EGP Final Report: MR-201611 - Underwater UXO Neutralization by Explosively-Generated Plasma

Munitions Response Projects

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EGPs are created by the focusing of a shock produced from an explosive driver 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 extent that plasma is produced. These EGPs have been measured in controlled experiments to travel at velocities as high as 21,000 km/s with temperatures of 20,000 K. Naval Surface Warfare Center Indian Head Division (NSWC IHD) can be used to perforate the casing of the Naval 5" round and neutralize the explosive fill by initiating a low order or deflagratory process. The EGP couples with the high-explosive fill resulting in a high temperature chemical decomposition along non-traditional kinetic pathways that results in rapid deflagration without detonation. The introduction of an EGP-based technology with a sealed waveguide for the remediation of underwater UXOs provides 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.

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LIST OF ACRONYMS

Acronym	Description
Al	Aluminum
ANSI	American National Standards Institute
AP	Ammonium Perchlorate
ARB	Arrhenius Burn Model
BIP	Blow-In-Place
CUNY	City University of New York
CVTX	Constant Volume Thermal Explosion
DDESB	Department of Defense Explosives Safety Board
DDT	Deflagration to Deontation Transition
DoD	Department of Defense
DODAC	Department of Defense Ammunition Code
EBW	Exploding Bridgewire
EGP	Explosively-Generated Plasma
EOD	Explosive Ordnance Disposal
ESFT	Shift in Zero Energy Factor
FOUO	For Official Use Only
HASP	Health and Safety Plan
HE	High-Explosive
ISO	International Organization for Standardization
JEOD	Joint EOD
LAMMPS	Large-Scale Atomic/Molecular Massively Parallel Simulator
LANL	Los Alamos National Labs
MD	Molecular Dynamics
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
NOSSA	Naval Ordnance Safety & Security Activity
NSWC IHD	Naval Surface Warfare Center Indian Head Division
ORM	Operational Risk Management
PN	Part Number
ReaxFF	Reactive Force Fields
SME	Subject Matter Expert
SOP	Standard Operating Procedure
USNA	U.S. Naval Academy
UXO	Unexploded Ordnance

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ABSTRACT

Introduction and Objectives

There is a need for 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. During a typical BIP procedure, the resulting shockwave and bubble formation/collapse from the detonation of the UXO produces pressures and acoustic noise that is detrimental to marine life. Explosively generated plasma (EGP) technology provides a method to neutralize UXO with minimal environmental impact (no detonation) while using a minimal explosive donor charge.

Technology Description

EGPs are created by the focusing of a shock produced from an explosive driver 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 extent that plasma is produced. These EGPs have been measured in controlled experiments to travel at velocities as high as 21,000 km/s with temperatures of 20,000 K. Naval Surface Warfare Center Indian Head Division (NSWC IHD) can be used to perforate the casing of the Naval 5" round and neutralize the explosive fill by initiating a low order or deflagratory process.The EGP couples with the high-explosive fill resulting in a high temperature chemical decomposition along non-traditional kinetic pathways that results in rapid deflagration without detonation. The introduction of an EGP-based technology with a sealed waveguide for the remediation of underwater UXOs provides 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.

Performance and Cost Assessment

In this effort, it was demonstrated that the designed EGP tool can perforate the steel cased Naval 5" round both on land and underwater. The tool initiates a slow burn of the explosive fill on land, resulting a burn completion time of between 10 and 20 minutes. Underwater, the reaction is quenched by inrushing water. A low-order solution was found that remediates underwater UXO. While this solution breaks the casing into several pieces, the solution does not detonate the munition. Cost of t parts he designed solution is estimated under $500.00 and is constructed from machined ABS plastic which minimizes fragmentation hazards.

Implementation Issues

Early designs under this effort used 3D printed parts. It was found that these parts did not have the proper tolerancing to keep water from penetrating the inside of the device, which caused the devices to fail. This problem was solved by switching to a machined plastic solution.

Publications

1. McCarthy D., Giannuzzi P., Schweigert I., Elert M., Gosney G., Emery S., "Interaction of Explosives with Explosively Generated Plasma", 16th International Detonation Symposium.

EXECUTIVE SUMMARY

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, 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 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 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.

Objectives

The primary objective of this effort was to develop an EGP tool for the remediation of the Naval 5" round in underwater scenarios. Emphasis was placed on minimizing underwater shock and bubble formation that is detrimental to marine life. This is done by ensuring that the developed tool does not initiation a high order reaction (or detonation) of the munition fill. The tool was designed to utilize the minimal mass driving charge required to perforate the casing of the munition and initiate the explosives inside.

Technology Description

EGPs are created by the focusing of a shock produced from an explosive driver via a conical waveguide. In the waveguide, the gases from the explosive along with the trapped air are accelerated and compressed to such extent that plasma is produced. Mach stems are formed at the cone wall and collapse on the center axis of the cone. When the Mach stems meet at the center axis, a jet of gas is produced along the axis with an even higher shock velocity and gas temperature. Figure 1 shows a concept drawing of an EGP tool. Figure 2 shows the modeled shock structure inside the cone.

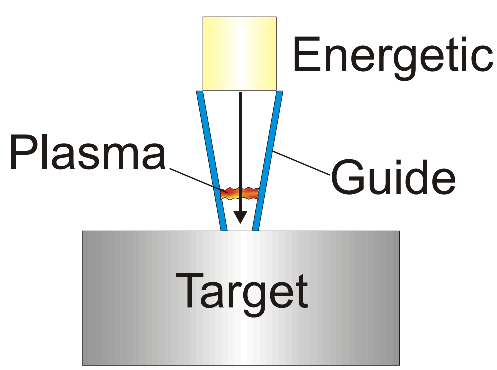


Figure 1. Schematic of Driver-Waveguide-Target

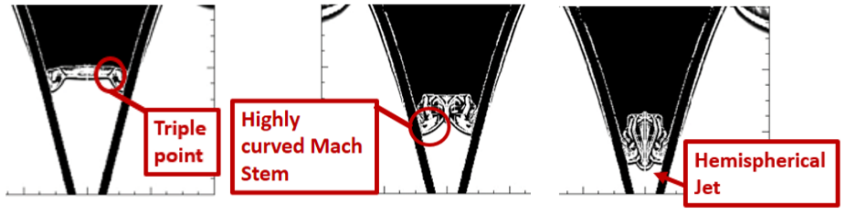


Figure 2. Shock Structure Inside the Cone (Modeled in Sandia hydrocode CTH)

In this effort, the velocity of the shocked gases was measured inside glass cones cone. Figure 3 shows images of the plasma inside the cone. Figure 4 shows the measured velocity of the shock both at the edge of the cone, as well as the jet velocity along the center axis.

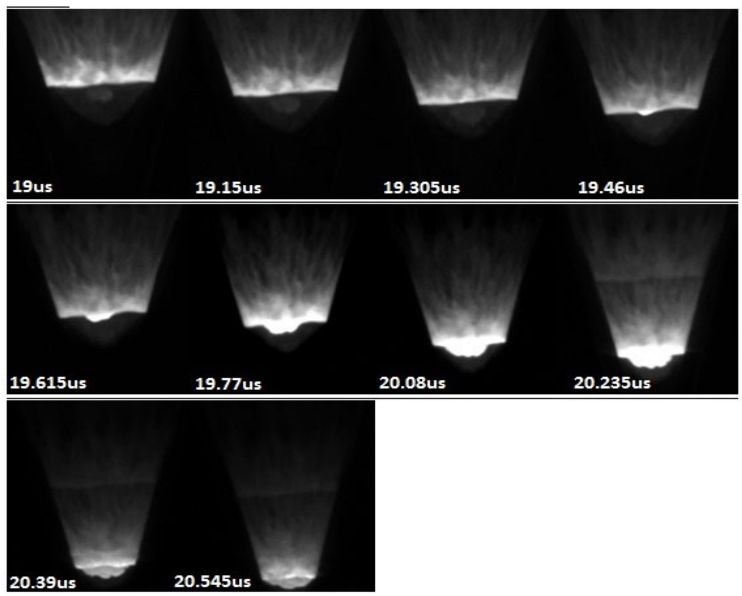


Figure 3. High Speed Images of Shocked Gas in a Glass Cone

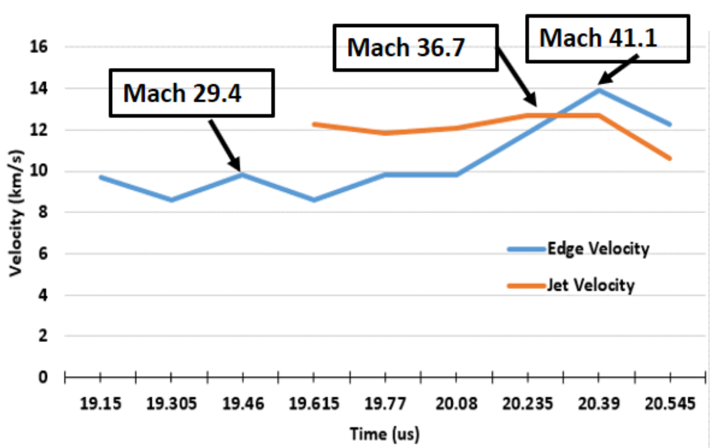


Figure 4. Measured Shock Velocity from the High Speed Images

In addition, the temperature of the shocked gas was measured by using a high speed streak spectrometer and fitting a blackbody curve fit to the collected spectra. The temperature of the shocked air in the cone was measured to be 20,000K on the center axis.

Performance Assessment

Year 1 of this effort focused on modeling how the Comp A-3 fill inside the Naval 5” round would respond to the hot gas flow from the EGP device. This was done using both chemical kinetics and molecular dynamics models. Once the decomposition of the material had been established, an Arrhenius burn model was developed in CTH (Sandia National Labs hydrodynamics code used by the DOD and DOE) so that modelers could predict the speed of the decomposition given a particular thermal insult.

In year 2, we conducted testing of simple EGP devices against the Comp A-3 explosive. 3D printed EGP devices with a C4 driving charge were used to perforated a ½” thick steel plate and flow hot gas onto a sample of Comp A-3 material confined in a steel tube beneath the EGP device. A low order response was found that would consume the explosive without detonating the material. Figure 5 shows the test setup used to evaluate the response of the confined Comp A-3 material. Figure 6 shows the setup hardware after the test. We can see that the EGP device ablates a large hole (approximately 1” in diameter) in the top ½” thick steel plate. The large fragments of the confining tube and lack of hole in the bottom plate indicates a low order response of the Comp A-3 to the hot gas flow form the EGP device. No residual Comp A-3 material was found following this experiment.

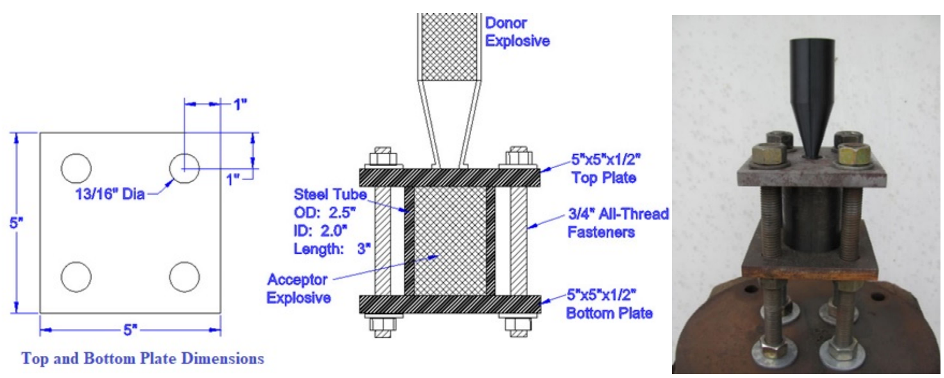


Figure 5. Hardware Used in Confined Prompt Initiation Testing

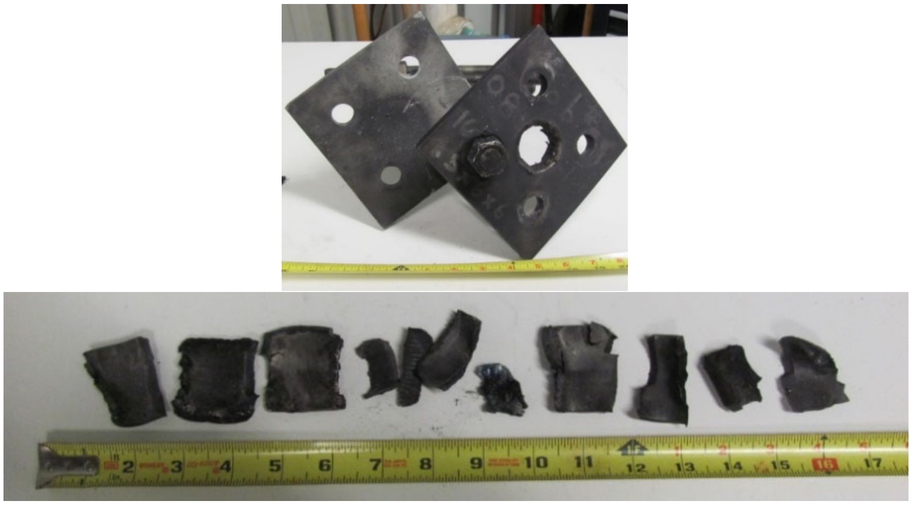


Figure 6. Hardware Following Testing – Top And Bottom ½" Steel Plate Hardware (Top) and Confining Steel Tube Hardware (Bottom)

When the standard pressure burn rate for the material was evaluated in confined clear tubes, it was found that the Comp A-3 material is consumed at a surprising slow rate due to the wax binder in the material. Figure 7 shows the burn progression for a 1 inch diameter column of Comp A-3 in a thick walled acrylic tube. Using a "soft ignition scenario", the burn rate of the material was measured to be 0.36 in/min.

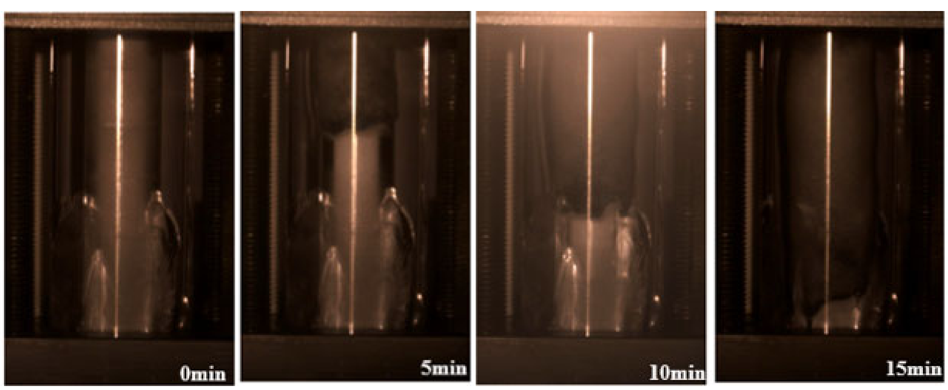


Figure 7. Images of Slow Burn Rate Measured when the Comp A-3 Material is Ignited with a Standard Squib and Small Amount of Thermite

Extensive tool down-selection and testing was carried out against the Naval 5" round in open air and submerged in fish tanks prior to depth testing (year 3). An EGP tool solution was found that would remediate the fill of the munition in both scenarios. In the open air scenario, a solution was found that would initiate a slow burn of the Comp A-3 material, remediating the fill in just under 20 minutes. A similar solution for the fish tank scenario could not be found. In this setup configuration, the water would rush in and quench the burning Comp A-3 material quickly after it was ignited. Instead, a solution was found that would initiate a low- order response of the fill, consuming it quickly without detonation. Large pieces of the munition casing were recovered after these tests (rather than small fragments that would result from a detonation). Figure 8 shows the open air and fish tanks test setups prior to testing. Figure 9 shows an image of the in progress open air test and punctured munition casing after testing. Figure 10 shows parts from one of the experiments conducted in a fish tank.

Figure 8. Open Air (Left) and Fish Tanks (Right) Test Setups Prior to Testing

Figure 9. Image of an in Progress Open Air Test (Left) and Punctured Munition Casing (Right) after Testing

Figure 10. Naval 5" Round Parts Following EGP Tool Testing in a Fish Tank Demonstrate a Low-Order Response

In year 3, testing was conduced at Lake Glendora (NSWC Crane) at depth. An underwater test arena was constructed so that munitions (with attached EGP tools) could be lowered to depth and tested. A submersible net was lowered below the munition using electric hoists so that remaining munition parts could be easily brought back up to the surface. Figure 11 shows the test arena used for testing.

Figure 11. Year 3 Test Arena at NSWC Crane

Results similar to that observed in the fish tank experiments were obtained at depth. In these experiments, a solution was found that would low-order the Naval 5" round. Figure 12 shows the munition remnants following one of the experiments. In this experiment the peak pressure measured at 100ft and 200 feet was reduced by between 70 and 80 percent and the peak impulse was reduced by roughly 90%, compared to a high order baseline experiment, accomplishing project goals.

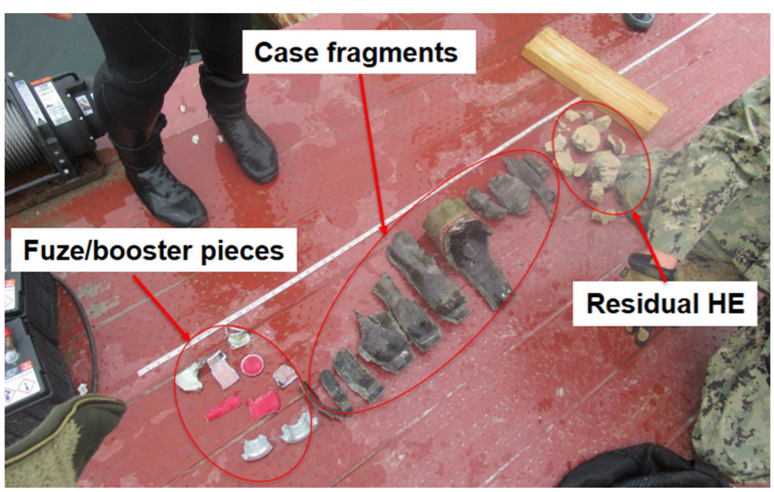


Figure 12. Residual Naval 5" Round Parts after an EGP Tool Test at Depth

Cost Assessment

The final EGP tool design is constructed from machined ABS plastic parts. Multiple attachment methods and points are provided and described in the final CAD drawing set. The donor charge used is C4 which is readily available to most EOD units. The total cost for multiple machined EGP tools is estimated at $400.00 per tool.

Implementation Issues

Much of the testing conducted at depth in year 3 was unsuccessful due to water leakage problems with the first iteration of the designed tool constructed from 3D printed parts. When water enters the conical section of the EGP tool, shock and high temperature gas flow is not transmitted from the donor charge to the target munition casing. This results in insufficient penetration of the munition casing and failure of the device to remediate the fill. The problem was fixed by switching to machined plastic parts. This system has been pressure pot tested and has proven its ability to resist leakage into the cone at depths of 200ft. A finalized CAD drawing set (with part tolerances) is included in the final report.

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, 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 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 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 extent that plasma is produced. These EGPs were 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 Division (NSWC IHD) 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 [2].

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 resulting 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 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 [3]. 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 not requiring 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 Year 1 - Molecular Dynamics Modeling of Plasma-Energetic Material Interactions

The objective of the first year's effort was to utilize molecular dynamics modeling to simulate the EGP-energetic fill interaction that results in the experimentally-observed, deflagration-only response for EGP neutralization of cased/confined explosives. Both NSWC IHD and Los Alamos National Labs (LANL) demonstrated successful deflagration-only responses from cased and confined explosives.

Commonly used continuum modeling tools such as the Sandia National Labs CTH hydrocode is ideal for describing the propagation of shockwaves and the deformation of solids, but it is incapable of describing chemical decomposition and deflagration. It was decided that a molecular dynamics (MD) code needed to be employed to accurately capture the plasma interaction with an energetic material. MD simulations were implemented in the first year of this effort to describe chemical bond breaking and formation processes resulting from the plasma-energetic interaction in a pure explosive (i.e., RDX).

In order to meet the criteria for success at the end of this first year effort, collaborations were established with molecular dynamics experts at the U.S. Naval Academy (USNA) and the City University of New York (CUNY) who have extensive experience modeling shock chemistry phenomena and plasma-matter interactions, respectively. Deliverables from these collaborations include computational values for reaction potentials and reactive force fields (ReaxFF) that capture bond formation/breaking to describe the plasma induced chemical reactions. With such deliverables, classical MD tools such as Large-Scale Atomic/Molecular Massively Parallel Simulator (LAMMPS) were employed to describe the non-traditional, kinetic decomposition pathways that result from the EGP process. It is expected the results from these MD simulations will enable temperature and pressure gradients to be modeled during year 2 efforts with CTH.

This project addresses the following need for environmentally-acceptable remediation techniques for underwater ordnance disposal where UXO cannot be moved to the surface and rendered safe. The current protocol calls for a BIP procedure where an explosive charge is utilized to detonate the UXO in place. During a typical BIP procedure, the resulting shockwave and bubble formation/collapse from the detonation of the UXO produces pressures and acoustic noise that is detrimental to nearby structures and marine life. The working hypothesis for this project is: if EGP technology can be employed to defeat UXO sources, then UXO can be neutralized in place with minimized environmental impact (no detonation), as well as significantly reduce the release of toxic explosive chemicals.

In the first year of the project, the primary objective was to optimize the EGP device design: the achievement of this objective is a major milestone. A typical EGP device is comprised of an energetic driver charge and a conical waveguide, which is affixed to a target (see Figure 2). For this project, the target UXO is a WWII-era naval 5-inch/38 caliber gun round filled with Composition A-3 (Comp A-3): a mixture of 95% RDX and 5% polycrystalline wax. To ensure remediation, the coupling between the driver charge, the conical waveguide, and the target UXO must be determined explicitly to develop an EGP device that minimizes explosives required while enabling metal penetration through ~1/2-inch thick casing and yielding a deflagration-only response from the UXO. In the first year, optimal coupling was determined utilizing computational modeling in combination with both legacy and new data.

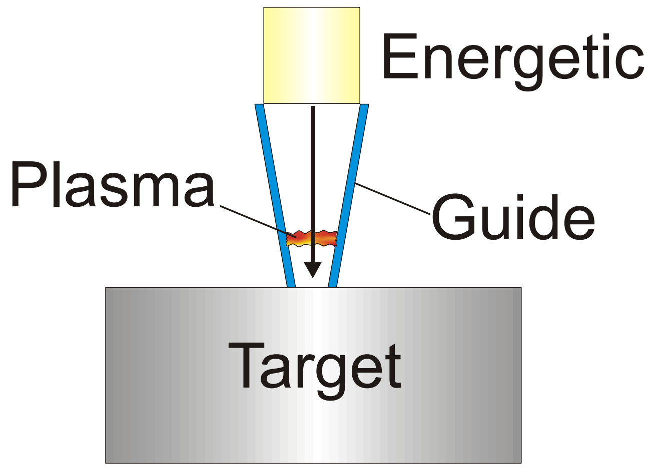


Figure 2. Typical EGP Configuration

The Go/No-Go decision point for this project seeks to answer the following question: "Can the computational modeling tools developed in year 1 predict the deflagration-only response to the extent follow-on testing in years two and three are justified?" The decision criteria will be based upon CTH hydrocode modeling results, calibrated with MD temperature calculations and detailed RDX kinetic reaction models to simulate the prior-observed deflagration-only response. The deflagration-only response was observed in above water experiments several times [2,4].

1.2.1 Technical Approach

The first year's efforts to optimize the EGP device and its coupling to the target UXO were accomplished through the utilization of a computational modeling flow process where the response of RDX molecules to high heat and high heating rates was tracked and fed into a kinetic model for RDX. This in turn provided an Arrhenius burn model for utilization in predicting system response via CTH hydrocode modelling. This flow process is diagrammed in Figure 3.

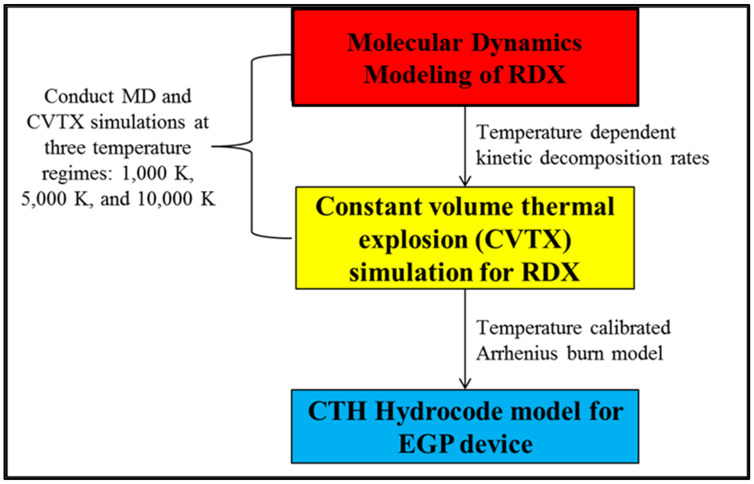


Figure 3. Molecules to System Level Response Modeling

MD simulations were carried out by collaborators professor Mark Elert and Midshipman Ryan Le at the U.S. Naval Academy to examine the effect of plasma-generated heating on crystalline α-RDX. The ReaxFF bond-order potential[5] available in the LAMMPS MD suite[6] was used, allowing realistic bond-breaking and bond-forming processes to occur in the simulations. The force field parameters developed by Wood et al.[7] for nitrogen-containing energetic materials were employed. To simulate the effect of plasma heating, several molecular layers at one end of an RDX crystal were maintained at a fixed high temperature. Periodic boundary conditions were employed in the transverse directions.

Thermal run-away and explosions due to chemical reactions in rapidly heated RDX were simulated by project collaborator Dr. Igor Schweigert of the U.S. Naval Research Laboratory using the detailed chemical kinetics model Cantera[8]. In these simulations, rate equations describing chemical reactions were integrated to yield time-dependent temperature and speciation profiles as functions of the initial temperature of unreacted RDX. The profiles were then analyzed to extract the times-to-explosion and final temperatures as predicted by the model. To simplify the integration, the reactions were assumed to be homogenous and to occur under constant-volume, adiabatic conditions, wherein all released chemical energy was spent on further heating the material. This approximation, referred to as Constant Volume Thermal Explosion (CVTX), is commonly used to predict ignition delays in propellant formulations[9]. Figure 4 shows the progression of the explosive through the CVTX simulations. The explosive is assumed to be rapidly and uniformly heated to a target initial temperature (Step 1). The ensuing reactions under adiabatic, constant-volume conditions are explicitly modeled using a detailed chemical kinetics model (Step 2).

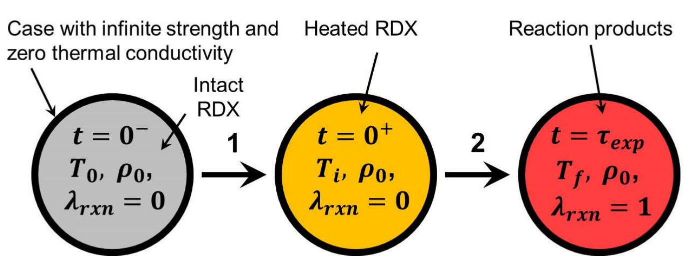


Figure 4. CVTX Simulations

The detailed kinetics model combines two global decomposition reactions and more than 200 elementary reactions describing thermal oxidation of decomposition products. The two decomposition reactions were taken from the T-jump measurements by Thynell, et al.[10]. The thermal oxidation of decomposition products was described using a detailed kinetics model derived by Yetter, et al.[11]. The gas-phase enthalpies of formations and constant-volume heat capacities were used for all species, including RDX. The material density was kept fixed at 1.81 g/cm^3, which is approximately the density of the α polymorph at room temperature and pressure. Note that the model reaction rates depend only on species concentrations, therefore no equation of state was needed to integrate the rate equations. The initial temperature of unreacted RDX was the only parameter varied in this study.

CTH hydrocode modeling was utilized by the project team at NSWC IHD to model the propagation of shockwaves from an explosive driver charge. It was also utilized to track the velocity and pressure of the detonation gases as they interacted with the propagating shockwave in the waveguide. The resulting deformation of a case wall and resulting penetration into the target UXO's explosive fill was tracked to capture the system level response resulting from the EGP phenomena. A typical CTH simulation setup for an EGP device is depicted in Figure 5.

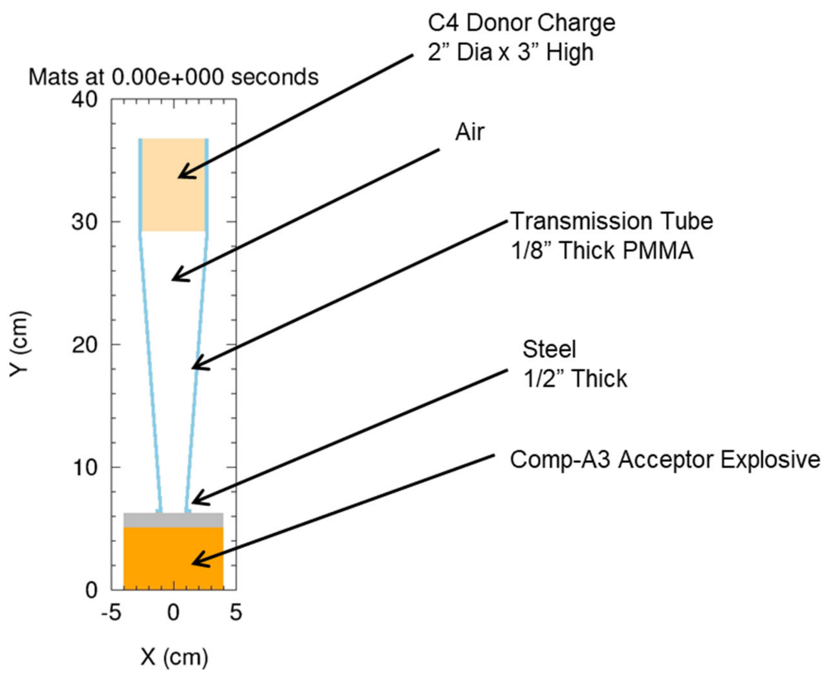


Figure 5. CTH Model for EGP Process on Target UXO

1.2.2 Results and Discussion

The simulation setup detailed above was employed to meet the milestones of the first year and to address the Go/No-Go decision point for the project. The results of each model and how the results culminated in the final modeling effort are detailed in the proceeding sections.

1.2.3 Detailed Kinetics (Candera) Modeling Results

The time-dependent temperature and speciation profiles for reacting RDX were computed for three initial temperatures: 1000, 2000, and 5000K (see Figure 6). Time-dependent temperature (black) and speciation profiles (RDX - blue, reaction products - red) obtained in the CVTX simulations. For temperatures above 5000 K, the adaptive solver Cantera[8] failed to integrate the rate equations, possibly due to the large difference in the rates of the initial decomposition reactions and subsequent thermal oxidation reactions. Attempts were made to mitigate this issue by decreasing the time step in the numerical integration, although even 5×10^7 integration points were insufficient to ensure a successful integration.

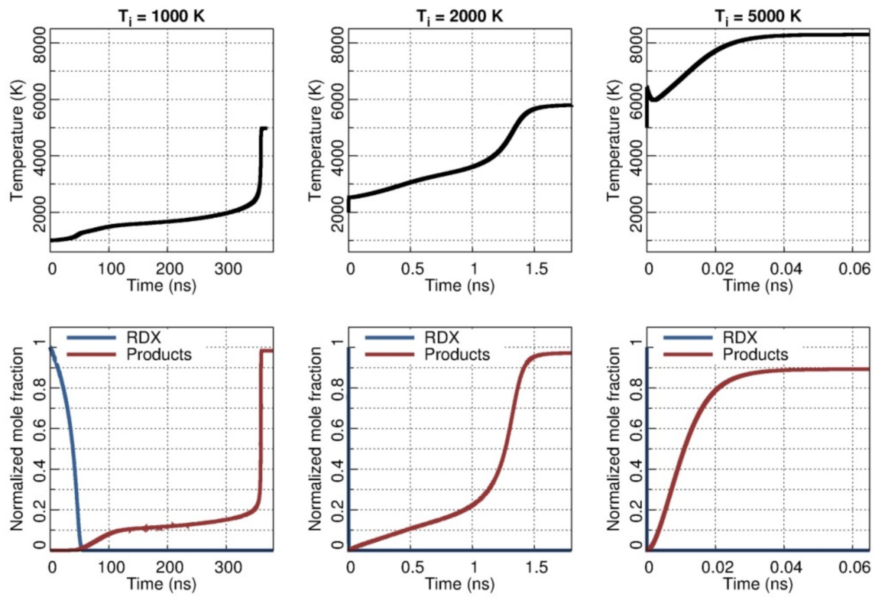


Figure 6. Time Dependent Temperature / Speciation Profiles

Arrhenius burn model parameters were found using the 1000K and 5000K temperature-time curves as shown in Figure 6. These parameters are based upon both the final temperatures obtained in the CVTX scenario and the area under the curves when this temperature is obtained. Appendix A shows the burn model form, the fitted parameters, and the calculated agreement with the data generated using detailed kinetics modeling.

1.2.4 Molecular Dynamics Modeling Results

LAMMPS MD simulations were performed with the thermostatted region held at 1000, 5000, and 10,000K. At the lowest temperature, very little reactivity was observed and heat propagated slowly down the length of the crystal. At 5,000 and 10,000K, however, significant decomposition of the RDX molecules occurred and the reaction front propagated more rapidly (see Figure 7 and Figure 8). Propagation speeds on the order of hundreds of meters per second were observed, indicating fast deflagration but no detonation at these time scales. The position of the reaction front (temperature higher than one-half the thermostat value) versus time for three different thermostat temperatures is shown in Figure 6. Figure 7 shows the temperature profiles for 5,000K simulation at various times, showing rate of front propagation.

Final decomposition products including H_2O and CO_2 were observed in high percentages behind the reaction front. These products clearly show complex multi-step kinetic processes are occurring on a very fast time scale. Additional quantitative analysis of the decomposition processes in year 2 would increase the accuracy of kinetic models and mesoscale continuum models utilized in the prediction of large scale behavior of RDX subjected to EGP heating.

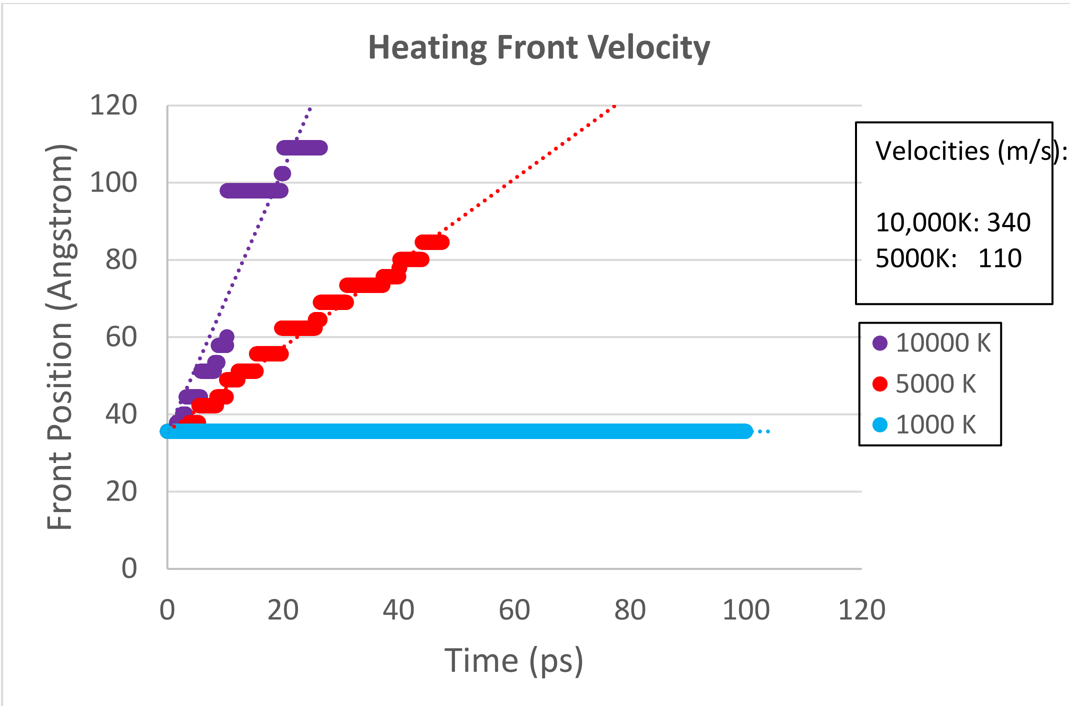


Figure 7. Position of Reaction Front vs. Time for Different Thermostat Temperatures

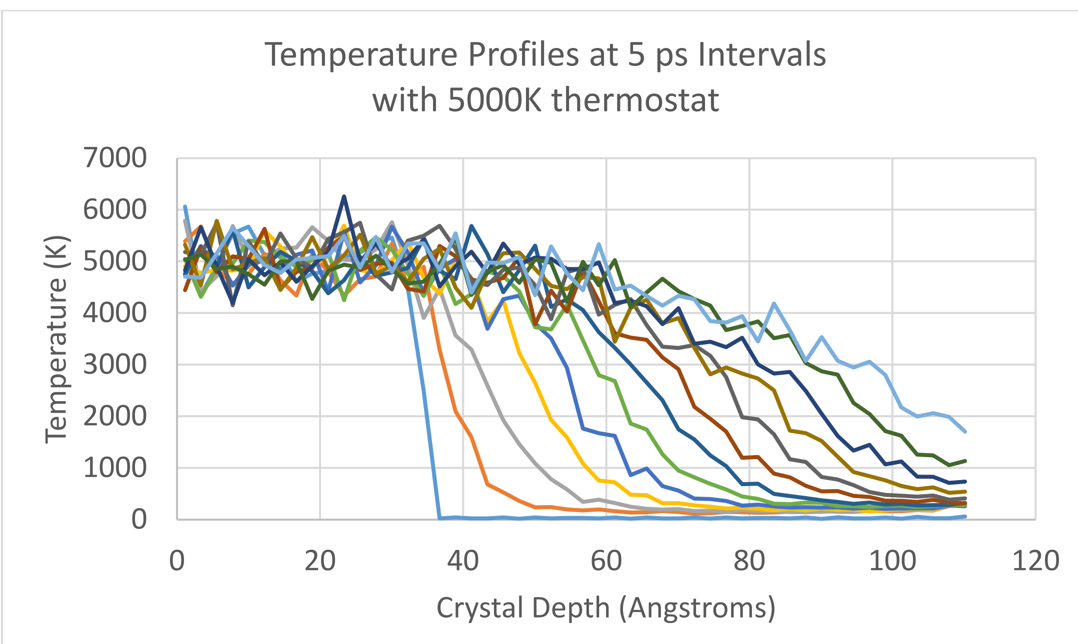


Figure 8. Temperature Profiles

1.2.5 MD Temperature Model vs. Arrhenius Burn Model

The temperature-time results of the MD model for the 5,000K reaction of an RDX molecule were evaluated against the Arrhenius burn model developed from the detailed kinetics computed from a CVTX sample of RDX with an initial temperature of 5,000K. As shown in Figure 9, the MD curve has much the same qualitative shape as that seen in the Arrhenius burn model. Figure 8 shows the temperature-time curves for the developed Arrhenius burn model, detailed kinetics model and molecular dynamics model (initial temperature = 5000K).

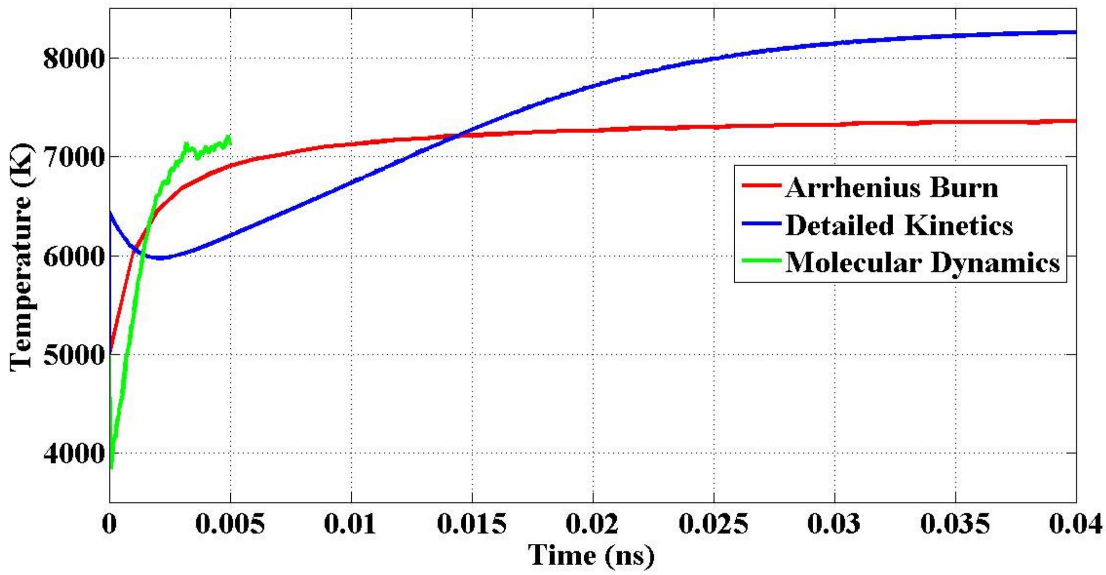


Figure 9. Temperature Time Curves

1.2.6 CTH Results with Tuned Arrhenius Burn Model

CTH hydrocode modeling was performed in order to assess the capability of the EGP device to pierce the steel casing of a 5-inch/38 caliber gun round without detonating its Comp-A3 target. The simulated geometry is shown in Figure 5. The specifics of the Arrhenius burn model used to represent the Comp-A3 target are discussed in Appendix A. The simulation was run using 2-D cylindrical symmetry with adaptive meshing (the highest resolution was 150 microns) and was allowed to run out to time of 75 microseconds. Breaching of the case was observed at 55 microseconds. Figure 10 shows the temperature and extent of target reaction for the CTH simulation at 75 micro seconds (listed as XRN in the figure) at the end of simulation. Tan regions indicate zones below contour thresholds. No reaction/detonation was observed in the target explosive during the 20 microseconds in which the EGP was in contact with the target which provides an indication that the target explosive will burn-out rather than detonate. The CTH model will be validated and refined using test data gathered during Year 2.

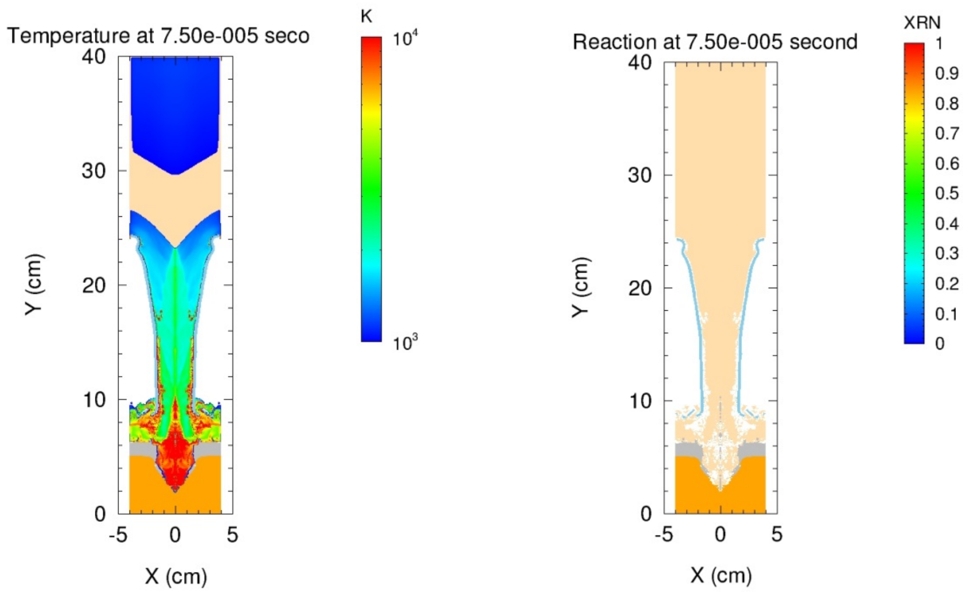


Figure 10. Temperature and Target Extend of Reaction for the CTH Simulation

1.2.7 Year 1 Conclusions

Utilizing the results of the detailed RDX reaction kinetics at high temperatures, in conjunction with the observations of the MD simulations, an Arrhenius burn model for RDX raised to EGP temperatures was developed for CTH. The tuned Arrhenius model was incorporated into CTH hydrocodes that enabled the simulation of an EGP device penetrating ½ inch steel case and interaction with an RDX fill. The resulting simulation predicted zero detonation (explosive reaction below threshold) of the Comp-A3 target, a result in line with NSWC IHD's prior experimental work on testing EGPs against TNT-filled cased surrogates[2] and Comp-B filled artillery shells [unpublished], and Los Alamos National Lab's testing against PBX-9501filled copper cylinders[4].

1.3 Year 2 - Optimization of Driver – Waveguide - Target Coupling and Penetration / Neutralization Testing of Cased Explosives

Year 2 efforts occurred in two phases. The first phase primarily focused on continuum modeling of the driver-waveguide-target system which yielded a set of optimized waveguide geometries and driver mass. A smaller, secondary modeling effort extended the first year's MD simulations to describe temperature and reaction behavior stemming from the plasma-casing interaction. This combined modeling effort reduced the amount of demonstration testing and by extension the time and cost of the total effort. Continuum modeling was conducted in-house by solid mechanics modeling subject matter experts (SME) at NSWC IHD. This effort utilized CTH hydrocode that describes the shock compression of the air in the EGP waveguide, and yielded the particle velocities and pressures associated with the process. The CTH hydrocode also incorporated the results of the first year's MD simulation effort and the MD results of the plasma-case interaction to enable CTH to more accurately describe the bulk effect on a target munition (including internal pressures and temperatures) both underwater and on dry land.

The second phase of year 2 efforts evaluated the performance of the EGP technology on remediating UXOs and provided validation of the developed continuum models. The performance portion determined the upper limits on thickness of case that could be penetrated and the maximum volume of explosive that can be neutralized. The metrics of interest were case thickness and volume of explosive that could be neutralized, relative to the net explosive weight of the driver and the waveguide configuration. In order to obtain this information, full scale outdoor range testing was conducted at the NSWC IHD EOD campus ranges. The testing was broken into a series of tests that included instrumentation to not only capture performance, but also provide a measure of internal pressure and temperature, plasma velocities in the waveguide, and casing penetration rates used to validate both MD and CTH models.

Test Series 1 was comprised of case penetration tests. Steel witness plates were exposed to EGP events produced under waveguide-driver configurations determined by modeling and simulation efforts to have a high probability of providing high particle velocity and temperature, but not cause a low order event sympathetically with the initiation of the driver charge. The measured metrics included depth of penetration into the plate, diameter of crater/hole in the plate, and quantity of material ablated away from the steel plate during the process.

Test Series 2 determined the upper limit of the mass of explosive that can be thermally decomposed by EGP for a fixed driver charge (net explosive weight determined from Phase 1 results). The tests utilized a steel witness plate (representative of the case thickness of the naval 5-inch/38 caliber round) as a cover to a confined explosive of known mass. A range of masses were exposed to EGP, and the upper limit of thermal decomposition was measured.

1.3.1 Thermal Characterization Testing

The purpose of the first series of tests was to investigate the temperature of the leading shock front (and close behind gas flow) in the EGP tool. For these experiments, the shape of the EGP cone was similar to that used in the final tool design. C4 was used as the explosive driver in these experiments. In these tests, a Sydor streak camera and Acton spectrometer were used to characterize the light in the EGP cone. The axis of the cone was pointed at a UV lens (Thorlabs f = 100mm and 1 inch diameter) which was coupled to UV fiber (Thorlabs 400um 0.22NA) that lead back to the spectrometer. Figure 11 shows the test setup used in these experiments.

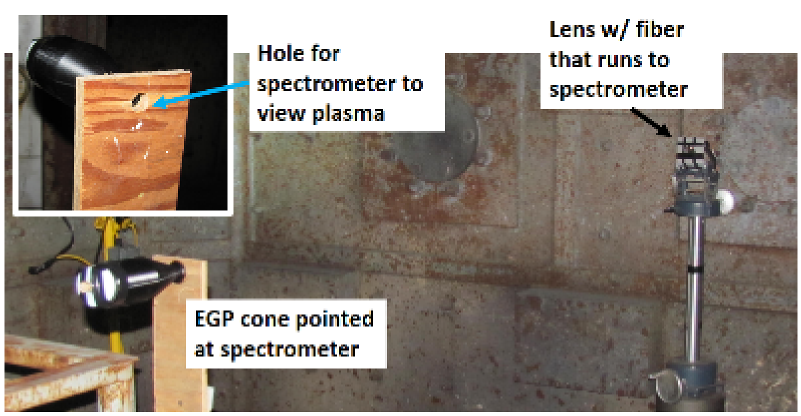


Figure 11. Thermal Characterization Test Setup

The spectrometer data was calibrated against the known peaks from a mercury lamp and the intensity of the measurements was calibrated against a 3000K blackbody lamp source. Spectrograms were generated over 100ns intervals (the maximum temporal resolution of the equipment) for the duration that the shock traveled down the length of the EGP cone. The intensity of the light generated by the EGP device was found to be greatest at approximately 15μs after the driving charge was initiated. Figure 12 shows the reduced spectrometer data taken at that time. The streak camera used a 150 line per mm grating and was blazed at 300nm (which is why the data drops off below that wavelength). The red line is a blackbody curve fit at 20,000K. The agreement of the data to the curve fit between 350 and 500 nm suggests the temperature of the shock front in the EGP device is close to this value.

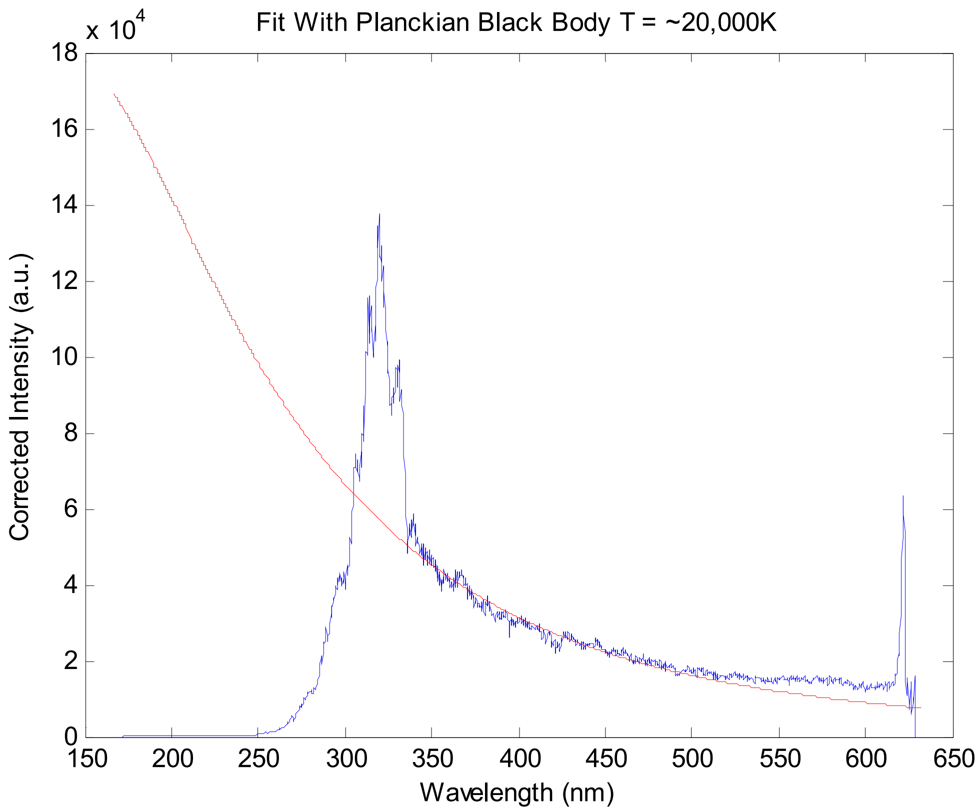


Figure 12. Reduced Spectrometer Data

Glass cones of the same half angle were used to visualize the shock velocity inside the EGP device. The light generated inside the cone is used to visualize the plasma speed at the edge of the cone from the side. A 2-inch by 2-inch Pentolite pellet was used as the driving charge in order to ensure a more symmetric shock into the EGP device. The detonation velocity of Pentolite is similar to C4, making it an appropriate choice for these experiments. Figure 13 shows the test setup.

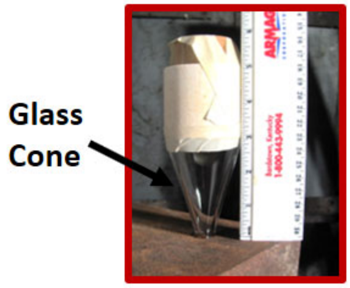


Figure 13. Test Setup

A Specialised Imaging SIM16 framing camera was used to visualize the plasma in the cone. Images were taken at 150ns intervals using a 5ns exposure setting. Figure 14 shows the images taken as the plasma transversed the length of the cone. The brightly illuminated region contains the shock front as it travels down the cone. In the first three frames, only the edge of the shock against the inner wall of the cone is visible. After that, jetting along the center axis of the cone becomes visible as it accelerates past the outer shock edge.

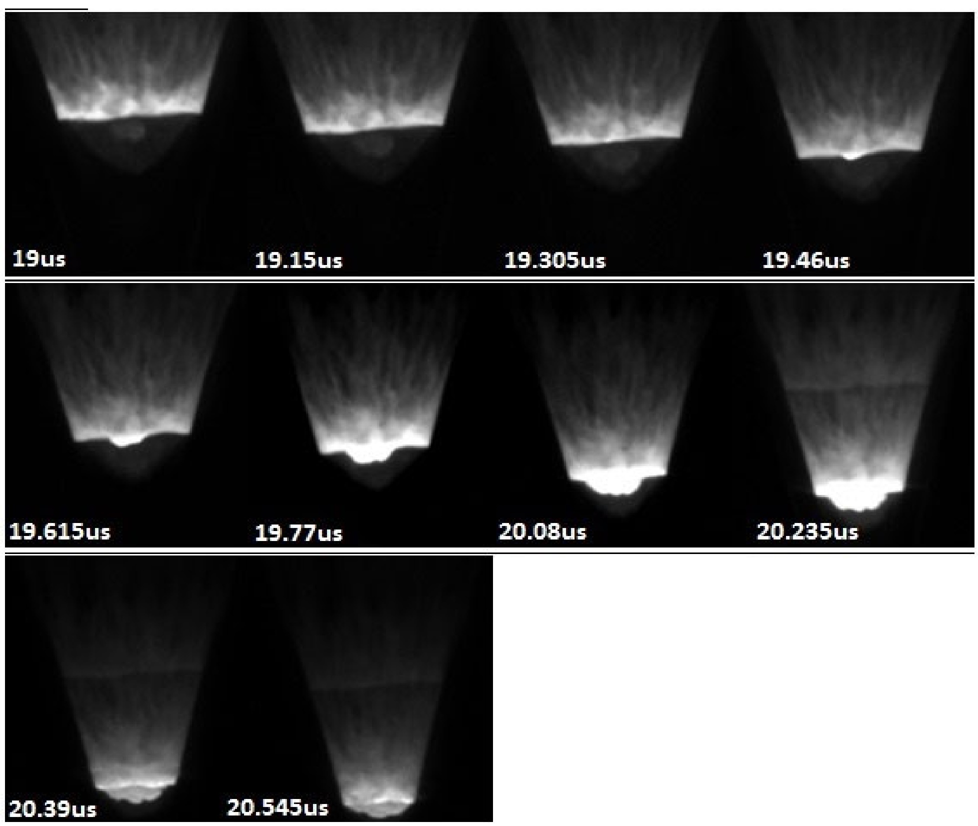


Figure 14. High Speed Images of Plasma in the Glass Cone

A downward velocity can be found from the gathered images. Figure 15 shows the velocity of the shock at the cone edge (inner surface of the cone) and the jet formed along the center axis of the cone.

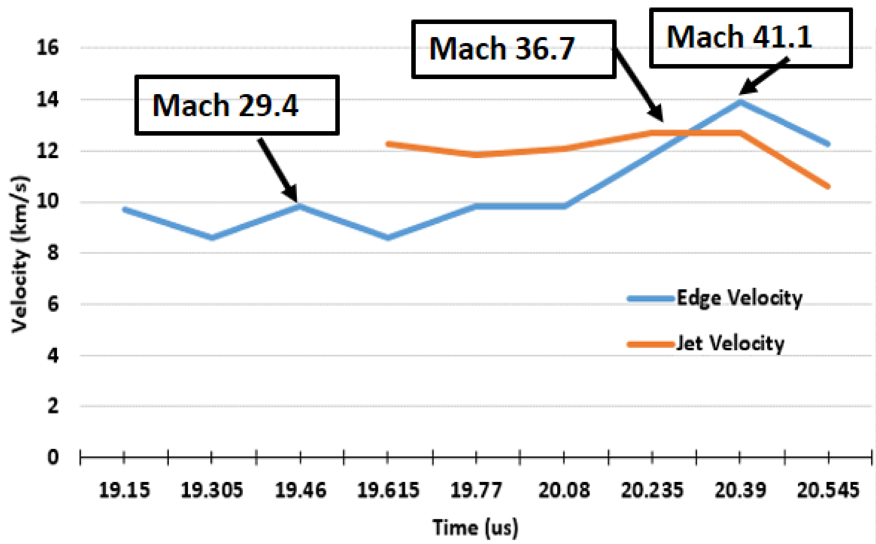
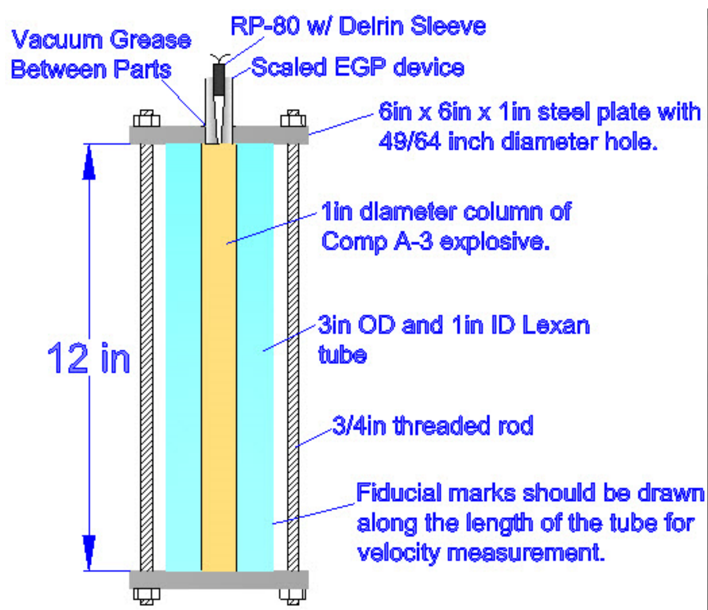


Figure 15. Velocity of Shock at Edge of Cone and Jet

Using shock tables in air, the temperature in a shock wave moving at 11.8 km/s (very close to the recorded velocity) can be found to be 20,000K[12]. It was concluded that the blackbody curve fit using spectral data is accurate.

1.3.2 Burn Rate Characterization Testing

Burn rate tests were designed to determine the speed of the reaction of the composition A-3 explosive (acceptor) in a confined system. In these tests, the acceptor explosive was constructed using multiple 1-inch diameter Comp A-3 pellets confined in a heavy walled transparent Lexan tube. The length of the tube and pellet stack was 12 inches long. Figure 16 shows both a drawing and picture of one of the test setups.



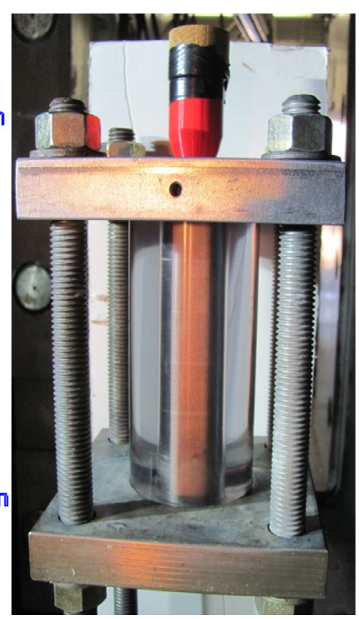


Figure 16. Burn Rate Test Setup

In some of the tests performed, an EGP device was placed in direct contact with the Comp A-3 acceptor material (as shown in Figure 15), while in experiments an EGP device was fired through a ½ inch thick steel plate at the top of the stack. In one of the tests, a small quantity (2g) of thermite was placed in direct contact with the Comp A-3 material in order to quantify the slowest attainable burn rate of the material (the burn rate that would be obtained with a zero pressure thermal initiation). The experiment was important since a non-overdriven burn rate can be used to compare this material to other known energetics. Table 1 gives an outline of the experiments performed and a look at the results.

Table 1. Burn Rate Experiment Breakdown

Test #	EGP Contact with A-3	EGP Cone Height	EGP Driving Charge	Results
1	Yes	1.35 in	203mg	Penetration of Comp A-3, but no initiation
2	Yes	1.43 in	20.96g	High order response of Comp A-3, All material consumed
3	No – fired through 1/2in plate	2.525 in	141.14g	Dying initiation of Comp A-3, 45% of material unconsumed
4	No – fired through 1/2in plate	2.9 in	252.16g	Initially high order but dying initiation of Comp A-3, 10% of material unconsumed
5	No EGP – 2g Thermite (Al/Fe_2O_3) in direct contact with Comp A-3			Very slow (0.006in/s) but complete burn of Comp A-3

Two cameras were used to record these tests. A high-speed camera (1 Mfps) was used to document detonation or fast deflagration events. A second, 30-60 fps camera was used to record longer duration burning that occurred.

Initially, the size of the EGP device was reduced and put in direct contact with the Comp A-3 material so that the upper part of the Lexan tube would not be overstressed by the device itself. This was done by drilling a 0.75-inch hole in the upper steel plate. In the first test, the Comp A-3 material required significant thermal impulse (relatively long duration heat transfer) in order to ignite. Figure 17 shows images of perforation (0.82 inch) into the top of the Comp A-3 material that failed to ignite the material.

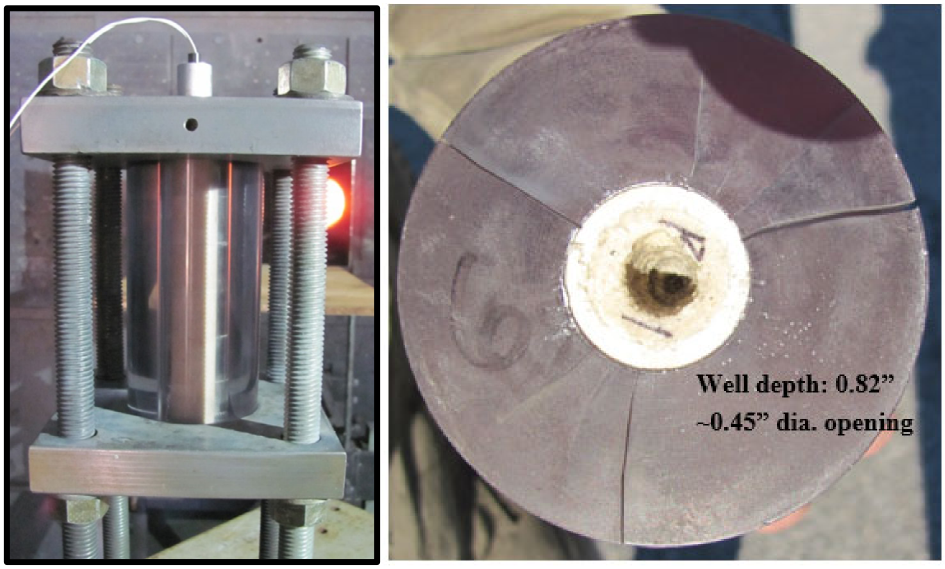


Figure 17. Test 1 Setup (L) / Resulting Perforation of EGP Gases into Comp A-3 Acceptor (R)

In Test 2, a larger EGP device was positioned directly in contact with the acceptor material. This time, the result was a high order detonation of the Comp A-3 material. Figure 18 shows a circular hole in the ½ inch baseplate indicating detonation of the acceptor for its entire length. Following the first two tests, it was decided a larger EGP device (fired through a ½-inch steel plate) would be required to impart the required heat transfer need to initiate the desired reaction in the acceptor material without initiating a detonation.

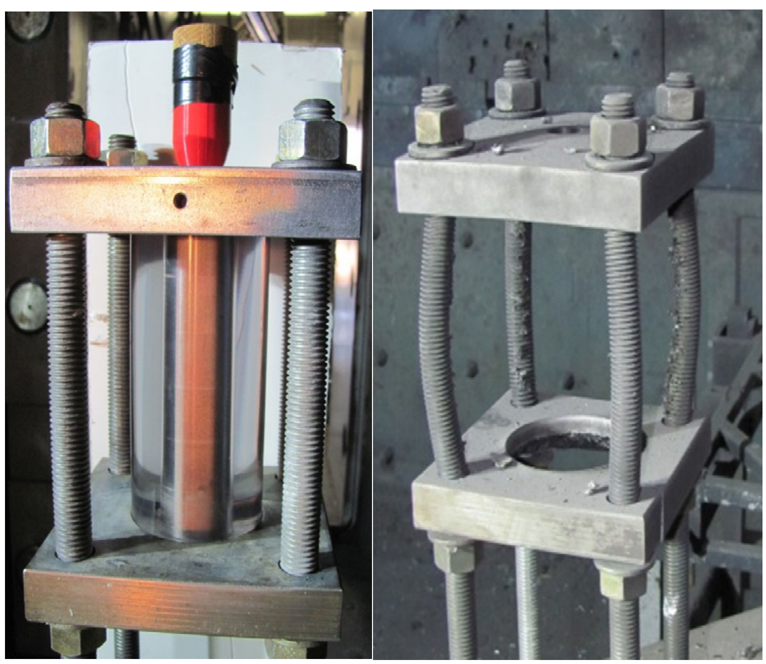


Figure 18. Test 2 Setup (L) / Resulting Circular Hole in Baseplate (R)

In Test 3, a larger EGP device (containing a 141g driving C4 charge) was used to perforate a ½-inch thick steel plate, and then flow larger quantities of gas into the Comp A-3 material. In this test, the EGP device had no problem perforating the ½-inch steel plate and initiated an initial reaction of the acceptor material. The burn died out about halfway down the tube (likely due to venting at the top of the tube), however, and left about 45% of the Comp A-3 in the tube unconsumed. Figure 19 shows the remaining hardware after the experiment.

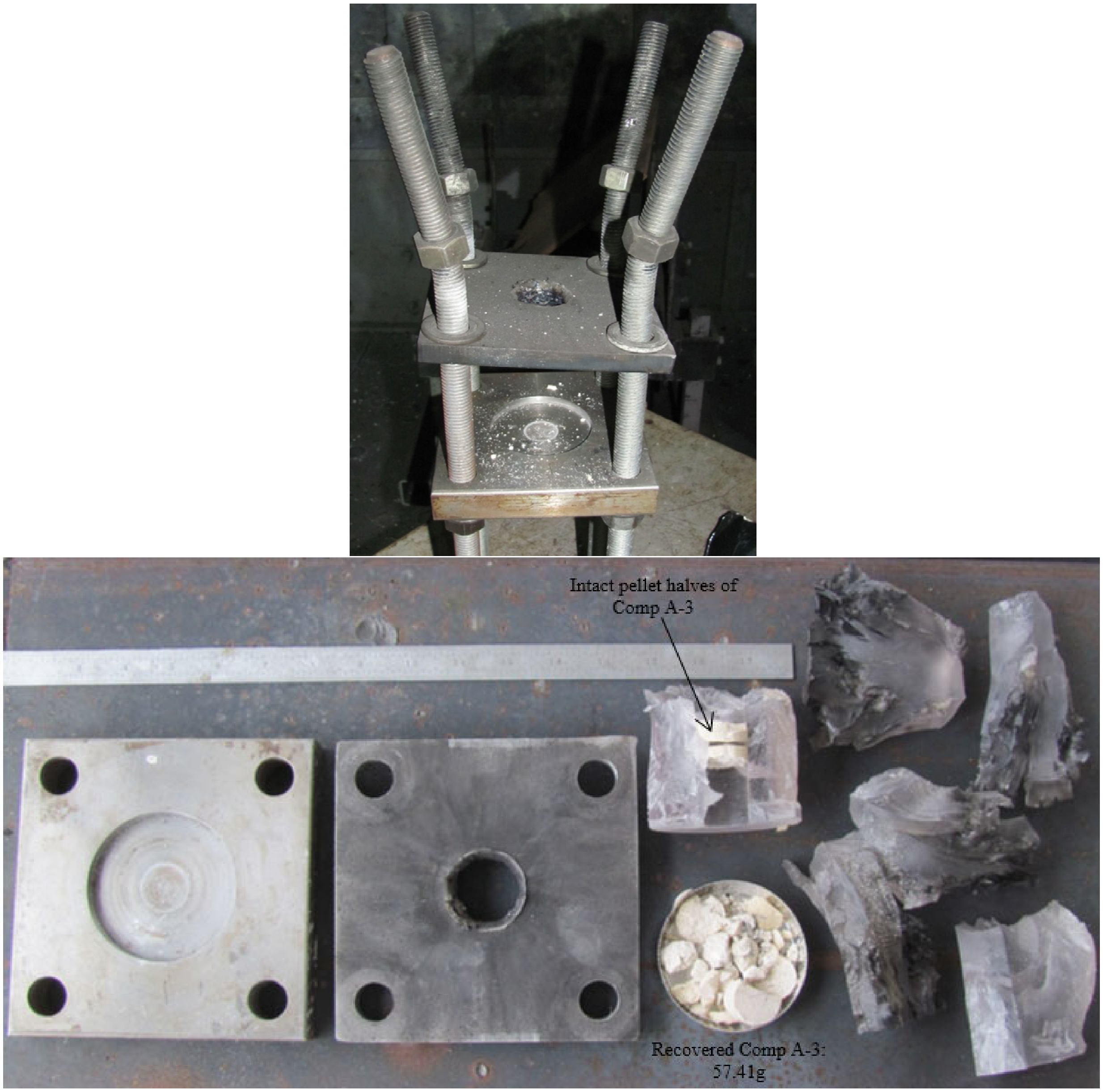


Figure 19. Hardware after Testing (Top) / Disassembled Parts (Bottom)

Test 4 was conducted to confirm the results of Test 3. In this test, the size of the EGP device was scaled up in an attempt to consume all of the acceptor material. The result of Test 4 was a partial detonation of the Comp A-3. Initially, the burn progresses down the top half of the tube at a velocity of about 2 km/s. However, once again, the burn dies out before it reaches the bottom the tube. Ten percent of the Comp A-3 material was left unconsumed in this test. Figure 20 shows the hardware following the test.

Figure 20. Hardware after Testing

Figure 21 shows high-speed images of the burn as it progressed.

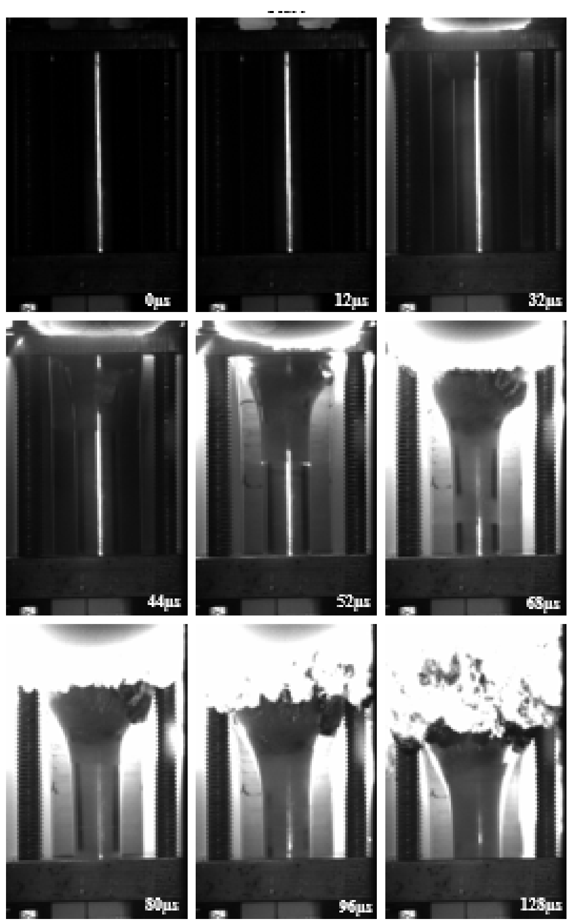


Figure 21. High-Speed Images

It was determined that visualization of a steady state burn, using an EGP device for initiation, was unlikely with the current setup. In order to better understand why the material was more difficult to thermally initiate than other explosives, a “soft” (zero pressure) method of initiation was pursued in Test 5. This time, a small quantity (2g) of thermite was placed in contact with the top of the acceptor column. The column of Comp A-3 did burn to completion, however very slowly. The average burn rate down the length of the column was only 0.006 in/s, a speed that resembles candle-like behavior. Figure 22 shows images of the burn as it progressed.

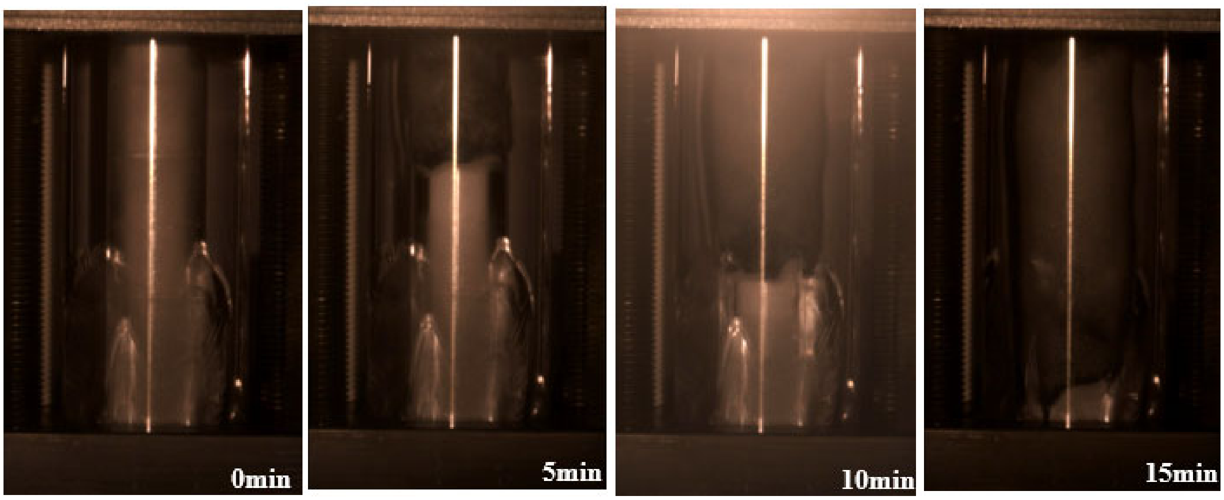


Figure 22. Test 5 Slow Burn in Comp A-3

1.3.3 Burn Rate Characterization Conclusions

- The Comp A-3 material requires significant heat transfer (long duration heating) in order to initiate the material. Larger EGP devices with a driving charge weight of at least 100g are better suited to initiate this material due their increase gas flow duration.
- As expected, the 3-inch diameter Lexan tubes used in these experiments were insufficient to contain the stresses imparted by the larger EGP devices. This resulted in early time pressure relief which is likely responsible for incomplete burning of the Comp A-3 material.
- The Comp A-3 will continue to burn if ignited. However, the inherent zero-pressure burn rate of the material is much slower than other explosive formulations. This can lead to problems in achieving slow burn rates in underwater applications, since water is much more likely to rush in and extinguish any reaction.
- It is believed that the hard wax binder in the Comp A-3 formulation is what is driving the slow burn rate of the material. Waxes have both a large heat capacity requiring greater amounts of heat for transfer to occur and require a phase change from solid to liquid before burning of the material can occur.

1.3.4 Small Scale Prompt Initiation Testing

1.3.4.1 Background on Prompt Initiation Test Setup and Testing

The purpose of the prompt initiation tests was to assess what size EGP device would be appropriate to ensure the device does not immediately detonate the Comp A-3 material in a small sample size. Although these tests do not guarantee the designed tool will not detonate the material in a naval 5-inch round, it does provide a good starting point for larger scale tests using a more economical test setup. The test setup was developed in a previous effort funded by NSWC IHD to quickly access the response of a variety of conventional and insensitive explosive formulations. The results were documented in the open distribution 16th International Detonation Symposium paper "Interactions of Explosives with Explosively Generated Plasma" [2]. A drawing of the test setup is shown in Figure 23.

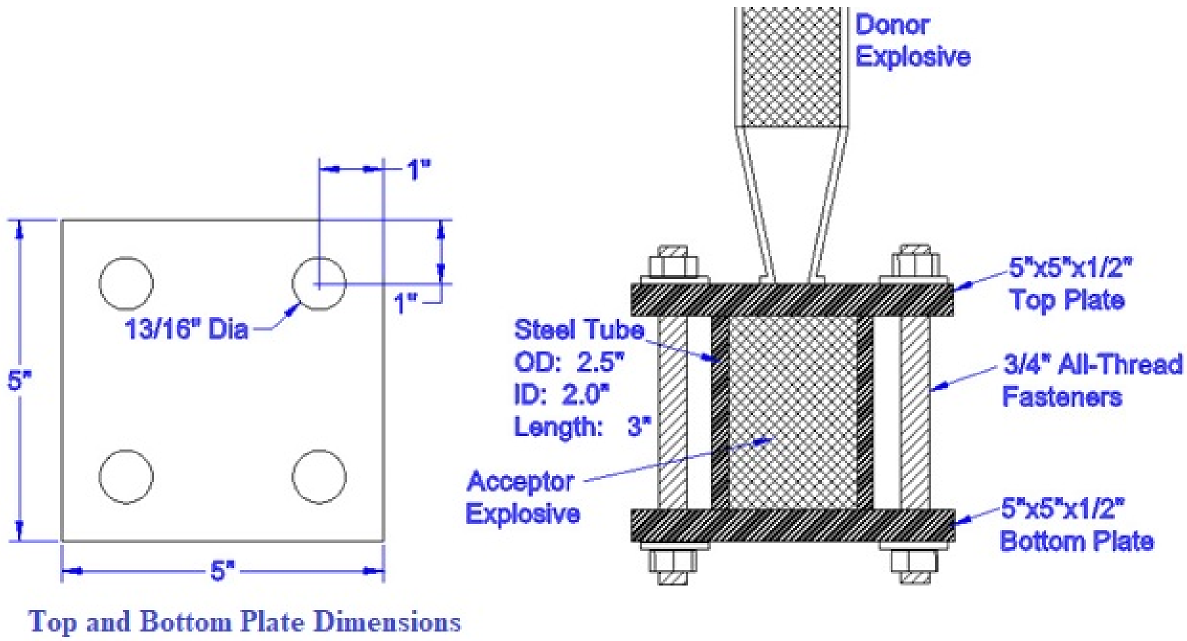


Figure 23. Prompt Initiation Test Setup

Testing of previous fielded explosive materials showed that explosive compositions containing ammonium perchlorate (AP), aluminum (Al) or inert binders were easily ignited and eventually consumed by an EGP device capable of penetrating a ½-inch thick steel plate. Table 2 shows data taken from the Interaction of Explosives with Explosively Generated Plasma", 16th International Detonation Symposium[2]. Explosive formulations have been generalized to fit this open distribution document. More detailed formulation information can be provided to ESTCP at the distribution D level.

Table 2. Previous Tests Conducted on Other Explosive Formulations

Acceptor	Waveguide	Acceptor Mass	Percent Acceptor Consumed
AP-Al Explosive 1	1.5" D Long	125 g	0%
AP-Al Explosive 1	2" D Long	257 g	82.6%
AP-Al Explosive 2	2" D Long	288 g	100%
AP-Al Explosive 2	2" D Short	244 g	99.4%
Al-Inert Explosive 1	2" D Long	248 g	100%

Al-Inert Explosive 1	2" D Long	246 g	98.6%
Al-Inert Explosive 2	2" D Short	250 g	98.9%

The typical response for these previous tests was ignition of the explosive material followed by a burning of the material lasting around 1-2 minutes, depending on the composition itself. After the EGP device perforated the top steel plate, and hot gases were allowed to ignite the material, the gases from the burning acceptor explosive vented through the hole in the top plate created by the EGP. Figure 24 shows what the test looked like after the experiment and the remnants of the burned explosive.

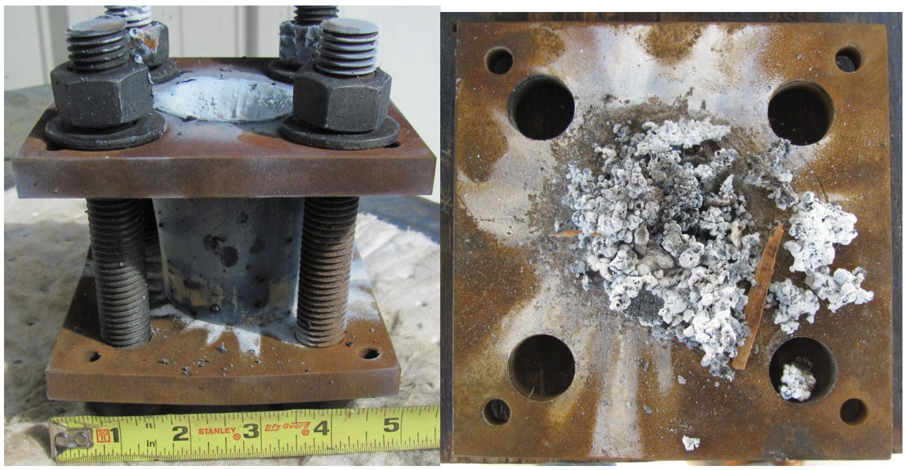


Figure 24. Post-Test Hardware (L) / Burned Explosive (R)

1.3.4.2 Prompt Initiation Testing of Comp A-3 Material

In this effort, the prompt initiation test setup was again utilized to evaluate the initiation response of the Comp A-3 material to an EGP device. In all cases, the donor charge was hand-packed C4 in the top of the EGP device. The EGP device itself was 3-D printed ABS plastic as in previous experiments. The EGP device was fired through a ½-inch thick steel plate at the top of the assembly. Pressed 2-inch diameter Comp A-3 pellets were positioned in the steel tube. The wall thickness of the tube was ¼-inch thick. Table 3 shows an outline of the prompt initiation tests performed and the results.

Table 3. Prompt Initiation Test Breakdown

Test #	EGP Cone Height	EGP Driving Charge	Results
1	2.125	105.32g	Perforation of the top plate, but minimal burning of the Comp A-3 material
2	9	252.77g	Very little perforation of the steel plate. No burning of the Comp A-3 material
3	2.844	251.94g	Perforation of top plate and complete (fast) consumption of Comp A-3 material

The first test used a smaller (roughly 105g) C4 driving charge in the EGP device. The device was capable of burning a clean hole in the ½-inch steel top plate. However, the smaller charge was not able to initiate and consume the Comp A-3 material in the steel tube below. Most of the material in the steel tube was recovered. This result provided evidence that a larger EGP device was required to overcome the thermal properties of the Comp A-3 material. Figure 25 shows pretest and post-test photos of the experiment.

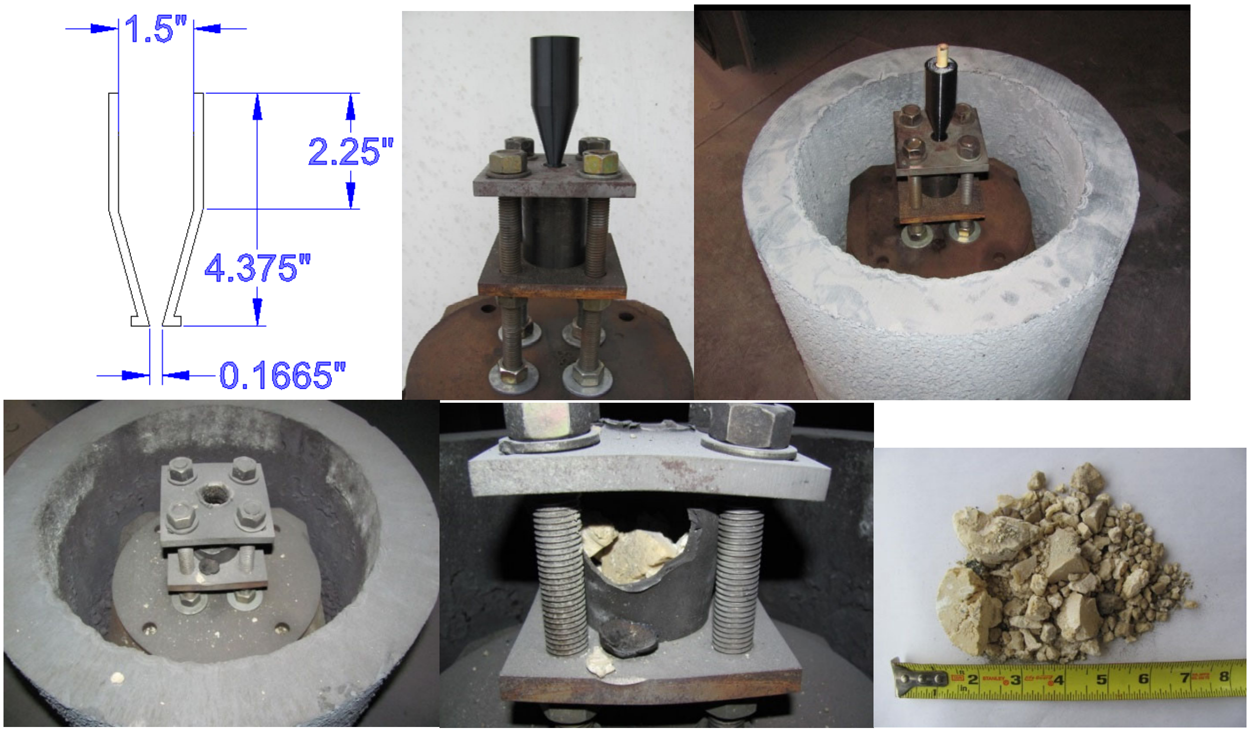


Figure 25. Test 1 EGP Cone Drawing (top left) / Pretest (top) / and Post-Test (bottom)

In the second test, a larger EGP device containing both a larger driving charge (252g) and longer cone was used. In previous experiments, this larger cone was able to petal open the steel plate. However, supported by the hard (relatively for explosives) Comp A-3 material, very little perforation of the top plate occurred so no hot gases were able to flow into the acceptor. Figure 26 shows Test 2 before and after test results.

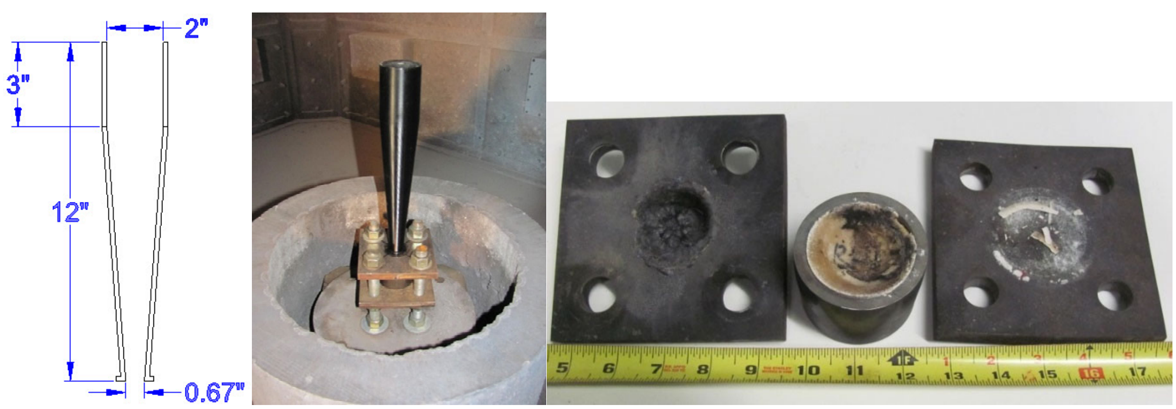


Figure 26. Test 2 EGP Cone Drawing (left) / Pretest (middle) / Disassembled Post-Test (right)

In Test 3, the length of the cone was shortened while keeping the same driving charge (making the angle of the cone similar to that used in the first test). This setup was better able to burn through the top ½-inch thick steel plate. The larger charge was used to impart more gas and pressure on the Comp A-3 material. In this experiment, all of the acceptor explosive was consumed. The steel tube split apart, but in large pieces, suggesting a low order or slow build-up event. A detonation within the steel tube would have produced much smaller fragments perforated the bottom steel plate, which did not occur. Figure 27 shows before and after pictures of Test 3.

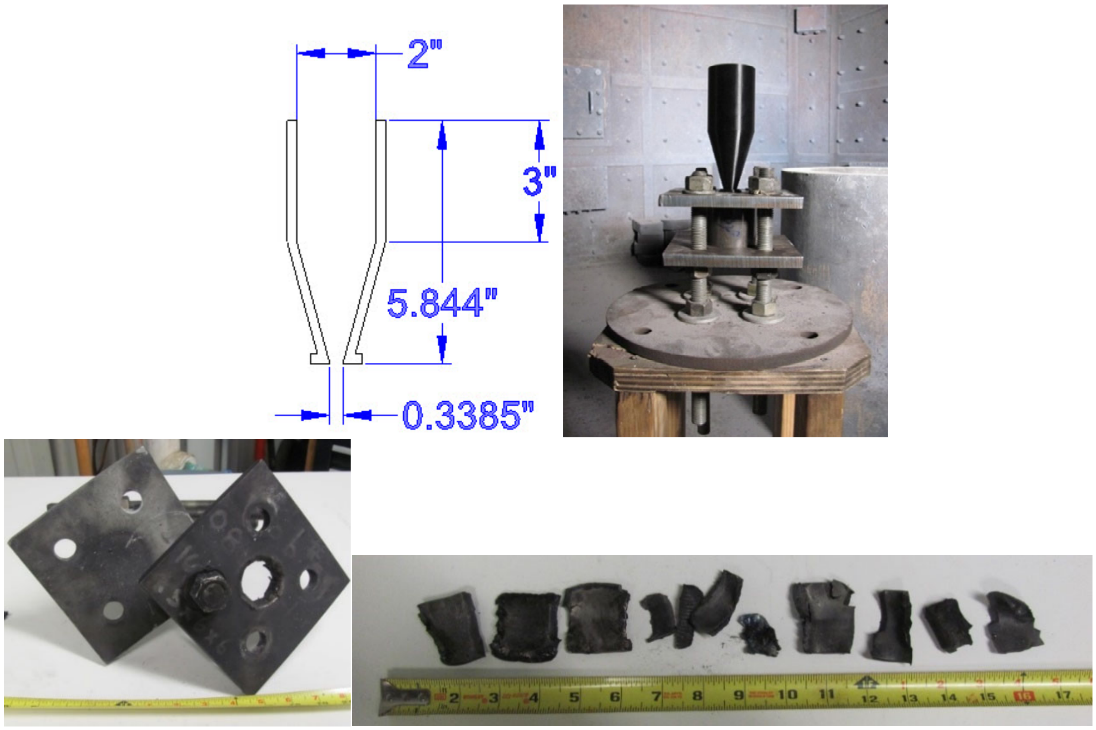


Figure 27. Test 3 EGP Cone Drawing (top left) / Pretest (top right) / Disassembled Post-Test (bottom)

1.3.4.3 Prompt Initiation Test Conclusions

- Through the prompt initiation tests, an EGP tool was found that would consume all of the acceptor material without causing an immediate high order detonation. This result gave a starting point (EGP design) for full scale testing on land.

- The EGP cone shape would be similar to that used in Test 3 and would likely require a similar donor charge used in that test, although some variation of the charge size was allowed in the next series.

1.3.5 Full Scale Above Ground Testing

The purpose of these tests was to demonstrate the ability of the developed EGP tool to safely burnout or low order full-up 5-inch rounds both in air and in a simulated underwater environment (a fish tank). The majority of EGP tools tested were mass-scaled variants of the "optimum" design (a 16.25° waveguide with a 250g driver charge) used in small scale testing (three of the shots used alternate waveguide angles). As in previous testing, all of the EGP devices were 3-D printed out of ABS plastic. For air shots, tool geometry was the same used in small scale testing, sans the addition of a curved mount to ensure proper coupling with the roughly cylindrical 5-inch rounds. The tools used in fish tank shots featured a modified geometry and were coated in a brushable epoxy in order to make them waterproof. Test targets were MK 99 Mod 4 5-inch/38 projectiles with a MK 403 MT/PD fuze and a MK 379 Mod 1 auxiliary fuze. The targets were all over 40 years old (the production lot was from 1978) and the explosives inside them even older (dating from 1968-1976).

1.3.6 Full Scale Test Setup and Overview of Results

Testing was divided into three sets. Set 1 consisted solely of air shots and was meant to gain an initial idea of the full scale target response and to observe the effects of charge size. Set 2 consisted of both air shots and water shots. The air shots examined the effects of charge size, waveguide angle, tool placement, and using multiple EGP devices at once. The water shots were meant to examine some of the effects of moving underwater and to evaluate candidates for full scale underwater testing. Set 3 consisted solely of water shots and was meant to further study the underwater response of the targets. The last set of tests was initially unplanned: they were performed when it was realized there were left over test assets still available. Figure 27 shows the full scale test setup.

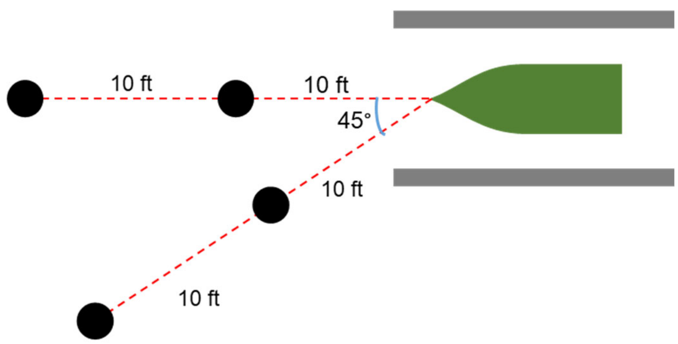


Figure 28. Full Scale Test Setup (Black Dots Represent Pressure Gauges)

An example air/fish tank shot is shown in Figure 29. Instrumentation varied depending on the test set. Set 1 had pressure gauges located placed according to the spacing in Figure 27. Set 2 used the same pressure gauge layout as set one and had two high-speed cameras (one focused near field, the other far field) and one normal camera. Set 3, being initially unplanned, had no instrumentation.

Figure 29. Full Scale Tests in Air (Left) and in a Fish Tank (Right)

A quick overview of test results is shown in Table 4. A detailed breakdown of results can be found in Appendix F.

Table 4. Full Scale Test Results

Shot #	Shot Type	Device	Charge Placement	Driver Mass (g)	Peak Overpressure (psi)	Result	Burn Time (min)	% HE Remaining
1-0	Air	Baseline high order	N/A	N/A	16.34	High order	N/A	0%
1-1	Air	0.562 scale 16.25° cone	8” from base	142g	2.369	Burnout	18	<1%
1-2	Air	0.665 scale 16.25° cone	8” from base	164g	2.745	Burnout	18	<1%
1-3	Air	16.25° cone	8” from base	250g	3.336	Burnout	16	<1%
1-4	Air	16.25° cone	8” from base	250g	3.372	Burn transitioning to low order	8	<1%
1-5	Air	16.25° cone	8” from base	250g	3.347	Burn	18	<1%
2-1	Air	1.25 scale 16.25° cone	8” from base	313	5.569	Low order	N/A	<1%
2-2	Air	2 x 0.5 scale 16.25° cone	6” and 10” from base	125+125	3.071	Burnout	10	50%
2-3	Air	2 x 0.625 scale 16.25° cone	6” and 10” inches from base	156+156	3.832	Burnout	17	<1%
2-4	Air	10° cone	8” from base	250	3.421	Burn transitioning to low order	15	5%
2-5	Air	12° cone	8” from base	250	3.209	Burnout	21	<1%
2-6	Air	2 x 0.75 scale 16.25° cone	8” from base, arranged radially	188+188	3.451	Burnout	16	5%
2-7	Air	2 x 0.875 scale 16.25° cone, radial placement	8” from base, arranged radially	219+219	6.138	Low order	N/A	<1%
2-8	Air	14° cone	8” from base	250	3.259	Burnout	14	5%
2-9	Fish Tank	Underwater 16.25° cone	8” from base	250	1.589	Low order	N/A	5%
2-10	Fish Tank	Underwater 0.875 scale 16.25° cone	8” from base	219	2.057	Low order	N/A	<1%
2-11	Air	Underwater 0.875 scale 16.25° cone	8” from base	219	3.040	Burnout	21	<1%
2-12	Fish Tank	Underwater 0.5 scale 16.25° cone	8” from base	125	0.818	Quenched burn	N/A	>95%

Shot #	Shot Type	Device	Charge Placement	Driver Mass (g)	Peak Overpressure (psi)	Result	Burn Time (min)	% HE Remaining
2-13	Fish Tank	Underwater 0.625 scale 16.25° cone	8” from base	156	2.050	Low order	N/A	30%
3-1	Fish Tank	Underwater 16.25° cone	6” from base	250	Not recorded	Low order	N/A	5%
3-2	Fish Tank	Underwater 16.25° cone with bubble wrap	8” from base	250	Not recorded	Low order	N/A	20%
3-3	Fish Tank	Underwater 16.25° cone with reduced charge load	8” from base	187	Not recorded	Low order	N/A	2%
3-4	Fish Tank	Underwater 0.875 scale 16.25° cone with bubble wrap	8” from base	219	Not recorded	Low order	N/A	5%
3-5	Fish Tank	Underwater 0.625 scale 16.25° cone with bubble wrap	8” from base	156	Not recorded	Quenched burn	N/A	>95%
3-6	Fish Tank	Underwater 0.875 scale 16.25° cone	8” from base	219	Not recorded	Low order	N/A	<1%
3-7	Fish Tank	Underwater 0.875 scale 16.25° cone	8” from base	219	Not recorded	Low order	N/A	10%

1.3.7 Full Scale in Air Results

The majority of air shots resulted in burnout of the target with burn times ranged from 15 to 20 minutes. An example burn is shown in Figure 30 and the results in Figure 31. The burns produced bright red jets of flame shooting out of the penetration hole. Flame jet size/intensity varied with time, often undergoing one or more “jumps” (rapid increases in flame brightness/height before returning to normal) before dying down. In general, the burns destroyed the booster while leaving the primary and auxiliary fuzes in place.

Figure 30. Target Burning Out

Figure 31. Target Post Burnout

Residual material from the burns took the form of a fine black ash (see Figure 32). Analysis of the ash from one shot showed that it contained approximately 0.023% RDX and 0.013% HMX. The relatively high concentration of HMX in the ash – modern "in-spec" RDX is supposed to contain only 10% HMX at most – is believed to be due to poor 60s-70s era quality control rather than the burn. Analysis of underburned material from one of the rounds, which used the same lot of explosives, showed similar ratios of RDX to HMX.

Figure 32. Ash/Booster Cup Pieces Found Inside Burnt Out Target

Some of the rounds were occasionally observed to "pop" while burning, after which point the flame jets would briefly increase in intensity. This effect is believed to be due to either the booster cooking off or a slight detonation to deflagration transition (DDT) in some of the fill. On two occasions this effect was strong enough to low order the rounds; fragments from both events were large and heavily warped suggesting a pressure rupture of the casing.

Out of all the variables examined, only charge size appeared to have any effect on target response. Too large a charge mass, whether in a single or multiple EGP tools, would cause a target to immediately low order: too small and burning would end prematurely. Burn time itself was otherwise unaffected.

Overall, the target response to EGP appears to be a two-stage process. In the first stage, the plasma/detonation products make their way into the target and reacted with some the explosives to produce an internal cavity. Once this ends, the remaining HE appears to undergo a surface regression burn (a la a solid rocket motor). The flame "jumps" (if not caused by the booster itself) are likely due to the burn encountering regions of increased surface area, i.e., the booster well and/or cracks (whether pre-existing or caused by booster cook-off, DDT, etc.).

1.3.8 Full Scale in Fish Tank Results

Unlike the air shots, the water shots either low ordered (see Figure 33) or only slightly burned the targets (see Figure 34). The low order shots produced varying amounts of residual HE, ranging from 70% to near complete consumption. What residual HE that was produced generally appeared to originate from the rear of the targets, suggesting the reaction from the booster charges. The non-low ordered targets were all found to have small blackened cavities filled with water post-firing. It appears that the EGP was able to start some burning in these targets before inflowing water quenched the reaction. Similar to the air shots, driver charge size determined the target reaction. Below some critical value (in between 125 and 156 grams) the result is a quenched burn; above said value the result is a low order. Reducing underwater tamping by wrapping the charges in bubble wrap appeared to raise this critical value.

Based on the target response, it appears the additional tamping provided by the water is "over driving" the EGP tools. The effect appears similar to that seen when using a metal EGP tool, i.e., the waveguide holds together longer driving more plasma/hot detonation products into the target. This in turn boosts the temperature and pressure inside the target to the point that what would be a burn in open air instead transitions into a low order reaction. While the water appears to be boosting the performance of the EGP tools, the fact the gap between a quenched burn and a low order was approximately 20 grams of HE combined with the time it takes for burn to occur in air suggests that achieving a true "underwater burnout" is impossible, at least for comp A3.

Figure 33. Remains of Fish Tank Shot that Low Ordered

Figure 34. Remains of Fish Tank Shot that Incompletely Burnt Out

1.3.9 Full Scale Testing Conclusions

- On land: The chosen EGP tool was able to successfully burn out the targets. Burn times were approximately 15-20 minutes and were able to consume 95+% of the target HE.

- In water: The chosen EGP tool was able to low order the targets. The increased tamping of the water appears to be overdriving the tools. Attempts to achieve an underwater burn by reducing charge size or reducing tamping with an artificial air gap were unsuccessful. Inflowing water appears to have quenched whatever reaction occurred inside the targets.

1.4 Year 3 - Underwater Testing and Evaluation

1.4.1 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.

1.4.2 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. The geometric design 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 device used in this effort will be constructed of a 3-D printed ABS plastic. A C-4 donor charge will be used to create the shock and detonation gases to translate the transmission tube and interrogate the target. The donor charge will be initiated using a Risi RP-83 Exploding Bridgewire (EBW) detonator. Efforts in years one and two of this program determined the working range of donor charge sizes and EGP system dimensions through a combination of modeling and testing. In year two, that design was optimized for the 5-inch/38 caliber round through surface testing and aquarium tank testing. Figure 35 is a drawing of the finalized EGP device to be employed.

Figure 35. 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 5.

Table 5. 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 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[13]. Larger marine life (mammals) have a safe peak impulse threshold of 5 psi-ms, while smaller marine life (fish) have a peak impulse threshold range of 20-50 psi-ms[14]. 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 unfuzed underwater with C-4 packed fuzewells to established a blast pressure baseline. The remaining 17 will be tested with unarmed MK 403 Mechanical Time/Point-Detonating (MT/PD) fuzes.

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 in Indiana (Figure 36). 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 36. 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 NSWC 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 37 shows a picture of the catch net and electric hoists at the four corners of the net.

Figure 37. 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 6. 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 6. 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 38) 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 fuze, which contains Tetryl in the primer and booster charges. The projectile uses a MK 51 steel body. This all-up configuration is assigned a Navy Ammunitions Logistics Code (NALC) of D292 and a National Stock Number (NSN)/Department of Defense Ammunition Code (DODAC)/Part Number (PN) of 1320010133174.

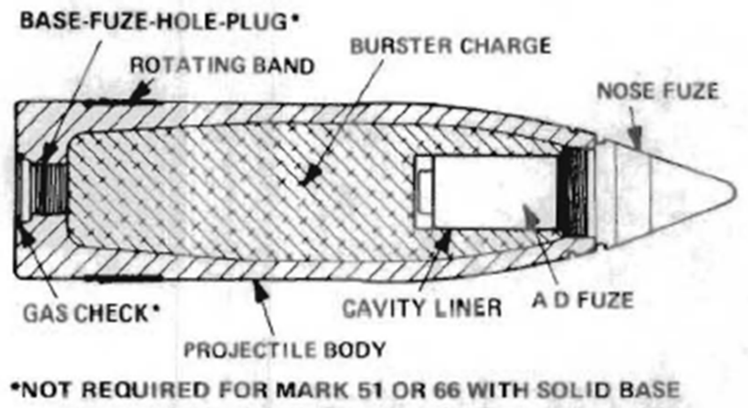


Figure 38. MK 51, 5-Inch/38 Round

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 39 for each of the EGP tests.

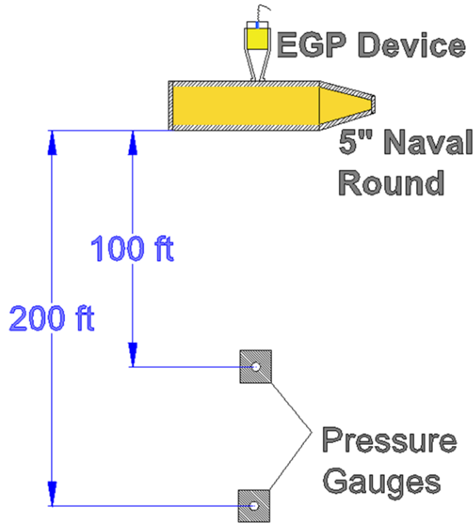


Figure 39. Pressure Probe Configuration for EGP Tests

The critical instrumentation used in this series was the underwater PCB Piezotronics pressure probes. Details of the probes are included in Appendix C, to include their National Institute of Standards and 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 squad 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 C.

5.7 Experimental Procedures

General safety precautions and procedures are covered in the Lake Glendora Standard Operating Procedure (SOP). The 5-inch/38 caliber rounds were delivered and tested fuzed. The test day procedures followed in this series are shown in Table 7.

Table 7. Test Day Procedures

Configuration	Description
5-inch/38 MT/PD (Baseline)	• Pack fuzewell of unfuzed 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

Configuration	Description
	• Recover divers and return to a safe area and fire per the Lake Glendora SOP CR-JXRN-LGTF-P-0036 • 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 • Recover divers and return to a safe area and fire per the Lake Glendora SOP CR-JXRN-LGTF-P-0036 • 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 40). 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 140 gram charge of C-4 was used to initiate the booster in the 5-inch round. Figure 40 is a picture of the charge prior to lowering it to depth.

Figure 40. 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. In Figure 41, 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 8. A measured peak pressure of approximately 130 psi and 0.4 psi-ms was recorded in the baseline tests.

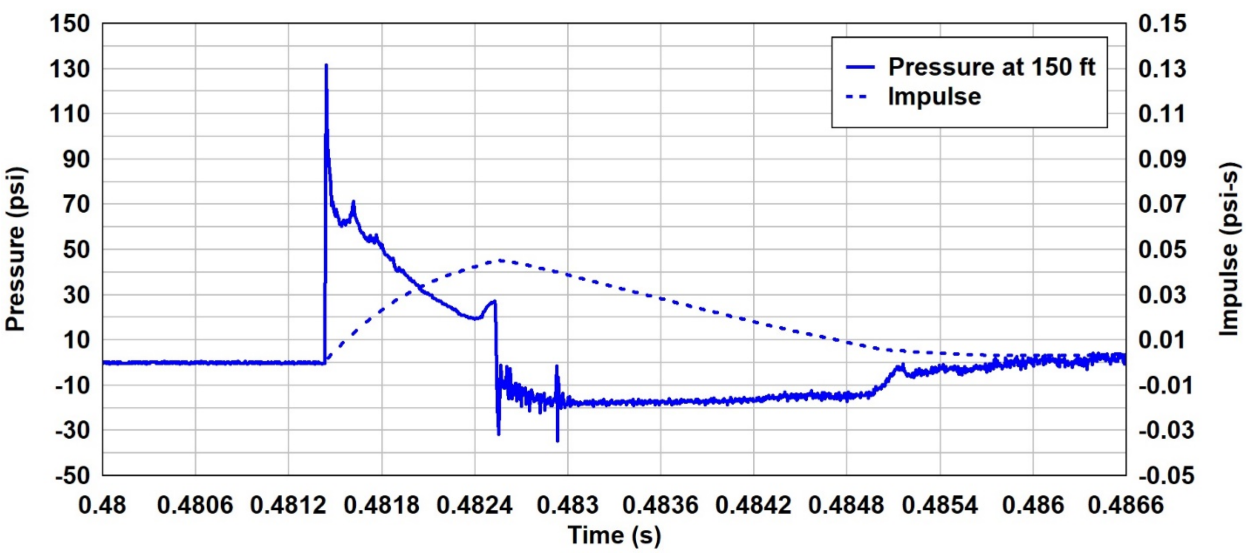


Figure 41. Typical Pressure and Impulse Data Recorded at 150 Foot and 20 Foot Depths

The energy spectral density of the baseline shots was numerically derived from pressure-time data using a method described in Appendix D. Peak energy flux and the frequency of the peak are summarized in Table 10. Since the hydrophones ceilinged during the baselines, only the tourmaline gauge data was analyzed. Figure 42 presents one of the baseline shots. As a point of comparison, energy spectral density was calculated using an analytical method (also described in Appendix D) combined with similitude relations (again, see Appendix D). 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[15] and old experimental data[16],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 these divergences are discussed in Appendix D.

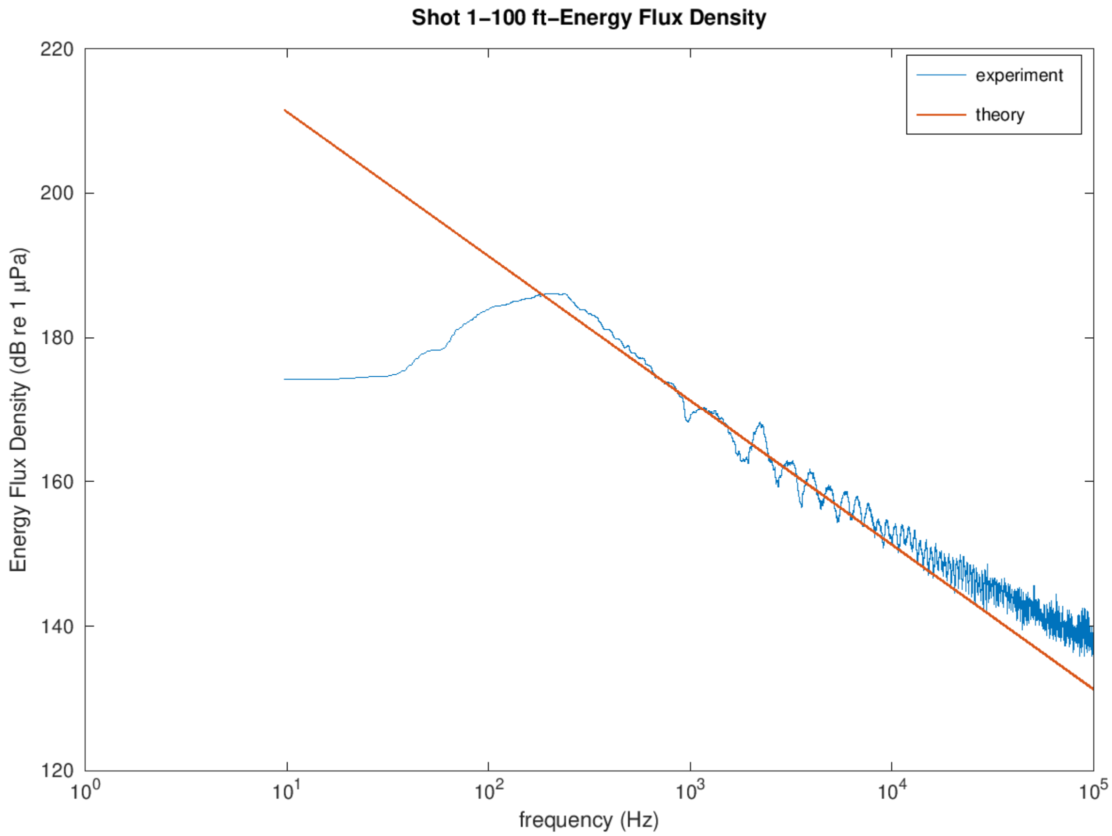


Figure 42. Energy Flux Density Spectra for Baseline Shot

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 43 shows the EGP device attached to the round prior to being lowered to depth.

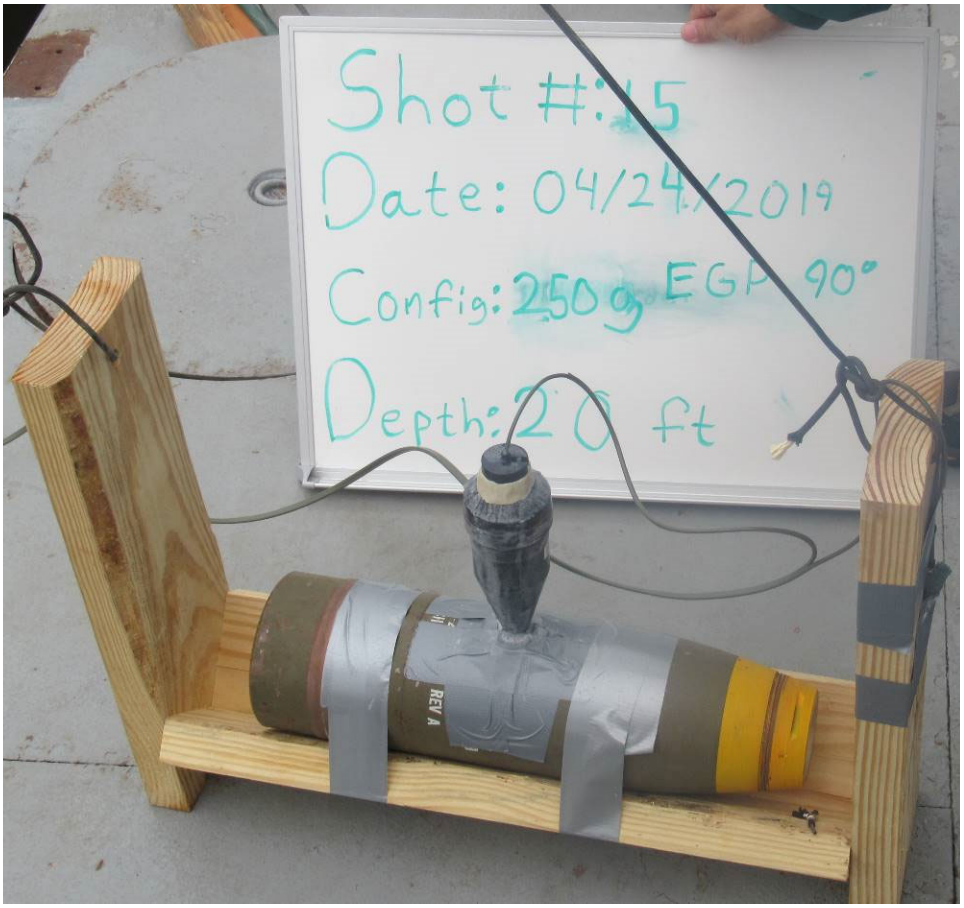


Figure 43. EGP Device Attached to Naval 5-Inch Round

In some of the tests, water was successfully kept 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 fuze was ejected from the round. It is assumed that an ejected fuze 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 44 shows an ejected fuze 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 44. 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 be completely consumed and all components of the UXO are readily accessible following this type of response. Figure 45 shows the pieces of the naval 5-inch/38 caliber round following testing.

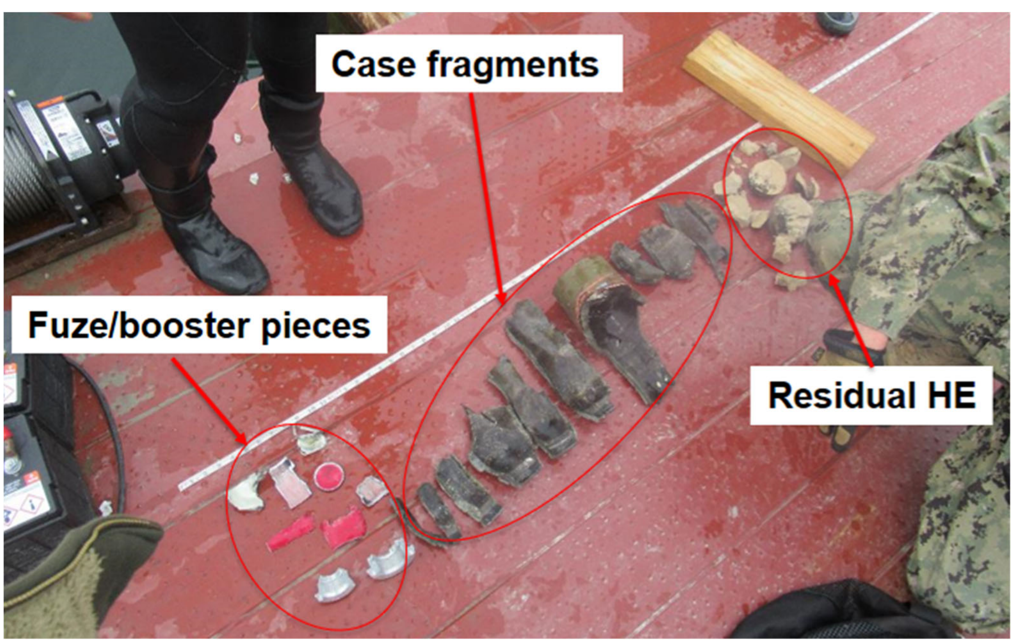


Figure 45. UXO Components Following Low Order Reaction

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 46 shows the recorded pressure and impulse from the EGP test. Table 8 shows some important measured peak pressures and calculated impulses at 100 feet and 200 feet from the charge.

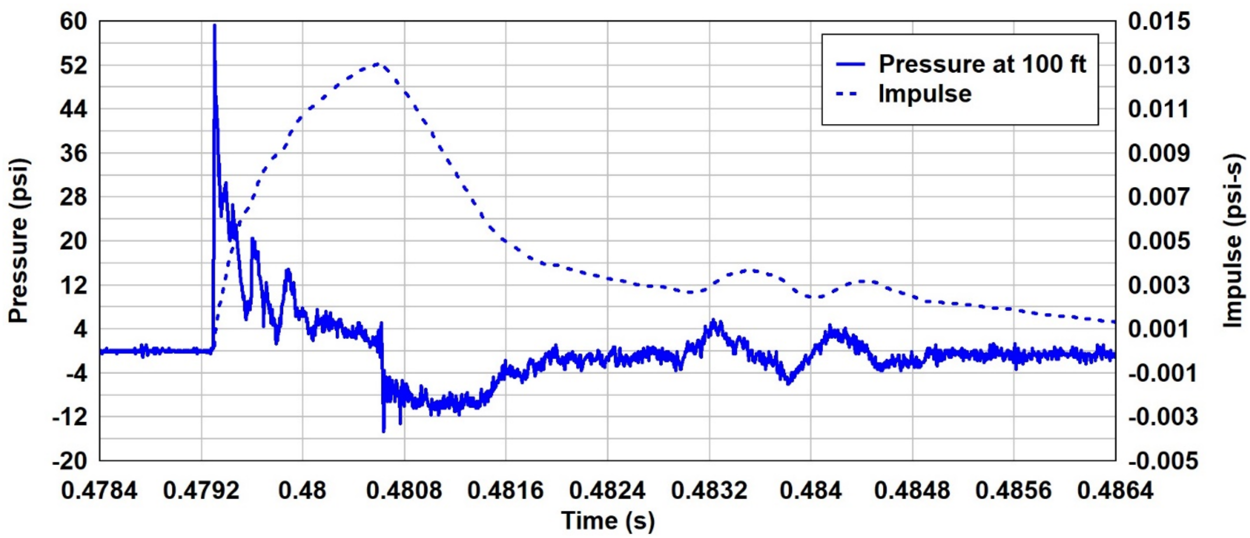


Figure 46. Recorded Pressure and Impulse in EGP Low Order Event

Table 8. 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 Fuze	80.67	0.0158	47.33	0.0134
250g EGP	20	Low Order Response	59.32	0.0096	22.07	0.0039
Bare 250g C-4 Charge**	N/A	N/A	82.32**	0.01423**	35.93**	0.0075**
Percentage Reduction*			72.3%	87.4%	76.4%	90.3%
Criteria Success – Section 3.1.3			✓	✓	✓	✓

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

***Calculated from similitude parameters for C-4*

Animal impact assessments were performed using data collected in the SEAWOLF[19] and Kilma et al[20] assessments. The assessments outline the impact reduction for a 12.2 kg dolphin calf and both "small" and "large" sea turtles. Figure 47 and Figure 48 provide a visual arc for the

Animal impact assessments were performed using data collected in the SEAWOLF FEIS[19] and Kilma et al[20] 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 (using similitude) and calculating the standoff distances at which the thresholds occur for dolphin calves and sea turtles. Figure 47 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.

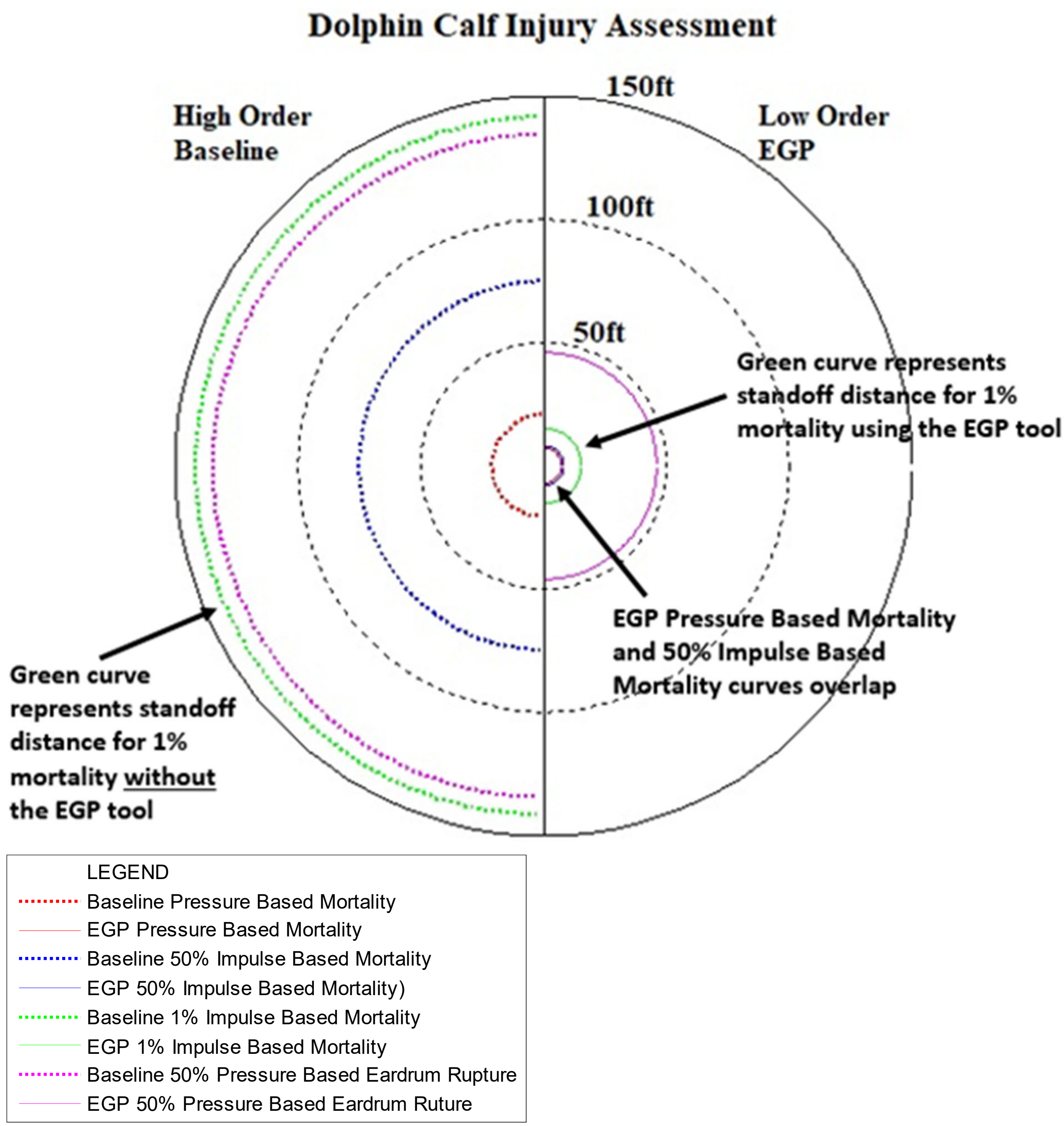


Figure 47. Radial Arcs for Projected Impacts to Dolphin Calf

Figure 48 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.

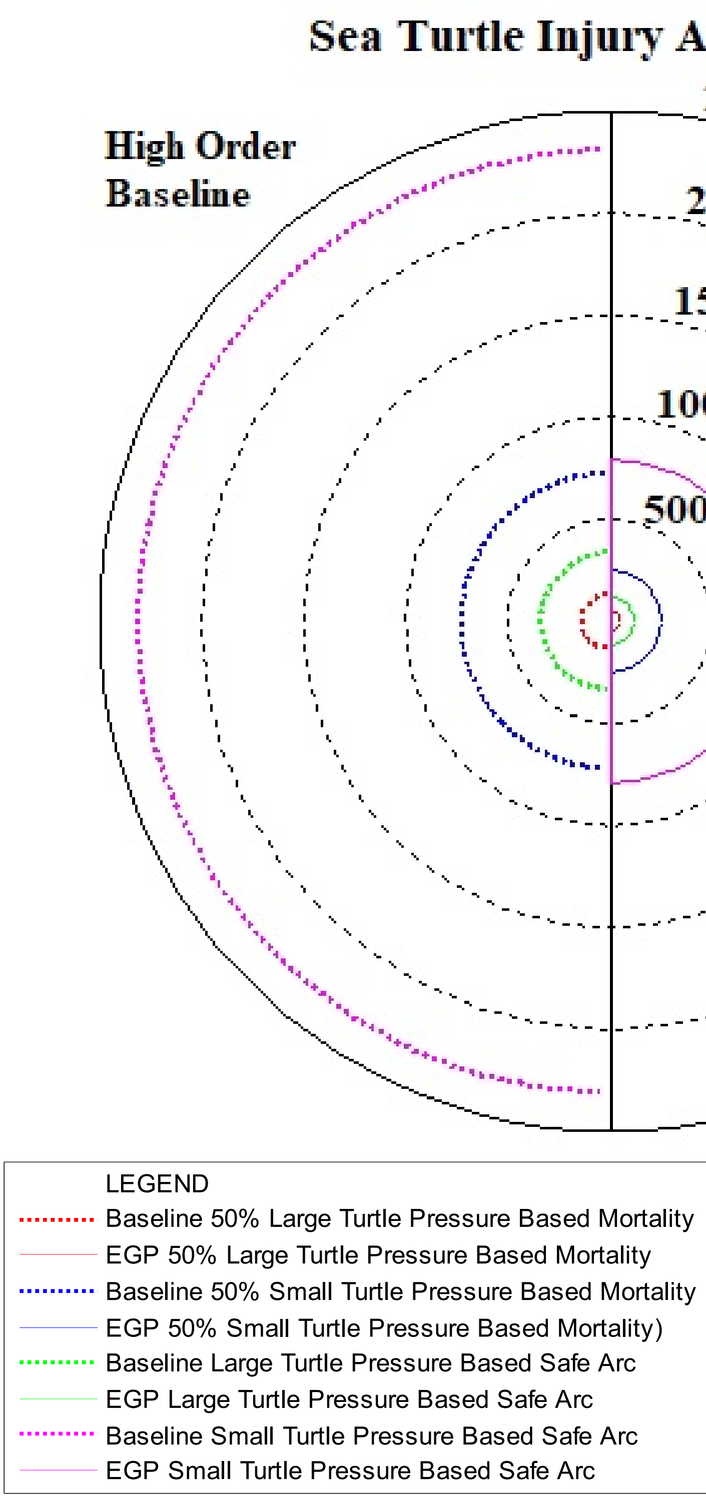


Figure 48. Radial Arcs for Projected Impacts to Small and Large Sea Turtles

Table 9 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 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 9. 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[19]
**Data collected by Kilma et al[20]
***Data collected by CHURCHILL draft FEIS

Spectral energy density was calculated using the same methods as the baseline data and presented in Figure 49. While looking through the data, it was discovered no hydrophone data was recorded for the EGP shots. Discussions with test personnel revealed they had removed the hydrophones after the issues observed during the baselines. 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[17]. 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[18]. Like the baselines, the peak energy flux frequency appears to have been shifted forward by surface cut-off.

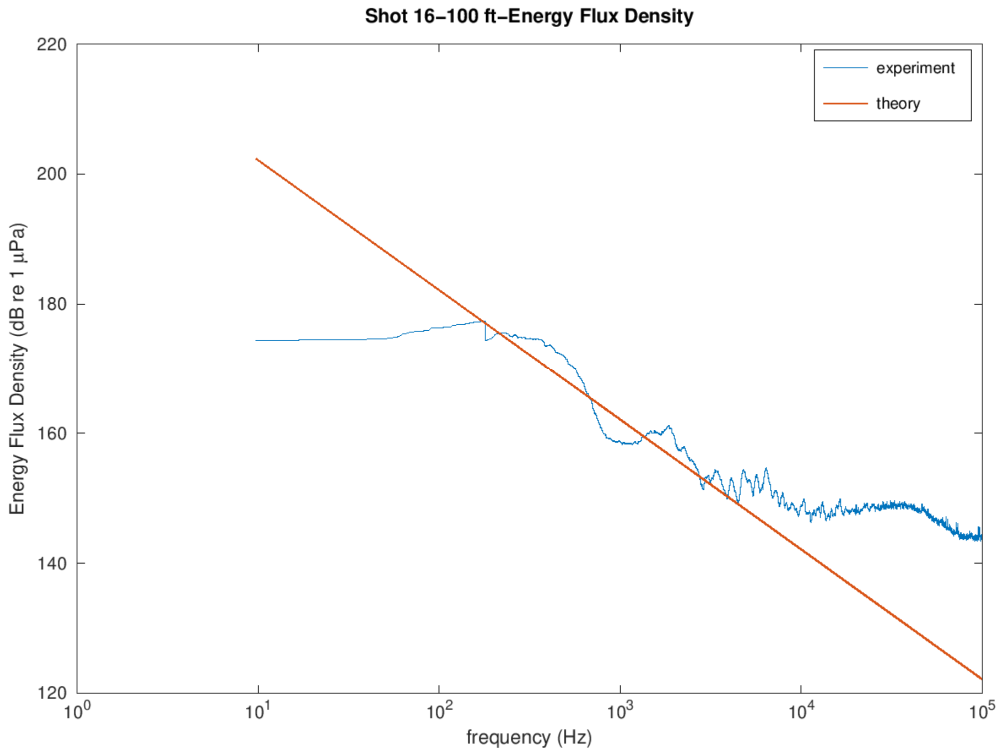


Figure 49. Energy Flux Density Spectra for Low Order Shot

Table 10 outlines the peak energy flux and the frequency of the peak flux seen in the baseline (20 foot depth), EPG ejected fuze (50 foot depth), and EGP low order (20 foot depth) tests.

Table 10. 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 50 shows the modeled EGP Case Penetration at 43µs with and without 1 inch of water in the device.

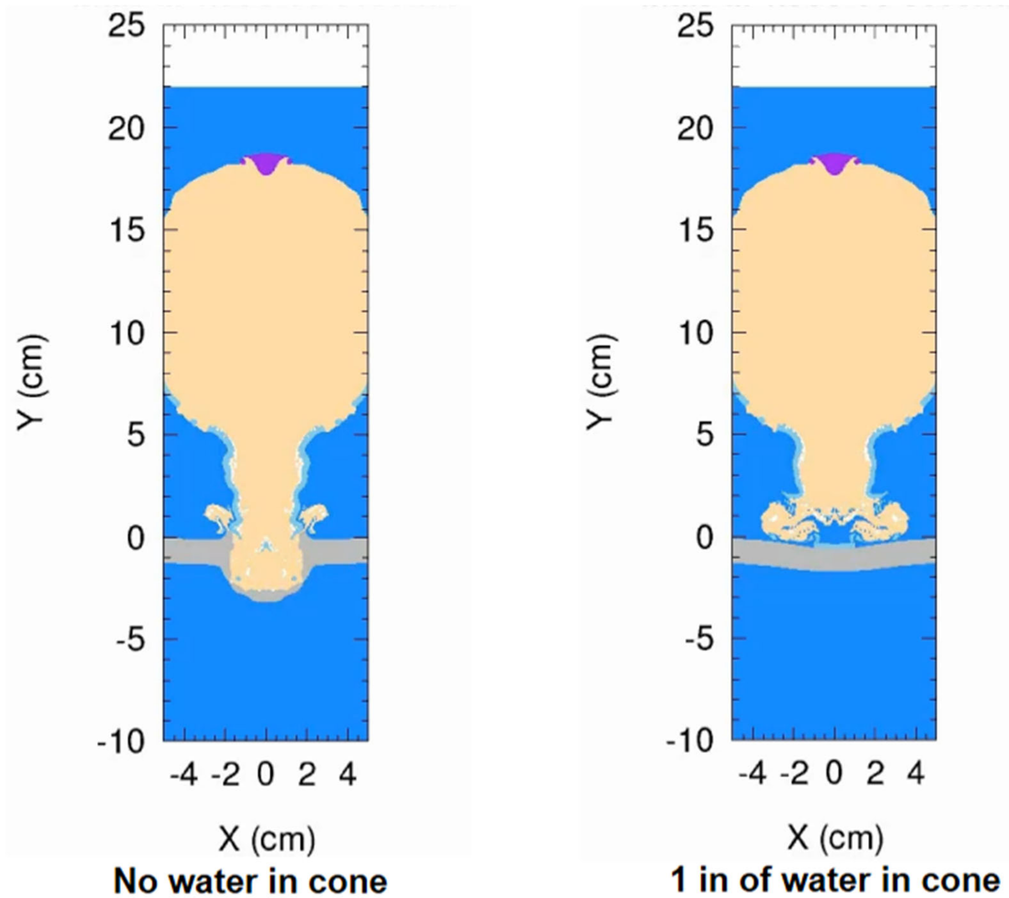


Figure 50. Modeled EGP Case Penetration

Several of the early EPG tests conducted at failed to penetrate the casing of the naval 5-inch/38 rounds. Figure 51 shows one case in which penetration was not achieved.

Figure 51. 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 52).

Figure 52. 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 IHD contacted Edward Braithwaite at NRL and Peter Traykovski at Woods Hole Oceanographic Institution for improving waterproofing of the current tool design. A new tool design was 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 and gaps in waterproof coating of the 3D printed material. Based on this, the device was re-engineered to be made of machined plastic and to incorporate triple O-rings.

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.

Stripped down test assets (lacking external hardware for mounting, cap placement, etc but otherwise functionally equivalent) have been produced and successfully leak tested at 200ft for 2 hours. Figure 53 shows these system improvements.

Figure 53. Updated Waterproof EGP Device Design

7.2 Leak Testing (Pressure Pot Testing)

Figure 54: Before and after leak testing of the new design

As previously mentioned, leak testing of a stripped down version of the new design at room temperature have already been completed. Leak testing was performed by placing the devices in a water filled pressure pot pressurized to 200 ft of seawater equivalent for 2 hours. Water infiltration was measured by both changes in tool mass and visual inspection. Due to difficulties putting the tool together, the new design was only tested with two O-rings. 10 room temperature tests were performed. Despite the reduced number of o-rings, all 10 tests were successful.

Based on the success of the room temperature tests, leak testing will repeated for cold water conditions (achieved by adding ice to the pressure pot). If 10 out 10 coldwater tests are successful then the new design will be considered ready for testing at Lake Glendora.

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 Figure 37 and Figure 39). Although leak testing will be performed prior to arriving at Lake Glendora, the first tests performed onsite 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 where 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 140 grams charge of C-4 on the booster of the munition.

At least three 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 6. 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 fuze of the device.

Table 11 shows the proposed test matrix that will be followed at the Lake Glendora test range.

Table 11. 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
e	EGP Test 10	80

7.4 Go/No-Go Criteria

Table 12 outlines the testing to be conducted in the proposed effort along with Go/No-Go criteria for each test.

Table 12. 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 13 outlines the efforts and cost associated with additional validation testing at Lake Glendora.

Table 13. 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 machined plastic prototype. The use of machined material is required for waterproofing reasons. While 3D printing would be ideal from a field acquisition point of view, waterproofing 3D printed parts in a consistent and practical (i.e. doable in the field with minimal training and without expensive equipment/materials) has proven to be incredibly difficult if not impossible. 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.

The estimated cost of the tool is approximately $400 per item for a machined item, 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 14.

Table 14. Cost Assessment

Cost Element	Data to be Tracked
Device Cost: $400.00	Per device cost in $/device • Derived from material costs and shop time required to manufacture a single prototype
Explosive Driver Cost: $20.00	Cost of C-4 in $/pound • Derived from material cost at time of demo

9.0 SCHEDULE OF ACTIVITIES

Task Name	FY21			
	Q2 JAN-MAR	Q3 - APR	Q3 - MAY	Q3/4 JUN-JUL
Preparation for Demo	Test Plan			
Demo Testing at Lake Glendora		1 Week		
Data Analysis			1 Month	
Final Report				2 Months

10.0 MANAGEMENT AND STAFFING

Name	Roles	Code	Phone Extension
George Torres* NSWC IHD	Demo Test Director	D27	(301) 744-5183
Thomas Douglas* NSWC IHD	Principle Investigator	D22	(301) 744-5159
Samuel Emery* NSWC IHD	Co-Principle Investigator	R12	(301) 744-4166
Daniel McCarthy* NSWC IHD	Project Engineer/Data Recorder	D26	(301) 744-5075
Paul Giannuzzi* NSWC IHD	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 IHD	Navy EOD Liaison / Service Rep	FLTLAU	301-744-6828
Marine EOD Det Rep NSWC IHD	USMC EOD Liaison / Service Rep	MCD	301-744-6814

*POCs for demonstration testing

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APPENDIX A. HEALTH AND SAFETY PLAN (HASP)

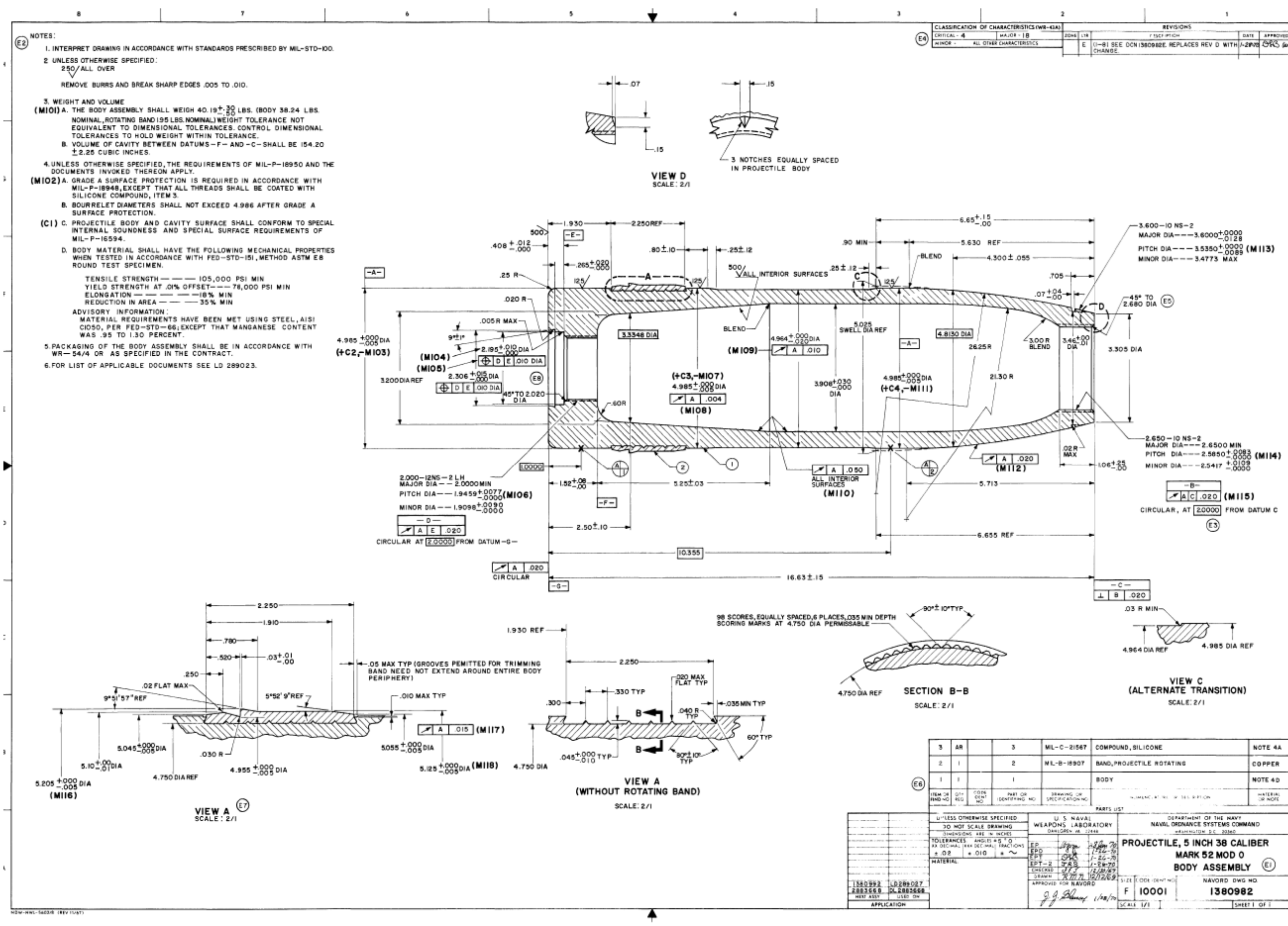
Lake Glendora Test Facility is an explosive test range with site approval for ordnance operations through Naval Ordnance Safety & Security Activity (NOSSA) and Department of Defense Explosives Safety Board (DDESB).

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 the limited release, For Official Use Only (FOUO) document "Land and Waterborne Ordnance Operations Onboard Lake Glendora Test Facility; SOP# CR-JXRN-LGTF-P-0036" which cannot be provided in this documentation plan. All operations will be conducted to the reference site SOP that also includes medical and evacuation instructions.

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



APPENDIX C. PRESSURE PROBE / HYDROPHONE SPECIFICATIONS

CALIBRATION CERTIFICATE

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

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

aws

Sensitivity*: 0.9890 mV/PSI
143.4 mV/MPa

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

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

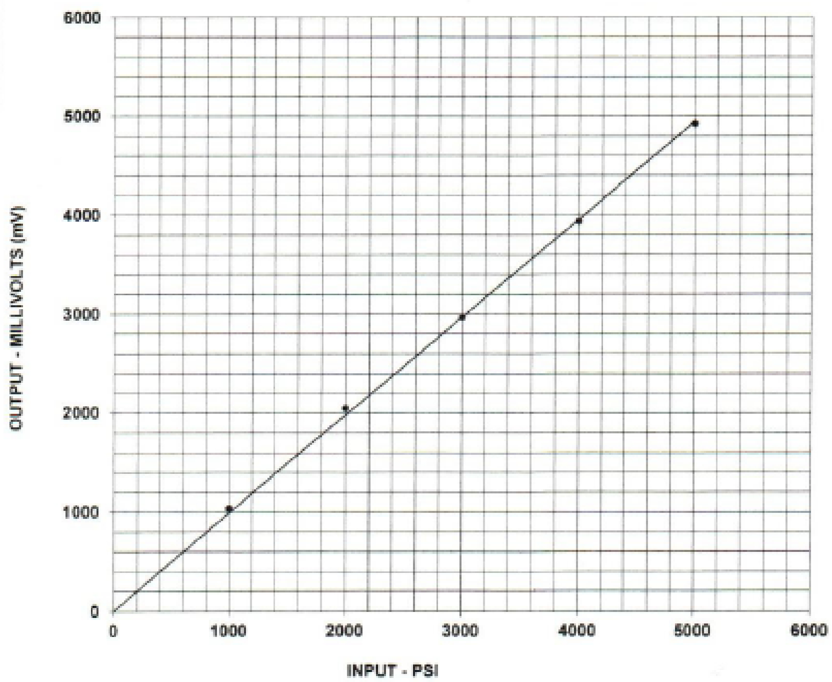
Cert #: 712908

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

Sensitivity*: 5.105 mV/PSI
740.3 mV/MPa

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

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

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

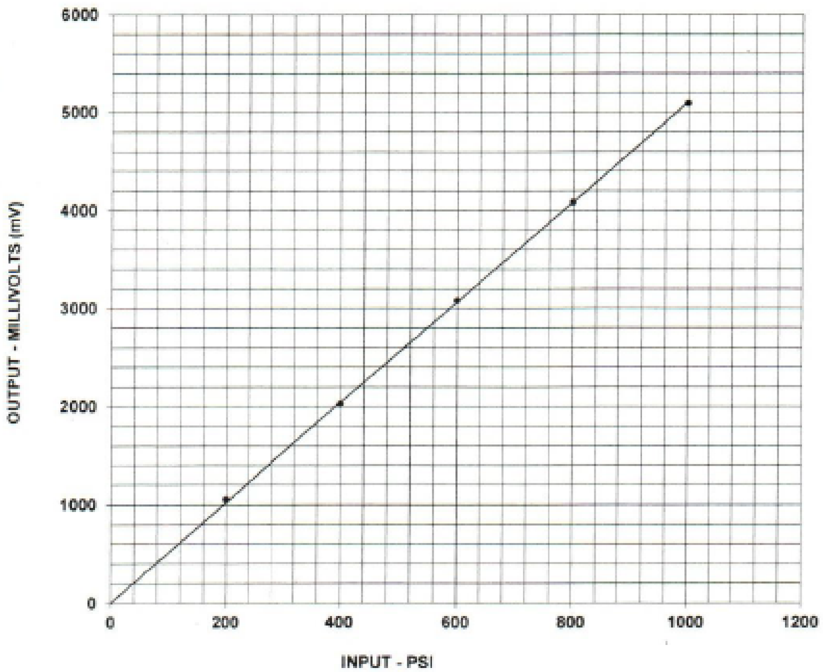
Cert #: 712892

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.
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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21120 Johnson Road
Long Beach, MS 39560

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

1133/1/1 Hydrophone Information

09/28/18

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 D. 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[15]:

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

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 to

$$E_1 = \frac{8}{\rho c}\left(\frac{\left(\frac{P_1}{t_1}\right)}{\frac{1}{T_1^2} + 4\pi^2 f^2}\right)^2 \tag{2b}$$

where

P_1=peak bubble pressure
T_1=bubble period

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

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

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

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

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

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

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[16].

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 some feature other than shock and bubble impulse is dominating at low frequencies, namely surface cut-off. The exact cause of the high frequency divergence is unknown. A brief literature survey turned up no information; past studies (e.g., [15, 16, 21]) appear to have been unconcerned about frequencies beyond 10 kHz: the peak operating frequency of cold war era U.S. sonar systems.

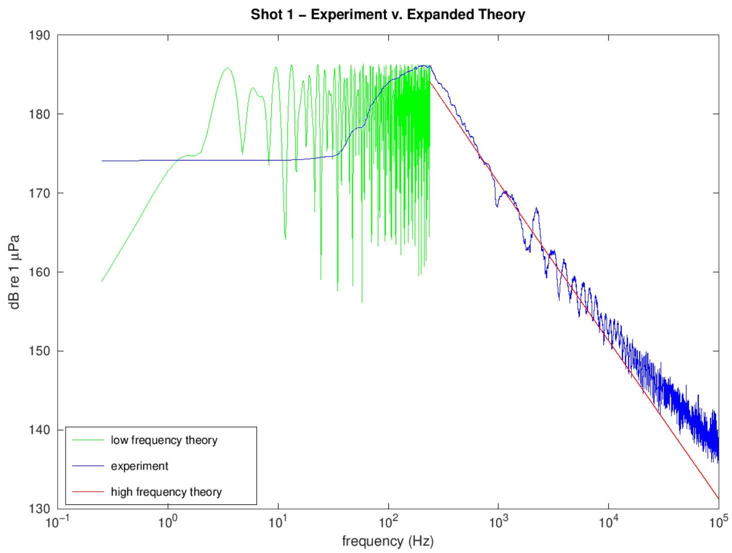

Figure 55. Experiment vs. Expanded Theory for Shot 1 at 100 Feet

APPENDIX E. ARRHENIUS BURN MODEL DEVELOPMENT METHODOLOGY

An Arrhenius burn model (ARB) was developed for the high temperature initiation of RDX in CTH by EGP using the following one-step burn relationship:

$$\frac{d\lambda}{dt} = (1-\lambda)Fe^{\left(-\theta/_{T}\right)}$$

where

$$\theta = \theta_o(1 + A_P P)$$

and

λ=ratio of unreacted and reacted material

T=material temperature

$\theta_o =$ Activation Temperature = 1.86557 eV.

(from Hobbs M. L., et al., "Modeling RDX Ignition", JANNAF CPIAC CD-53.)

The above one-step burn relationship was fitted to the high temperature chemical kinetic mappings for RDX provided by the CVTX simulations. Utilizing the results of the CVTX simulations at 1000K and 5000K RDX, the frequency factor (F) and pressure coefficient (A_P) were determined by numerical integration of the temperature-time histories of the detailed kinetic results. An iterative process was then used to find values of F and A_P that produce similar values to these integrals at both 1000K and 5000K in CTH model runs. The resulting values were determined to be:

$F =$ Frequency Factor = 3.084×10^{15}

and

$A_P =$ Pressure Coefficient = 1.155×10^{-11}.

To reduce differences between the one-step relation and the detailed RDX kinetic results, a shift in zero energy factor (ESFT) was applied in the Arrhenius model in order to better match the final temperatures with those seen in the detailed kinetics model. The CTH Mie Gruneisen RDX EOS is used for the unreacted material and the Sesame EOS is used for the reacted material in the one-step model. An ESFT was applied to the product gas Sesame EOS, and the ESFT result was

ESFT = Shift in energy zero applied to product gas equation of state = -4.4934×10^{10}.

The ratio of the final reacted temperatures and integrated areas predicted by the CTH one-step Arrhenius model to the detailed kinetic models are shown in Table 15.

Table 15. Ratios of CTH One-Step Arrhenius Model to the Detailed Kinetic Results

	$T_i = 1000K$	$T_i = 5000K$
$\frac{T_f(CTH)}{T_f(kinetics)}$	1.1572	0.8901
$\frac{Integral\ (CTH)}{Integral\ (kinetics)}$	1.0978	0.9614

APPENDIX F. FULL SCALE TEST RESULTS

Shot Number: 1-0 (high order calibration)
Date: 9/12/18
Target: 5-inch/38 in air with fuze/booster removed
Tool: N/A
Placement: 8 inches from the base with tape
Explosive Mass: 142 g (packed into fuzewell)
Reaction Category: High Order
Peak Overpressure: 16.34 psi
HE Remaining: 0%
Fuze/Booster Status: N/A

Figure 56. Shot 1-0 Setup

Summary: The weight of explosives packed into the fuzewell was chosen to match the NEW of the smallest EGP device. The round high ordered as expected. Fragments were large, but of a consistent size.

Figure 57. Case Fragments

Shot Number: 1-1
Date: 9/12/18
Target: 5-inch/38 in air
Tool: 0.562 scale Boswell
Placement: 8 inches from the base with epoxy
Explosive Mass: 142 g
Reaction Category: Burn
Peak Overpressure: 2.369 psi
HE Remaining: <1%
Fuze/Booster Status: Fuze in place, booster destroyed

Figure 58. Shot 1-1 Setup

Summary: The round burned for ~18 minutes. A column of bright red flame was observed shooting out of the penetration hole. The flame was initially fairly laminar, but became much more turbulent right before the round went out. A few times during the course of the burn, the flame sputtered out before reappearing, possibly due to ash buildup.

The target was found intact with the fuze still attached. The case was still hot 1 hour after the burn stopped. The green casing paint appears to have been burned off by the flames, revealing the underlying red primer. The interior of the case was filled with black ash. The fuze was removed using a half block of C-4. The fuze removal dented the nose of the casing but appears to have caused no other damage. This, combined with presence of booster cup pieces inside the body, suggests that the booster was burned out as well.

Figure 59. Target Post-Firing

Figure 60. Ash Inside the Casing

Figure 61. Ash and Booster Cup Pieces Poured out of the Casing

Shot Number: 1-2
Date: 9/13/18
Target: 5-inch/38 in air
Tool: 0.665 scale Boswell
Placement: 8 inches from the base with epoxy
Explosive Mass: 164 g
Reaction Category: Burn
Peak Overpressure: 2.745 psi
HE Remaining: <1%
Fuze/Booster Status: Intact and in place

Figure 62. Shot 1-2 Setup

Summary: The round burned for ~18 minutes, during which time large amounts of smoke were produced. Flames were not readily apparent from the range camera feed.

The target was found intact with the fuze still attached. The case was still hot 1 hour after the burn. Damage to the paint was reduced compared to shot 1, consistent with the lack of visible flames. The case was found filled with black ash. The fuze removal with a ½ block of C-4 broke the casing into several large fragments, suggesting the booster in the nose was not consumed by the burn.

Figure 63. Target Post Firing

Figure 64. Ash Inside the Casing

Figure 65. Case Fragments Post Fuze Removal

Shot Number: 1-3
Date: 9/13/18
Target: 5-inch/38 in air
Tool: Boswell
Placement: 8 inches from the base with epoxy
Explosive Mass: 250 g
Reaction Category: Burn
Peak Overpressure: 3.36 psi
HE Remaining: <1%
Fuze/Booster Status: Ejected, fuze intact, booster destroyed

Figure 66. Shot 1-3 Setup

Summary: The round burned for ~16 minutes. The burn produced large amounts of smoke and flames were not readily apparent. At the end of the burn, the fuze popped off the round and was thrown a few feet away.

The target was found intact with the fuze popped off. Once again the casing was filled with black ash. No unreacted explosive material was apparent. The booster cup was found split apparent with a small amount of CH-6 remaining inside. The booster appears to have cooked off and ruptured due to pressure buildup which in turn ejected the fuze.

The burning response of the target was unexpected, as the 250 gram Boswell previously detonated one of the surrogates 5-inch targets. Age is believed to be the cause of the discrepancy; the rounds themselves are quite old (they were loaded in 1976) and explosives inside them even older (one of the lots of A-3 used dates back to 1968).

Figure 67. Target Post Firing

Figure 68. Ash Inside the Casing

Figure 69. Fuze and Booster Remains

Shot Number: 1-4
Date: 9/13/18
Target: 5-inch/38 in air
Tool: Boswell
Placement: 8 inches from the base with tape
Explosive Mass: 250 g
Reaction Category: Burn transitioning to low order
Peak Overpressure: 3.372 psi
HE Remaining: <1%
Fuze/Booster Status: Destroyed

Figure 70. Shot 1-4 Setup

Summary: The round burned for ~8 minutes before low ordering. During the burn, a column of red flame was observed erupting from the penetration hole. The low order threw fuze and case fragments out of the front and back sides of the barbette respectively, suggesting that it was the booster and/or material in the nose that reacted.

The case was found split into three pieces consisting of two halves of the steel pieces and the rotating band. The case appears to have bulged before fracturing, suggesting a pressure rupture. Like shot 1, the flame appears to have burned of the top layer of paint. No unreacted explosive material was found.

Figure 71. Case Fragment 1

Figure 72. Case Fragment 2

Figure 73. Close-up of Penetration Hole

Shot Number: 1-5
Date: 9/13/18
Target: 5-inch/38 in air
Tool: Boswell
Placement: 8 inches from the base with tape
Explosive Mass: 250 g
Reaction Category: Burn
Peak Overpressure: 3.347 psi
HE Remaining: <1%
Fuze/Booster Status: Intact and in place

Figure 74. Shot 1-5 Setup

Summary: The round burned for ~18 minutes. The burn produced large amounts of smoke. Flames were not readily apparent.

The target was found intact with the fuze still attached. The casing was filled with black ash with no unreacted material readily apparent. Hand probing inside the round revealed the booster was still intact. The casing appears to have cracked in the region near the fuzewell. This may have caused a loss of confinement and hence allowed the booster to survive. Due to the intact booster, fuze removal with a full block of C-4 fragmented the case.

Figure 75. Ash Inside Target

Figure 76. Crack in Casing Near Nose

Shot Number: 2-1
Date: 12/11/18
Target: 5-inch/38 in air
Tool: 1.25 scale Boswell
Placement: 8 inches from the base with tape
Explosive Mass: 313 g
Reaction Category: Low Order
Peak Overpressure: 5.569 psi
HE Remaining: <1%
Fuze/Booster Status: Destroyed

Figure 77. Shot 2-1 Pre-Firing

Summary: The target immediately low ordered after firing. The casing was broken into several large fragments. The fracture surfaces were rough, indicating brittle failure. The fuze and booster were similarly broken into large fragments. A literal handful of residual HE was found. The pieces showed some slight charring, suggesting they started reacting before being ejected from the target.

Figure 78. Shot 2-1 Target Remains

Figure 79. Residual HE from Shot 2-1

Shot Number: 2-2
Date: 12/11/18
Target: 5-inch/38 in air
Tool: 2 x 0.5 Scale Boswell
Placement: 6 and 10 inches from the base with tape
Explosive Mass: 125 g + 125 g
Reaction Category: Burn
Peak Overpressure: 3.071 psi
HE Remaining: 50%
Fuze/Booster Status: Intact

Figure 80. Shot 2-2 Pre-Firing

Summary: The target burned for roughly 10 minutes before dying out. The burn produced large amounts of smoke and no visible flames. The casing was found intact and covered in ash. Roughly half of the explosive fill was still present inside the round. All reaction appears to have been due to the front charge. The rear charge, while able to penetrate the round, did not cause any reaction in the fill. Examinations inside the target with a borescope (no pictures were taken) showed that the burning had stopped right before reaching the booster.

Figure 81. Shot 2-2 Post Firing

Figure 82. Details of Rear Penetration Hole on Shot 2-2

Shot Number: 2-3
Date: 12/11/2018
Target: 5-inch/38 in air
Tool: 2 x 0.625 Scale Boswell
Placement: 6 and 10 inches from the base with tape
Explosive Mass: 156 g + 156 g
Reaction Category: Burn
Peak Overpressure: 3.832
HE Remaining: <1%
Fuze/Booster Status: Fuze in place, booster destroyed

Figure 83. Shot 2-3 Pre-Firing

Summary: The target burned for roughly 17 minutes during which a jet of flame shot out of the front penetration hole. Roughly 7 minutes into the burn the round popped and the flame "jumped" (i.e., growing taller and brighter); this is believed to be the booster igniting. The casing was found intact and was hot to the touch 30 minutes after burning had ceased. The paint showed signs of burning around the front (but not the back) penetration hole, consistent with the single observed jet of flame. The interior of the target was filled with ash and booster cup pieces.

Figure 84. Shot 2-3 Post Firing

Figure 85. The Penetration Holes from Shot 2-3

Shot Number: 2-4
Date: 12/12/18
Target: 5-inch/38 in air
Tool: 10 Degree Cone
Placement: 8 inches from the base with tape
Explosive Mass: 250 g
Reaction Category: Burn to Low Order
Peak Overpressure: 3.421
HE Remaining: 5%
Fuze/Booster Status: Destroyed

Figure 86. Shot 2-4 Pre-Firing

Summary: The target burned for 15 minutes before exploding. The burn was smoky for roughly 10 seconds after which a flame appeared. After 13 minutes, the target popped and flame jumped, indicating the booster had begun to react. The casing was broken into a couple of large fragments and appears to have been "peeled" open. A few fist sized pieces of HE were found inside the barbette. Based on their shape they appeared to be from the rear of the target.

Figure 87. Flame Jet from Shot 2-4

Figure 88. Shot 2-4 Flame Jet "Jumping"

Figure 89. Shot 2-4 Remains

Figure 90. Residual HE from Shot 2-4

Shot Number: 2-5
Date: 12/12/18
Target: 5-inch/38 in air
Tool: 12 Degree Cone
Placement: 8 inches from the base with tape
Explosive Mass: 250 g
Reaction Category: Burn
Peak Overpressure: 3.209 psi
HE Remaining: <1%
Fuze/Booster Status: Fuze in place, booster destroyed

Figure 91. Shot 2-5 Pre-Firing

Summary: The target burned for 21 minutes. The burn started smoky before a flame appeared roughly eight seconds later. Ten minutes in, the flame jet briefly disappeared before jumping back up, indicating the booster had ignited. Thirteen minutes in, the target popped and the flame jet again grew stronger, though with different coloration than the previous jump. The casing was found intact with charred paint and a crack running lengthwise down the round. The crack was likely formed after the target popped. The crack may have allowed air into the target, causing the second flame jump. Alternatively the second jump may be due to fracturing in the unreacted HE, increasing its surface area and therefore reaction rate. The case was filled with black ash; the booster cup was petaled open and still attached to the fuze.

Figure 92. Shot 2-5, First Flame Jump

Figure 93. Shot 2-5, Second Flame Jump

Figure 94. Shot 2-5 Post-Firing

Figure 95. Petaled Booster Cup Inside the Target

Shot Number: 2-6
Date: 12/12/18
Target: 5-inch/38 in air
Tool: 2 x 0.75 Scale Boswell
Placement: 8 inches from the base arranged radially with tape
Explosive Mass: 188 g + 188 g
Reaction Category: Burn
Peak Overpressure: 3.451
HE Remaining: 5%
Fuze/Booster Status: Fuze in place, booster destroyed

Figure 96. Shot 2-6 Pre-Firing

Summary: The target burned for roughly 16 minutes. The burn was initially smoky; flames appeared out of the right and left holes after 30 and 50 seconds respectively. The flame jets jumped at the 5 minute mark, indicating the booster had begun to burn. At the 14 minute mark, the round popped and the flames jumped again. The target was found intact with the paint burned off. Interestingly, the white lettering was also burned off, something that was not seen on any previous shots. No cracking was observed on the casing, suggesting that the second flame jump is due to fracturing in the unreacted HE. The interior of the round was filled with ash and booster cup was petaled open. Some residual HE was found inside towards the base.


Figure 97. Shot 2-6, First Flame Jump


Figure 98. Shot 2-6, Second Flame Jump

Figure 99. Shot 2-6 Post-Firing

Figure 100. Residual HE from Shot 2-6

Shot Number: 2-7
Date: 12/12/18
Target: 5-inch/38 in air
Tool: 2 x 0.875 Scaled Boswell
Placement: 8 inches from the base arranged radially with tape
Explosive Mass: 219 g + 219 g
Reaction Category: Low Order
Peak Overpressure: 6.138 psi
HE Remaining: <1%
Fuze/Booster Status: Destroyed

Figure 101. Shot 2-7 Pre-Firing

Summary: The target immediately low ordered. The casing was broken into several large fragments with rough edges. No residual HE was found.

Figure 102. Shot 2-7 Remains

Figure 103. Shot 2-7 Remains - Pieces of Penetration Holes and Booster Cup

Shot Number: 2-8
Date: 12/12/18
Target: 5-inch/38 in air
Tool: 14 Degree Cone
Placement: 8 inches from the base with tape
Explosive Mass: 250 g
Reaction Category: Burn
Peak Overpressure: 3.259 psi
HE Remaining: 5%
Fuze/Booster Status: Fuze in place, booster destroyed

Figure 104. Shot 2-8 Pre-Firing

Summary: The target burned for 14 minutes. Flames appeared 10 seconds after firing. Ten minutes after firing, smoke began to leak out of the interface of the round and auxiliary fuze. After 11 minutes, the target popped and the flame disappeared before jumping back up 20 seconds later. The casing was intact with burned paint and the fuze still in place. The booster cup was once again petaled open. Some residual HE was found towards the base

Figure 105. Shot 2-8 Post-Firing

Figure 106. Residual HE from Shot 2-8

hot Number: 2-9
Date: 12/13/18
Target: 5-inch/38 in fish tank with kiddie pool for sample collection
Tool: Underwater Boswell Cone
Placement: 8 inches from the base with tape
Explosive Mass: 250 g
Reaction Category: Low Order
Peak Overpressure: 1.589
HE Remaining: 5%
Fuze/Booster Status: Destroyed

Figure 107. Shot 2-9 Pre-Firing

Summary: The target unexpectedly low ordered, destroying the fish tank and kiddie pool. The casing was broken into several large pieces with rough edges. The bottom of the booster cup was found intact. Strangely, pieces of the booster cup walls appeared to have been crushed inward. Residual HE was found outside the barbette in the form of small chunks.

Figure 108. Shot 9 Remains

The two bottom fragments are from the booster cup.

Figure 109. Residual HE from Shot 2-9

Shot Number: 2-10
Date: 12/13/18
Target: 5-inch/38 in fish tank
Tool: 0.875 Scaled Underwater Boswell Cone
Placement: 8 inches from the base with tape
Explosive Mass: 219
Reaction Category: Low Order to High Order?
Peak Overpressure: 2.057 psi
HE Remaining: <1%
Fuze/Booster Status: Destroyed

Figure 110. Shot 2-10 Pre-Firing

Summary: The target exploded producing a mixture of small and large fragments. From high speed video, round appears to have begun reacting ~780 microseconds after firing, briefly producing a very bright light. The fragments had edges indicative of both brittle and ductile fracture. Surface features of the round were still readily apparent on fragments. No residual HE was found. Taken all together, this may indicate the target HE partially detonated.

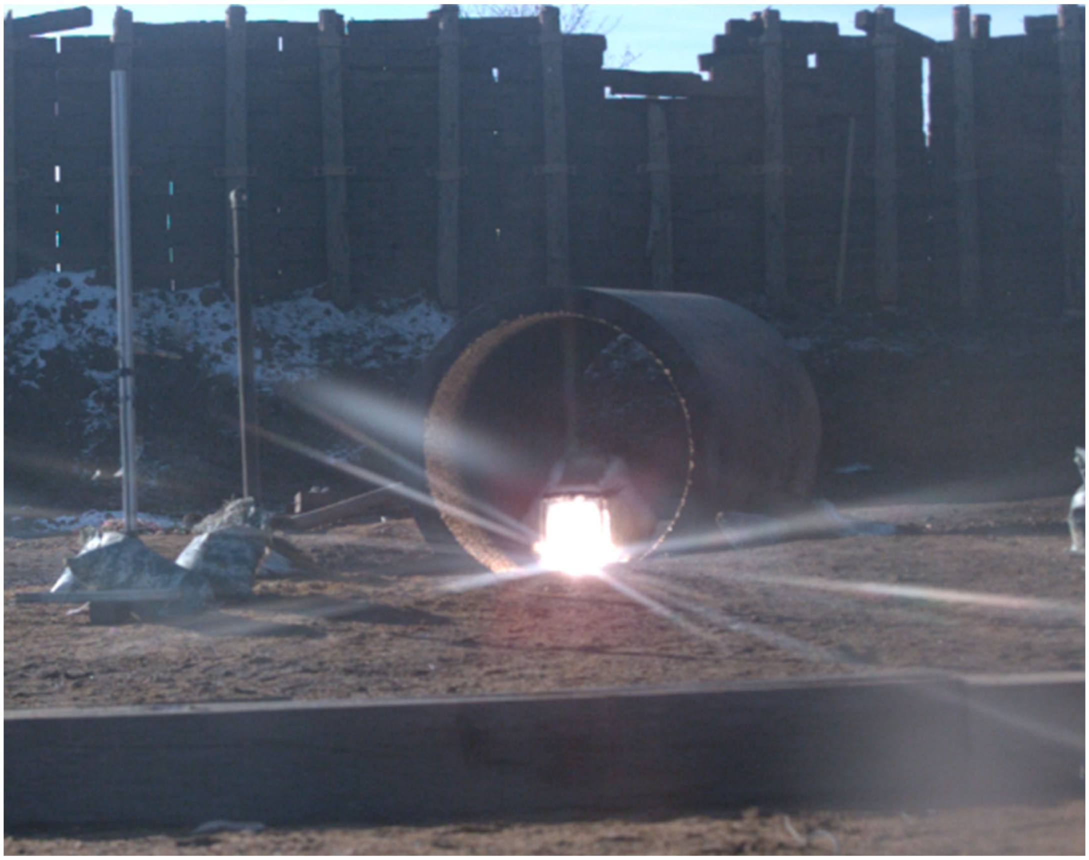

Figure 111. Shot 2-10 Reacting ~700 Microseconds after Firing

Figure 112. Shot 2-10 Remains

Shot Number: 2-11
Date: 12/13/18
Target: 5-inch/38 in air
Tool: 0.875 Scaled Underwater Boswell
Placement: 8 inches from the base with tape
Explosive Mass: 219 g
Reaction Category: Burn
Peak Overpressure: 3.040 psi
HE Remaining: <1%
Fuze/Booster Status: Fuze in place, booster destroyed

Figure 113. Shot 2-11 Pre-Firing

Summary: This was a repeat of shot 10 done in air to determine whether it was the fish tank or the underwater design causing the targets to low order. The target burned for 21 minutes with flames appearing 20 seconds after firing. The flame jumped twice: first at 17 minutes and then (after the round popped) at 19 minutes. The casing was found intact with the fuze still attached. The interior of the casing was filled with ash and booster cup pieces. No residual HE was found.

Figure 114. Shot 2-11 Post Firing

Figure 115. Close-up of Penetration Hole from Shot 2-11

Shot Number: 2-12
Date: 12/13/18
Target: 5-inch/38 in fish tank
Tool: 0.5 Scaled Underwater Boswell
Placement: 8 inches from the base with tape
Explosive Mass: 125 g
Reaction Category: Incomplete burn
Peak Overpressure: 0.818 psi
HE Remaining: >95%
Fuze/Booster Status: Intact

Figure 116. Shot 2-12 Pre-Firing

Summary: The target appears to have started burning before the reaction was quenched by inflowing water. The casing was intact and both the fuze and booster were undamaged. A water filled, blackened cavity was present where the tool had penetrated the target.

Figure 117. Shot 2-12 Post-Firing

Figure 118. Close-up of Blackened Cavity from Shot 2-12

Shot Number: 2-13
Date: 12/13/18
Target: 5-inch/38 in fish tank
Tool: 0.625 Scaled Underwater Boswell
Placement: 8 inches from the base with tape
Explosive Mass: 156 g
Reaction Category: Low Order
Peak Overpressure: 2.050 psi
HE Remaining: 30%
Fuze/Booster Status: Destroyed

Figure 119. Shot 2-13 Pre-Firing

Summary: The target low ordered producing large fragments. From high speed video, the target took 700 microseconds to react, briefly producing a small amount of light. Most fragment pieces had rough edges, though some from the fuze/booster region showed signs of shear. Residual HE was found scattered outside the barbette.

Figure 120. Shot 2-13 Reacting at 700 Microseconds

Figure 121. Shot 2-13 Remains

Shot Number: 3-1
Date: 01/09/19
Target: 5-inch/38 in fish tank
Tool: Underwater Boswell Cone
Placement: 6 inches from the base with tape
Explosive Mass: 250 g
Reaction Category: Low Order
Peak Overpressure: Not recorded
HE Remaining: 5%
Fuze/Booster Status: Destroyed

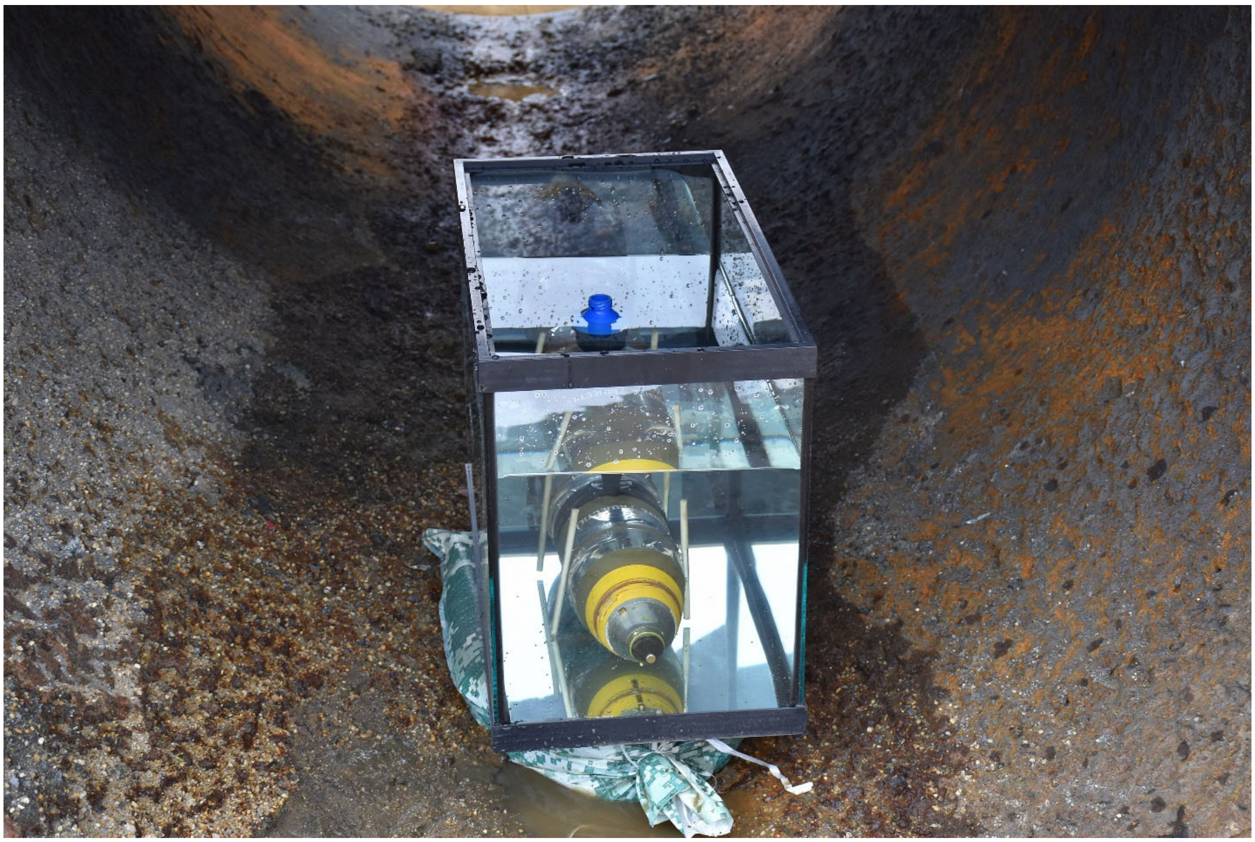

Figure 122. Shot 3-1 Pre-Firing

Summary: This shot was meant to capture what effect (if any) going through a thicker part of the casing would have on target response. The target low ordered producing large fragments with rough edges. The baseplate was found intact and embedded in the fragment catch behind the barbette; it was too deeply buried to be removed. A couple of fist sized pieces of residual HE were found.

Figure 123. Shot 3-1 Remains

Figure 124. Shot 3-1 Remains with Residual HE

Shot Number: 3-2
Date: 01/09/2019
Target: 5-inch/38 in fish tank
Tool: Underwater Boswell Cone with Bubble Wrap
Placement: 8 inches from the base with tape
Explosive Mass: 250 g
Reaction Category: Low Order
Peak Overpressure: Not recorded
HE Remaining: 20%
Fuze/Booster Status: Destroyed

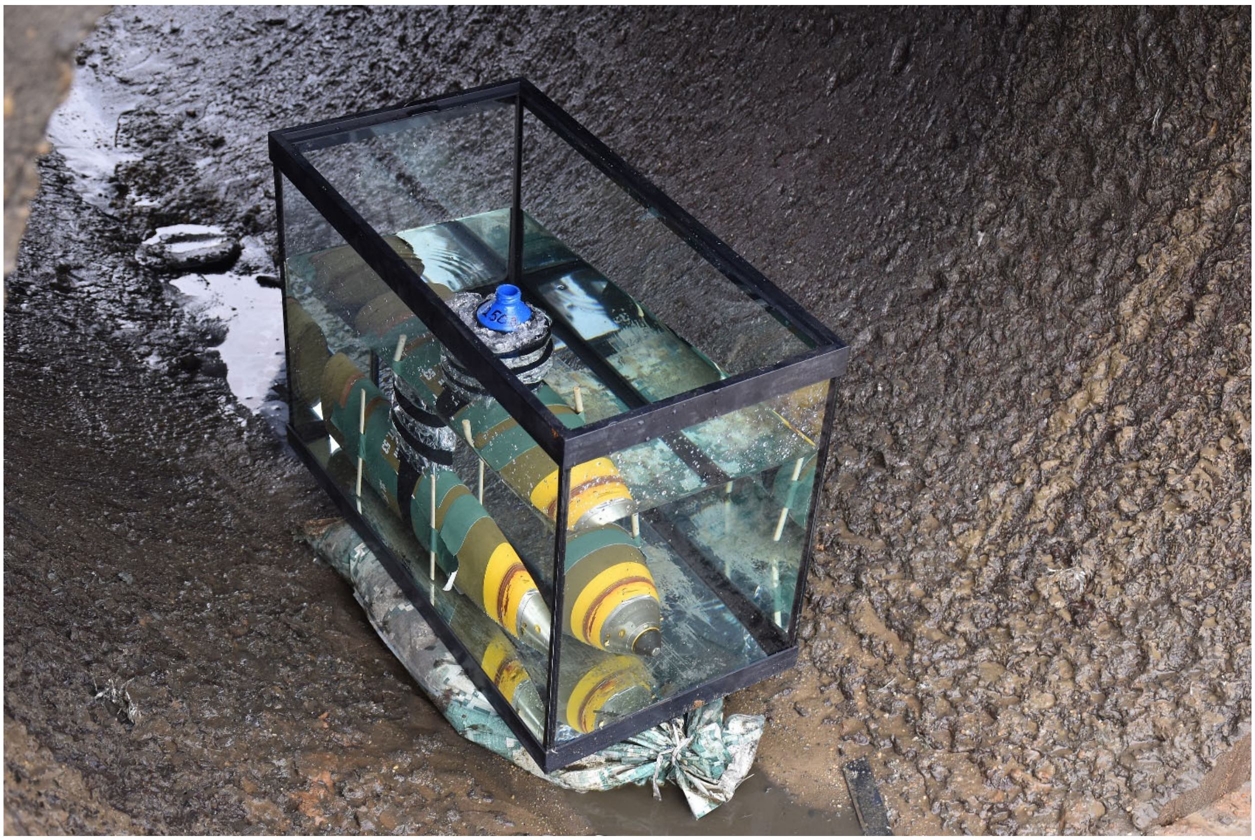

Figure 125. Shot 3-2 Pre-Firing

Summary: This was the first of several tests examining the effects of an outer air gap formed with bubble wrap on target response. It was hoped the air gap would reduce reaction violence by decreasing coupling between the EGP tool and the target. The target low ordered, producing large frag with rough edges (though pieces from the fuze/booster region showed some evidence of shear). The fuze was launched into the camera shield, destroying both it and the shield. A roughly 3-inch tall section of HE from the base was found. The fragments had a characteristic W-shaped bend to them. The target appears to have bulged in two different places (immediately behind the EGP tool and near the fuze/booster) before failing.

Figure 126. Shot 3-2 Remains with Residual HE

Figure 127. Shot 3-2 Fragment Showing W-Shaped Bulging

Shot Number: 3-3
Date: 01/09/2018
Target: 5-inch/38 in fish tank
Tool: Underwater Boswell Cone with Reduced HE Load
Placement: 8 inches from the base with tape
Explosive Mass: 187 g
Reaction Category: Low Order
Peak Overpressure: Not Recorded
HE Remaining: 1-2%
Fuze/Booster Status: Destroyed

Figure 128. Shot 3-3 Pre-Firing

Summary: The target low ordered producing large, rough-edged fragments. The fragments showed the same double bulging as shot 3-2. A few small pieces of residual HE were found.

Figure 129. Shot 3-3 Remains

Figure 130. Shot 3-3 Remains

Shot Number: 3-4
Date: 01/09/2019
Target: 5-inch/38 in fish tank
Tool: 0.875 Scaled Underwater Boswell Cone with Bubble Wrap
Placement: 8 inches from the base with tape
Explosive Mass: 219 g
Reaction Category: Low Order
Peak Overpressure: Not Recorded
HE Remaining: 5%
Fuze/Booster Status: Destroyed

Figure 131. Shot 3-4 Pre-Firing

Summary: The target low ordered, producing large, rough-edged fragments. Strangely, residual HE (in the form of small chunks) was thrown very far (i.e., >100 ft) forward.

Figure 132. Shot 3-4 Remains

Figure 133. Close-up of Residual HE from Shot 3-4

(the piece with threading is an unrelated shard of PVC)

Shot Number: 3-5
Date: 01/172018
Target: 5-inch/38 in fish tank
Tool: 0.625 Scaled Underwater Boswell with Bubble Wrap
Placement: 8 inches from the base with tape
Explosive Mass: 156 g
Reaction Category: Incomplete Burn
Peak Overpressure: Not Recorded
HE Remaining: >95%
Fuze/Booster Status: Intact

Figure 134. Shot 3-5 Pre-Firing

Summary: Like shot 2-12, the target appears to have begun reacting before being quenched by in flowing water, leaving behind a small blackened cavity.

Figure 135. Shot 3-5 Post-Firing

Figure 136. Cavity Formed in Target from Shot 3-5

Shot Number: 3-6
Date: 02/05/19
Target: 5-inch/38 in fish tank
Tool: 0.875 Scaled Underwater Boswell
Placement: 8 inches from the base with tape
Explosive Mass: 219 g
Reaction Category: High Order?
Peak Overpressure: Not Recorded
HE Remaining: None
Fuze/Booster Status: Destroyed

Figure 137. Shot 3-6 Pre-Firing

Summary: The target was broken into a mixture of small and large fragments. The fragments had sharp, sheared edges and an iridescent sheen which may indicate the target at least partially high ordered. Interestingly, the base of the booster cup was found undeformed and intact (though still removed from the booster cup walls), suggesting that whatever reaction occurred, it did not start with the booster.

Figure 138. Shot 3-6 Remains (Intact Booster Cup Base at the Bottom Right)

Figure 139. Close-up of Small Frag from Shot 3-6

Shot Number: 3-7
Date: 02/05/19
Target: 5-inch/38 in fish tank
Tool: 0.875 Scaled Underwater Boswell
Placement: 8 inches from the base with tape
Explosive Mass: 219 g
Reaction Category: Low Order
Peak Overpressure: Not Recorded
HE Remaining: 10%
Fuze/Booster Status: Destroyed

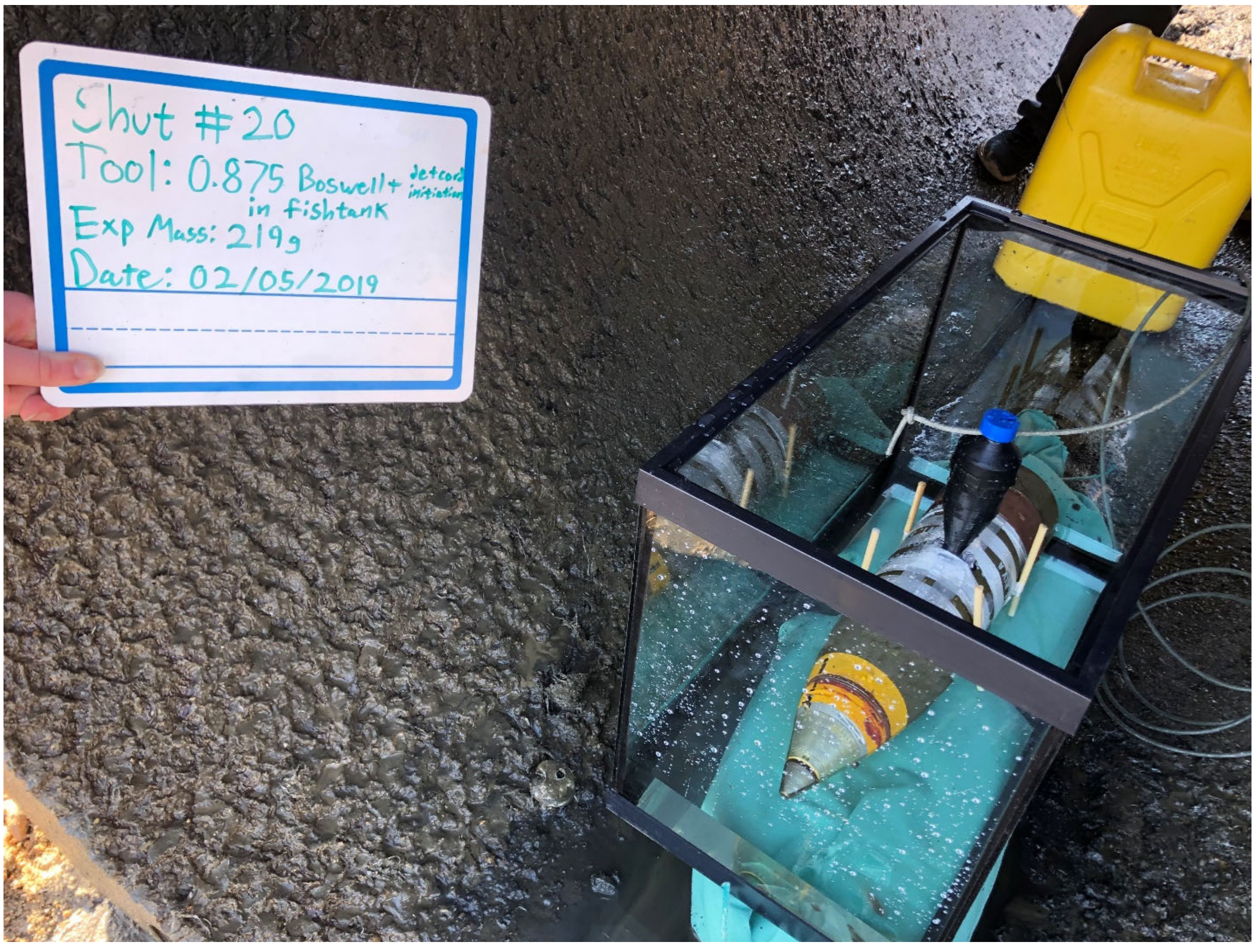

Figure 140. Shot 3-7 Pre-Firing

Summary: This was a repeat of shot 3-6 initiated with det cord and datasheet instead of a blasting cap. The target was broken into large, rough-edged fragments. The fragments exhibited the same W-shaped bulging seen in shots 3-2 and 3-3. A roughly 1 inch tall section of HE (broken into several pieces) from the base of the target was found.

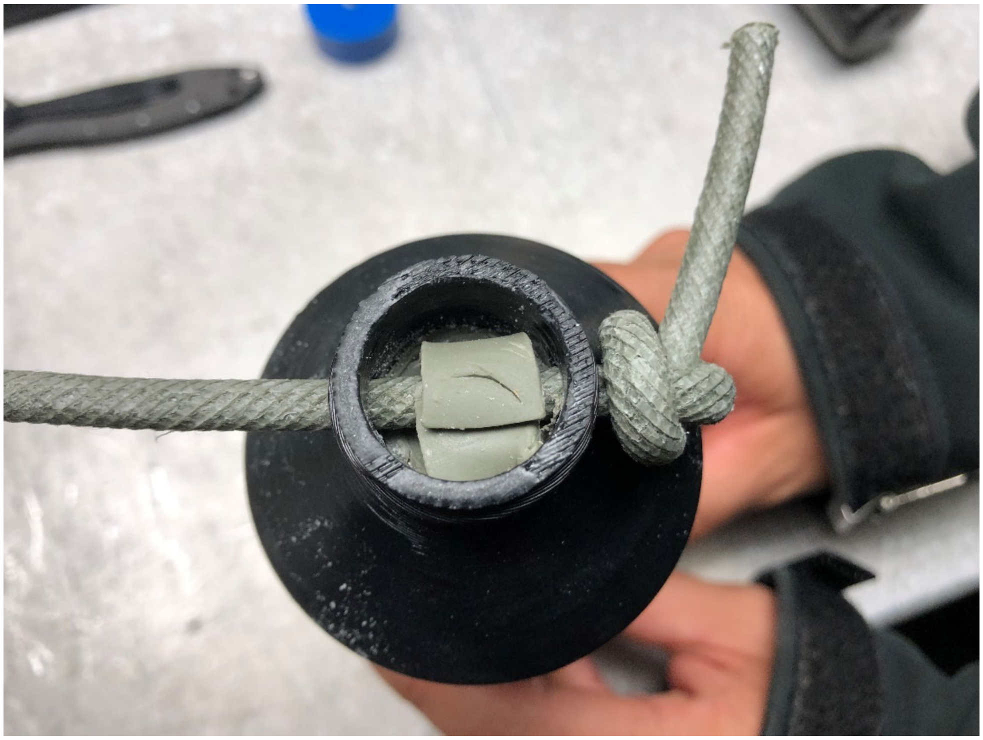

Figure 141. Firing Train for shot 3-7

Figure 142. Shot 3-7 Remains