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Copper-Based Torpedo Guidance Wire: Applications and Environmental Considerations

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ADMINISTRATIVE INFORMATION

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EXECUTIVE SUMMARY

STUDY OUTLINE AND GOALS

Military expended materials (MEM) are items abandoned in the marine environment after use during Navy training and testing exercises. A better understanding of the potential environmental impacts of these materials is needed to ensure regulatory compliance required for continued and uninterrupted training and testing in support of the Navy warfighter. Copper-based guidance wire was identified as a MEM of concern. The goal of this study was to define and evaluate potential environmental impacts related to copper-based guidance wire left at sea. This report focuses on potential impacts caused by copper-based torpedo guidance wire, although results and recommendations hold true for additional guidance wire with similar specifications.

Torpedo range tests are conducted on an annual basis at five primary ranges. These ranges include the Atlantic Undersea Test and Evaluation Center (AUTEC) in the Bahamas; Dabob Bay in Washington; the Pacific Missile Range Facility (PMRF) in Hawaii; Nanoose Bay in British Columbia, Canada; and the Southern California Range Complex (SOCAL). Combined, these ranges offer the Navy a broad spectrum of training environments and conditions.

The conceptual approach used in this study was to identify potential impact pathways from torpedo guidance wire to marine organisms and evaluate each pathway through empirically derived data and/or best available peer-reviewed literature. The approach focused on site-specific environmental characteristics and marine species relevant to the training areas where copper guidance wire is used. To assess potential environmental impacts caused by torpedo guidance wire, a conceptual evaluation pathway (CEP) was developed. The CEP was developed to describe and visualize the known, expected, and/or predicted relationships between potential stressors and ecological receptors. The CEP provides the basis for development of experimental design or data gathering to assess the potential stressors. The stressors identified for torpedo guidance wire are both a chemical stressor, leached copper, and a physical stressor, entanglement hazard. A series of experiments and analyses, highlighted below, were conducted to evaluate the various stressors identified in the CEP:

In-situ Dome Testing: This experiment was performed to establish real world leach rates for uncoated exposed copper wire. Leach rates were calculated over a wide temporal range to evaluate potential acute and chronic impacts. These experiments also aim to provide a better understanding of copper release rates over time rather than the use of a standardized corrosion rate.

Abrasion Level versus Copper Release Rate: These experiments were performed on coated guidance wire to investigate the release rate of copper under various states of simulated wire coating degradation.

Mechanisms of Plastic Coating Degradation: A literature review of plastic coating performance and degradation mechanisms were reviewed to evaluate long-term coating performance and the potential for environmental release of copper.

Toxicity Testing: Bioassays of two different sensitive marine species (*Strongylocentrotus purpuratus* and *Mytilus galloprovincialis*) were performed on leachate water from the *in-situ* dome testing to investigate the potential toxic response of marine organisms.

Copper Dispersion Modeling: Mathematical model(s) were used to evaluate copper dispersion through the water column and into the sediments from the source guidance wire.

Empirical Sinking Rate: Experiments were performed to establish and/or validate sinking rates of torpedo guidance wire through the water column.

Mathematical Model of Sinking Wire: A mathematical model for sinking guidance wire was established to verify experimental data derived from empirical sinking rate experiments and extrapolate through various depths within the water column.

Breaking Strength: Breaking strength experiments were conducted on torpedo guidance wire to assess impacts related to potential entanglement.

Species Presence and Behavior: A literature review was conducted to identify potential marine species that may be impacted by guidance wire. The review focused on presence within training areas where guidance wire is used, animal size, feeding behavior, and diving behavior.

RESULTS

In-situ Dome Testing

Leach rate testing over the 183-day exposure period showed two unique periods of copper release values; initial release from days 1–29, followed by a more steady-state period from days 29–183. During the initial release period, mean copper release rates increased from 3.8 $\mu g\ mm^{-1}\ d^{-1}$ on day 1 to 5.9 $\mu g\ mm^{-1}\ d^{-1}$ on day 15. There was an order of magnitude drop in release from day 15 to day 29, when the mean release rate was 0.67 $\mu g\ mm^{-1}\ d^{-1}$. A more steady-state release rate was observed from day 29 throughout the remainder of the study where release rates were 0.67 to 0.17 $\mu g\ mm^{-1}\ d^{-1}$. The peak release rate was observed on day 15 at 5.9 $\mu g\ mm^{-1}\ d^{-1}$. A pseudo-steady-state release rate was calculated as 0.58 $\mu g\ Cu\ mm^{-1}$ using data from days 29–183. The cumulative release of copper from the torpedo guidance wire during the 183-day exposure period was 171.2 $\mu g\ Cu\ mm^{-1}$.

Abrasion Level versus Copper Release Rate

Copper release rates from five treatments of abraded guidance wire were measured over a 45-day period, and agreed with rates observed in the *in-situ* dome testing. The level of abrasion, or wire exposure, for the five treatments were 0 (fully coated), 25, 50, 75, and 100% (uncoated). Copper release rates did not exhibit a linear increase relative to the level of abrasion treatment. The 0 and 25% treatments resulted in no wire exposure along the length of the wire; only the tips of the wire had exposed copper. The 50% treatment had minimal areas of exposed copper, with exposure areas ranging from 1 to 5 mm. The 75% treatment yielded larger areas of coating failure resulting in exposed wire sections up to 30 mm in length. The 100% treatment was completely exposed copper wire. Statistical analysis of copper release rates from the five treatments found three groups were significantly different from each other. Group one consisted of the 0, 25, and 50% treatment, while the 75 and 100% treatment were considered unique groups. Copper release rates for the 0, 25, and 50% treatment had release rates below 0.2 $\mu g\ mm^{-1}\ d^{-1}$ over the course of the study. The 75% treatment had a maximum release of 3.5 $\mu g\ mm^{-1}\ d^{-1}$, while the 100% treatment had a maximum release of 10.3 $\mu g\ mm^{-1}\ d^{-1}$. These data suggest that the wire would need to be exposed to enough abrasive action to reduce the plastic coating to between 50 and 75% of its starting condition before any significant copper release was observed.

Mechanisms of Plastic Coating Degradation

Torpedo guidance wire consists of a copper wire core surrounded by a polyethylene coating. Degradation of the wire may be related to chemical breakdown or mechanical abrasion. Polyethylene is a robust plastic polymer that resists corrosion and biodegradation (Czagas, 1998; Van der Zee et al., 1994; Cundell, 1974). Polyethylene performs especially well in an environment such as the ocean floor where there is high pressure, low temperature and little to no ultraviolet (UV) exposure (Czagas, 1998; Van der Zee et al., 1994). Additionally, for copper to leach into the environment the coating would need to degrade far enough to expose portions of the wire, not simply weaken it. As

chemical or microbial degradation of the plastic coating is extremely unlikely, the only process that may expose the copper wire would be mechanical degradation. The primary mechanism for degradation caused by physical processes would be abrasion associated with movement along the sea floor. The majority of the guidance wire would be found on the deep ocean floor where currents speeds are relatively low. Additionally, the substrate or sediment types found in the training areas are generally soft sediment or sand and will not provide strong abrasive resistance.

Toxicity Testing

Toxicity testing was performed in conjunction with each of the nine sampling days for the *in-situ* dome experiment. The test species *Strongylocentrotus purpuratus* was used on all sampling events, while *Mytilus galloprovincialis* was used during one sampling event. Toxicity resulting from guidance wire leachate had a mean Effect Concentration (EC) 50 of 23.7 $\pm$6.9 Cu µg l^{-1}, a mean Lowest Observable Effect (LOEC) of 21.2 $\pm$7.1 Cu µg l^{-1}, and a mean No Observed Effect Concentration (NOEC) of 10.6 $\pm$3.5 Cu µg l^{-1}. The sampling event with the greatest toxicity resulted in an EC50 of 15.5 Cu µg l^{-1}, while the least toxic event found an EC50 of 33.8 Cu µg l^{-1}. The most environmentally conservative (worst case) endpoint during all of the testing showed that the copper concentration at which no effect was observed to be 5.0 µg l^{-1}, while the lowest observed effect concentration was 10.1 µg l^{-1}. The toxicity test performed with *Mytilus galloprovincialis* on sampling day 91 resulted in an EC50 of 10.0 Cu µg l^{-1}, and LOEC of 14.6 Cu µg l^{-1}, and an NOEC of 7.3 Cu µg l^{-1}.

Copper Dispersion Modeling

A simple dispersion model was developed using the copper release rates (peak release and pseudo steady state) from the *in-situ* dome testing and typical currents found at the ocean floor. It was assumed that 1 mm of wire would be exposed, based on the exposed ends of the wire after breakage when the wire separated from the torpedo/ship. Estimated water column concentrations were very low. The copper concentrations during peak release within a distance of 1 mm from the wire were calculated to be 0.01 µg L^{-1}. These values are well below background copper concentrations in open ocean environments, which have an average reported value of 0.26 µg L^{-1} (Chester, 1990). The values are also orders of magnitude lower than the copper water quality criteria of 3.9 µg L^{-1} (chronic) and 4.1 µg L^{-1} (acute). The input parameters of the model were changed to assess an extreme exposure scenario of 10 mm of exposed wire under nearly quiescent current conditions. Under this unlikely scenario, the highest water column concentration at 1 mm from the source was 1.11 µg L^{-1}, which is still below the water quality criteria (WQC), and decreased to background concentrations at a distance of only 4 mm from the source.

Empirical Sinking Rate

Torpedo guidance was filmed falling through the water column with a high-definition video camera at 60 frames per second. The average sinking rate of the guidance wire was 0.24 m s^{-1} with a standard deviation of 0.09 m s^{-1}. These data compare well with previously reported values of ~0.2 m s^{-1}.

Mathematical Model of Sinking Wire

A model of sinking guidance wire based on drag coefficient, buoyant forces, Reynolds number, and the wire's physical properties (thickness, density, length) was used to extrapolate across various depths and distances within the water column. The model output resulted in an estimated sinking rate of 0.17 m s^{-1}, which agree well with empirically measured sinking rate and previously reported values.

Breaking Strength

The breaking strength of the tested guidance wire was 40.4 pounds. This value is within the range of values presented in various Naval Environmental Assessments which report the breaking strength of the wire as 28 pounds (DoN, 1996 (U)), 30 pounds (DoN, 2002), 38 pounds (Environmental Sciences Group, 2005), and 42 pounds (DoN, 2008 SOCAL). Additionally, the official military specs for the wire alone, without plastic coating, lists the breaking strength as 27.3 pounds (MIL-HDBK-419A); it is assumed that the addition of the plastic coating makes the wire more robust, bringing the breaking strength up to the measured 40.4 pounds.

Species Presence and Behavior

As with any foreign object introduced into the marine environment, torpedo guidance wire has potential to pose physical hazards, specifically entanglement, to marine life. The primary concern regarding entanglement with torpedo guidance wire is for marine mammals and sea turtles whose swimming or feeding behaviors place them near the ocean floor. Additionally, an emphasis was placed on those animals with benthic feeding habits. A list of known marine mammals and sea turtles identified in the range areas was assembled, resulting in 89 animals. The list was narrowed down to 22 animals whose diving or feeding patterns may place them near the ocean floor at each respective range. These 22 animals were further evaluated for entanglement potential. Only one animal, the gray whale (*Eschrichtius robustus*), feeds by sifting through deep ocean sediment. However, its feeding grounds are not in the range areas as they are known only to migrate through the range areas and have their primary feeding grounds farther north near the Bering and Chukchi Seas (Highsmith et al., 2006; Swartz, Taylor, and Rugh, 2006; Jones and Swartz, 2002).

CONCLUSIONS AND RECOMMENATIONS

Torpedo guidance wire abandoned in the marine environment results in a potential chemical stressor in the form of leached copper. Evaluation of copper leached into the marine environment as a potential chemical stressor suggests that there is no negative impact to the water column, sediments, and organisms living within these environments. The robust nature of the plastic coating coupled with eventual burial of the material limits exposure of the copper wire to seawater, thus minimizing copper leaching into the environment. Predicted water column and sediment copper concentrations are below the water quality criteria, sediment guidelines, and predicted toxicity endpoints. Evaluation of the data herein suggests that torpedo guidance wire does not present a chemical hazard to the marine environment.

Torpedo guidance wire abandoned in the marine environment results in a potential physical stressor in the form of an entanglement hazard. Evaluation of the guidance wire as a potential physical stressor suggests that there is an extremely low entanglement potential for animals found within the range areas. The physical characteristics of the wire (breaking strength and reluctance to looping or coiling) and sea floor habitat types, coupled with minimal exposure potential to marine mammals (based on diving and foraging behaviors) minimizes any potential entanglement threat. Evaluation of the data herein suggests that torpedo guidance wire does not present a physical hazard in the marine environment.

Copper-based torpedo guidance wire presents little to no environmental risk at the Navy training ranges currently using them. The potential impacts of previously expended guidance wire should have no near or long term negative affects to marine water and sediment quality, as well as marine animals found within the training ranges. The continued use of guidance wire in similar scope and formulation as evaluated herein should not present any future deleterious environmental impacts.

ACRONYMS AND ABBREVIATIONS

ADCAP	Advanced Capability
ASTM	American Society for Testing and Materials
AUTEC	Atlantic Undersea Test and Evaluation Center
BARSTUR	Barking Sands Tactical Underwater Range
BSURE	Barking Sands Underwater Range
C_d	Drag Coefficient
CV	Coefficient of Variance
DBRC	Dabob Range Complex
DoD	Department of Defense
DoN	Department of Navy
EA	Environmental Assessment
HARPS	Harbor Research Platform System
HEPA	High Efficiency Particle Air
ICP-MS	Inductively Coupled Plasma with detection by Mass Spectrometry
MK	Mark
Mod	Model
NIST	National Institute of Standards & Technology
NUWC	Naval Undersea Warfare Centers
PMRF	Pacific Missile Range Facility
Re	Reynolds Number
SOAR	Southern California Anti-Submarine Warfare Range
SOCAL	Navy's Southern California Range Complex
SRM	Standard Reference Material

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1. INTRODUCTION

1.1 HISTORY OF U.S. WIRE-GUIDED TORPEDOES

Since its invention by Robert Whitehead in 1866, the torpedo has become a central component of United States naval warfare (Friedman, 1998). Numerous torpedoes were designed and redesigned to incorporate contemporary technologies and overcome the challenges presented in underwater warfare.

The Navy's use of a wire guidance system as a control mechanism for torpedoes was first implemented with the design of the Mark 39 Model 1 (MK 39 Mod 1) (Friedman, 1998). The wire guidance system became popular and was included in the design of many of the subsequent torpedoes, including the MK 45 and 37, which replaced the MK 39. The MK 45, released in the late 1950s, was a wire-guided nuclear warhead designed to have a large enough impact radius to overcome errors in sonar fire controls, though it was soon decided that passive homing systems were far more useful, reliable, and necessary and should be included on all torpedoes, leading to the development of the MK 37 (Friedman, 1998). The MK 37 was originally a gyro-guided torpedo released in 1956; in the 1960s, Mods 1 and 2 were designed and released, including wire guidance capability among other newer technologies (Friedman, 1998). Both the MK 45 and 37 were replaced with the currently used MK 48, which was designed for long-range targets, capable of high speeds at deep depths, equipped with a wire guidance system as well as an acoustic homing device (Friedman, 1998).

1.2 CURRENT U.S. NAVY WIRE-GUIDED TORPEDO

The Navy's currently used heavyweight wire-guided torpedo, the MK 48, is used by both submarines and their anti-submarine counterparts. Since its introduction to the fleet in the 1970s, the MK 48 has undergone numerous modifications to incorporate the newest technologies and safety measures into its design (Cowell and Whitman, 2000). Revisions to improve communications, the command control unit, and homing control unit led to MK 48 Mods 3 and 4 (DoN, 1996 (U)). In the 1980s, the demand for a torpedo equipped to battle the Soviet's deep-diving nuclear submarines resulted in the design and production of the MK 48 Mod 5 Advanced Capability (ADCAP) Torpedo (DoN, 1996 (U)). Both the MK 48 ADCAP and the more recent modification – MK 48 ADCAP MOD – can function with or without wire guidance (Cowell and Whitman, 2000). The U.S. Navy currently uses various modifications of the MK 48, all of whose specifications remain confidential and are thus not included in this report (DoN, 1996 (U)).

A wire-guided control system allows users to make last-minutes tactical decisions and convey instructions from a firing vessel to a moving torpedo to overcome target evasion tactics (Environmental Sciences Group, 2005). In an operational exercise, single-strand copper guidance wire is ejected from both the vessel and the torpedo at launch, creating a connected and closed tactical decision system for torpedo users (Environmental Sciences Group, 2005). When fired on the range, the procedure differs slightly, as only the wire spool on the weapon is released; the ship wire remains unfurled (Environmental Sciences Group, 2005). The wire is detached from both ends at the completion of the weapon's run and is left to fall to the ocean floor (Environmental Sciences Group, 2005).

1.3 WIRE SPECIFICATIONS

Torpedo guidance wire is 98.78 to 99.30% copper, in accordance with military standards (Military Specification [Mil]-W-82599). Both components of the ship and weapon system wires are the same copper alloy. In recent years, a copper-cadmium alloy was replaced with a copper-magnesium alloy, HPC-80EF; the wire specifications in Mil-W-82598 remain accurate with a direct substitution of magnesium for cadmium[1]. Though they are composed of the same material, the ship wire (uncoated) has a larger diameter, ranging from 0.0226 ±0.0002 inches, while the weapon wire's (uncoated) diameter lies within the range of 0.0201 ±0.0002 inches (Entwistle Company, No 23 and No 24 Hard Copper Wire material HPC-80-EF).

Following the specification in Mil-W-82599, the guidance wire is coated with an ionometric polyolefin of either DuPont® Surlyn 9720 or 9721[2]. This coating serves as protection for the wire and is essential to maintaining its integrity as a means of communication between the firing vessel and the launched weapon; the slightest nick in the copper wire impairs that communication (Environmental Sciences Group, 2005). The wire is further coated with insoluble graphite grease for lubrication, which acts as an added layer of protection against degradation as it lies on the ocean floor (Environmental 2005). The deployed wire is reported to weigh 1.5 grams per meter with a diameter of 0.04 inches.

1.4 NAVAL TEST RANGES

Torpedo range tests are conducted by the U.S. Navy on an annual basis. The MK 48 ADCAP torpedo is tested at five primary ranges: the Atlantic Undersea Test and Evaluation Center (AUTEC) in the Bahamas, Dabob Bay, the Pacific Missile Range Facility (PMRF) in Hawaii, Nanoose Bay, and the Southern California Range Complex (SOCAL)[3]. Combined, these ranges offer the Navy a broad spectrum of training environments and conditions.

1.4.1 AUTEC (Figure 1)

The Atlantic Undersea Test and Evaluation Center (AUTEC) is located east of Andros Island in the Bahamas and contains the deep submarine canyon known as the Tongue of the Ocean (TOTO) (DoN, 1996 (U)). The portion of TOTO used for torpedo testing is just to the east of the North Bite and covers an area approximately 20 miles wide and 20 miles to the north and 10 miles to the south of the Bite[4]. Depths at the range site vary from 900 to 2700 m, classifying it as a deep-water range (DoN, 1996 (U)). The depths in this portion of the TOTO are around 5000 ft, just 1 to 2 miles off shore[5].

1.4.2 Dabob Bay (Figures 2 A and B)

The Dabob Bay Range Complex (DBRC) consists of the waters of Dabob Bay and the Hood Canal Area in Kitsap and Jefferson Counties, Washington (DoN, 2002). Located near the Naval Undersea Warfare Centers (NUWC) Keyport Division, the DBRC is one of the Navy's leading underwater weapons research and development sites; approximately 4925 pounds of guidance wire are released annually into the bay (DoN, 2002). With depths ranging from 24 to 185 m and an average depth of 114.3 m, the DBRC is classified as a shallow-water range (DoN, 1996; DoN 2002).

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[1] Personal communication in 2011 with Commander Eric Campbell USN, U.S. Navy Undersea Weapons Program Office, for information on test ranges for the MK 48 and military specifications for torpedo guidance wire.
[2] *Ibid*.
[3] *Ibid*.
[4] Personal communication in 2012 with Marc Ciminello, AUTEC, at torpedo range at AUCTEC.
[5] *Ibid*

Figure 1: Google Earth™ map of Tongue of the Ocean with naval map overlay of AUTEC's weapon range where shaded area represents the test range (Google Earth; DoN, 1996 (U)).

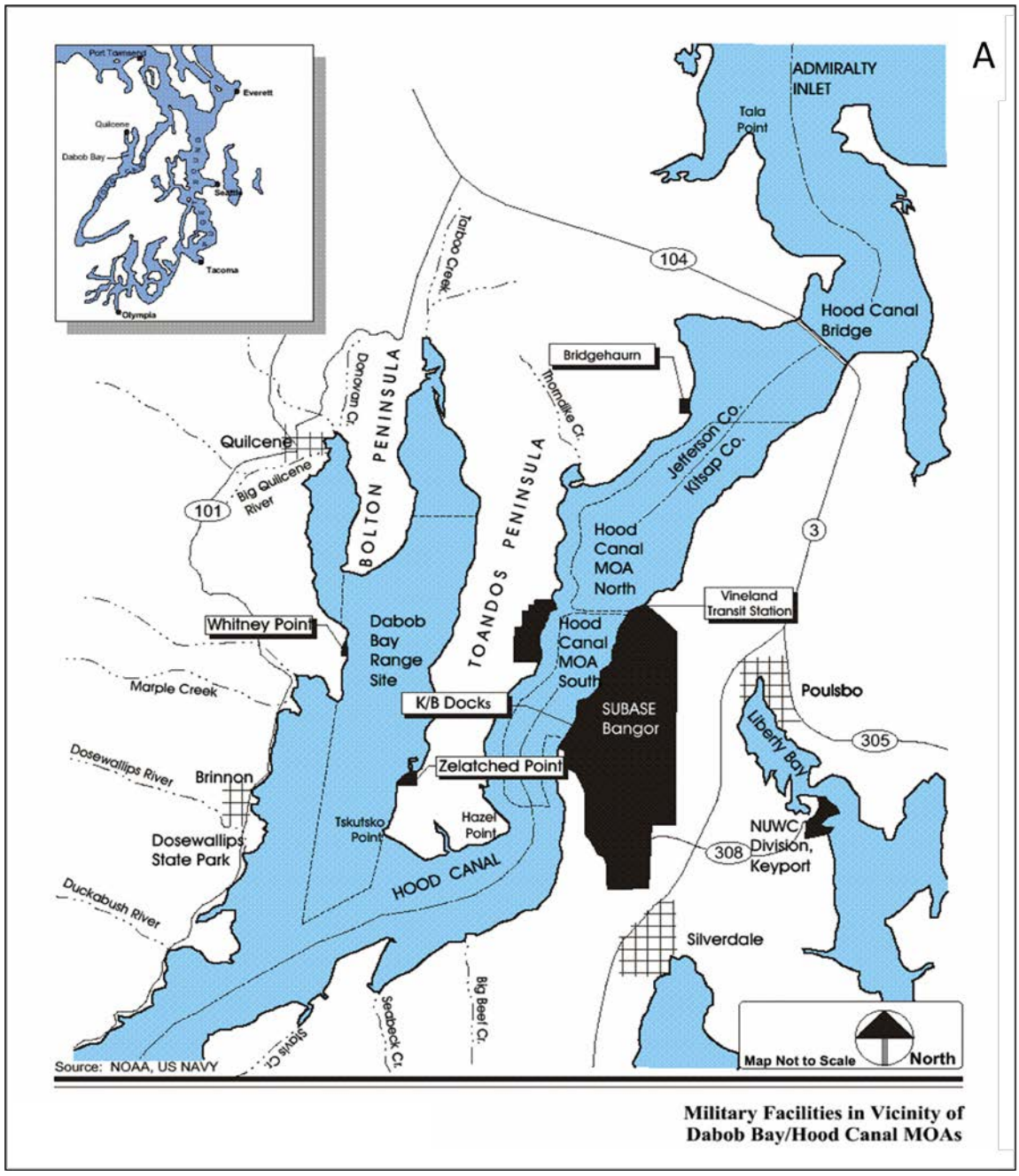

Figure 2A. Dabob Bay (DoN, 2002).

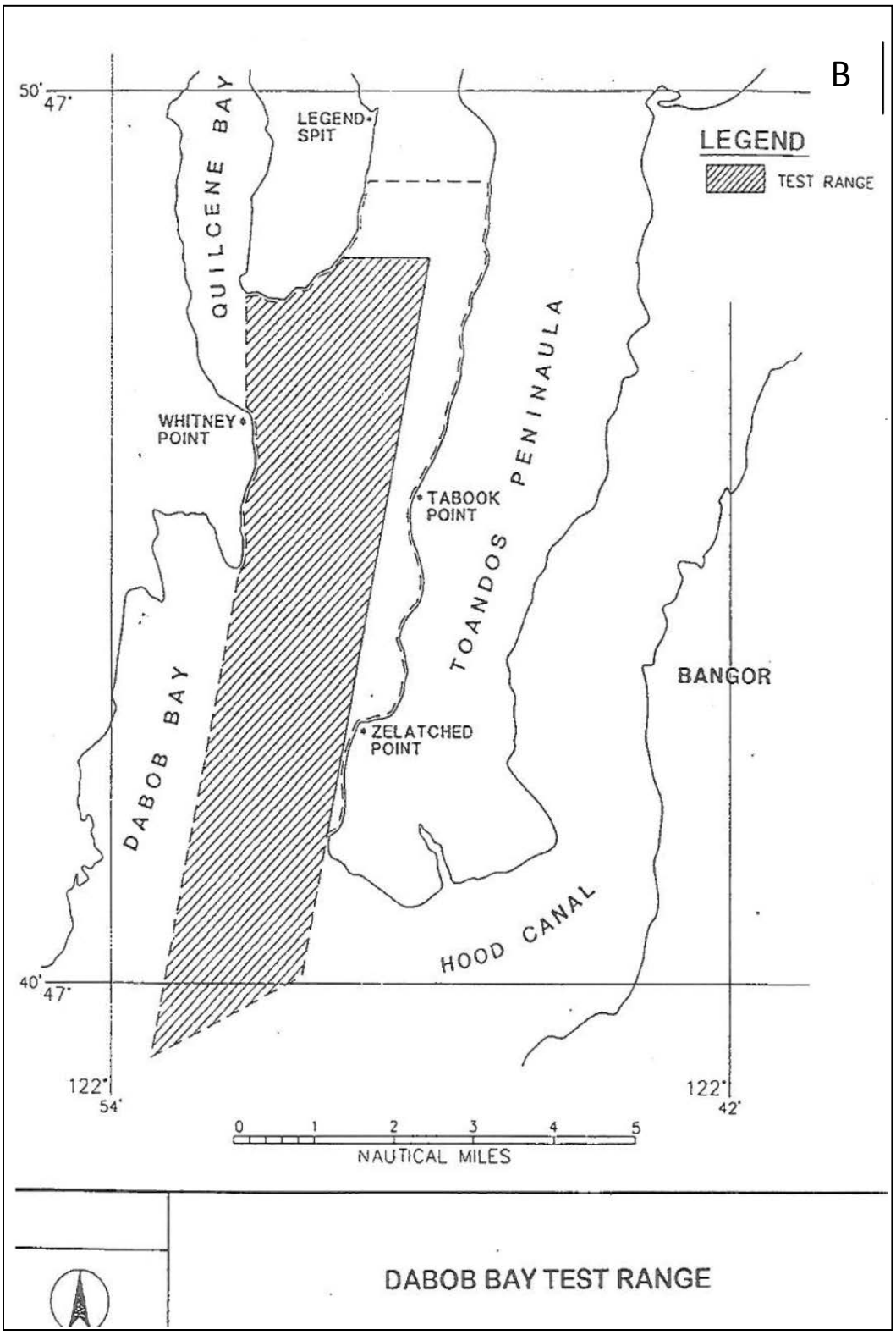

Figure 2B. Dabob Bay Test Range (DoN, 1996 (U)).

1.4.3 Hawaii PMRF (Figures 3 A and B)

The Hawaii Pacific Missile Range Facility (PMRF) is the focal point for most of the torpedo exercises near the Hawaiian Islands, as it is both a fleet training range and a fleet and Department of Defense (DoD) research, development, testing, and exercise (RDT&E) range (DoN, 2008 Hawaii). It is also the world's largest military test range proficient in subsurface, surface, air, and space activities (DoN, 2008 Hawaii). Located on the east coast of Kauai, the PMRF consists of 1020 nmi^2 of ocean and contains two deep-water ranges used for torpedo testing: Barking Sands Underwater Range (BSURE) and Barking Sands Tactical Underwater Range (BARSTUR). The depths of these waters rage from 1829 to 4572 m (BSURE) and 549 to 1829 m (BARSTUR)[6] (DoN 2008 Hawaii).

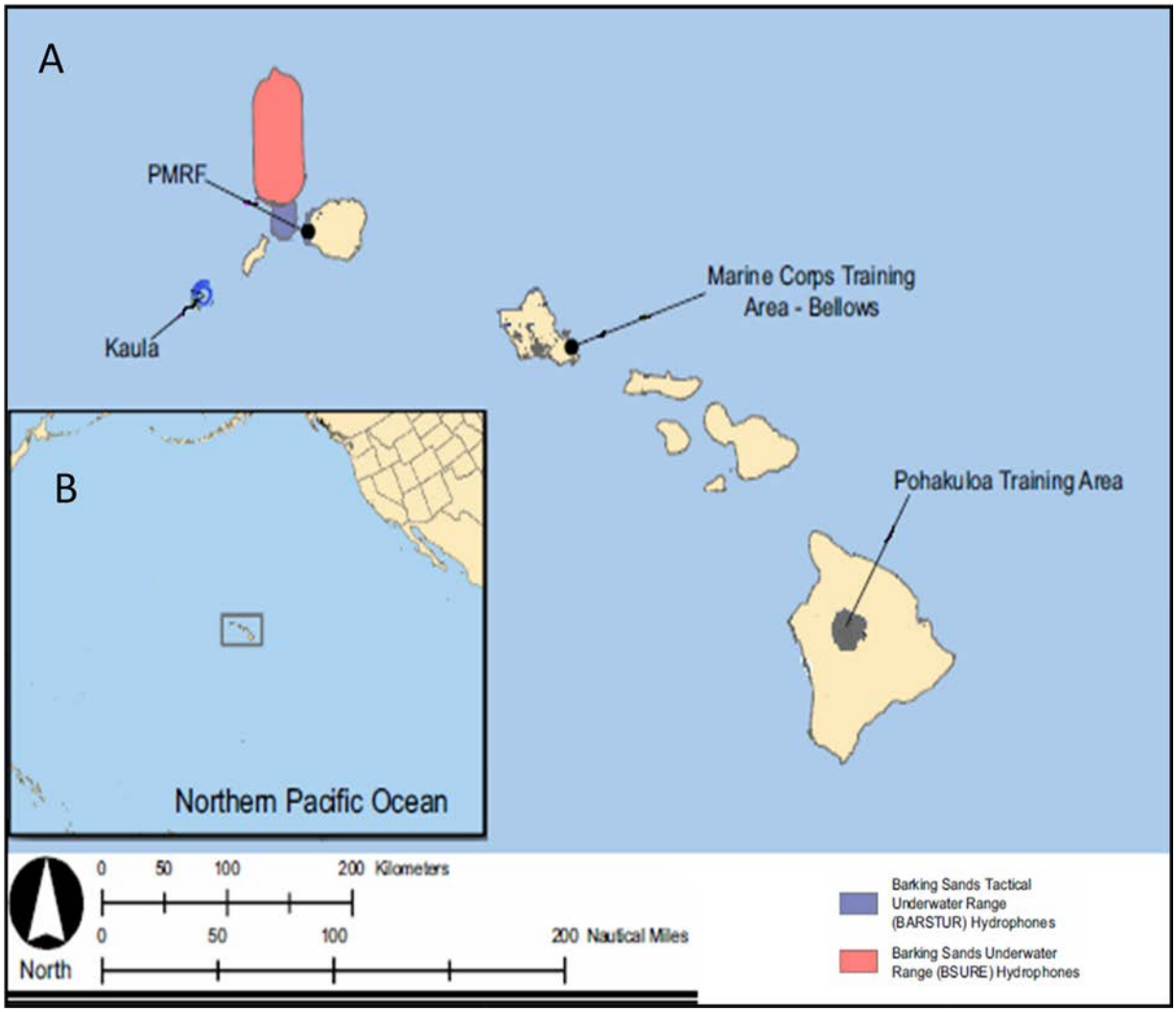

Figure 3. A) Map of Hawaii BARSTUR; B) BSURE Ranges (DoN 2008 Hawaii).

[6] Personal communication with Mike Jungles of Commander, Submarine Force U.S. Pacific Fleet about test ranges for the MK 48 and basic information on PMRF.

1.4.4 Nanoose Bay (Figures 4 A and B)

Nanoose Bay is home for the Canadian Forces Maritime Experimental and Test Range (CFMETR) sites. The bay is located near Nanoose, British Columbia and is utilized annually by both U.S and Canadian forces (Environmental Sciences Group, 2005). The Whiskey Golf Range, the primary host of heavyweight torpedo activities, is a deep-water range located outside of Nanoose Bay in the Strait of Georgia (Environmental Sciences Group, 2005). The depth readings at the range vary from 183 to 415 m (DoN, 1996 (U)). It is approximately 87 square miles and has an average depth of 400 m (Environmental Sciences Group, 2005).

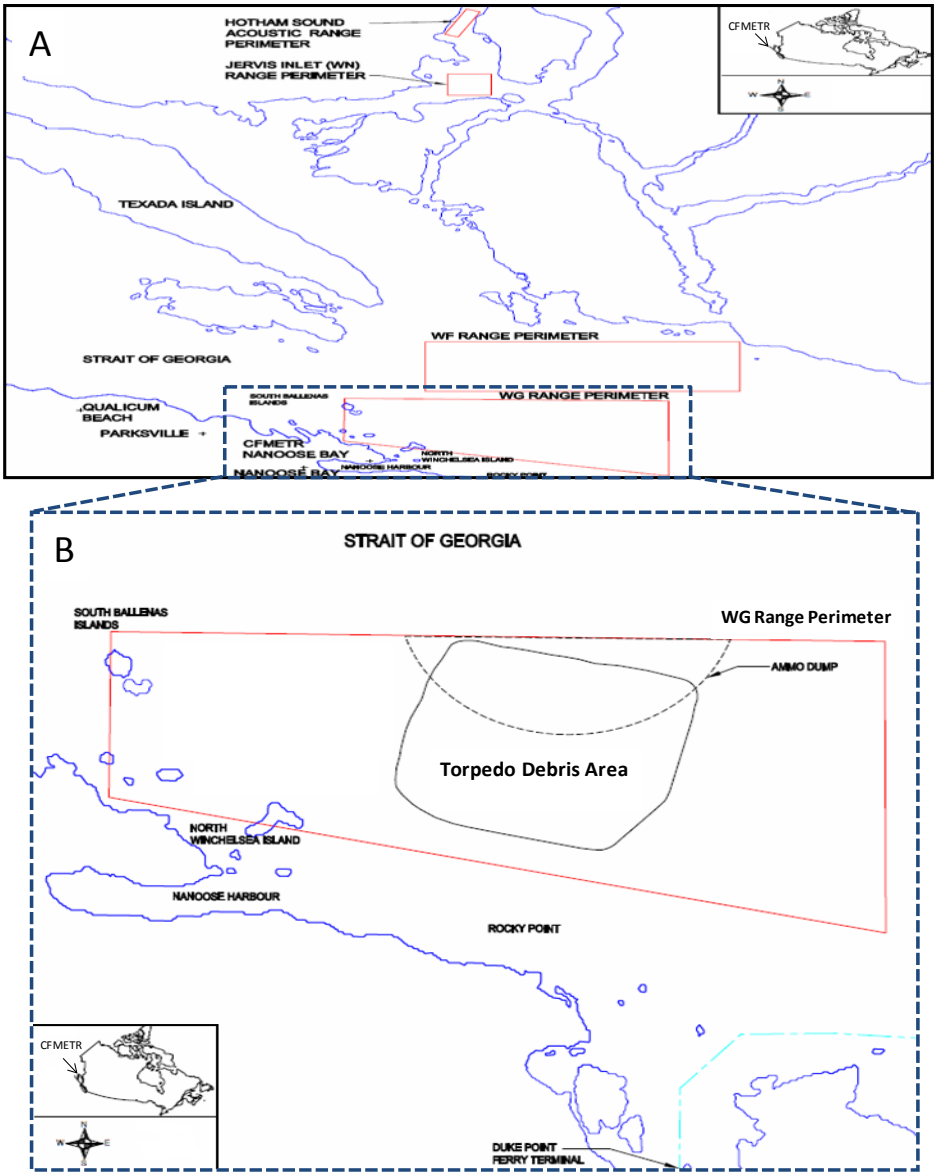

Figure 4 A and B. Map of Nanoose Bay with insert of Whiskey Golf Range (Environmental Sciences Group, 2005).

1.4.5 SOCAL Range (Figures 5 A and B)

Encompassing sea, land, and airspace off the coast of Southern California, the Navy's Southern California (SOCAL) Range Complex stretches from San Diego up to Dana Point (DoN, 2008 SOCAL). Most torpedo training exercises take place at the Southern California Anti-Submarine Warfare Range (SOAR)[7]. This is a deep-water range just off the west shore of San Clemente Island with an area of 670 square miles and average depths of 3600 to 5400 ft (1097 to 1646 m) (DoN, 2008 SOCAL).

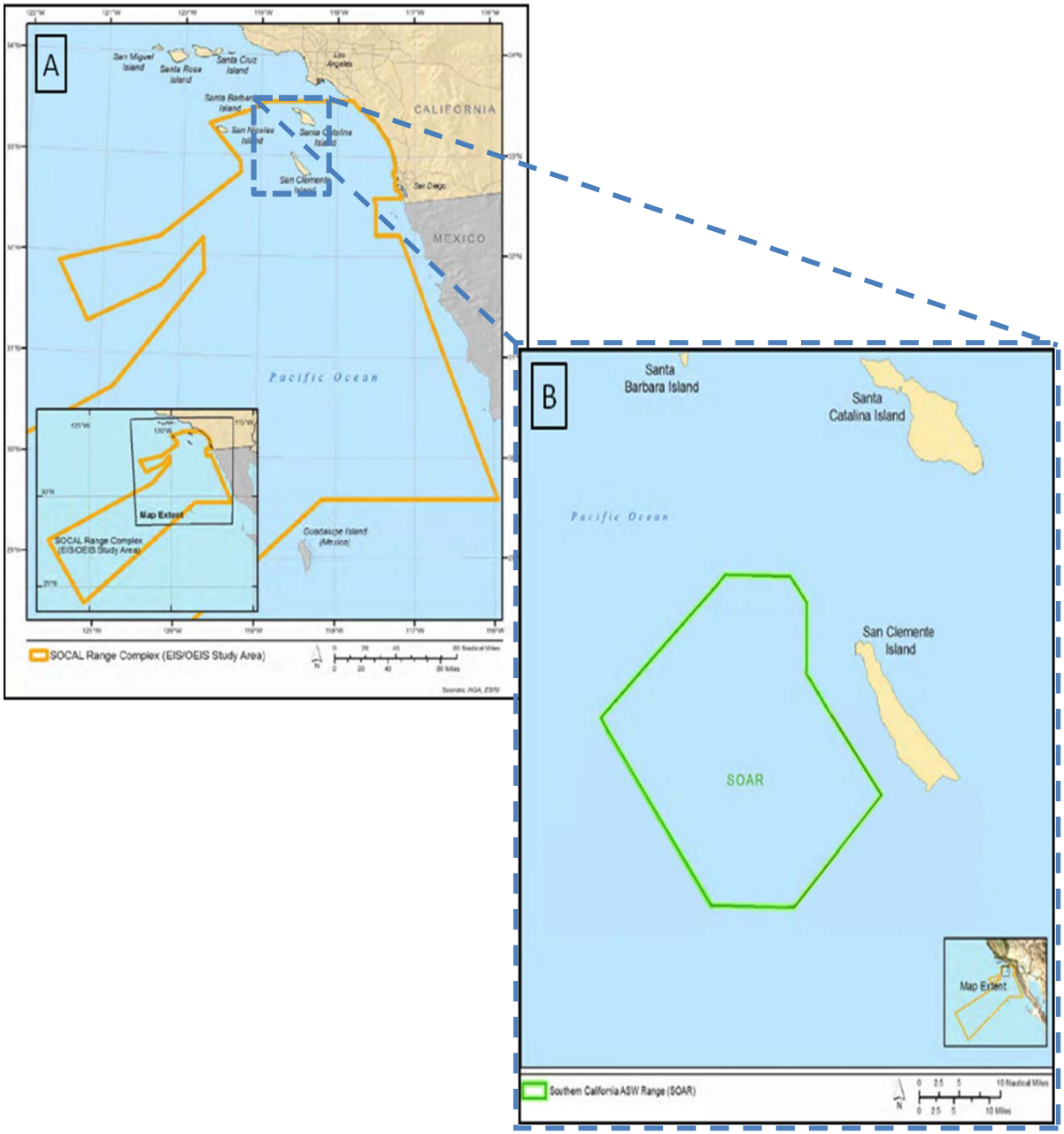

Figure 5 A and B: Map of SOCAL range with insert of SOAR (DoN, 2008 SOCAL).

[7] *Ibid.*

2. CONCEPTUAL APPROACH

The conceptual approach used in this study was to identify potential impact pathways from torpedo guidance wire to marine organisms and evaluate each pathway through empirically derived data and/or best available peer-reviewed literature. The approach focuses on site-specific environmental characteristics and marine species relevant to the testing areas described in Section 1.5 where copper guidance wire is used.

2.1 CONCEPTUAL EVALUATION PATHWAY

To assess potential environmental impacts due to torpedo guidance wire, a conceptual evaluation pathway (CEP) was developed. The CEP was developed to describe and visualize the known, expected, and/or predicted relationships between potential stressors and ecological receptors. The CEP provides the basis for development of experimental design or data gathering to assess the potential stressors.

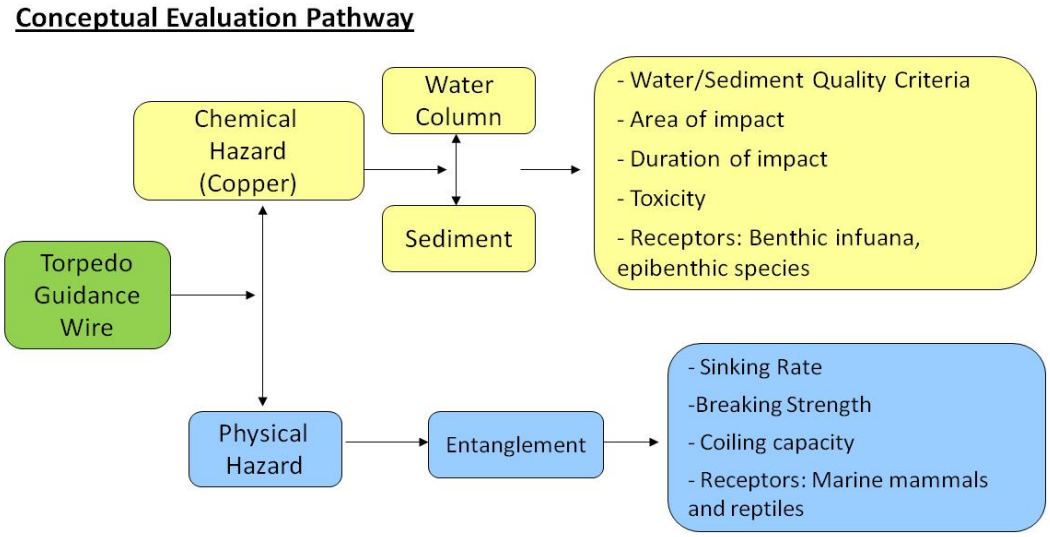

Figure 6. Conceptual Evaluation Pathway of potential environmental impacts caused by torpedo guidance wire.

2.2 EXPERIMENTAL DESIGN AND DATA REQUIREMENTS

Figure 7 outlines the various experiments conducted and data requirements fulfilled to evaluate the various stressors identified in the CEP.

In-situ Dome Testing: This experiment was performed to establish real-world leach rates for uncoated exposed copper wire. Leach rates were calculated over a wide temporal range to evaluate potential acute and chronic impacts and to gain a better understanding of copper release rates over time versus the use of a standardized corrosion rate.

Abrasion Level versus Copper Release Rate: These experiments were conducted to investigate the release rate of copper under various states of simulated wire coating degradation.

Mechanisms of Plastic Coating Degradation: A literature review of plastic coating performance and degradation mechanisms were reviewed to evaluate long-term coating performance and the potential for environmental release of copper.

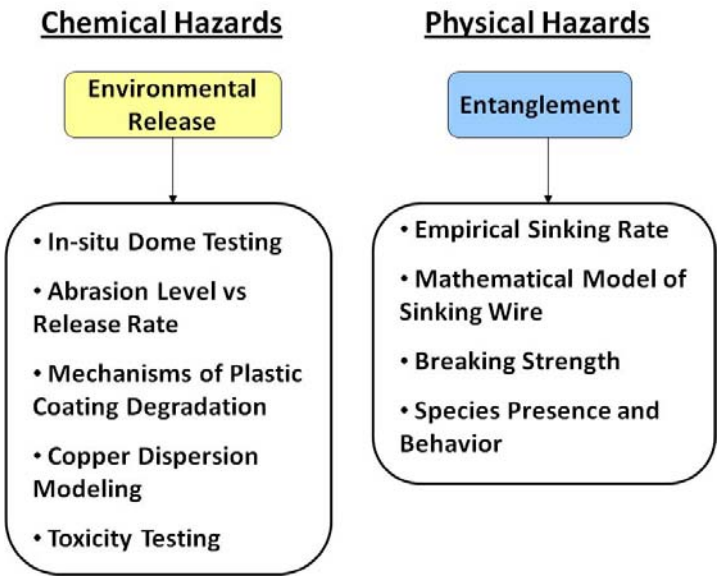

Figure 7. Various experiments and data requirements based on CEP. Colored blocks represent potential stressors, while blocks represent the various experiments and/or data requirements.

Toxicity Testing: Bioassays of two different sensitive marine species (*Strongylocentrotus purpuratus* and *Mytilus galloprovincialis*) were performed on leachate water from the *in-situ* dome testing to investigate the potential toxic response of marine organisms.

Copper Dispersion Modeling: Mathematical model(s) were used to evaluate copper dispersion through the water column and into the sediments from the source guidance wire.

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Mathematical Model of Sinking Wire: A mathematical model for sinking guidance wire was established to verify experimental data derived from empirical sinking rate experiments and extrapolate through various depths within the water column.

Breaking Strength: Breaking strength experiments were performed on torpedo guidance wire to assess impacts related to potential entanglement.

Species Presence and Behavior: A literature review was conducted to identify potential marine species that may be impacted by guidance wire. The review focused on presence within training areas where guidance wire is used, animal size, feeding behavior, and diving behavior.

2.3 EXPERIMENTAL METHODOLOGY

2.3.1 *In-Situ* Dome Testing

Copper release rates from the torpedo guidance wire were established using the SPAWAR Systems Center Pacific (Navy)-developed *in situ* release rate system, or dome system. The system was originally designed to obtain field data for determining biocide/metals release rates directly from in-service ship coatings. The dome system was previously shown to successfully measure copper and tributyltin (TBT) release rates directly from ship hulls, and 46-cm x 46-cm coated panels (Lieberman

et al., 1985; Valkirs et al., 1994; Valkirs et al., 2003). Modifications to the original sampling protocol were made to accommodate the testing of various copper-based materials, versus flat surfaces, and to alleviate the need of divers during sample collection. The dome system consisted of a 30.5 cm diameter polycarbonate 0.64-cm thick plastic dome, connected by two lengths of Teflon® (FEP) tubing to peristaltic pumps (Figure 8A and 8B). The Teflon peristaltic pump tubing was connected to two separate manifolds located on top of the dome; one of which draws water out of the dome from six outlet ports located around the perimeter of the dome, while the other manifold directs the return flow through six directional nozzle inlet ports (Figure 8A and 8B). The flow rate and ports were designed to provide gentle even mixing to simulate low-flow currents within the sealed dome. During leach rate testing, the dome is securely fitted around the testing material to create a closed system. Valkirs et al. (2003) provides greater detail on system design and material selection.

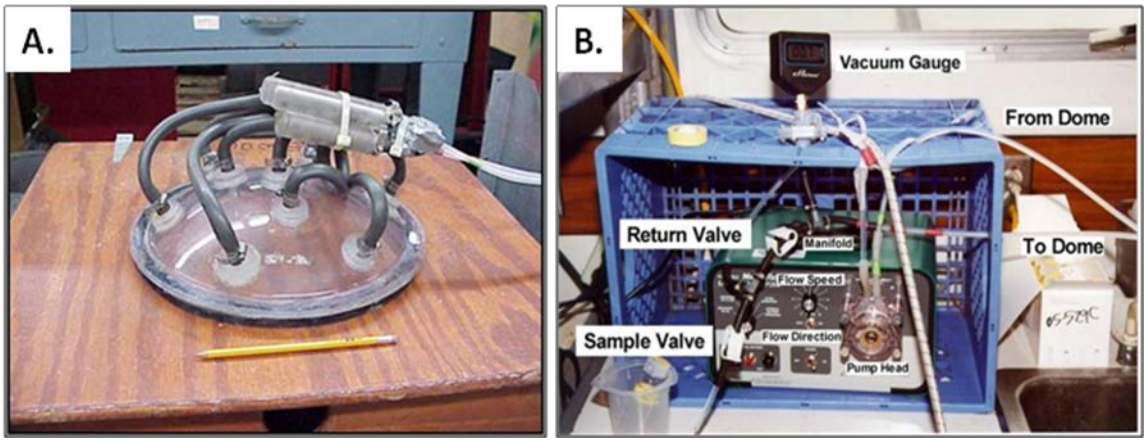

Figure 8. A) Dome system showing manifold; B) peristaltic pump used for circulating water through dome system and taking water samples.

To obtain leach rates from copper guidance wire exposed to seawater, uncoated guidance wire was obtained directly from the manufacturer (Entwistle Company, No 24 Hard Copper Wire material HPC-80-EF). Guidance wire was affixed to a 25.4-cm diameter, 0.5-in thick schedule 40-PVC sample ring. To quantify copper values being released, the surface area of exposed wire on the sample ring was optimized by weaving the wire through holes drilled in the lateral axis of the ring (Figure 9A). The outside of the sample ring was coated with JB Marine Weld to cover any exposed wire. Surface area of the exposed copper wire was then calculated by measuring the total length of wire inside the ring and the radius of the copper wire (0.29 mm). Rings were suspended to a fiberblass frame and rack. Racks were deployed in San Diego Bay from SPAWAR's Harbor Research Platform System (HARPS) (Figure 9B.). The HARPS is a 24-ft x 24-ft floating platform with a wet well extension designed for leach rate studies without the use of divers. The fiberglass racks with test samples are suspended vertically in the water column for the duration of the study. During testing days, the racks are raised slightly, and the frame with test samples are rotated horizontally so the testing rings are just below the water's surface (Figure 9C). During dome testing, the sample rings are placed on top of an arcrylic sheet to allow the domes to fit securely over the sample and achieve a vacuum seal. The sample rings have a 1-cm spacer to allow even water flow across the sample material. Figure 9D shows the domes deployed over the sample rings during leach rate testing (*note, materials in images from 9C and 9D are not guidance wire, but are representative of the sampling protocol).

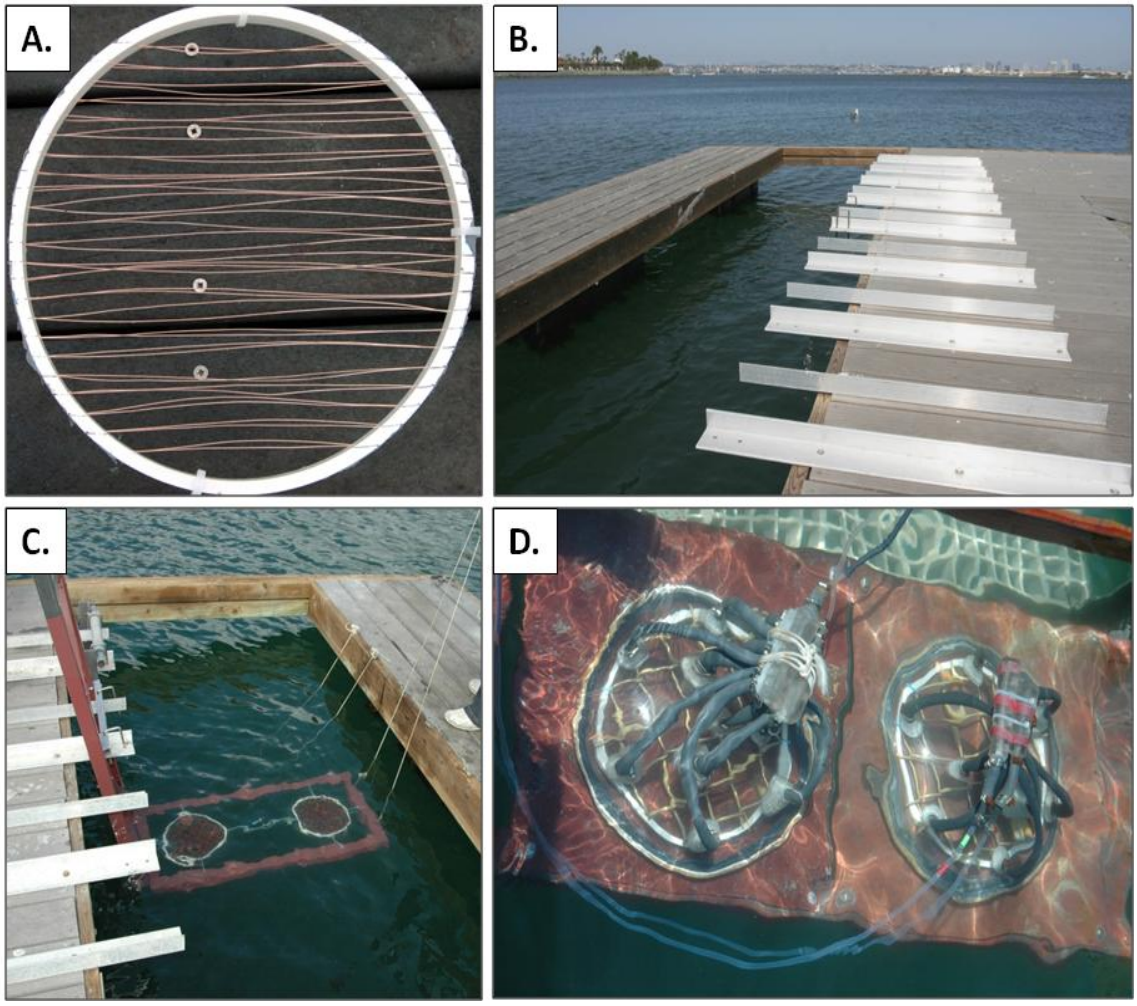

Figure 9. A, B, C, and D. *In situ* dome study.

Three replicate sample rings with guidance wire were deployed on August 23, 2011 (day 0). Leach rate tests using the domes were performed at nine different time intervals (days: 1, 8, 15, 29, 43, 65, 91, 183). Two dome systems were used during the sampling procedure.

Before leach rate testing began, the domes were submerged and water was circulated through the system for approximately 10 min to flush air from the tubing and equilibrate the system with ambient seawater. The domes were then positioned over the sample ring against the acrylic backed panel and water was slowly purged from the sampling line at the circulating pump until the dome gasket was secured and a slight vacuum was created in the now closed system. The vacuum established was sufficient to secure the dome to the surface without assistance. The seawater within the system was continuously circulated for the duration of the sampling. The pump flow speed was approximately 400 mL min^{-1}, and the dome volume was exchanged approximately 8.8 times per hour. Leach rate testing took place over the course of an hour, and 50-mL aliquots were withdrawn at 15-min intervals (0, 15, 30 45, 60 min) with the corresponding vacuum changes recorded. Of the 50-mL sample removed, 20 mL were saved for metals analysis, and the remaining 30 mL were used to create a composite sample to use for toxicity testing. The composite sample for toxicity testing was generated with water collected at each time point for all three replicates for a total of 15 samples, or 150 mL. All water samples were stored in a cooler with ice after sampling. Toxicity testing took place within

24 hours of sample collection, and water samples for copper analysis were acidified within allowable holding times established by U.S. Environmental Protection Agency (USEPA) testing protocols.

Water samples for copper analysis were collected in 30-mL, acid-cleaned, low-density polyethylene bottles, which were acidified to pH ≤2 with quartz still-grade nitric acid (Q-HNO_3) in a High Efficiency Particle Air (HEPA) class-100 all polypropylene working area. Copper concentrations were measured with a Perkin-Elmer SCIEX ELAN DRC II inductively coupled plasma with detection by mass spectrometry (ICP-MS; USEPA, 1994). If deemed necessary, samples were diluted with 0.1 N Q-HNO_3 made up in high-purity (18 MΩ cm^{-1}) water to minimize matrix-related interferences inherent to seawater. The samples were injected directly into the ICP-MS via a Perkin-Elmer Autosampler 100. Analytical standards were made with Perkin-Elmer multi-element standard solution (PEMES-3) diluted in 1N Q-HNO_3, which was matrix matched to the salinity of the test samples. Standards were analyzed at the beginning and end of the run. The analysis also included measurement of the Standard Reference Material (SRM) 1643e from the National Institute of Standards & Technology (NIST), and analytical blanks made up of 1N Q-HNO_3 after every five samples. A coefficient of variation (CV) of ≤5% for replicate measurements was observed, as well as a recovery within 15% of SRM 1643e.

Leach rate calculations were made using the copper concentrations of the analyzed samples from ICP-MS. Copper concentration within the dome system for each time point were calculated by multiplying the concentration from ICP-MS in μg L^{-1} by the volume of water in the dome and the tubing, which was obtained via initial system calibration. Initial dome volumes for the two systems were approximately 2.8 L. Volumes were corrected for water removed throughout the 1-hour testing. The measured copper value in micrograms of copper per liter multiplied by the system volume equals micrograms of copper per dome volume. These concentrations were then regressed against time (samples were taken 0, 15, 30, 45, and 60 min). The slope of this line represents micrograms of copper released per minute. The slope multiplied by 1440 (60 min per hour x 24 hours per day) results in micrograms of copper per dome d^{-1}. This value was then corrected by the linear length of the exposed copper wire, resulting in a final copper release rate in μg mm^{-1} d^{-1}.

2.3.2 Abrasion Level versus Release Rate

A series of experiments were performed to analyze various degrees of abrasion, wire exposure, and resulting copper release of coated copper guidance wire.

2.3.2.1 Wire Abrasion Methodology

Coated wire of 1-m length were affixed on one end to a stationary point. At the fixed end of the wire, two squares of 60 grit silicon carbide sandpaper measuring 3 cm^2 were placed over the wire. The sandpaper was held in place by a clamp with a measured force of 17.5 N. The sandpaper was then drawn along the length of the wire at approximately 0.25 m s^{-1}. To ensure the round wire was equally exposed to the abrasion action of the sandpaper, the clamp was separately pulled down two planes perpendicular to each other along the axis of the wire. These two separate abrasion runs constitute one "set." The sandpaper was replaced after each abrasion set.

An initial test was conducted to determine how many sets of abrasion runs were needed to completely strip the copper guidance wire of its polyethylene coating. An average of 16 sets was needed to completely expose the wire. Thus, to achieve various degrees of abrasion, the following number of sets were assigned for different percentages of abrasion treatment: 0%: 0 sets, 25%: 4 sets, 50%: 8 sets, 75%: 12 sets, and 100%: 16 sets. Three replicates of each abrasion treatment were prepared for use in the leach rate test.

2.3.2.2 Leach Rate Testing

Leach rate testing methodology was based on American Society for Testing and Materials (ASTM) Method D6442 (Standard Test Method for Determination of Copper Release Rate from Antifouling Coatings in Substitute Ocean Water). The test wires were placed in holding tanks with flow through seawater for the duration of the 45-day study. A constant flow of seawater was pumped into the tank at a flow rate to achieve approximately five turnovers per hour. As seen in the Figure 10, two tanks were used to store the wires. Samples were rotated from one tank to the other on testing days to prevent any artificial variations from the two tanks.

After an initial exposure period of 24 hours, leach rate measurements were taken on days 1, 3, 7, 10, 15, 22, 29, 36, and 45. Each test wire was placed in 1 liter of 0.45 micron-filtered seawater for 1 hour. The testing containers were made of polycarbonate, and had a 1.5-L capacity. Test containers were placed on a laboratory shaker to simulate a low-flow environment. At the end of the hour, an aliquot of the 1-L exposure water was taken for metals analysis of copper and zinc. Sample handling and preparation for ICP-MS analysis were identical to that used for the *in situ* dome test.

Leach rates for each of the test wire abrasion treatment and replicates were determined by the following equation:

$$Rgw = \frac{(Ccu \times V \times D)}{(T \times L)},$$

where R_{gw} = Copper release rate of test torpedo guidance wire, C_{cu} = Copper concentration measured in aliquot from holding tank, V = Volume of water in the test containers during exposure (1L), D = Hours per day (24), T = Exposure period (1 hr), and L = Linear length of test wire (1000 mm).

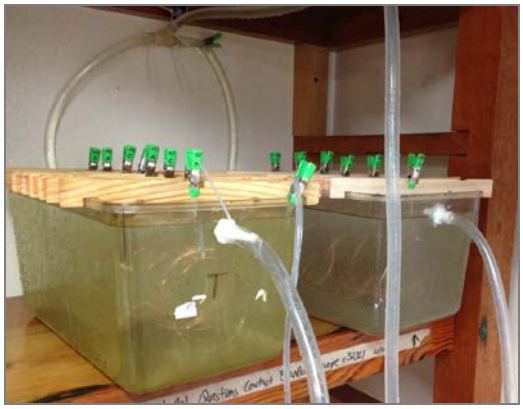

Figure 10. Abrasion testing flow tank.

2.3.3 Toxicity Testing

Toxicity testing was performed in conjunction with *in-situ* dome leach rate testing. Seawater collected during the *in-situ* leach rate testing for chemical analysis was used to generate a composite sample for subsequent toxicity testing. A 30-mL aliquot of each sample collected for chemistry (Time 0, 15, 30, 45, and 60) was composited for all three field replicates, for 450 mL. Toxicity testing utilized the 96-hour echinoderm embryo-larval development test with the purple sea urchin, *Strongylocentrotus purpuratus*. Toxicity testing was conducted on <4-hour-old *S. purpuratus* embryos. Gravid *S. purpuratus* were field collected locally in San Diego, California, and delivered by Nautilus Environmental, LLC. (San Diego, California) to the SSC Pacific Bioassay Laboratory on

the same day as toxicity testing. The sampling event on day 91 had an additional toxicity evaluation using the developing larvae of the Mediterranean mussel, *Mytilus galloprovincialis,* concurrently conducted with the *S. purpuratus*. Mussels were received from Carlsbad Aquafarm (Carlsbad, California) on the day of test initiation.

For all toxicity tests performed, the composite leachate samples were analyzed using a HACH DR/2400 spectrophotometer (Cu Porphyrin, HACH Method 8143) to estimate dissolved Cu concentration. Prior experience with the toxicity testing protocol indicated that the leachate samples would be highly toxic to sea urchin embryos if undiluted; therefore, the measured Cu concentrations were used to establish an appropriate dilution series that would be within range of expected response to *S. purpuratus* (dissolved Cu EC50 = 14.3 µg/L; Rosen et al., 2008). Leachate samples were diluted with 0.45-µm filtered seawater (FSW) to create concentrations of approximately 3.13, 6.25, 12.5, 25, 50, and 100 µg/L Cu. Concurrent reference toxicant tests using $CuSO_4$ were performed during each test to ensure normal sensitivity of the test organism batch. Prior to the introduction of organisms to test concentrations, pH, dissolved oxygen, temperature, and salinity measurements of each sample were made to ensure that conditions were within those tolerated by the test organism. Water quality measurements were conducted daily to ensure continuation of appropriate test conditions.

Data were analyzed using CETIS ©2011, Comprehensive Environmental Toxicity Information System software. The EC50, the NOEC, and LOEC were calculated; where the EC50 is the estimated median concentration at which 50% of the organisms were adversely affected, the NOEC is the concentration at which there was no observed effect upon the organisms, and the LOEC is the lowest concentration at which an effect is observed.

2.3.4 Dispersion Model

A dispersion model was developed to track the transport of copper from exposed portions of torpedo guidance wire to the water column. As the copper ions leach into the seawater, they travel through the water column primarily via diffusion (the dispersion of particles from a high to low concentration) and advection (the movement of a mass of fluid). In the case of torpedo guidance wire, the advection process is controlled by deep ocean currents while the dispersion process is a more complex function dependent on multiple time-dependent variables. Additionally, the copper released may be consumed by ocean life—both plant and animal—as it travels through the water column, become bound to particulate and organic matter, or be absorbed into the sediment. Due to the variability these factors present, it is unrealistic to model the exact movement of the released copper. In lieu of having the capability to model the exact fate of copper released into the water column, a simple dispersion model was created using the following assumptions:

1) A length of 0.1-cm (1-mm) wire was exposed at the end of the guidance wire. The exposure length is based on the exposed ends of the wire after breakage when the wire separated from the torpedo/ship. This model looks at the impact one exposed end of wire will have in the water column as it is assumed the terminal ends of the wire are miles apart. Consequently, the copper released from one end will not impact the release from the other end.

2) The copper will release solely into the water column and the copper does not move through the sediment upon which the wire rests. Though the copper will actually diffuse into the sediment, it will do so at a much slower rate. Therefore, to present the "worst-case" scenario for the water column, it is assumed that all the copper will be released into the water and the sediment component is ignored.

3) Copper will behave in a conservative manner; the entire amount released from the wire is assumed to remain in the water column. There will be no biological uptake or loss due to adsorption or binding to particulate matter.

4) Copper release rates used are based on data obtained from the *in-situ* dome testing (Section 4.1.1). The peak leach rate is 5.9 µg mm^{-1} d^{-1} and the pseudo-steady-state release rate is 0.58 µg mm^{-1} d^{-1}.

5) Diffusion is the primary means of movement through the water column. The diffusion coefficient used in the model is 10 cm^2 s^{-1} and represents the lower range of values used in hydrodynamic modeling to provide conservative and realistic dispersion rate.

Using these assumptions, the concentration of copper, C, at any distance from the guidance wire, x, can be approximated by

$$C(x) = \frac{M}{(2\pi x)D},$$

where C = copper concentration (µg cm^{-3}) and M = the mass released per second (µg s^{-1}).

This value is equal to the leach rate (µg mm^{-1} d^{-1}) multiplied by the length of wire exposed. With a 1-mm end exposed, we calculate the mass released per second as M_{peak} = 7.83E-05 µg s^{-1} (based on the peak leach rate), and M_{steady} = 1.25E-06 µg s^{-1} (based on the pseudo-steady-state leach rate).

- D = 10 cm^2 s^{-1} is hydrodynamic diffusion coefficient.

- x = is any distance from the exposed end of the wire (cm).

- The 2πxD term in the denominator of the equation accounts for the volume into which the mass of copper is released. If the copper were to release into the sediment as well as the water column, the release would be uniform in a 360° sphere around the copper source and the denominator would be 4πxD. However, since it is assumed that the copper will release more slowly into the sediment, we force the amount of copper that would have been released into sediment up into the water column by multiplying the concentration by 2.

2.3.5 Empirical Sinking Rate

After the torpedo wire is released from both the weapon and the ship, it falls to the ocean floor. An empirical study was conducted to measure the sinking rate of the wire.

Testers dropped 1- and 3-m lengths of wire underwater (in seawater) in front of a reference background with centimeter markings (Figure 11). The drops were filmed using an underwater camera (GOPRO Camera) that captures 60 frames per second.

The video clips were analyzed frame by frame to calculate the empirical sinking rate for the varying lengths of wire. Each film was analyzed by measuring the sinking rate over a range of frames, focusing on the portion of the film where the wire was directly in front of the camera (approximately the middle of the field of view) to ensure perspective did not skew the position recorded. For each video clip, the sinking rate was calculated for several numbers of frames. For example, one film would be analyzed by calculating a sinking rate using 15 frames, 10 frames, and 5 frames within the optimal field of view. These rates were then averaged and their standard deviation taken to ensure that the video was suitable for use and the terminal velocity of the wire was captured during filming. Approximately 15 videos of each wire length were suitable for analysis.

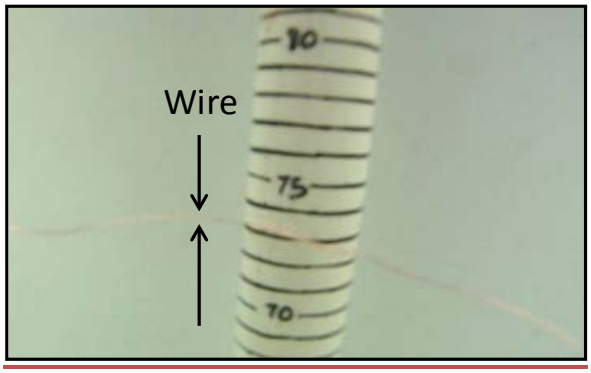

Figure 11. Snapshot of 1-meter wire falling.

2.3.6 Mathematical Model of Sinking Wire

To support the empirical sinking rate found, a mathematical model was used to estimate a reasonable range of values for the sinking rate of the wire (see Figure 12). A portion of the model is included in the report and the entire model may be found in Appendix A. Several assumptions were made to build the model:

1. The main forces impacting the wire are its weight, buoyant forces, and drag forces from the water column (ignore currents).
2. The wire remains stretched out in a straight line (if the wire were to coil up, it is assumed this would increase the rate at which it falls).
3. Terminal velocity is reached almost instantaneously; this model estimates the sinking rate, assuming terminal velocity has been reached.
4. A length of 13,250 m is sinking (maximum possible).
5. The wire is a smooth cylinder.

The forces on the wire falling at terminal velocity can be written: $F = F_d + F_b - F_w$,

where

$$F_d = C_d A \frac{1}{2} \rho_{water} U^2$$

F_d = Drag forces on the wire

C_d = dimensionless drag coefficient

A = area of the wire falling through water column = 12.62 m^2 (r = 0.0005 m)

ρ_{water} = density of seawater = 1027 kg m^{-3}

U = velocity of falling wire (sink rate), m s^{-1}

$$F_b = Vg\rho_{water}$$

F_b = Buoyant forces on the wire

V = volume of wire = 0.0094 m^3 (r = 0.0005 m, l = 13,250 m)

ρ_{wire} = density of wire = $\frac{\textbf{mass}}{\textbf{volume}}$ = 4073 kg m^{-3}

$$F_w = mg = Vg\rho_{wire}$$

F_w = Force on wire due to its weight

m = mass of wire = 0.0029 kg m^{-1}

g = 9.8 m s^{-2}

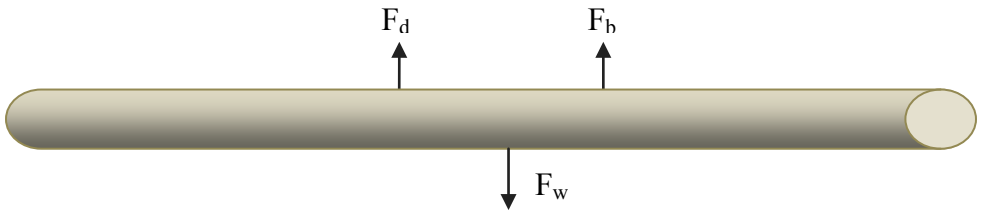

Figure 12. Free-body diagram of sinking wire.

The total force equation can then be rewritten as

$$ma = C_d A \frac{1}{2} \rho_{water} U^2 + V(\rho_{water} - \rho_{wire})g.$$

Assuming terminal velocity has been reached, the acceleration of the wire is equal to zero. Thus, the left-hand side of the equation becomes 0 and we solve for the velocity of the falling wire, U:

$$U = \sqrt{\frac{V(\rho_{water} - \rho_{wire})g}{C_d A \frac{1}{2} \rho_{water}}}.$$

To solve for the velocity of the wire, a reasonable value, or range of values must be established for the drag coefficient, C_d. The methodology used for determining C_d is discussed in its entirety in Appendix A.

2.3.7 Breaking Strength

Experiments were carried out to evaluate the breaking strength of torpedo guidance wire. The wire was suspended vertically from a fixed point and weights were incrementally added to the free end until wire breakage. The wire was wrapped around the fixed point several times and then clamped in place, creating a friction base to prevent the wire from slipping when weight was added to the free end. In a similar manner, the free end of the wire was then wrapped around a small plastic rod to which a C-clamp was attached, creating a platform for weights to be attached. The length of wire between the fixed point and free end of the wire was 1 m. Calibrated weights were added one at a time beginning with four 5-pound weights, followed by three 2.5-pound weights, and lastly, one-pound weights were added until wire failure. The weight of the rod and clamp was 0.5 pounds. The time interval between additional weights being added was 30 sec. Five different replicate trials were conducted.

3. RESULTS

3.1 CHEMICAL HAZARDS

3.1.1 *In-Situ* Dome Testing

The linear fit of the dome copper concentrations with sample collection time were good, ranging from $r^2 = 0.95$ to 0.99, allowing for calculation of leach rates from the slope of the regressed line. Copper release rates are presented in Figure 13. Mean copper release rates increased initially from day 1 through day 15 from 3.8 to 5.9 µg mm^{-1} d^{-1}. There was an order of magnitude drop in release from day 15 to day 29, when the mean release rate was 0.67 µg mm^{-1} d^{-1}. A more steady-state release rate is observed from day 29 throughout the remainder of the study, where release rates were 0.67 to 0.17 µg mm^{-1} d^{-1}. These data are consistent with other studies on copper paints and copper containing materials (Valkirs et al., 2003).

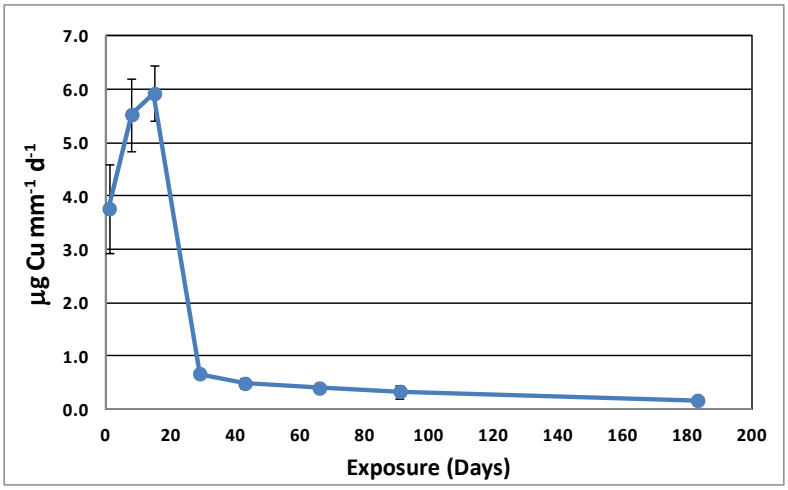

Figure 13. Copper release rate during the experiment. Values represent mean release rates with error bars showing plus ± one standard deviation.

The cumulative release of copper during the 183-day experiment can be calculated by the following equation (ASTM D6442):

$$R_{0183} = \sum \frac{(R_i + R_f)}{2(f - i)},$$

where,

R_{0183} = cumulative release (µg Cu mm^{-1}),

i and f = time elapsed (days) since the start of experiment for each pair of consecutive data points, i.e., day 0 and 1, 1 and 8, 8 and 15, 15 and 29, etc.

R_i and R_f = mean release rates (µg Cu mm^{-1} d^{-1}) for each set of triplicate dome deployments for each pair of consecutive days from the start of the trial through day 183, where day 0 (R_0) is taken as 0 (µg Cu mm^{-1} d^{-1}).

The cumulative release of copper from the torpedo guidance wire during the 183-day exposure period was 171.2 µg Cu mm^{-1}.

Similarly, if the release rate data exhibit a pseudo-steady state over the course of the experiment (ASTM D6442), the mean release during that time period ($\bar{R}_{PSS}$) can be calculated by the following equation (variables similar to equation x above, and):

$$\bar{R}_{PSS} = \frac{\sum \frac{[(R]_i + R_j)}{2(j-i)}}{\sum (j-i)}.$$

There appears to be a pseudo-steady-state release rate from days 29–183. The mean copper release rate ($\bar{R}_{PSS}$) during that time period was 0.58 µg Cu mm^{-1} d^{-1}.

3.1.2 Abraded Wire Release Testing

Copper release rates for the various levels of abrasion treatment on coated wire are presented below. Images of guidance wire exposed to various treatments are shown in Figures 14–17. The 0% and 25% treatments resulted in no wire exposure along the length of the wire; only the tips of the wire had exposed copper. The 50% treatment had minimal areas of exposed copper with exposure areas ranging from 1 to 5 mm. The 75% treatment resulted in larger areas of coating failure resulting in exposed wire sections up to 30 mm in length. The 100% treatment was completely exposed copper wire. Copper release rates varied among the five abrasion treatments (0%, 25%, 50%, 75%, and 100%), as well as temporally within each treatment during the 45-day experiment. Figure 18 shows copper release for the five abrasion treatments at individual testing days. Copper release rates for the 0%, 25%, and 50% treatment had release rates below 0.2 µg mm^{-1} d^{-1}, with similar temporal trends of highest release during day 1, followed by a general decreasing trend through day 45. The 75% and 100% treatments had similar temporal trends in release rates during the experiment, although the magnitudes of release rates were different. For each respective treatment (75% or 100%), release rates were similar on day 1 and day 3, peaked on day 7, then fell sharply, stabilizing through day 45. The 75% treatment had a maximum release of 3.5 µg mm^{-1} d^{-1}, while the 100% treatment had a maximum release of 10.3 µg mm^{-1} d^{-1}.

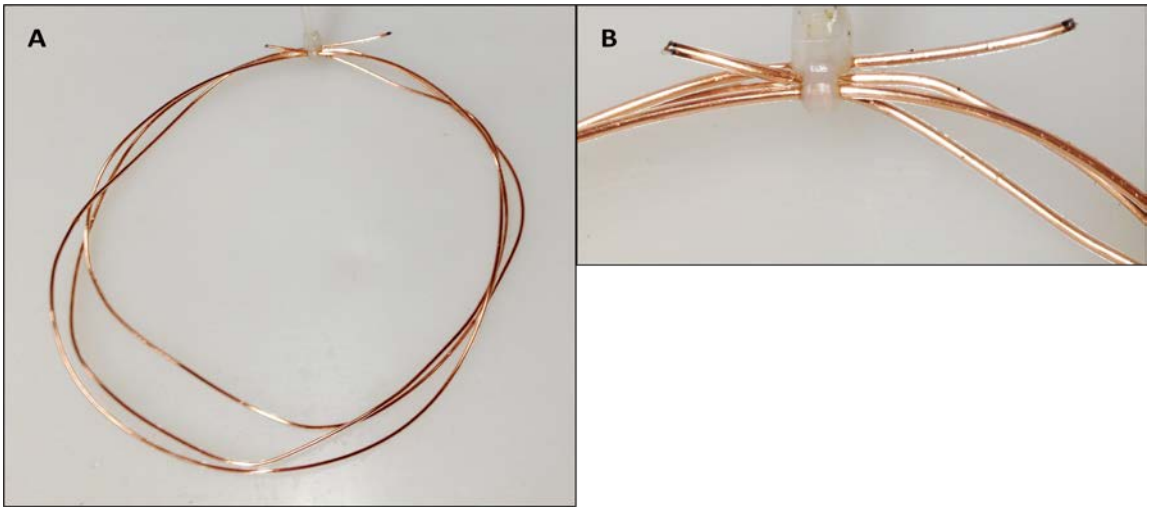

Figure 14. A and B are photos of 0% abraded wire on day 45; B shows corrosion on the terminal ends of wire.

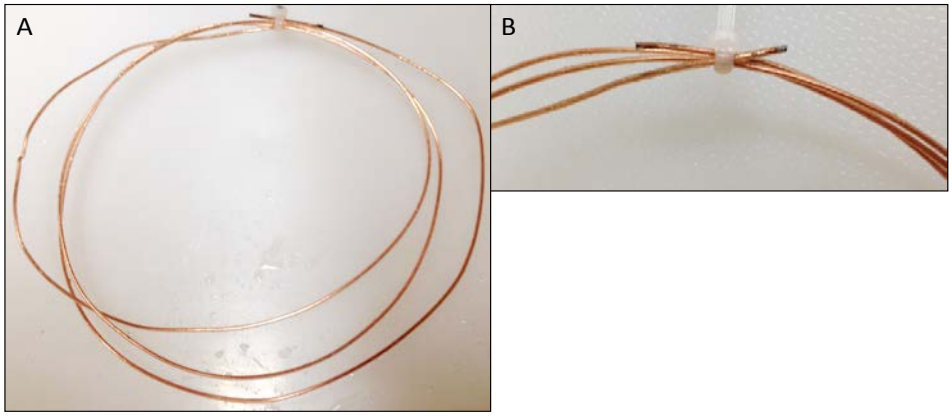

Figure 15. A and B are photos of 25% abraded wire on day 45; B shows corrosion on the terminal ends of wire.

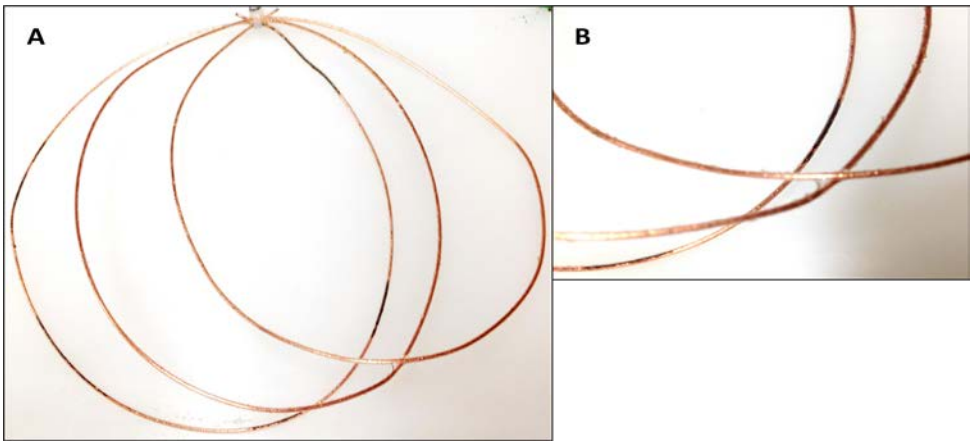

Figure 16. A and B are photos of 50% abraded wire on day 45; B is zoomed to show a small portion of exposed wire.

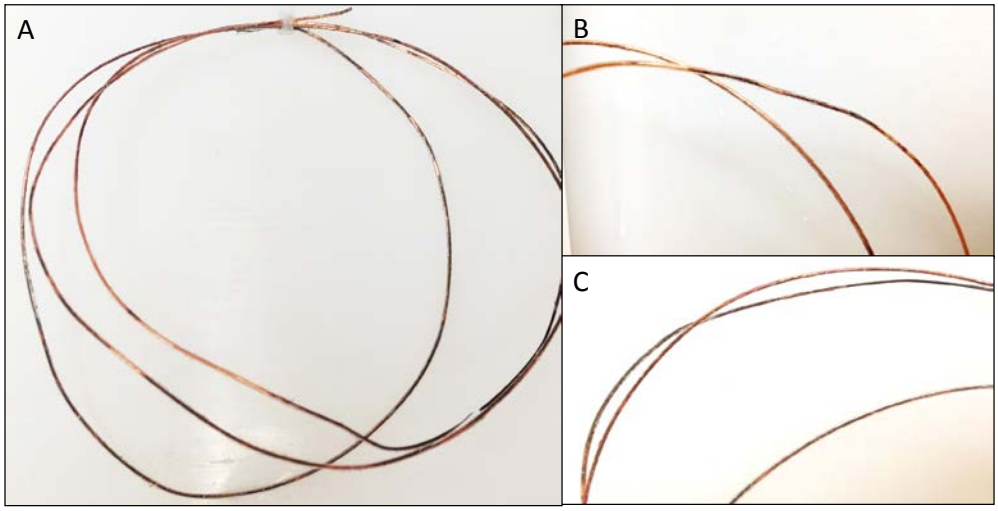

Figure 17. A and B are photos of 75% abraded wire on day 45; B and C are zoomed to show portions of exposed wire.

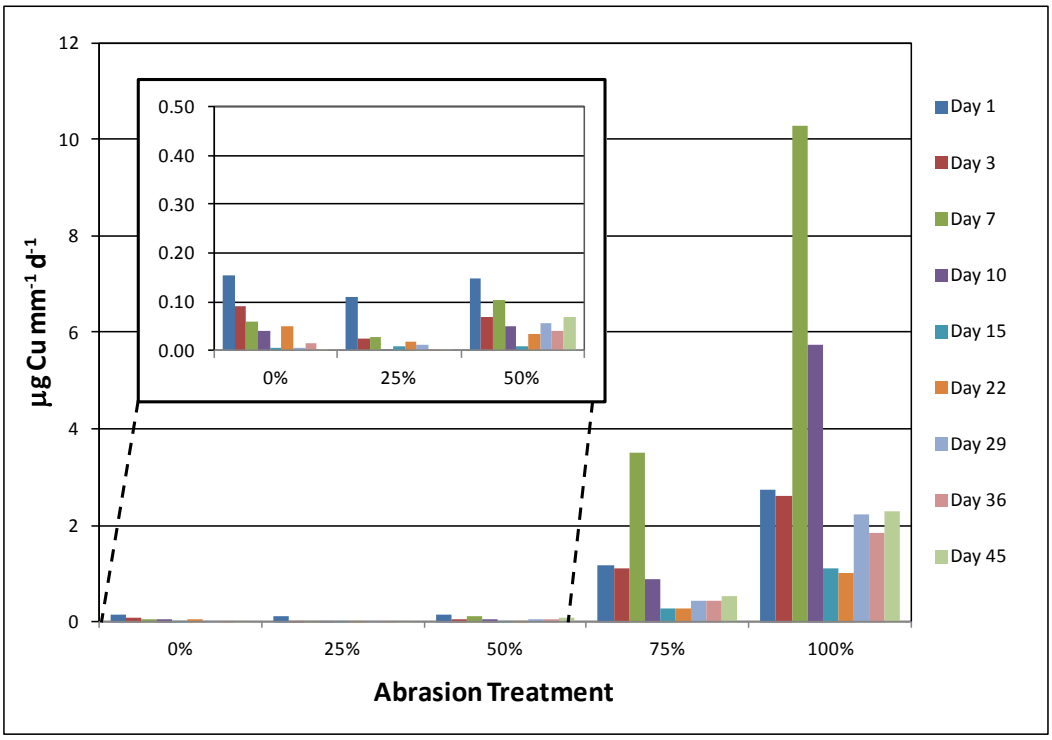

Figure 18. Release rates for the five treatments of abrasion testing. The 0%, 25%, and 50% treatments are also shown at reduced scale to allow for better visualization of the data.

Copper release rates did not exhibit a linear increase relative to the level of abrasion treatment. Figure 19 shows the observed copper release as well as the predicted copper release, where the predicted assumes a linear increase in release with percentage abrasion. The observed versus predicted plots were similar for all testing days, with Figure 19A, B, and C showing examples for testing days 1, 7, and 15, respectively. Copper release rates for the 0%, 25%, and 50% treatments were similar in magnitude. The first treatment, which showed an increase in copper release, was the 75% treatment, increasing further with the 100% treatment (Figure 20). Comparing release rates from abrasion treatments on individual sampling days, a 1-way ANOVA test showed a significant difference between the treatments for all sample days. Analysis using a student's t test for all possible comparisons resulted in three groups, which were significantly different from each other. The 0%, 25%, and 50% treatments made up one group, while the 75% and 100% treatment were considered unique groups (Figure 21). This held true for all sampling days excluding day 10, which only resulted in two groups, where the 100% treatment was one group and the remaining four treatments made up the second group.

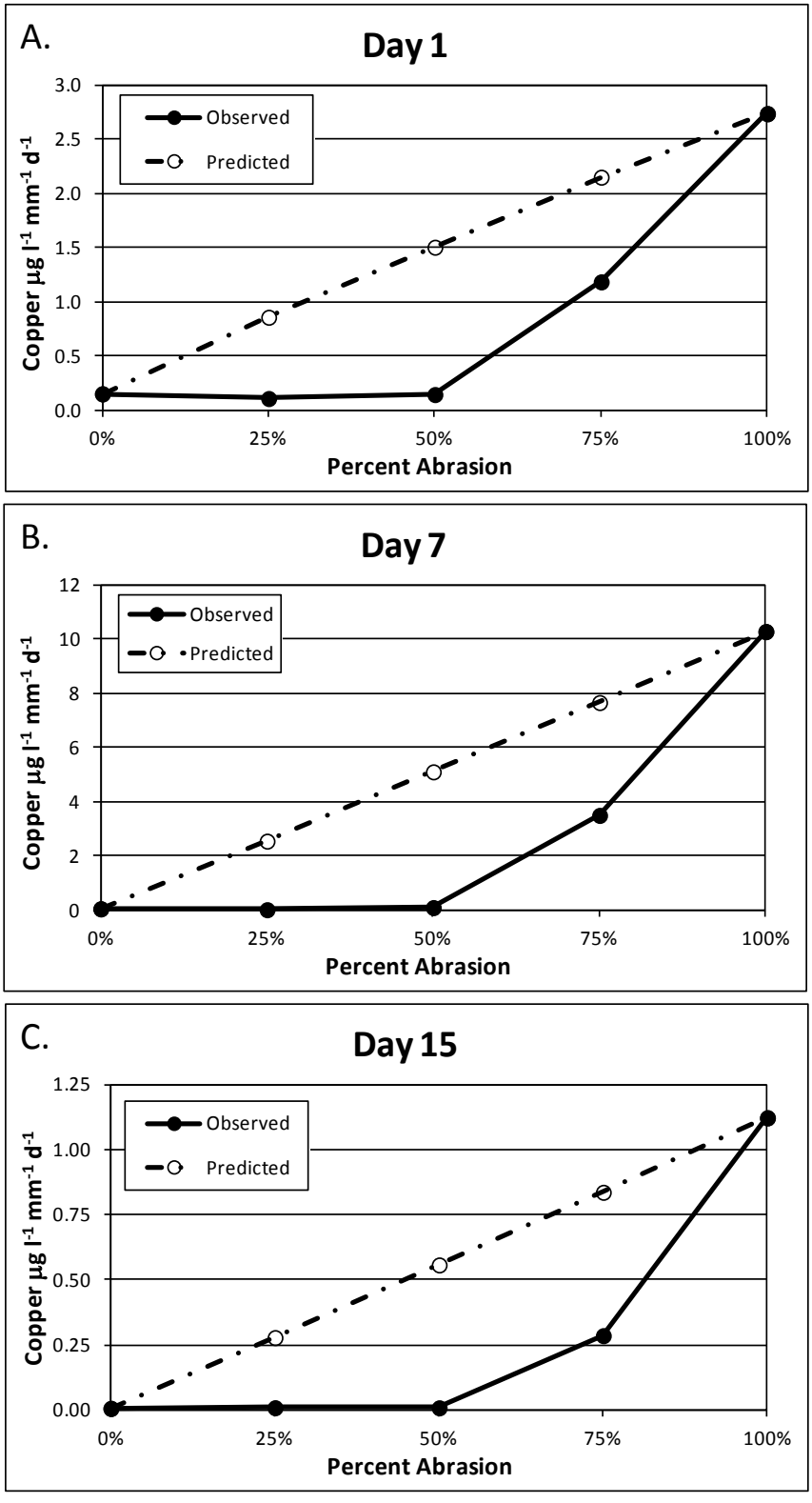

Figure 19. Observed and predicted copper release rates for the five abrasion treatments; A) Day 1, B) Day 7, and C) Day 15.

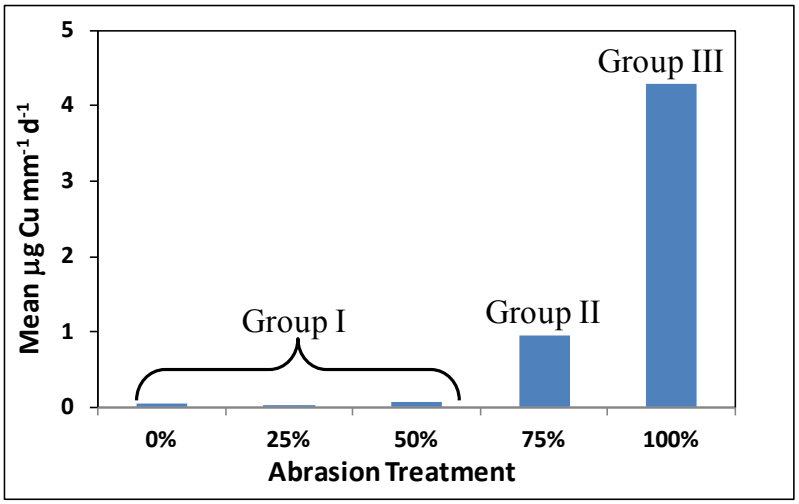

Figure 20. Mean copper release rates for each abrasion treatment during the 45-day testing period. Treatment groups are statistically significant from each other.

3.1.3 Toxicity Testing

Results from toxicity testing are shown in Table 1. Guidance wire toxicity results matched well with the Reference Toxicant testing (copper sulfate), assuring that inter-test variability is within the normal range of variability for the test species *Strongylocentrotus purpuratus*. Toxicity resulting from guidance wire leachate had a mean Effect Concentration (EC) 50 of 23.7 $\pm$6.9 Cu µg l^{-1}, a mean Lowest Observable Effect (LOEC) of 21.2 $\pm$7.1 Cu µg l^{-1}, and a mean No Observed Effect Concentration (NOEC) of 10.6 $\pm$3.5 Cu µg l^{-1}. The sampling event with the greatest toxicity resulted in an EC50 of 15.5 Cu µg l^{-1}, while the least toxic event found an EC50 of 33.8 Cu µg l^{-1}. The most environmentally conservative (worst-case) endpoint during all of the testing showed that the copper concentration at which no effect was observed to be 5.0 µg l^{-1}, while the lowest observed effect concentration was 10.1 µg l^{-1}. The toxicity test performed with *Mytilus galloprovincialis* on sampling day 91 resulted in an EC50 of 10.0 Cu µg l^{-1}, and LOEC of 14.6 Cu µg l^{-1}, and an NOEC of 7.3 Cu µg l^{-1}.

Table 1. Toxicity metrics from torpedo guidance wire and reference toxicity for *Strongylocentrotus purpuratus*.

	Guidance Wire (Cu µg l^{-1})			Ref Tox (Cu µg l^{-1})		
Sampling Day	**EC50**	**LOEC**	**NOEC**	**EC50**	**LOEC**	**NOEC**
1	33.8	26.5	13.3	27.8	24	17.2
8	16.2	15.3	7.7	13.4	12	8.4
15	27.8	24.7	12.3	26.1	24	17.2
29	31.8	14.1	7.0	16.1	12	8.4
43	23.5	27.4	13.7	17.9	17.2	12
64	18.5	22.5	11.2	19.5	17.2	12
91	22.3	29.1	14.5	17.0	17.2	12
183	15.5	10.1	5.0	15.3	12	8.4
Average	**23.7**	**21.2**	**10.6**	19.1	17.0	12.0
S.D.	**6.9**	**7.1**	**3.5**	5.2	5.0	3.6

3.1.4 Dispersion Model

Results from the water column dispersion model evaluating 1 mm of exposed copper wire are shown in Table 2 and Figures 21 and 22. Estimated water column concentrations were very low, and only shown to a distance of 10 cm from the source. The 1-mm exposed wire resulted in water column copper concentrations ranging from 1.25×10^{-2} µg L^{-1} to 1.25×10^{-4} µg L^{-1} for the peak release rate and 1.21×10^{-3} µg L^{-1} to 1.21×10^{-5} µg L^{-1} for the pseudo-steady-state (PSS) release rate.

Table 2. Water column copper concentrations in µg L^{-1} (ppb) from 1 mm of exposed wire at various distances under peak release and PSS release rates.

Distance from Source (cm)	Peak Release	PSS Release
0.1	1.25E-02	1.21E-03
1	1.25E-03	1.21E-04
2	6.23E-04	6.05E-05
3	4.15E-04	4.04E-05
4	3.11E-04	3.03E-05
5	2.49E-04	2.42E-05
6	2.08E-04	2.02E-05
7	1.78E-04	1.73E-05
8	1.56E-04	1.51E-05
9	1.38E-04	1.35E-05
10	1.25E-04	1.21E-05

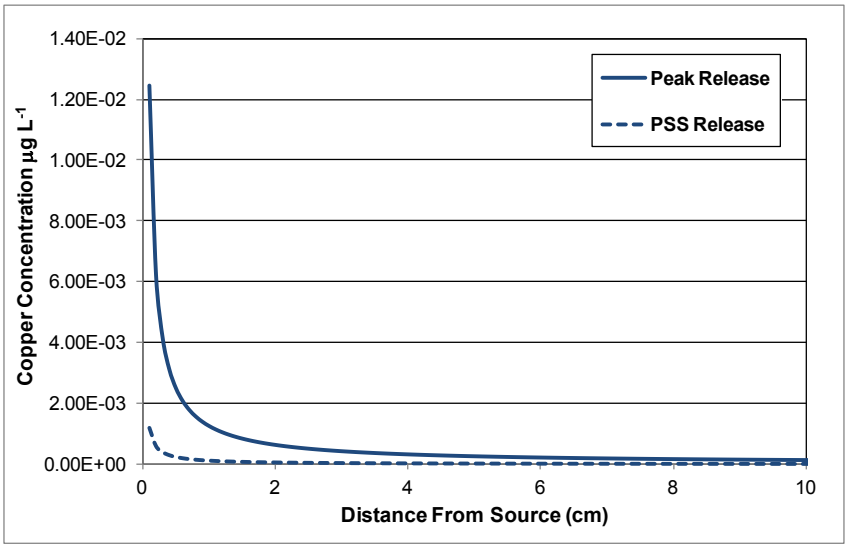

Figure 21. Water column copper concentrations at various distances from the source wire at peak release and PSS release rates.

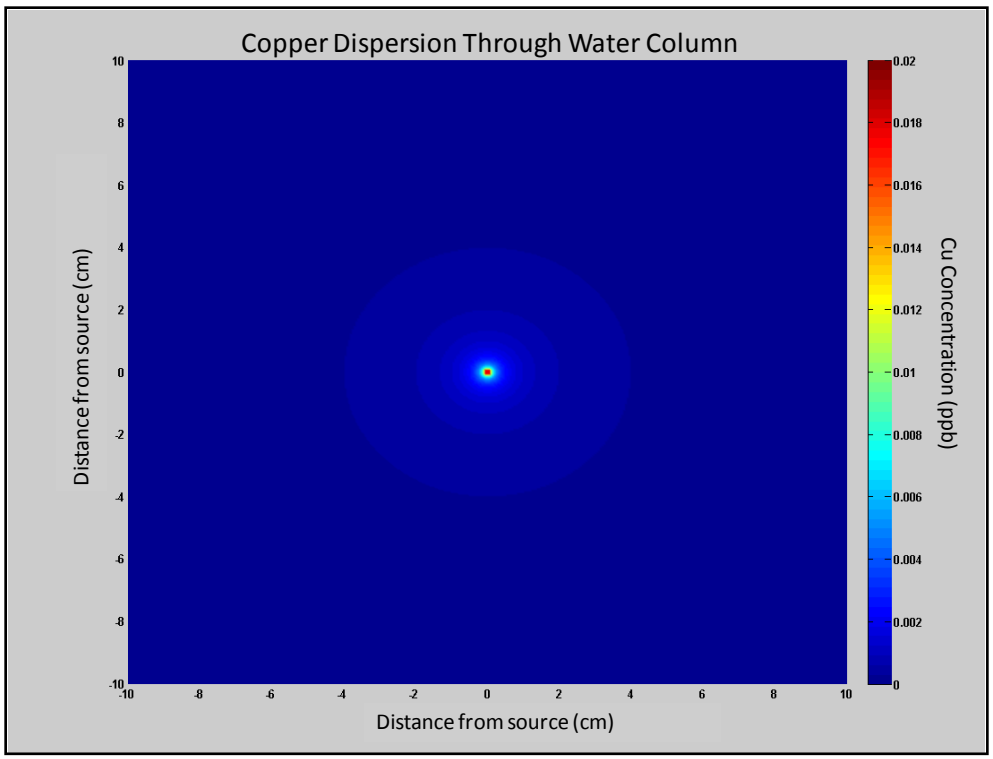

Figure 22. The copper concentration throughout the water column calculated from the peak leach rate and assuming 1 mm of wire are exposed. The source is located at the origin, and the plot shows a "top view" of the dispersion as if one was looking down through the water column to the wire resting on the floor.

3.2 PHYSICAL HAZARDS

3.2.1 Empirical Sinking Rate

A total of 120 video clips were analyzed for the potential to calculate the sinking rate of the guidance wire. Thirty video clips were deemed appropriate for use in calculating the sinking rate based on the criteria outlined in the methods section. All clips used were filmed at 60 fps. Sixteen video clips were of 1-m length wire, while 14 video clips were of 3-m length wire. The average sinking rate of the guidance wire was 0.24 m s^{-1} with a standard deviation of 0.09 m. Table 3 shows the individual sinking rate calculations for each film using 20, 15, 10, and 5 frames for analysis.

3.2.2 Mathematical Model of Sinking Wire

Using the methodology described in Appendix A, it was determined that the C_d for the sinking wire is ≈ 1.5 with corresponding Re = 101.45 (~10^2) and velocity of the wire, U = 0.170 m s^{-1}. Recall that the sinking rate found via the empirical study was ~ 0.23 m s^{-1}, which is close to the 0.17 m s^{-1} calculated here. Thus the mathematical model supports the empirical sinking rate of 0.23 m s^{-1} found in section 4.2.1. that the wire will fall at approximately 0.2 m s^{-1}.

3.2.3 Breaking Strength

The torpedo guidance wire had a mean breaking strength of 40.4 ±1.5 pounds. The breaking strength for the five test trials were as follows: 41, 38, 41, 40, and 42 pounds (Figure 23).

Table 3. Data from analysis of videos recording sinking guidance wire. Four time series were used in the analysis of each video clip based on the total number of frames analyzed (filmed at 60 frames per second).

	20 Frames Analyzed		15 Frames Analyzed		10 Frames Analyzed		5 Frames Analyzed		Mean of Frame Analyses	STDEV of Frame Analyses
Video File	Distance (cm)	Rate (cm s^{-1})	Distance (cm)	Rate (cm s^{-1})	Distance (cm)	Rate (cm s^{-1})	Distance (cm)	Rate (cm s^{-1})	Rate (cm s^{-1})	Rate (cm s^{-1})
1	6.8	20.3	5.0	20.0	3.8	22.5	1.8	21.0	**20.9**	**1.1**
3	7.5	22.5	5.8	23.0	3.8	22.5	2.0	24.0	**23.0**	**0.7**
53	8.0	24.0	6.0	24.0	4.0	24.0	2.0	24.0	**24.0**	**0.0**
54	8.0	24.0	6.0	24.0	4.5	27.0	2.0	24.0	**24.8**	**1.5**
55	7.0	21.0	5.0	20.0	3.5	21.0	1.5	18.0	**20.0**	**1.4**
56	9.0	27.0	6.3	25.0	4.0	24.0	2.0	24.0	**25.0**	**1.4**
57	9.0	27.0	7.0	28.0	4.5	27.0	2.3	27.0	**27.3**	**0.5**
58	7.0	21.0	5.0	20.0	3.8	22.5	1.8	21.0	**21.1**	**1.0**
60	7.5	22.5	5.8	23.0	4.0	24.0	1.8	21.0	**22.6**	**1.3**
61	8.0	24.0	5.8	23.0	4.0	24.0	2.0	24.0	**23.8**	**0.5**
62	7.5	22.5	5.5	22.0	3.8	22.5	2.0	24.0	**22.8**	**0.9**
63	7.8	23.3	5.8	23.0	4.0	24.0	2.0	24.0	**23.6**	**0.5**
64	7.5	22.5	5.8	23.0	3.5	21.0	1.8	21.0	**21.9**	**1.0**
65	8.0	24.0	6.0	24.0	4.0	24.0	2.0	24.0	**24.0**	**0.0**
66	7.0	21.0	5.0	20.0	3.3	19.5	1.5	18.0	**19.6**	**1.3**
67	9.0	27.0	7.0	28.0	4.5	27.0	2.3	27.0	**27.3**	**0.5**
69	7.0	21.0	5.8	23.0	4.0	24.0	2.0	24.0	**23.0**	**1.4**
74	10.0	30.0	6.8	27.0	5.0	30.0	2.3	27.0	**28.5**	**1.7**
75	9.8	29.3	7.0	28.0	4.8	28.5	2.3	27.0	**28.2**	**0.9**
76	8.5	25.5	6.0	24.0	4.0	24.0	2.0	24.0	**24.4**	**0.8**
77	8.5	25.5	6.0	24.0	4.0	24.0	2.0	24.0	**24.4**	**0.8**
80	7.0	21.0	5.3	21.0	3.8	22.5	1.8	21.0	**21.4**	**0.8**
83	7.0	21.0	5.5	22.0	3.8	22.5	2.0	24.0	**22.4**	**1.3**
84	-----	-----	7.0	28.0	4.8	28.5	2.3	27.0	**20.9**	**0.8**
85	7.3	21.8	5.0	20.0	3.3	19.5	1.8	21.0	**20.6**	**1.0**
86	9.8	29.3	7.0	28.0	5.0	30.0	2.5	30.0	**29.3**	**0.9**
88	7.8	23.3	5.8	23.0	3.8	22.5	2.0	24.0	**23.2**	**0.6**
89	8.8	26.3	6.3	25.0	4.3	25.5	2.3	27.0	**25.9**	**0.9**
90	9.0	27.0	7.0	28.0	4.8	28.5	2.3	27.0	**27.6**	**0.8**
95	9	27	7	28	4.75	28.5	2.25	27	**27.6**	**0.8**
								Mean	**24.0**	**0.9**

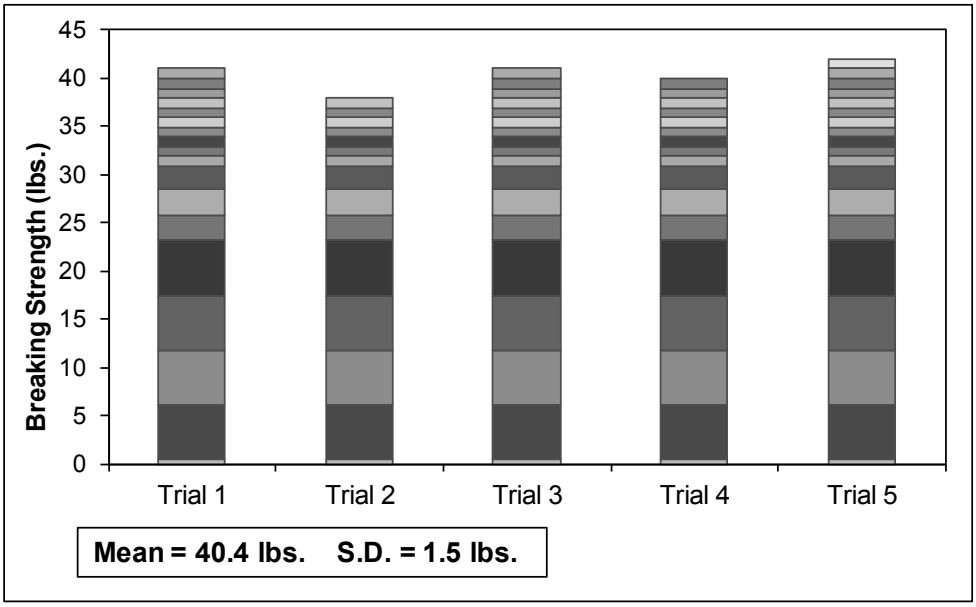

Figure 23. Breaking strength of torpedo guidance wire during the five different trials. Individual bands within a bar represent unique weight increments added during the trial before wire failure.

4. DISCUSSION

4.1 CHEMICAL HAZARDS

4.1.1 Plastic Degradation

Torpedo guidance wire consists of a copper wire core surrounded by a polyethylene coating. The polyethylene coating is a protective layer to ensure the effectiveness of the wire's communication capability. From an environmental perspective, the polyethylene coating acts as an effective barrier between the copper wire and surrounding marine environment, preventing copper from leaching into the water column. Polyethylene, a polymer that resists corrosion and biodegradation, is a robust plastic that will not quickly degrade over time (Czagas, 1998; Van der Zee et al., 1994; Cundell, 1974). In fact, the rate at which the biodegradation affects polyethylene is said to be negligible (Andrady, 2000). Polyethylene performs especially well in an environment such as the ocean floor where there is high pressure, low temperature, and little to no UV exposure (Czagas, 1998; Van der Zee et al., 1994). Additionally, for copper to leach into the environment the coating would need to degrade far enough to expose portions of the wire, not simply weaken it. The total mineralization of the coating, that is the complete breakdown of plastic to carbon dioxide and water, would most likely take hundreds of years (Andrady, 2000). The torpedo guidance wire is coated with a graphite lubricant prior to launch. This acts as an additional layer of protection from degradation. As chemical or microbial degradation of the plastic coating is extremely unlikely, the only process that may expose the copper wire would be mechanical degradation.

Based on the results from the abrasion tests (Sections 3.3.2 and 4.1.2) it appears unlikely that the copper wire would be directly exposed to seawater based on mechanical degradation. The primary mechanism for degradation due to physical processes would be abrasion associated with movement along the sea floor. The majority of the guidance wire would be found on the deep ocean floor where current flow is relatively slow. Additionally, the substrate or sediment types found in the training areas are generally soft sediment or sand and will not provide strong abrasive resistance. The results of the abrasion experiments show that copper release rates were not linear with the level of abrasion treatment. The wire would need to be exposed to enough abrasive action to reduce the wire coating to between 50% and 75% of its starting condition before any copper release was observed. Additionally, the abrasion experiment tests were performed in the absence of the graphite lubrication that would only further impede physical degradation. The amount of exposed copper wire is estimated as 1 mm. This estimate is based on tips being exposed after breakage when the wire separates from the torpedo/ship.

4.1.2 Environmental Release and Dispersion

4.1.2.1 Water Column

The amount of copper entering the water column from the torpedo guidance wire is extremely low. This is a function of both the amount of copper wire exposed and the leach rate of copper wire. Due to the robust nature of the polyethylene coating surrounding the copper wire, the inner copper will most likely only be exposed at the tips of the wire after breaking. This would expose approximately 1 mm of wire at each of the terminal ends of a long coil of guidance wire. The highest peak leach rate occurs within the first 8 to 29 days the wire is exposed to seawater, after which leach rates experience an order of magnitude decrease. A more steady-state release is then observed for the remaining time the wire is exposed to water. Based on the dispersion modeling, the copper concentrations during peak release within 1 mm from the wire were calculated to be 0.01 $\mu g\ L^{-1}$. These values are well below background copper concentrations in open ocean environments, which have an average

reported value of 0.26 µg L^{-1} (Chester, 1990). The values are also orders of magnitude lower than the copper water quality criteria of 3.9 µg L^{-1} (chronic) and 4.1 µg L^{-1} (acute). These water column concentrations represent the most realistic values based on release rate, wire exposure, and diffusion rate.

The hydrodynamic diffusion coefficient used for the dispersion model, 10 cm^2 s^{-1}, represents the lower range of values used in hydrodynamic modeling. This diffusion coefficient is representative of the low flow environment typically found at the ocean floor. For comparison, characteristic diffusion coefficients in a ravine environment range from 10^4 to 10^6 cm^2 s^{-1}, and in tidally driven estuarine environments are 10^6 to 10^8 (Schnoor, 1996). Table 4 shows water column copper concentrations under a hypothetical extreme case scenario of a nearly quiescent environment with a larger length of wire exposed compared to the inputs used in the dispersion model. The dispersion coefficient was reduced to 1 cm^2 s^{-1} and length of wire exposed was 10 mm. Under these unlikely scenarios, the highest water column concentration at 1 mm from the source is 1.11 µg L^{-1}, which still is below the WQC, and decreases to background concentrations at a distance of 4 mm.

Table 4. Table of release rates for various scenarios of guidance wire exposure.

	D = 10 cm^2 s^{-1}				D = 1 cm^2 s^{-1}			
Distance from source (mm)	1 mm exposed wire		10 mm exposed wire		1 mm exposed wire		10 mm exposed wire	
	Peak Release	PSS Release	Peak Release	PSS Release	Peak Release	PSS Release	Peak Release	PSS Release
1	0.01	< 0.00	0.11	0.01	0.12	0.01	1.11	0.11
2	0.01	< 0.00	0.06	0.01	0.06	0.01	0.55	0.05
3	< 0.00	< 0.00	0.04	< 0.00	0.04	< 0.00	0.37	0.04
4	< 0.00	< 0.00	0.03	< 0.00	0.03	< 0.00	0.28	0.03
5	< 0.00	< 0.00	0.02	< 0.00	0.02	< 0.00	0.22	0.02
6	< 0.00	< 0.00	0.02	< 0.00	0.02	< 0.00	0.18	0.02
7	< 0.00	< 0.00	0.02	< 0.00	0.02	< 0.00	0.16	0.02
8	< 0.00	< 0.00	0.01	< 0.00	0.02	< 0.00	0.14	0.01
9	< 0.00	< 0.00	0.01	< 0.00	0.01	< 0.00	0.12	0.01
10	< 0.00	< 0.00	0.01	< 0.00	0.01	< 0.00	0.11	0.01

Based on the results from the toxicity testing, water column concentrations would not reach levels that would have any toxic effect. This is true for all of the tests performed with *Strongylocentrotus purpuratus*, as well as for the single test performed with *Mytilus galloprovincialis.* Both *S. purpuratus* and *M. galloprovincialis* are highly sensitive to copper, and the absence of toxicity for these test species would translate to other marine species found in the training ranges (Rosen et al., 2008). The most sensitive endpoint during all of the toxicity testing showed that the copper concentration at which no effect was observed to be 5.0 µg l^{-1}, while the lowest observed effect concentration was 10.1 µg l^{-1}. These copper concentrations are well above any of the predicted water column concentrations from any of the dispersion scenarios. These data support the conclusion that copper leached from torpedo guidance wires has no potential negative environmental impact.

4.1.2.2 Sediments

It is predicted that as the guidance wire falls and settles to the ocean floor, it will sink into the soft sediment and ultimately become buried through the process of sedimentation. Each of the range floors are composed of soft sediments and have enough sediment movement to indicate that the wire would eventually be buried. This burial would slow the processes of corrosion and deterioration of the guidance wire (Ankley, 1996). Additionally, many deep ocean floors have anoxic conditions just a few centimeters below the surface that would render any leached copper unavailable to infaunal organisms as the wire became buried into this layer. In a study conducted on the deep ocean sediments of the Patton Escarpment (off the Southern California coast), the oxic layer reached 2.5 cm

below the surface; this value was said to be a suitable representation for deep ocean environments, so it is assumed that each of the range floors follow this guideline (Shaw, Gieskes, and Jahnk, 1990). Once the wire became buried in the anoxic layer, the sulfides present there would react with the copper released from the wire to form soluble sulfide complexes (Rivera-Duarte and Flegal, 1997). Any copper that leached from the wire into the anaerobic range floor sediments would become bound to acid-volatile sulfides present in the anaerobic sediments, rendering the copper unavailable to sediment dwelling marine organisms (Ankley et al., 1996). Until that time, the wire could be expected to release copper into the sediments. However, this release would be limited to the small amount of wire that is exposed (assumed to be only the terminal ends of the wire) as well as the time-dependent leach rate of the copper wire. By the time the wire became buried in the sediment, the leach rate of the wire would most likely have decreased significantly and very small amounts of copper would be released into the sediment and would not travel far from the wire source. As there is often little benthic life in the soft sediments of deep sea basins due to the soft floor, which is not a rich host for infaunal species (and none in the anoxic layer), there would be very minimal impact upon infaunal species from the copper released from the wire (Levings, Forman, and Tunnicliffe, 1983). The following section describes pertinent sediment conditions, sedimentation rates, and benthic life present at each of the ranges.

AUTEC

The range site at AUTEC contains a sediment floor consisting of fine sediments and an accretion of planktonic debris that form from calcareous ooze (DoN, 1996 (U); DoN, 1997). The bulk sedimentation rates for the southern portion of the associated Tongue of the Ocean have been recorded as 0.10 mm/yr^{-1} (Droxler and Schlager, 1985). As the wire comes to rest on the range floor, it may sink into the soft sediments, partially burying the wire; sedimentation would be expected to completely bury the wire in the following years. The floor is described as “almost barren” and hosts little to no benthic fauna (DoN, 1996 (U)).

Dabob Bay

The shallow water range found in Dabob Bay is composed primarily of mud and soft sediment (DoN 2002). Previous Navy environmental assessments predict that the guidance wire will sink and become buried in the soft sediment that c*oats the floor of Dabob Bay (DoN, 2002). Additionally, sediments are estimated to accrue at a rate* of 0.69 to 1.12 mm/yr^{-1} on the seafloor of Dabob Bay; these sediments would be expected to bury the guidance wire within a relatively short time (Furlong and Carpenter, 1988; Carpenter, Petersen, and Bennett, 1985; WDOE, 1991). The majority of the seafloor of Dabob Bay in the testing area is composed of anoxic surface and subsurface sediments, though there is at least one location on the range floor where there is a 1 to 2 cm surface layer of aerobic sediments (Crecelius, 2001; DoN, 2002). Samples taken from two places along the floor of Dabob Bay showed the benthic life consisted of polychaete worms, bivalves, crustaceans, and other invertebrates (Striplin, Sparks-McConkey, Davis, and Svendsen, 1991).

Hawaii

Reflecting the volcanic nature of the nearby islands, much of the ocean floor at the Hawaiian test ranges consists of black volcanic sand in combination with typical deep sea sediment (DoN, 1996 (U)). The floor at the BARSTUR range has occasional basalt rock outcrops along with a mixture of volcanic and silty sands (DoN, 1996 (U)). Likewise, the floor at BSURE is a mixture of brown silt and volcanic sands (DoN, 1996 (U)). The benthic life in the deep seas offshore Kauai hosts a sparse, but diverse benthic community. Cone shells, deep-sea corals, pen shells, and tritons may be found in

the unconsolidated sediments of the deep sea floor (DoN, 2005; Smith, Drazen, and Mincks, 2006). In the deep abyssal plains at BSURE (3000 to 5000 m), there may be various invertebrates, including crustaceans, polychaetes, and elasipod holothurians which are able to survive in the harsh environment of cold temperatures and high pressures at this depth (DoN, 2008 Barking Sands).

Nanoose Bay

Nanoose Bay's Whiskey Golf range is composed of mainly soft sediment and would therefore be unlikely to contain areas where the wire would become caught or tangled (Environmental Sciences Group, 2005). The middle portion of the range is a level basin composed of mud with occasional rock outcroppings found along the sides (DoN, 1996 (U)). Sedimentation rates on the floor of Nanoose Bay are expected to be between 3.30 to 7.37 mm/yr^{-1} (Picardand Hill, 2005). These sedimentation rates would effectively bury the wire—even a tangled wire—within a few years. Due to the soft sediment floor, the Whiskey Golf Range hosts a very meager benthic community consisting primarily of amphipod crustaceans, arthropodas, echinoderms, molluscas, and polychaetas (Environmental Sciences Group, 2005).

SOCAL Range

The deep offshore water substrate where the torpedo would be released at the SOCAL range floor consists of grayish silty sand and soft sediment according to both the 1996 Naval Assessment and the more recent Environmental Assessment of the range (DoN 1996 (U); DoN 2008). Sedimentation rates for two nearby basins, Catalina Basin and the San Nicolas Basin, measure to be between 0.13 to 0.20 mm/yr^{-1} (Emery, 1960; Smith and Hamilton, 1983; Fornes, 1999). The sediments in many of the deep sea basins in the Southern California area are anaerobic at the surface level (Dailey, Reish, and Anderson, 1993). Benthic life in the deep sea basins of the SOCAL range is extremely limited; this lack of life is most likely a result of high sedimentation rates and the potential anaerobic environment present on the sea floor (DoN 2008 SOCAL). The prominent species in these deep basins are polychaete worms, ophiuroids, gastropods, and mollusks (DoN 2008 SOCAL).

4.1.3 Overall Chemical Impacts

Torpedo guidance wire abandoned in the marine environment results in a potential chemical stressor in the form of leached copper. Evaluation of copper leached into the marine environment as a potential stressor suggests that there is no negative impact to the water column, sediments, and organisms living within these environments. The robust nature of the plastic coating coupled with eventual burial of the material limits exposure of the copper wire, thus minimizing copper leaching into the environment. Predicted water column and sediment copper concentrations are below the water quality criteria, sediment guidelines, and predicted toxicity endpoints. Evaluation of the data herein suggests that torpedo guidance wire does not present a chemical hazard to the marine environment.

4.2 PHYSICAL HAZARDS

4.2.1 Entanglement

As with any foreign object introduced into the marine environment, torpedo guidance wire has the potential to pose physical hazards to marine life. The main issue of concern is entanglement, as the torpedo wire would not cause smothering or be ingested. Entanglement may also cause strangulation, starvation, a heightened vulnerability to predation, infection, and possible death (Fowler, 1987; Commonwealth of Australia, 2008a; Derraik, 2002). Exposure to torpedo guidance wire occurs during two distinct time periods, the first while the wire is sinking through the water column and the

second after the wire settles on the sea floor. Potential harm due to entanglement is based both exposure to the guidance wire and the physical properties of the wire.

4.2.1.1 Guidance Wire Physical Characteristics

Entanglement potential is related to the inherent physical properties of the entanglement hazard. In general, entanglement risk is greater from lines and ropes with higher breaking strengths and more complex structures (Kraus, 2012). However, once entangled, rope diameter and breaking strength does not necessarily relate to injury severity, especially in more complex structures or gear configurations (Kraus, 2012). Complex structures may include various nets and multi-lined rigging as well as a monofilament line that loops and coils together to form a larger mass. Fishing gear most commonly associated with entanglement, especially for large marine mammals, includes long vertical lines, pot trawls, lobster gear, and gill nets (Kozuck, 2003; Neilson, 2006). An analysis breaking strength to rope diameter for entanglement of several whale species had data ranging from about 500- to 10,000-pound breaking strength and 0.2 to 1.0 inches in diameter (Kraus, 2012). Additionally, a potential mitigation measure for entanglement of whales was using "weak rope" that had breaking strengths of 600 to 1200 pounds. While this example is specific to whales, it provides an example of breaking strengths, which may allow the animal to escape an entanglement scenario. Monofilament fishing line, one of the primary entanglement hazards for mammals. has breaking strengths up to 650 pounds. Table 5 lists the breaking strengths for popular brands of monofilament, braided, and fluorocarbon fishing line.

Table 5. Breaking strengths for types of fishing line.

Monofilament		Braided		Flourocarbon	
Brand	**Breaking Strength (pounds)**	**Brand**	**Breaking Strength (pounds)**	**Brand**	**Breaking Strength (pounds)**
ANDE	2 to 400 [1]	PowerPro	5 to 250 [2]	Ande	10 to 150 [1]
Hi-Seas	4 to 400 [3]	Hi-Seas	6 to 200 [3]	Hi-Seas	6 to 25 [3]
Momoi	0.33 to 200 [4]	Momoi	~12 to 170 [4]	Momoi	3 to 30 [4]
Suffix	1 to 650 [5]	Suffix	4 to 130 [5]	Suffix	2 to 400 [5]
1 – Ande 2 – PowerPro 3 – Hi-Seas Fishing Line 4 – Momoi Fishing Line 5 – Rapala Fishing Line					

The breaking strength of the tested guidance wire was 40.4 pounds. This value is within the range of values presented in various Naval Environmental Assessments that report the breaking strength of the wire as 28 pounds (DoN, 1996 (U)), 30 pounds (DoN, 2002), 38 pounds (Environmental Sciences Group, 2005), and 42 pounds (DoN, 2008 SOCAL). Additionally, the official military specification for the wire alone, without plastic coating, lists the breaking strength as 27.3 pounds (MIL-HDBK-419A). The addition of the plastic coating makes the wire more robust, bringing the breaking strength up to the 40.4 pounds. The copper wire core coupled with the plastic coating of the guidance wire yields a more rigid core that resists coiling and looping compared to traditional fishing line and gear. The relatively low breaking strength and resistance to looping and coiling suggest that torpedo guidance wire does not have a high entanglement potential compared to other entanglement hazards.

4.2.1.2 Water Column Exposure

Exposure to torpedo guidance wire within the water column may occur during the time when the wire sinks through the water column after launch. Potential exposure time is based on water depth and sinking rate of the wire. The results of the empirical sinking rate measurements for this study were 0.24 m s^{-1}, and are supported by mathematical modeling of sinking wire. These data compare well with previously reported values of approximately 0.2 m s^{-1} (DoN, 1996 (U)). Using the

maximum depths for the five test ranges, potential exposure times were approximated for each of the ranges.

These times are conservative estimates for the maximum time the wire would be in the water column, as these are the maximum depths from the surface to the ocean floor, not from the specific depth the torpedo is launched. Additionally, the average depth of the range could be considerably shallower than the maximum depth, and thus the times presented in Table 6 are the worst-case scenario. Although the wire remains in the water column on the order of minutes to hours, individual animal exposure times would be significantly less because the wire is in motion sinking to the sea floor. Based on the sinking rate of 0.24 m s^{-1}, for any given 10 m of depth, the wire would only be present for approximately 42 seconds. In addition, following guidelines prescribed in OPNAV 5090 1C, the Navy takes preventative measures to avoid marine mammal impacts before releasing torpedoes during training activities. Navy procedure prior to releasing torpedoes at test ranges requires that surveys be conducted to determine if marine mammals are present in the range area of the torpedo study; the torpedo will not be released until the absence of marine mammals is confirmed (DoN, 2002; Environmental Sciences Group, 2005; DoN, 1996). Based on the sinking rate of the wire and preventative measures in place, the potential for entanglement while the wire is in the water column is low.

Table 6. Maximum time to rest for sinking guidance wire at five range sites.

Range	Nanoose Bay	Dabob Bay	SOCAL Range	Hawaii PMRF		AUTEC
				BSURE	BARSTUR	
Maximum Depth (m)	415	185	1646	1829	4572	2700
Approximate Time to Rest (min)	28.8	12.8	114	127	318	188

4.2.1.3 Sea Floor Exposure

Exposure to torpedo guidance wire within the sediment may occur after the wire settles on the seafloor following a launch event. Sediment type and sea floor features influence the potential for entanglement. A study done on submarine cables suggested that most entanglements were due to either looping in cables that rested above the seafloor (i.e., remained unburied) or in cables that were stretched across deep canyons or similar bathymetric features (Olen and Dugan, 2010). This can be applied to guidance wire as well, inferring that areas with rocky bottoms or deep canyons pose an increased threat as the wire has a higher likelihood of becoming looped or tangled on rocky features than it does on soft sediment. Conversely, areas lacking such bottom features pose less of an entanglement hazard. The deep ocean floor in the area of the test ranges are typically composed of soft sediment and not rock (see Section 4.1.2.2 above for description of range floors) and have sedimentation rates to effectively bury the wire over the course of a few years. (DoN, 1996 (U)). The soft sediment ocean floor present at all the test ranges poses little to no hazard for entanglement as there are few places the wire could become caught and tangled. Additionally, entanglement potential is only a concern for marine animals that are found living or feeding near the ocean floor. The greatest wire exposure potential is for marine animals that have direct contact with the sea floor, such as those who feed by sifting through deep ocean sediment.

4.3 SPECIES OF CONCERN

The primary concern regarding entanglement with torpedo guidance wire is for marine mammals and sea turtles whose swimming or feeding behaviors place them near the ocean floor, with an

emphasis on those animals that are benthic feeders. A list of known marine mammals and sea turtles identified in the range areas was assembled (The full list can be found in Appendix B). The list was narrowed down to mammals whose diving or feeding patterns may place them near the ocean floor at each respective range (Table 7). This section evaluates the identified species for entanglement potential based on presence within a range and diving/foraging behavior.

Table 7. Marine mammals with deep diving behavior and possible benthic feeding behavior at test ranges.

Common Name	Name of Species	Range	Benthic Feeder	Swimming Speed (kph)/ Diving Depth (m)	Adult Weight (pounds)	Adult Length (m)
Beaked Whales						
Arch Beaked Whale	*Mesoplodon Carlhubbsi*	Hawaii[2, 4] SOCAL [2,5]	Possible[2]		3,150.48[20]	5.38[20]
Baird's Beaked Whale	*Berardius bairdii*	Dabob[2] Bay Nanoose Bay[2] SOCAL[2, 5]	Yes[2]		14,200[20]	10 to 2.8[20]
Blainville's Beaked Whale	*Mesoplodon Densirostris*	Hawaii[2, 4] SOCAL[5]	Yes[2]	61/1500[2]	22,738[20]	4.5 to 8[20]
Cuvier's Beaked Whale	*Ziphius carvirostris*	AUTEC[2] Dabob[2] Hawaii[2, 4] Nanoose[2] SOCAL[2]	Yes[2]	6/1500[2] Dive to 1888m[21]	660,088[20]	5.1 to 7.5 (Average 6.1 m)[20]
Gervais' Beaked Whale	*Mesoplodon europaeus*	AUTEC[2]	Yes[2]	6/1500[2]	25,928[20]	3.7 to 5.2[20]
Japanese Beaked Whale	*Mesopldon gingkodens*	Hawaii[2] SOCAL[2]	Possible[2]			5.3[19]
Longman's Beaked Whale	*Indopacetus pacificus*	Hawaii[4]	Yes[2]			6 to 9[14]
Perrin's Beaked Whale	*Mesoplodon perrini*	SOCAL[5]	Yes[5]			Male: 3.9[8] Female: 4.4[8]

Table7: Table of marine mammals with deep diving behavior and possible benthic feeding behavior at test ranges. (Continued)

Common Name	Name of Species	Range	Benthic Feeder	Swimming Speed (kph)/ Diving Depth (m)	Adult Weight (pounds)	Adult Length (m)
Sowerby's Beaked Whale	Mesoplodon Bidens	AUTEC[2]	Yes[2]	6/1500[2, 16]	2,200–2,900[16]	5.05 to 5.5[20]
Stejneger's Beaked Whale	*Mesoplodon stejnegeri*	SOCAL[2]	Possible[2]	150[17]	35,207[17]	5.7[17, 19]
Other Whales						
Gray Whale	*Eshrichtius robustus*	Dabob Bay[2, 3] Nanoose Bay[6]	Yes [2, 3, 20]	10/170[9]	30,800-77,000[20]	13 to 15.2[20]
Pygmy Sperm Whale	*Kogia breviceps*	Dabob[2] Hawaii[2, 4] SOCAL[2, 5]	Yes[2]	12,200+[2]/ at least 300[15]	8,808[20]	2.42 to 3.7m[20]
Dolphins						
Bottlenose Dolphin	*Tursiops truncatus*	AUTEC[2] Dabob[2] Hawaii[4] SOCAL[2]	Yes[2]	30+/600[2]	300-1400[12]	1.8 to 3.8[12]
Pinnipeds						
Elephant Seal	*Mirounga angustirostris*	Nanoose Bay[2] SOCAL[2, 5]	Yes[10]	U/1610[2] /400-800[7]	Males: 4,400[13] Females: 1,200[13]	Males: 4[13] Females: 3[13]
Harbor Seal	*Phoca vitulina richardsi*	Dabob[2]	Yes[1]	30/300[2]	Male: 191.4[1] Female: 143[1]	Male: 1.6[1] Female: 1.48[1]
Stellar Sea Lion	*Eumetopias jubatus*	Nanoose[6] Dabob[2, 3]	Possible[2]	U/250[11]- 400[18]	Male: 2464[11] Female: 770[11]	Male: 3.25[11] Female: 2.90[11]
Turtles						
Leatherback Sea Turtle	*Dermochelys coriacea*	SOCAL[5] Dabob[3]	Yes[2]	9.3/1000[2]	1600[3]	2.4[3]

1 Burns
2 DoN, 1996 (U)
3 DoN, 2002
4 DoN, 2008 Hawaii
5 DoN, 2008 SOCAL
6 Environmental 2005
7 Hindell and Perrin, 2002
8 Jefferson and Webber, 2008
9 Jones and Swartz, 2002
10 Le Boeuf et al., 2000
11 Loughlin, 2002
12 NOAA Bottlenose Dolphin
13 NOAA Northern Elephant Seal
14 NOAA Longman's Beaked Whale
15 NOAA Pygmy Sperm Whale
16 NOAA Sowerby's Beaked Whale
17 NOAA Stejneger's Beaked Whale
18 NOAA Stellar Sea Lion
19 Pitman, 2002
20 Reidenberg and Laitman, 2002
21 Tyack et al., 2006

4.3.1 Whales

4.3.1.1 Beaked Whales

Beaked whales are known as deep divers and suction feeders (Heyning and Mead, 1996). A number of beaked whales fall within the family of Mesoplodont whales, which are also known to forage near the ocean floor and have throat grooves that appear to enable the whale to feed via suction (Pitman, 2002; Baird et al., 2006; DoN, 2007). These throat grooves are thought to allow the whale to distend the lower portion of their jaw, creating a larger oral cavity into which they may suck in their prey and swallow them whole (Pitman, 2002; Heyning and Mead, 1996). However their feeding habits do not include digging through sediment for their prey or sifting through sediment, a habit which would place them at higher risk for entanglement. Sightings of these whales are very rare due to their affinity towards deep water, shy nature, and ability to stay underwater for long periods of time, which have been recorded to average 48 to 68 minutes; these characteristics have made beaked whales, both within and without the Mesoplodont family, very difficult to study and severely limit the amount of information collected on them (Pitman, 2002). Despite their elusive behavior, a number of beaked whales have been identified as present at one or more of the five ranges relevant to this study (DoN, 1996 (U); DoN, 2002; DoN, 2007; DoN, 2008 SOCAL; DoN, 2008 Hawaii; Environmental Sciences Group, 2005).

4.3.1.2 Arch (Hubb's) Beaked Whale (Mesoplodont carlhubbsi)

The arch beaked whale, otherwise known as Hubb's beaked whale, has been sighted within the Southern California Operational Area (DoN, 1996 (U); DoN, 2008). The rare sightings of this Mesoplodont whale in Southern California have occurred to the north of the SOCAL range, closer to Santa Barbara area and not the waters where the MK 48 is tested off San Clemente Island (Mead, 1989). The Navy assessment conducted in 1996 listed these whales as a resident at the Hawaiian ranges; however, a more recent study conducted in 2008 did not.

4.3.1.3 Baird's Beaked Whale (Berardius bairdii)

Baird's beaked whales have a diet consisting of benthic fish and cephalopods, in addition to intermittent feeding upon mackerel, sardine, and saury (Kasuya, 2002; Walker, Mead, and Brownell, 2002; Ohizumi, Isoda, Kishiro, and Kato, 2003). Though rare, there have been sightings of Baird's beaked whale near the SOCAL range area as well as the Dabob and Nanoose Ranges (DoN, 1998; DoN, 1996 (U)).

4.3.1.4 Blainville's Beaked Whale (Mesoplodon densirostris)

The Blainville's beaked whale is known as a deep diver, with a mean maximum depth recorded to be 833 m in a range of approximately 500 to 1000 m (Arranz et al., 2010; Davis et al., 1998; Reeves, Stewart, Clapham, and Powell, 2002). Analysis of the captured whale's stomach provides evidence that Blainville's beaked whales tend to forage in deep benthic environments (Arranz et al., 2010). Blainville's beaked whale may inhabit the deep ocean waters at the Hawaiian and Southern California ranges (DoN, 2008 Hawaii; DoN, 2008 SOCAL; DoN, 1996).

4.3.1.5 Cuvier's Beaked Whale (Ziphius carvirostris)

Cuvier's beaked whale has been recorded to dive down to approximately 1450 meters (Baird et al., 2006b). Cuvier's beaked whales have throat grooves suggesting they, like many beaked whales, feed primarily via suction (Heyning and Mead, 1996). One study conducted suggests that gouge marks found on deep-sea mud volcanoes in the Mediterranean are formed as Cuvier's beaked whales chase down and feed upon benthic prey (Woodside, David, Frantzis, and Hooker, 2006). One of the easiest

beaked whales to identify, Cuvier's beaked whales has been sighted at the SOCAL, Dabob, Hawaii, Nanoose, and AUTEC ranges (DoN, 2008 Hawaii; DoN, 2008 SOCAL; DoN, 1996 (U)).

4.3.1.6 Gervais' Beaked Whale (Mesoplodon europaeus)

The Navy environmental assessment (EA) conducted in 1996 reported the Gervais' beaked whale was found at the AUTEC range (DoN, 1996 (U)). The whale's skittish behavior has made it difficult to sight, as is true with most beaked whales. Nevertheless, the Gervais' beaked whale is thought to use suction to feed on prey on cephalopods, mysid shrimp, and smaller fish in deep ocean waters (NOAA: Gervais' beaked whale).

4.3.1.7 Japanese Beaked Whale—Ginkgo toothed whale (Mesoplodon gingkodens)

The Japanese beaked whale, also known as the Ginkgo toothed whale, is rarely seen; most of the information collected on this Mesoplodont comes from analysis of stranded whales (Mead, 1989). One study recorded 13 stranding records on the Japanese beaked whale, one of which was found on the Del Mar, California coastline and another in Baja California (Mead, 1989). These stranding records imply the whale's presence in SOCAL waters and possibly in the SOCAL range area.

4.3.1.8 Longmans' Beaked Whale (Indopacetus pacificus)

One of the larger beaked whales, Longman's beaked whale, is an average 6 to 7 m in length (NOAA Longman's Beaked Whale). As with most beaked whales, Longman's is difficult to recognize and is often identified incorrectly. They are listed as a resident of Hawaiian waters, and are suspected to occupy the waters at BARSTUR and BSURE (DoN, 2008 Hawaii).

4.3.1.9 Perrin's Beaked Whale (Mesoplodon perrini)

Up until 2002, Perrin's beaked whale had been incorrectly identified as Hector's beaked whale (Dalebout et al., 2002). This mis-classification has greatly limited the amount of information collected specifically on Perrin's beaked whale (DoN, 2008 SOCAL). It was correctly identified as a separate species from Hector's beaked whale in Southern California, when four whales were stranded just north of San Diego (Dalebout et al., 2002). It is suspected to inhabit Southern Californian waters which may place it in the range area off San Clemente Island, though it has not been sighted in the exact range area (DoN, 2008 SOCAL).

4.3.1.10 Sowerby's Beaked Whale (Mesoplodon bidens)

There is little information on this Mesoplodont whale. However, the naval study conducted in 1996 listed this whale as a possible year-round resident at the AUTEC range (DoN, 1996 (U)). Like most beaked whales, it is as deep diver and suction feeds on small fish and cephalopods (NOAA Sowerby's Beaked Whale).

4.3.1.11 Stejneger's Beaked Whale (Mesoplodon stegnegeri)

Once again, the only recording of this whale at the test range sites comes from the Navy's 1996 study. They recorded Stejneger's beaked whale as being present at the SOCAL range (DoN 1996 (U)). They too, are thought to be deep ocean dwellers and foragers (NOAA Stejneger's Beaked Whale).

4.3.2 Other Whales

4.3.2.1 Gray Whale (Eschrichtius robustus)

Gray whales are the most coastal of all great whales and the majority of their feeding takes place in shallow waters over continental shelves at depths of 4 to 120 m, though they may infrequently venture into deep open ocean waters (Jones and Swartz, 2002). They are one of the few whales that feed primarily by sifting through sediments (Jones and Swartz, 2002). When suction feeding, Gray whales swim with

their head parallel to the seafloor and suck in sediments, often leaving gouges, called "feeding pits," on the ocean floor (Jones and Swartz, 2002). They filter their prey out of the sediment using their short baleen plates (Jones and Swartz, 2002). Their prey often consists of crustaceans, mollusks, and bristle worms (DoN, 1996 (U); Oliver, Slattery, Silberstein, and O'Connor, 1983). Gray whales may pass through both the Whiskey Golf Range in Nanoose Bay and test range in Dabob Bay during their annual migration pattern (Environmental Sciences Group, 2005; DoN, 2002). Their annual migration takes them from their summer feeding grounds in the Arctic, to a winter breeding ground in southern subtropical waters as far south as Mexico (Jones and Swartz, 2002). Their primary feeding grounds are in the Bering Sea, Chukchi Sea, Beaufort Sea, and east Siberian Sea (Jones and Swartz, 2002). Gray whales generally do not feed during their migration period (Jones and Swartz, 2002), thus it is unlikely that gray whales would be found sifting through sediments at Nanoose or Dabob Bay.

4.3.2.2 Pygmy Sperm Whale (Kogia breviceps)

The pygmy sperm whale generally inhabits deep ocean waters. Analysis of their prey suggests that these whales spend most of their time in the mesopelagic and bathypelagic zones (West et al., 2009). Analysis of their stomach contents and jaw structure, however, indicates that they may also feed near the ocean floor (NOAA Pygmy Sperm Whale). Much like beaked whales, the pygmy sperm whale has a shy cryptic nature that has made it difficult to study and severely limited the amount of information gathered on the species (DoN, 2008 Hawaii). Pygmy sperm whales are sporadic visitors to SOCAL waters though resident in Hawaiian waters (DoN, 2008 Hawaii; DoN, 2008 SOCAL).

4.3.3 Dolphins

4.3.3.1 Bottlenose Dolphin (Tursiops truncates)

The bottlenose dolphin is a resident of Hawaiian waters (DoN, 2008 Hawaii; Baird, Gorgon, and Webster, 2002; Baird et al., 2003). They have also been spotted at the AUTEC, SOCAL, and Dabob ranges (DoN, 1996 (U)). In a study of the bottlenose dolphin within Hawaiian waters, it was proposed that there were two populations in the area, one of which inhabited shallow offshore waters with a depth of less than 199 m, and the other which occupied deeper waters—400 to 900 m in depth (Baird, Gorgon, and Webster, 2002; Baird et al., 2003). Analysis of the dolphin's stomach revealed deep-sea fish, suggesting the dolphin dives more than 500 m (Reeves et al., 2002).

4.3.4 Pinnipeds

4.3.4.1 Elephant Seal (Mirounga angustirostris)

Analysis of stomach contents reveal that elephant seals feed on a various epipelagic and mesopelagic cephalopods, teleosts, *Merluccius productus*, crustaceans, elasmobranchs, cyclostomes, and tunicates (Le Boeuf et al., 2000). Though the majority of feeding is on epipelagic and mesopelagic species, males have been seen feeding on benthic dwelling elasmobranchs (Condit and Le Boeuf, 1984). Additional evidence of the seals' benthic preferences comes from entanglement reports. In one case, two northern elephant seals were found caught in fishing line at the ocean floor, which was 200 m from the surface (Condit and Le Bouef, 1984). They are regularly seen at the SOCAL range (DoN, 2008 SOCAL).

4.3.4.2 Harbor Seal (Phoca vitulina richardsi)

Though their prey varies from season to season, studies suggest that they feed on primarily fish; one study showed that 73.8% of their diet consisted of fish (Heithaus and Dill, 2002). These seals are regular residents at the SOCAL and Dabob Ranges (DoN 2002; DoN 2008 SOCAL). Harbor seal diving behavior is generally tied to foraging efforts, with the majority of dives occurring at 5 to 40 m, occasional dives to 100 m, and more rare deep dives at 400 to 500 m (Lesage, Hammill, and Kovacs,

1999; Frost, Simpkins, and Lowry, 2001; Burns, 2002; Hastings et al, 2004; Eguchi and Harvey, 2005).

4.3.4.3 Steller Sea Lion (Eumetopias jubatus)

Though this mammal is listed as a possible visitor to the SOCAL waters, it is considered extremely rare for them to be present and thus very unlikely that they would be threatened by the wire at the SOCAL range (DoN, 2008). It is listed as a yearly visitor to both the Nanoose and Dabob ranges which fits with its habit of feeding in near shore waters as both Nanoose and Dabob are bay ranges, unlike the other ranges that occupy more of an open ocean environment (DoN 2002; Environmental Sciences Group, 2005; NOAA Stellar Sea Lion). Stellar sea lions generally dive to depths at 20 to 250 m, but in near-shore, waters tend to be approximately 20 m (Loughlin, 2002).

4.3.5 Turtles

4.3.5.1 Leatherback Sea Turtle (Dermochelys coriacea)

One of the few sea turtle's whose diving depth would enable it to reach the floors of the test ranges included in this study, the Leatherback Sea Turtle is known to occupy the SOCAL, Dabob, and AUTEC ranges (DoN, 2008 SOCAL, DoN, 2002, DoN, 1996 (U)). They may be benthic feeders (DoN, 1996 (U)).

4.3.6 Summary

Out of the list of mammals presented above, only gray whales feed by sifting through deep ocean sediment. However, their feeding grounds are not in the range areas, as they are known only to migrate through the range areas and have their primary feeding grounds farther north near the Bering and Chukchi Seas (Highsmith, Coyle, Bluhm, and Konar, 2006; Swartz, Taylor, and Rugh, 2006; Jones and Swartz, 2002). The Cuvier Beaked Whale may also practice some sort of hunting/feeding that places them in contact with the sea floor, however, the study done focused only on deep-sea volcanoes in the Mediterranean and there is no evidence that these whales practice similar feeding habits in other deep sea environments (Woodside et al., 2006). Suction feeders, such as found in beaked whales, feed primarily by sucking in their prey from the water column, not the ocean floor. It is unlikely that any of the deep-diving whales listed above would come in contact with the wire; however, if an encounter did occur, considering the size and swimming speed of the mammals listed, their propensity to become fatally entangled is low, as any mammal that might become caught in the wire would be able to break free due to the wire's low breaking strength.

4.3.7 Overall Physical Impacts

Torpedo guidance wire abandoned in the marine environment results in a potential physical stressor in the form of an entanglement hazard. Evaluation of the guidance wire as a potential stressor suggests that there is an extremely low entanglement potential for animals found within the range areas. The physical characteristics of the wire (breaking strength and reluctance to looping or coiling) and sea floor habitat types, coupled with minimal exposure potential to marine mammals, based on diving and foraging behaviors, minimizes any potential entanglement threat. Evaluation of the data herein suggests that torpedo guidance wire does not present a physical hazard in the marine environment.

5. CONCLUSIONS AND RECOMMENDATIONS

The use of copper-based torpedo guidance wire presents small to no environmental risk at the Navy training ranges currently using them. The potential impacts of previously expended guidance wire should have no near- or long-term negative affects to marine water and sediment quality, as well as marine animals found within the training ranges. The continued use of guidance wire in similar scope and formulation as evaluated herein should not present any future deleterious environmental impacts.

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Appendix A: Model for Sinking Guidance Wire

For completeness, the entire model is included below.

To support the empirical sinking rate found, a mathematical model was used to estimate a reasonable range of values for the sinking rate of the wire (Figure A-1). A number of assumptions were made to build the model:

1. The main forces impacting the wire are its weight, buoyant forces, and drag forces from the water column (ignore currents).
2. The wire remains stretched out in a straight line (if the wire were to coil up it is assumed this would increase the rate at which it falls).
3. Terminal velocity is reached almost instantaneously; this model estimates the sinking rate assuming terminal velocity has been reached.
4. A length of 13,250 m is sinking (maximum possible).
5. The wire is a smooth cylinder.

The forces on the wire falling at terminal velocity can be written:

$$F = F_d + F_b - F_{w,} \tag{A1}$$

where,

$$F_d = C_d A \frac{1}{2} \rho_{water} U^2 \tag{A2}$$

F_d = Drag forces on the wire
C_d = dimensionless drag coefficient
A = area of the wire falling through water column = 12.62 m^2 (r = 0.0005 m)
ρ_{water} = density of seawater = 1027 kg m^{-3}
U = velocity of falling wire (sink rate), m s^{-1}

$$F_b = Vg\rho_{water} \tag{A3}$$

F_b = Buoyant forces on the wire
V = volume of wire = 0.0094 m^3 (r = 0.0005 m, l = 13,250 m)
ρ_{wire} = density of wire = $\frac{\text{mass}}{\text{volume}}$ = 4073 kg m^{-3}

$$F_w = mg = Vg\rho_{wire} \tag{A4}$$

F_w = Force on wire due to its weight
m = mass of wire = 0.0029 kg m^{-1}
g = 9.8 m s^{-2}

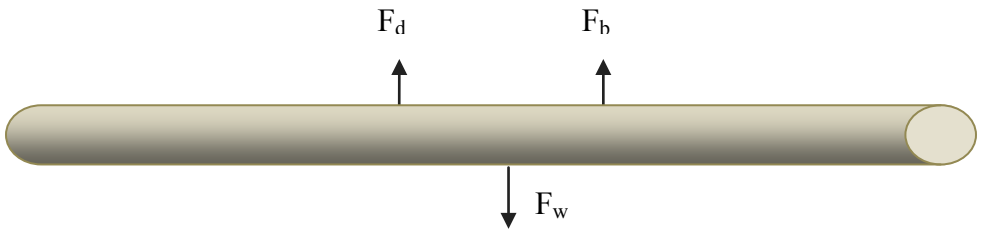


Figure A-1. Free-body diagram of sinking wire.

The total force equation can then be rewritten:

$$ma = C_d A \frac{1}{2} \rho_{water} U^2 + V(\rho_{water} - \rho_{wire})g \quad \text{(A5)}$$

Assuming terminal velocity has been reached, the acceleration of the wire is equal to zero. Thus, the left-hand side of the equation becomes 0 and we solve for the velocity of the falling wire, U:

$$U = \sqrt{\frac{V(\rho_{water} - \rho_{wire})g}{C_d A \frac{1}{2} \rho_{water}}} \quad \text{(A6)}$$

To solve for the velocity of the wire, a reasonable value, or range of values must be established for the drag coefficient, C_d.

Determining the C_d of the free-falling torpedo guidance wire

The drag coefficient, C_d, of an object is found empirically or by using the relationship between the drag coefficient and Reynolds number - the ratio of inertial and viscous forces in a fluid - of the object (Shapiro, 1961). Figure A-2 shows the approximate relationship between C_d and Re for a smooth cylinder; this relationship has been established through empirical tests Figure A-2).

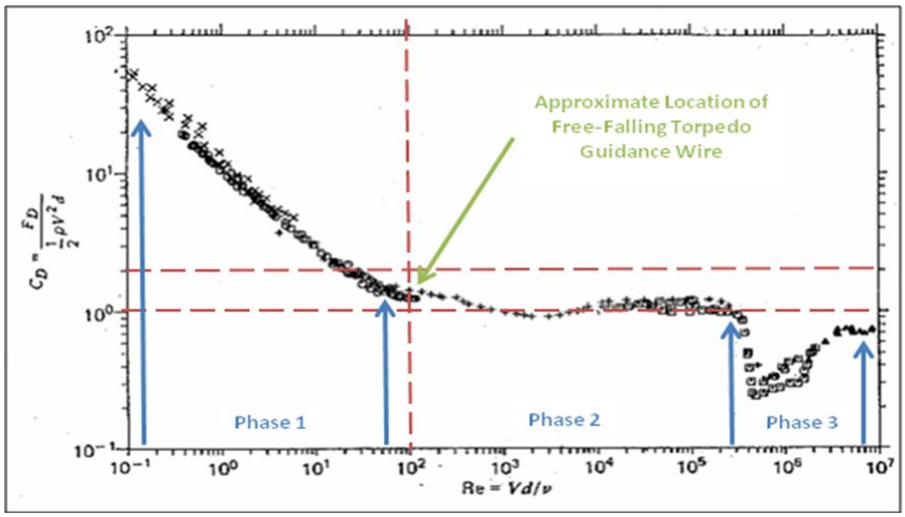


Figure A-2: Relationship between Re and C_d for a smooth cylinder (Panton, 2005).

The Reynolds number is defined as

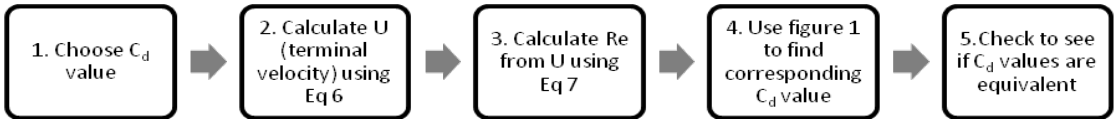
$$\mathrm{Re} = \frac{\rho U d}{\mu} = \frac{U d}{\upsilon}, \tag{A7}$$

where ρ = density of seawater, U is velocity of wire, d is diameter of wire, μ is the dynamic viscosity of seawater, and υ is the kinematic velocity of seawater. As Re is dependent on the velocity of the falling wire, there is no way to directly calculate Re and sequentially C_d. However, the relationship between Re and C_d can be used to solve for the velocity, υ.

As shown in the figure above, the relationship between the Reynolds number and C_d for a smooth cylinder goes through three "phases" (marked by blue arrows on graph). Initially with Re $< \sim 40$, the relationship is somewhat linear with C_d ranging from approximately 70 down to just above 1 before reaching an almost constant value of $C_d \approx 1.2$, while Re ranges between 70 and $\sim 10^5$. For Re values beyond this, a cylinder falling through a fluid where the boundary layer has become turbulent, C_d dips and rises between approximately 0.2 and 1.2.

From a brief analysis of the graph, there is a high probability the wire will fall with a $C_d \approx 1.2$ since this value is dominant in the relationship between C_d and Re. A series of calculations were performed using C_d values to approximate the actual C_d, Re, and U of the falling wire. In order to narrow in on the correct range of C_d values to use for the falling wire, the end points of the "phases" of the wire (the values marked by the blue arrows on the graph) were tested as explained below.

An estimated C_d value is plugged into equation 6 and a value for U is determined. Using this U, Re can be solved for via equation 7. Subsequently the graph is then used to locate the C_d which corresponds to the calculated Re. If the initial C_d and the resulting C_d match, then the appropriate value has been chosen (or approximate value). *It is important to note that these are approximations as the relationship between C_d and Re is only empirical and values are estimated using the graph and not actually calculated. That being said, they are as good an estimation as can be made with the available information.* The steps are laid out below:



C_d values of 10, 1.2 and 0.7 were chosen to give generalized direction as to the location of the torpedo guidance wire on the graph of the relationship between C_d and Re. Note that the values marking the end of phase three were not incorporated in the calculations as it is reasonable to assume the wire would not be falling fast enough on its own to be creating such a turbulent layer. The table below shows the Cd, U, and Re values calculated by following the steps given above.

Chosen C_d	**10**	**1.2**	**0.7**
Calculated U	0.066	0.190	0.249
Calculated Re	39.291	113.42	148.51
C_d from Re	~8	~1.5	~1.5
Match	No	Yes	No

Hence, the original assumption that the wire must be falling with a drag coefficient ≈ 1.2 appears to be correct. Further investigation into the range around 1.2 reveals that a $C_d = 1.5$ yields as close to a perfect match as is possible with this method. The corresponding Re = 101.45 ($\sim 10^2$) and U = 0.170 m s^{-1}. This point on the above graph is marked with a green arrow.

APPENDIX B: FULL LIST OF MARINE MAMMALS AT RANGE SITES

Table Marine Mammals Present at Range Sites					
Mammal	AUTEC[1]	Dabob[1, 2]	Hawaii[1, 3]	Nanoose[1, 4]	SOCAL[1, 5]
Arch Beacked Whale			x		
Atlantic Ridley Sea Turtle	x				
Atlantic Spotted Dolphin	x				
Baird's Beaked Whale					x
Blainville's Beaked Whale			x		
Blue Whale	x		x	x	x
Bottlenose Dolphin	x		x		x
Bryde's Whale	x		x		x
California Sea Lion		x		x	x
Clymene Dolphin	x				
Cuvier's Beaked Whale	x		x		x
Dall's Porpoise		x		x	x
Dense Beaked Whale	x				
Dwarf Sperm Whale	x		x		x
Eastern Pacific Green Sea Turtle					x
False Killer Whale	x		x		x
Fin Whale	x		x		x
Fraser's Dolphin	x		x		
Gervais' Beaked Whale	x				
Green Sea Turtle	x		x		
Gray Whale	x	x	x	x	x
Guadalupe Fur Seal					x
Harbor Porpoise		x		x	
Harbor Seal		x		x	
Hawaiian Monk Seal			x		
Hawksbill Sea Turtle	x		x		
Humpback Whale	x	x	x	x	x
Japanese Beaked Whale			x		
Killer Whale	x	x	x	x	x
Leatherback Sea Turtle	x	x		x	x
Loggerhead Sea Turtle	x		x	x	x
Long-Beaked Common Dolphin					x
Longfin Pilot Whale	x				
Longman's Beaked Whale			x		
Melon-Headed Whale	x		x		x
Minke Whale	x	x	x	x	x
North Atlantic Right Whale	x				
North Pacific Right Whale			x		x
Northern Elephant Seal		x	x	x	x

Table of Marine Mammals Present at Range Sites Continued					
Mammal	AUTEC[1]	Dabob[1, 2]	Hawaii[1, 3]	Nanoose[1, 4]	SOCAL[1, 5]
Northern Fur Seal		x		x	x
Northern Right Whale Dolphin			x		x
Olive Ridley Sea Turtle					x
Pacific Harbor Seal					x
Pacific Ridley Sea Turtle	x				
Pacific White Sided Dolphin		x		x	x
Pantropical Spotted Dolphin	x		x		x
Perrin's Beaked Whale					x
Pygmy Killer Whale	x		x		x
Pygmy Sperm Whale	x		x		x
Risso's Dolphin	x		x		x
Rough-Toothed Dolphin	x		x		x
Sea Otter					x
Sei Whale	x		x	x	x
Short Finned Pilot Whale	x		x		x
Short-Beaked Common Dolphin			x		x
Sowerbey's Beaked Whale	x				
Sperm Whale	x		x	x	x
Spinner Dolphin	x		x		x
Stejneger's Beaked Whale					x
Stellar Sea Lion		x		x	x
Striped Dolphin	x		x		x
True's Beaked Whale	x				
West Indian Manatee	x				
White-Sided Dolphin	x				
1 DoN 1996 2 DoN 2002 3 DoN 2008 Hawaii 4 Environmental 5 DoN 2008 SOCAL					
Note: Highlighted Cells are those animals whose feeding and diving behavior put them in proximity to the sea floor					

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Military expended materials (MEM) are items abandoned in the marine environment after use during Navy training and testing exercises. A better understanding of the potential environmental impacts of these materials is needed to ensure regulatory compliance required for continued and uninterrupted training and testing in support of the Navy warfighter. Copper-based guidance wire identified as a MEM of concern. The goal of this study was to define and evaluate potential environmental impacts related to copper--based guidance wire left at sea. This report focuses on potential impacts due to copper-based torpedo guidance wire, although results and recommendations hold true for additional guidance wire with similar specifications.

Copper based torpedo guidance wire presents little to no environmental risk at the Navy training ranges currently using them. The potential impacts of previously expended guidance wire should have no near or long term negative affects to marine water and sediment quality, as well as marine animals found within the training ranges. The continued use of guidance wire in similar scope and formulation as evaluated herein should not present any future deleterious environmental impacts.

15. SUBJECT TERMS

Environmental Science: military expended materials, conceptual evaluation pathway, torpedo guidance wire, entanglement threats, leached copper, chemical hazard, physical hazards

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