacts to a Dolphin Calf (12.2 kg) due to high order round (Left) and EGP low order (Right). Eardrum rupture pressure (pink), 1% impulse mortality (green), 50% impulse mortality (blue), and lethal pressure (red) as indicated.

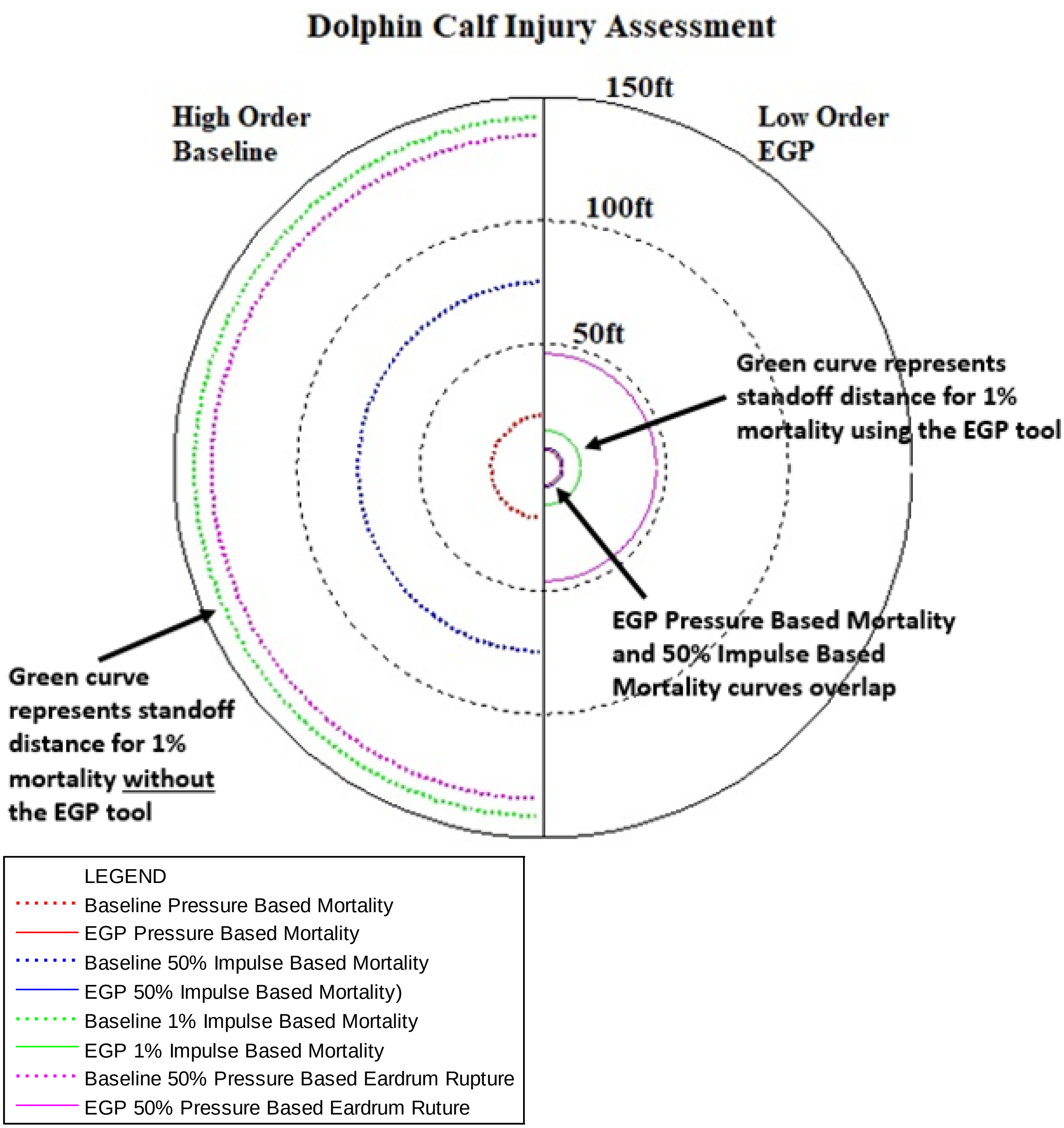

Figure 13. Radial Arcs for Projected Impacts to Dolphin Calf

Figure 13 shows the Radial Arcs for projected impacts to a small and large Sea Turtles due to high order round (Left) and EGP low order (Right). Safe arcs for small (pink) and large (green) and 50% Mortality for small (blue) and large (red) turtles; presented for both baseline and EGP responses.

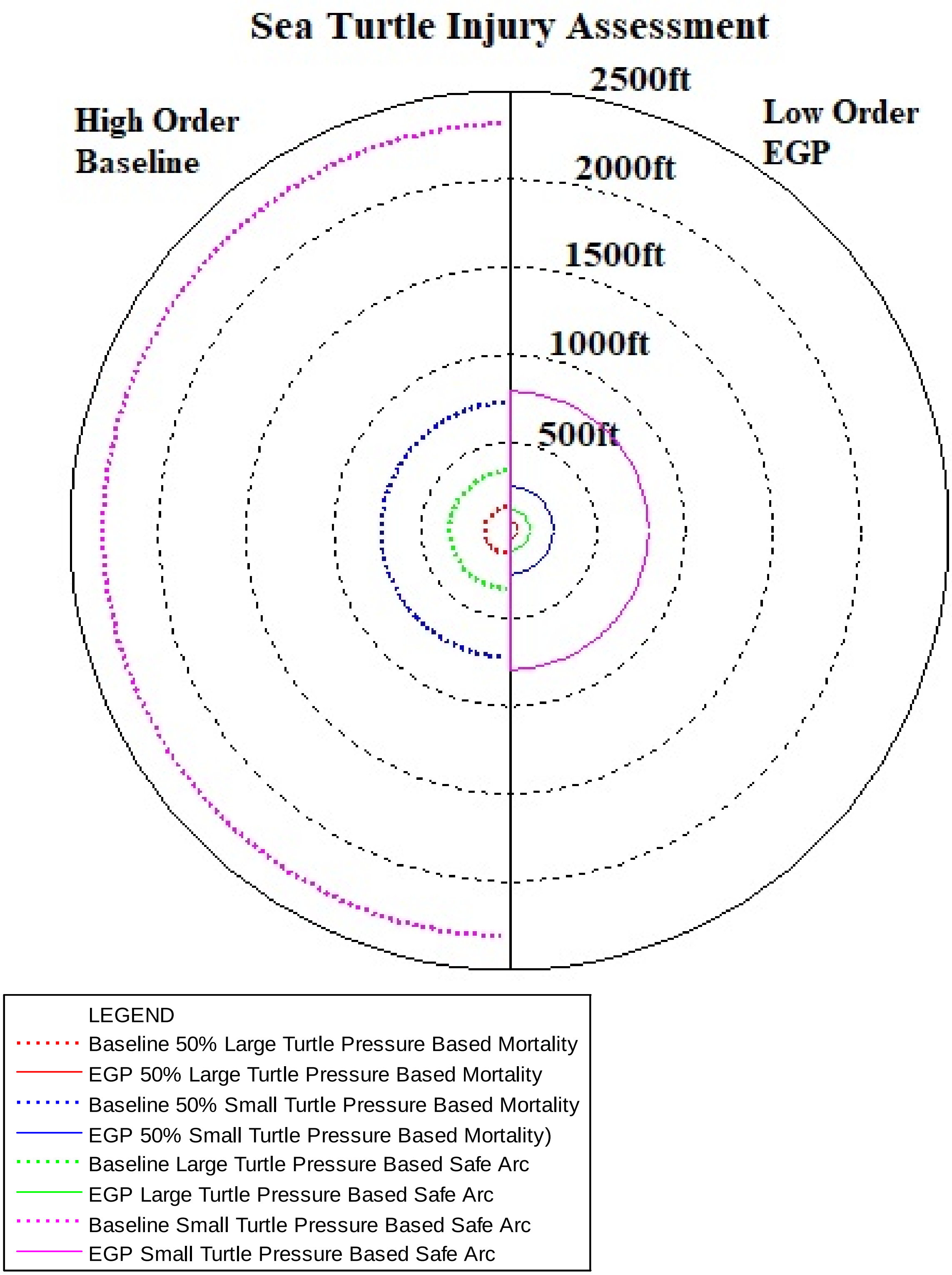

Figure 14. Radial Arcs for Projected Impacts to Small and Large Sea Turtles

Table 5 outlines the arc radii (seen visually in the above figures) for each case. Reference data from the animal studies is also given. It is important to note that although the average reduction in standoff is 71% when using the EGP tool to cause a low order event, the average reduction in affected water volume (and reduction in affected dense populations) is 97.5%.

Table 5. Summary of Pressure / Impulse Safety Thresholds & Radial Distances for Baseline and EGP Shots

Assessment	Reference Value	High Order Baseline Experiment (ft)	Low Order EGP Experiment (ft)	Percent Reduction in Standoff Distance
Dolphin Calf				
Pressure Based Mortality	1400psi*	20.8	7.1	**66%**
50% Impulse Based Mortality	99.5psi-ms*	74.9	8.1	**89%**
1% Impulse Based Mortality	55.1psi-ms*	141.7	15.3	**84%**
50% Eardrum Rupture	150psi***	134.6	46.0	**66%**
Sea Turtle				
Large Turtle 50% Pressure Based Mortality	150psi**	134.6	46.0	**66%**
Small Turtle 50% Pressure Based Mortality	20psi**	725.6	248.2	**66%**
Large Turtle Pressure Based Safe Arc	50psi**	337.2	115.4	**66%**
Small Turtle Pressure Based Safe Arc	5psi**	2312.4	791.0	**66%**
Average Reduction in Standoff				**71%**
Average Reduction in a Spherical Volume Impacted				**97.5%**

*Data collected by SEAWOLF FEIS [16]
**Data collected by Kilma et al [17]
***Data collected by CHURCHILL draft FEIS

Spectral energy density was calculated using the same methods as the baseline data and presented in Figure 15. While looking through the data, it was discovered that no hydrophone data had been recorded for the EGP shots. Discussions with test personnel revealed that they had removed the hydrophones after the issues observed during the baselines. That being said, the effects of ambient underwater noise can distort a hydrophone's recording of an explosive pulse. The records produced by the tourmaline gauges are likely more accurate and therefore a better choice for analysis (Reference 7). Like the baseline shots, the majority of the energy was within the 100-1000 Hz band. The overall magnitude was 5-10 dB below that seen in the baselines. Compared with the baselines, the EGP shots had a greater portion of their energy distributed at high (>1000 Hz) frequencies. This effect appears to be due to charge weight rather than the EGP device itself (Reference 8). Like the baselines, the peak energy flux frequency appears to have been shifted forward by surface cut-off.

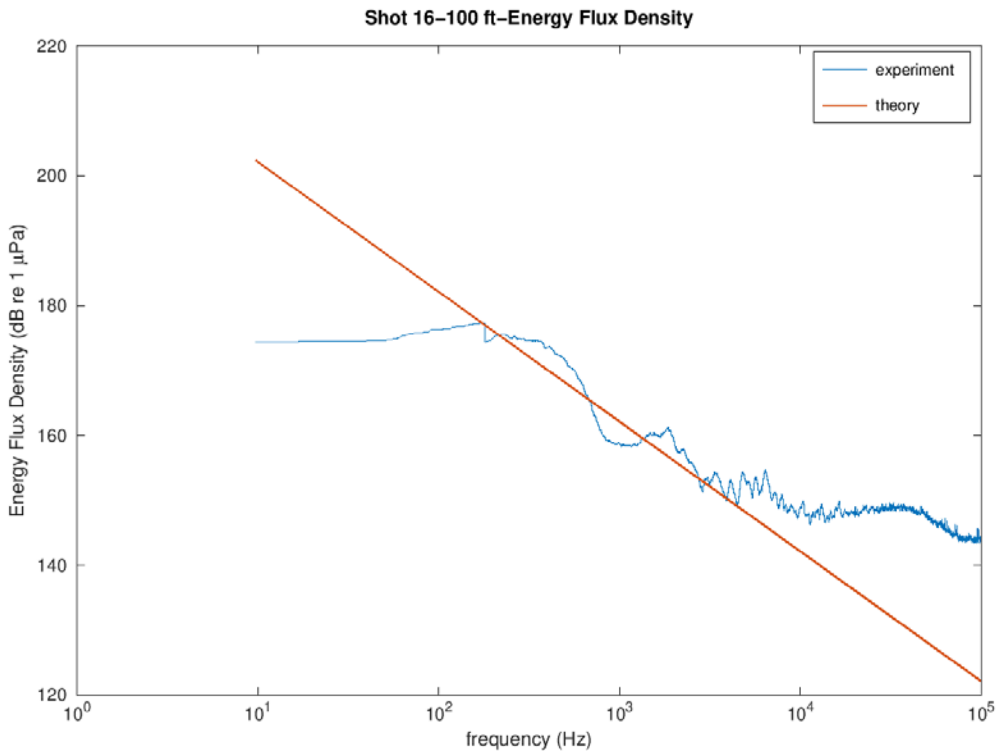

Figure 15. Energy Flux Density Spectra for Low Order Shot

Table 6 outlines the peak energy flux and the frequency of the peak flux seen in the baseline (20 foot depth), EPG ejected fuse (50 foot depth), and EGP low order (20 foot depth) tests.

Table 6. Peak Energy Flux and Frequency of Peak Flux

Experiment	Response	Peak Energy Flux (dB re 1 μPa)	Frequency of Peak Flux (Hz)	Percent Reduction from Baseline
Baseline	High Order	186.11	238	N/A
250g EGP	Ejected Fuze	177.39	179.75	86%
250g EGP	Low Order	181.38	179.75	66%

6.3 Challenges / Lessons Learned

In the majority of the tests performed, water was able to penetrate into the EGP transmission tube (cone) which resulted in severely reduced penetration of the steel casing of the Naval 5-inch round. Modeling efforts in CTH have shown that even a small amount of water in the cone of the EGP device will cause the device not to perforate the steel case of the munition. Figure 16 shows the modeled EGP Case Penetration at 43µs with and without 1 inch of water in the device.

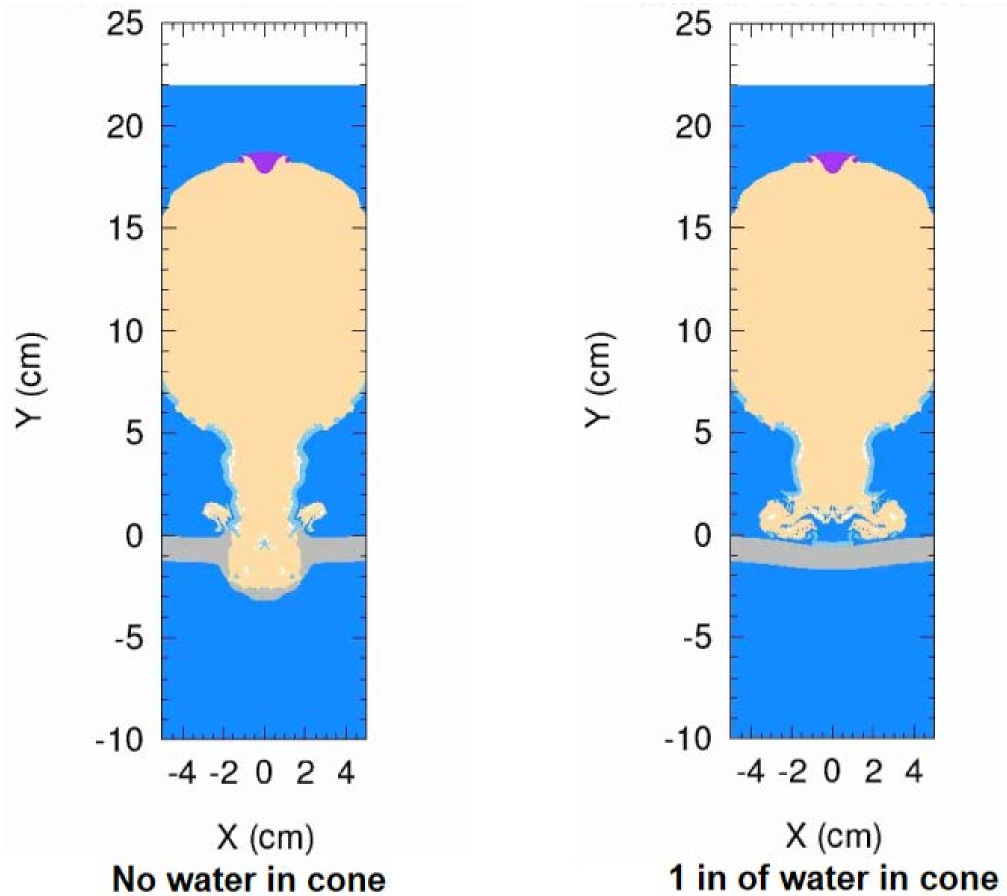

Figure 16. Modeled EGP Case Penetration

Several of the early EPG tests conducted failed to penetrate the casing of the Naval 5 inch/38 rounds. Figure 17 shows one case in which penetration was not achieved.

Figure 17. Poor Case Penetration

These models, along with test results from Lake Glendora, demonstrate that waterproof seals are a critical component of underwater EGP design.

In one experiment, an EGP device was assembled and lowered to a depth of 20 feet for 10 minutes. The device was then brought back to the surface and disassembled to find over an inch of water in the conical section (Figure 18).

Figure 18. Water Inside EGP Device after Submersion

Although operational challenges still need to be addressed, the developed EGP tool has proven capable of meeting the pressure and impulse reduction requirements outlined in Section 3.1.3. The reduction in standoff for animal life that can be achieved compared to traditional BIP procedures is significant. The tool provides an inexpensive means of drastically reducing standoff distances in instances when underwater ordnance cannot me safely moved and remediated elsewhere.

7.0 VALIDATION TEST PROPOSAL

7.1 EGP Tool Design Changes

NSWC IHEODTD has contacted Edward Braithwaite at NRL and Peter Traykovski at Woods Hole Oceanographic Institution with regard to improving waterproofing of the current tool design. A new tool design has been drafted with several safeguards to prevent water from entering the system.

A new series of pressure pot testing was conducted on the old EGP tool design. Testing showed the cause of previous water leakage to be the threading between the charge and the waveguide. Based on this, the device was re-engineered to incorporate tighter tolerancing (at the limit of what the 3-D printers are reasonably capable of) and triple o-rings coated with grease.

As an added precaution, the cap well was also sealed off by adding a layer of plastic between the detonator and the main driving charge of the EGP. To ensure this would not affect initiation, both simulations and small scale testing were performed to determine the maximum allowable barrier thickness. New hardware was added to the device to allow the placement of a booster charge to ensure 100% reliability.

Finally, the wall thickness at the end of the EGP tool where it meet the UXO has been increased. This will ensure that the water cannot penetrate the 3-D printed plastic at its thinnest location.

Stripped down test assets (lacking the cone and external hardware for mounting, cap placement, etc.) have been produced and successfully leak tested at 100 feet for 4 hours. Full systems will be constructed and pressure pot tested shortly. Figure 19 shows these system improvements.

Figure 19. Updated Waterproof EGP Device Design

7.2 Leak Testing (Pressure Pot Testing)

Once discussions are complete with Mr. Braithwaite and Mr. Traykovski, 10 copies of the modified design will be printed and leak tested (pressure pot) to a depth of 100ft for four hours. The tools will be tested at two (2) temperatures; room temperature (~20°C) and near freezing (ice will be added to the pressure pot). If 10 out of 10 devices pass leak testing, at both temperatures, the new design will be ready for testing at Lake Glendora against the Naval 5-inch round.

7.3 Validation Testing Against Naval 5-Inch Round

Testing against the Naval 5-inch round will be conducted at Lake Glendora. The test setup will be similar to that used in the last series (shown in Figures 3 and 5). Although leak testing will be performed prior to arriving at Lake Glendora, the first tests performed on-site will be to verify that water is no longer penetrating the EGP tool. A weighted tool will be lowered to various depths for an interval of 20 minutes, brought back to the surface, and examined to see if any water found its way into the inside of the cone. This exercise will be performed at each depth that the tool will be tested, plus the maximum depth of the facility at the test location (~100 feet).

Following the onsite leak testing, baseline tests will once again be performed. These tests will be performed at each depth that the EGP tool performance will be evaluated. The location of the underwater pressure transducers will be at the same standoff from the charge in the baseline tests as in tests where the EGP tool is used. In these tests, no EGP tool will be fielded. The Naval 5-inch round will be initiated using a 140g charge of C-4 on the booster of the munition.

At least three (3) tests with the EGP tool will be performed at each depth. The size of the EGP device may be varied (if necessary) as in the last test series. The EGP explosive driver weights used in the last test series are shown in Table 2. The explosive drivers used in the proposed test series will be similar to that used in the last test series. If an EGP fails to produce a satisfactory response, the size of the explosive driver may be varied. Successful tests will be repeated three times at each depth. Three successful tests will be performed at the 20 foot depth before moving on to the 50 foot depth. Success of an EGP test is gauged by:

1) Not causing a high order reaction of the Naval 5-inch round
    a. Determined from both pressure gauge records and case fragment size.
2) Consuming a large (measured) quantity of the explosive fill in the munition.
3) Breaking the case of the munition into multiple pieces and exposing the energetic for easy disposal.
4) Causing enough overpressure in the munition to eject the fuse of the device.

Table 7 shows the proposed test matrix that will be followed at the Lake Glendora test range.

Table 7. Proposed Lake Glendora Test Matrix

Test Number	Test Type	Depth (ft)
1	Leak Test 1	20
2	Leak Test 2	50
3	Leak Test 3	80
4	Leak Test 4	Range Depth (~100)
5	Baseline Test 1	20
6	Baseline Test 2	50
7	Baseline Test 3	80
8	EGP Test 1	20
9	EGP Test 2	20
10	EGP Test 3	20
11	EGP Test 4	50
12	EGP Test 6	50
13	EGP Test 7	50
14	EGP Test 8	80
15	EGP Test 9	80
16	EGP Test 10	80

7.4 Go/No-Go Criteria

Table 8 outlines the testing that will be conducted in the proposed effort along with Go/No-Go criteria for each test.

Table 8. Go/No-Go Criteria

Line	Task	Location	Criteria	No-Go
1	Design and build 10 EGP tools	Indian Head		
2	Conduct pressure pot testing of 10 devices at ambient temp	Indian Head	Dry cone interior	Go to 1
3	Conduct pressure pot testing of 10 devices at near freezing	Indian Head	Dry cone interior	Go to 1
4	Conduct baseline testing at 20, 50, 80 foot depths	Crane	Measure pressure at 100 and 200 ft	Cancel testing until results can be achieved
5	Conduct 3 EGP tests at 20 foot depth	Crane	Obtain successful response as outlined in Section 7.3	Change EGP size and repeat step
6	Conduct 3 EGP tests at 50 foot depths	Crane	Obtain successful response as outlined in Section 7.3	Change EGP size and repeat step
7	Conduct 3 EGP tests at 80 foot depths	Crane	Obtain successful response as outlined in Section 7.3	Change EGP size and repeat step

7.5 Validation Test Cost

Table 9 outlines the efforts and cost associated with additional validation testing at Lake Glendora.

Table 9. Validation Test Cost

Task	Cost
Revamp CAD drawings and 3-D print 10 EGP tools	$32k
Conduct pressure pot testing of 10 EGP tools	$41k
3-D print required assets for off-site testing and obtain Naval 5" rounds	$44k
Write test plan and Indian Head Time and Travel to conduct testing at Crane (Lake Glendora)	$42k
NSWC Crane cost for 1 week of testing	$65k
Write Final Report with finalized CAD drawings	$56k
Total	**$280k**

8.0 EGP TOOL COST ASSESSMENT

The EGP 5-inch/38 caliber remediation prototype is a 3-D print-on-demand prototype tool. The 3-D print-on-demand concept is ideal for two reasons. First, the tool can be acquired and used inexpensively in most areas of the world in small quantities (without having to procure large orders to realize cost savings). Secondly, the tool can be tailored easily to different UXO remediation scenarios. Different munitions, with varying case thicknesses and explosive fills, will require slightly modified variants of the EGP tool in-order to realize the desired response (be it "low-order" or even slower deflagration responses). As data is compiled with different munitions, different EGP variants can be inexpensively tested and utilized if the tool is 3-D printable.

The estimated cost of the tool is approximately $10 per item for 3-D printed items, and the anticipated reduction in cost of the explosive in the donor is 90% over that for explosive charges used in BIP procedures (by cost of C-4 per pound). The demonstration will refine these estimates and provide a final assessed cost. Cost elements follow in Table 10.

Table 10. Cost Assessment

Cost Element	Data to be Tracked
Device Cost	Per device cost in $/device • Derived from 3-D printer feedstock consumed and shop time expended in printing a single prototype device for demo
Explosive Driver Cost	Cost of C-4 in $/pound • Derived from material cost at time of demo

9.0 MANAGEMENT AND STAFFING

Name	Roles	Code	Phone Extension
George Torres* NSWC IHEODTD	Demo Test Director	D27	(301) 744-5183
Thomas Douglas* NSWC IHEODTD	Principle Investigator	D22	(301) 744-5159
Samuel Emery* NSWC IHEODTD	Co-Principle Investigator	R12	(301) 744-4166
Daniel McCarthy* NSWC IHEODTD	Project Engineer/Data Recorder	D26	(301) 744-5075
Paul Giannuzzi* NSWC IHEODTD	Project Engineer/Pressure Probe Operation	R12	(301) 744-4866
Dennis Cecil* NSWC Crane	Lake Glendora Test Facility Director & RSO/Range Support	JXRN	(812) 268-5992 X 225
Tom Laughlin* NSWC Crane	Instrumentation Support/Pressure Probe Operation	JXRR	(812) 268-5992 X 228

NSWC Crane* JXRN Personnel	Explosive Handler/Range Support	JXRN	(812) 268-5992 X 225
Ronny Lawson* NEDU	NEDU Diver Support	O2	(850) 230-3165
NAVEODFLTLAU Rep NSWC IHEODTD	Navy EOD Liaison / Service Rep	FLTLAU	301-744-6828
Marine EOD Det Rep NSWC IHEOTD	USMC EOD Liaison / Service Rep	MCD	301-744-6814

*POCs for Demonstration testing

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APPENDIX A. LIST OF ACRONYMS

Acronym	Description
ANSI	American National Standards Institute
BIP	Blow-In-Place
DoD	Department of Defense
DODAC	Department of Defense Ammunition Code
EBW	Exploding Bridgewire
EGP	Explosively-Generated Plasma
EOD	Explosive Ordnance Disposal
HASP	Health and Safety Plan
HE	High-Explosive
ISO	International Organization for Standardization
JEOD	Joint EOD
MT/PD	Mechanical Time/Point-Detonating
NALC	Navy Ammunitions Logistics Code
NEDU	Navy Experimental Diving Unit
NIST	National Institute of Standards & Technology
NSN	National Stock Number
NSWC IHEODTD	Naval Surface Warfare Center Indian Head EOD Technology Division
ORM	Operational Risk Management
PN	Part Number
SME	Subject Matter Expert
SOP	Standard Operating Procedure
UXO	Unexploded Ordnance

APPENDIX B. HEALTH AND SAFETY PLAN (HASP)

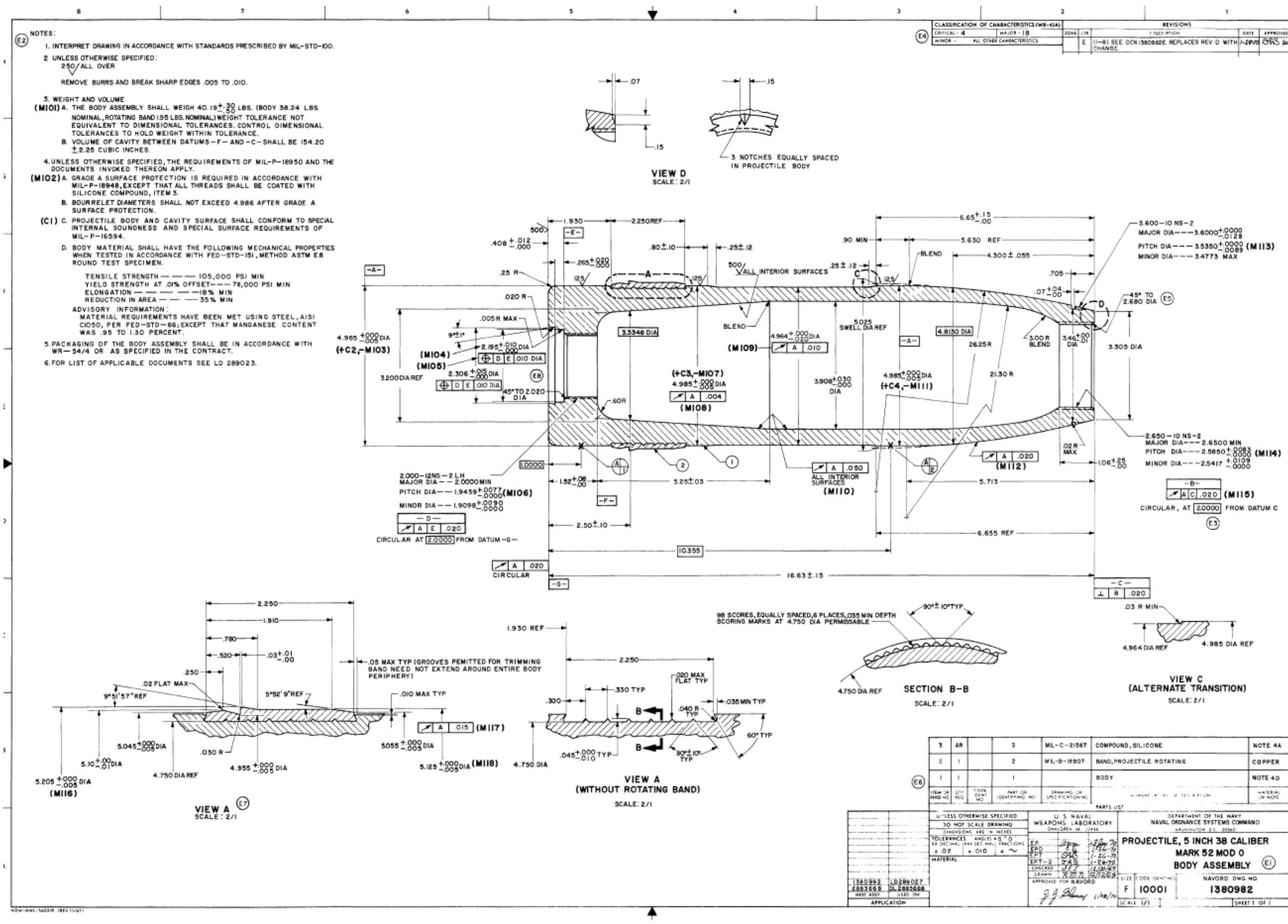
Lake Glendora Test Facility is an explosive test range with site approval for ordnance operations through NOSSA and DDESB.

They have completed their Environmental Assessment and approval was granted through the Indiana Department of Environmental Management.

There are no endangered species at the facility.

All additional HASP details can be found in a limited release document which cannot be named or provided in this documentation plan. All operations will be conducted to the reference site SOP that also includes medical and evacuation instructions.

APPENDIX C. MK 51, 5-INCH / 38 ROUND



APPENDIX D. PRESSURE PROBE / HYDROPHONE SPECIFICATIONS

CALIBRATION CERTIFICATE

Model: W138A05/038CY100AD
Serial #: 11097
Description: Pressure Sensor
Type: ICP

Date: 9/7/2018 aws
By: William Swanson, Cal. Tech.
Station: 913 Dyn. High Pressure (Test Procedure AT601-8)

Sensitivity*: 0.9890 mV/PSI
143.4 mV/MPa

Temp: 71 deg F [22deg C]
Humidity: 57 %

Linearity*: 1.4% FS
Uncertainty:** +/- 3 %

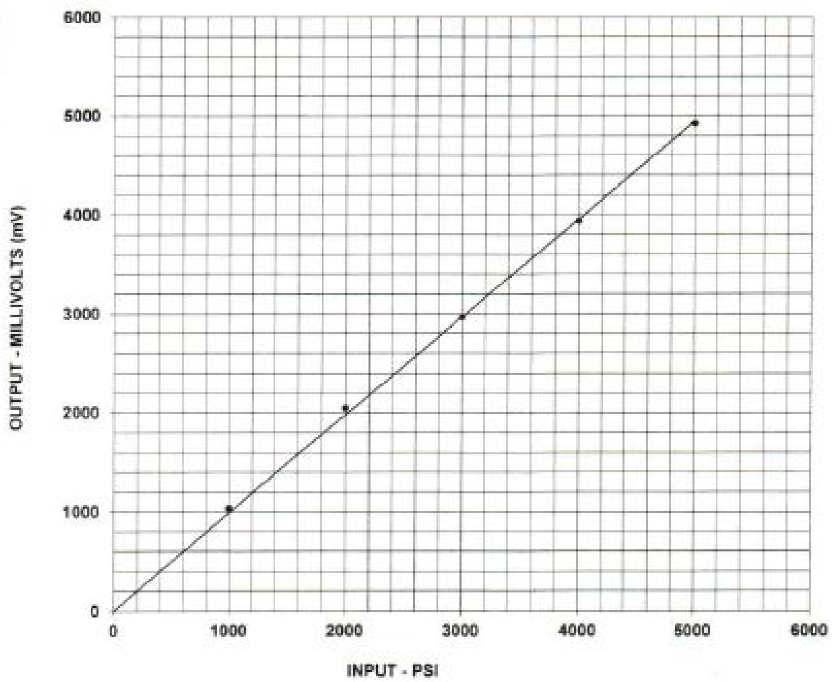
Cert #: 712908

Bias: 11.5 VDC

* Zero based, least-squares straight line.

** Measurement uncertainty represented using a coverage factor of k=2 which provides a level of confidence of approximately 95 %.

Condition of Unit:
As Found: Not applicable
As Left: In tolerance, new unit



TEST DATA

INPUT (PSI)	OUTPUT (mV)
1000	1034
2000	2048
3000	2965
4000	3937
5000	4925

Notes:
1 STATION #17
2 Calibration is traceable to NIST up to 15,000 psi static and is accredited to ISO 17025 and ANSI/NCSL Z540.3.
3 NIST traceability through PCB control # CA 1075.
4 This certificate may not be reproduced, except in full, without written approval from PCB Piezotronics, Inc.

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Page 1 of 1

CALIBRATION CERTIFICATE

Model: W138A01/038CY100AD
Serial #: 11094
Description: Pressure Sensor
Type: ICP

Date: 9/7/2018
By: William Swanson, Cal. Tech.
Station: 913 Dyn. High Pressure (Test Procedure AT601-8)

Sensitivity*: 5.105 mV/PSI
740.3 mV/MPa

Temp: 70 deg F [21deg C]
Humidity: 58 %

Linearity*: 0.7% FS
Uncertainty:** +/- 3 %

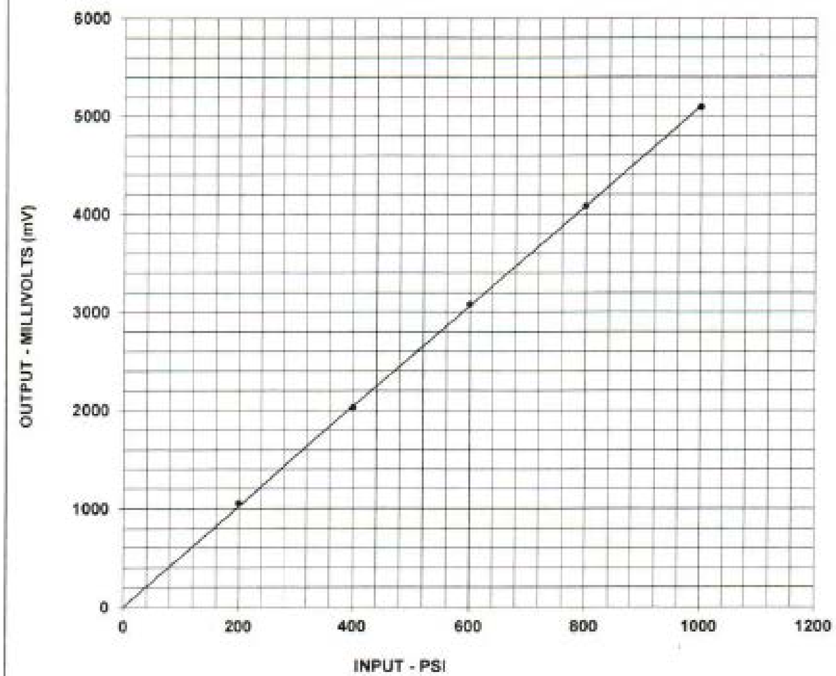
Cert #: 712892

Bias: 11.1 VDC

* Zero based, least-squares straight line.

** Measurement uncertainty represented using a coverage factor of k=2 which provides a level of confidence of approximately 95 %.

Condition of Unit:
As Found: Not applicable
As Left: In tolerance, new unit



TEST DATA

INPUT (PSI)	OUTPUT (mV)
200	1055
400	2028
600	3082
800	4083
1000	5092

Notes:
1 STATION #17
2 Calibration is traceable to NIST up to 15,000 psi static and is accredited to ISO 17025 and ANSI/NCSL Z540.3.
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21120 Johnson Road
Long Beach, MS 39560

Tel. (228) 868-6632
Fax (228) 868-6645
hightechinc@att.net

09/28/18

1133/1/1 Hydrophone Information
Model# HTI-99-HF / 3V / -200dB
Connector: Impulse IE2M-5/8
Cable Length: 8 meters

Current Mode Hydrophone	
Supply Voltage	12VDC
Termination Resistor	50 ohms

Connector Code

Pin 1	Power/Signal Out
Pin 2	Return/GND

Test Data

Serial Number	Hydrophone Sensitivity dB re: 1V/uPa	Current mA
1133001	-199.4	7.36
1133002	-199.6	7.20
AVG	**-199.5**	**7.28**
VAR	**0.0**	**0.01**
STD	**0.1**	**0.12**
MAX	**-199.4**	**7.36**
MIN	**-199.6**	**7.20**
DIF	**0.2**	**0.17**
+\-	**0.10**	**0.08**
Hydrophone Count:	**2**	

Sensitivity was measured using the comparison method
Reference hydrophone = 999902
Measurements traceable to USRD NewPort, RI

Hydrophones listed on this page:
- Leaked less than 0.1uA @ 27VDC after 1hr @ 100PSI hydrostatic pressure
- Passed shield integrity test
- Has the same Polarity Response

APPENDIX E. FREQUENCY ANALYSIS

To determine how the explosive energy was partitioned with respect to frequency, pressure data were converted into an energy spectral density using the following:

$$E_m = \frac{\Delta t}{\rho c}\left|\sum_{n=0}^{N-1} p_n e^{-\frac{2\pi i n m}{N}}\right|^2 \tag{1}$$

where

E_m=component of energy flux at frequency m/(NΔt)

ρ=water density

c=water sound speed

Δt=sampling interval

p_n=pressure sample at time nΔt

N=total number of pressure samples

The summation term was calculated with a fast Fourier transform. As a point of comparison, the energy spectral density for each shot was also calculated using an analytical expression from Weston (Reference 5):

$$E_{total}(f) = E_0(f) + E_1(f) \tag{2}$$

E_0 is the shock energy spectrum equal to

$$E_0(f) = \frac{2P_0^2}{\rho c\left(\frac{1}{\theta^2} + 4\pi^2 f^2\right)} \tag{2a}$$

where

P_0=peak shock pressure

θ=shock decay constant

f=frequency

E_1 is the energy spectrum of the first bubble pulse equal

$$E_1 = \frac{8}{\rho c}\left(\frac{\left(\frac{P_1}{T_1}\right)}{\frac{1}{T_1^2} + 4\pi^2 f^2}\right)^2 \tag{2b}$$

where

P_1=peak bubble pressure

T_1=bubble period

Shock and bubble parameters were calculated using similitude relations of the standard form:

$$P_0 = k_p\left(\frac{W^{1/3}}{R}\right)^{\alpha_p} \tag{3a}$$

$$\theta = k_\theta W^{\frac{1}{3}}\left(\frac{W^{1/3}}{R}\right)^{\alpha_\theta} \tag{3b}$$

$$P_1 = k_{pb}\frac{W^{1/3}}{R} \tag{3c}$$

$$T_1 = K\left(\frac{W^{1/3}}{Z^{5/6}}\right)\left(1 - 0.1\frac{A_{max}}{D}\right) \tag{3d}$$

$$A_{max} = J\left(\frac{W}{Z}\right)^{1/3} \tag{3f}$$

Where

W=charge weight
R=distance from charge
A_{max}=maximum bubble radius
D=charge depth
Z=hydrostatic head (charge depth plus atmospheric head)
k=similitude coefficients
α=similitude coefficients

Since no similitude parameters could be found for comp A-3, parameters for C-4 used instead for everything except bubble pressure. Both explosives are of similar densities (1.6 g/cc) and contain similar proportions of RDX. For lack of anything better, bubble pressure was calculated using parameters for TNT (Reference 6).

The above analytical method over predicts energy at low frequencies and under predicts it at high frequencies. To address the low frequency issues, Weston suggests representing the shock and bubble pulses by their impulses (both positive and negative). At the same time, to capture more of the high frequency energy, a second bubble pulse spectrum (using the same equations as the first with reduced magnitude) can be included.

An example of the expanded analytical method is shown in Figure A-1. Neither the low frequency nor the high frequency corrections match experimental data very well. At best, the low frequency theory matches the peak magnitude of the experiment. This discrepancy suggests that some feature other than shock and bubble impulse is dominating at low frequencies, namely surface cut-off (Reference 11). The exact cause of the high frequency divergence is unknown. A brief literature survey turned up no information; past studies (e.g., [References 5, 6, and 11] appear to have been unconcerned about frequencies beyond 10kHz (the peak operating frequency of cold war era U.S. sonar systems).

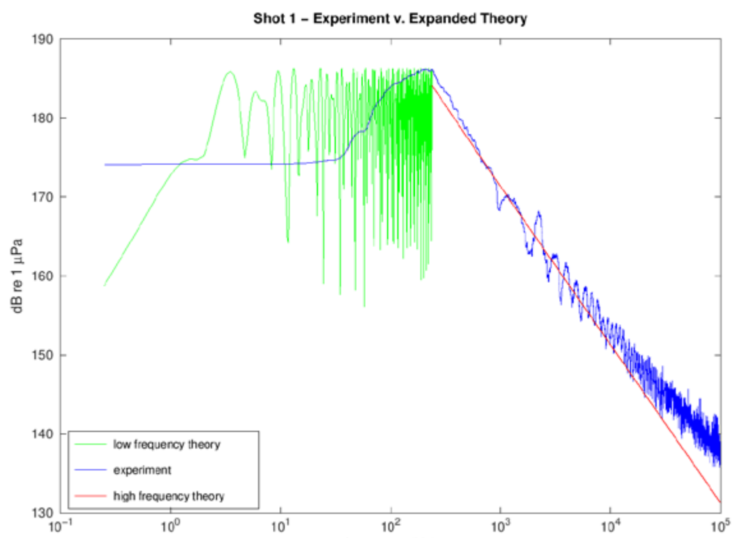

Figure A-1. Experiment vs. Expanded Theory for Shot 1 at 100 Feet