

WORKSHOP REPORT

Informal Workshop on Burial and Mobility Modeling of Munitions in the Underwater Environment

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SERDP and ESTCP Office

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Acronyms

DoD – Department of Defense
EM – Electromagnetic
ERDC – US Army Engineer Research and Development Center
ESTCP – Environmental Security Technology Certification Program
FY – Fiscal Year
GPS – Global Positioning System
IMPACT35 – 3D rigid body impact burial prediction model
IMU – Inertial Measurement Unit
LIDAR – Light Detection and Ranging
MBES – Mine Burial Expert System
MM – Mobility Model
MR – Munitions Response
NAVFAC – Naval Facilities Engineering Command
NRL – Naval Research Laboratory
ONR – Office of Naval Research
PI – Principal Investigator
PMRF – Pacific Missile Range Facility
RAS – Risk Assessment System
RI – Remedial Investigation
SERDP – Strategic Environmental Research and Development Program
STRIKE35 – Bomb Maneuvering Model for Obstacle Clearance
UnMES – Underwater Munitions Expert System
USACE – U. S. Army Corps of Engineers
USBL – Ultra-short Baseline
UXO – Unexploded Ordnance
WAA – Wide Area Assessment

Preface

The Strategic Environmental Research and Development Program (SERDP) hosted an informal workshop on “Burial and Mobility Modeling of Munitions in the Underwater Environment” on 30 June – 1 July 2014, at the Holiday Inn Arlington in Arlington, Virginia. The purpose of the informal workshop was to allow SERDP project teams to: 1) collaboratively share research progress with peers; 2) identify needs for integration of observations and modeling efforts; 3) comprehend the concerns of DoD site managers; 4) define a path forward; and 5) clearly state the product expected to culminate from all relevant project efforts. The 15 attendees represented 10 institutions. Their participation was greatly appreciated.

The strategy for achieving the informal workshop objectives was developed by the coordinating committee led by Dr. Joseph Calantoni (Naval Research Laboratory), Dr. Herbert Nelson (SERDP), and Dr. Michael Richardson (Institute for Defense Analyses). The report was written and compiled by the members of the coordinating committee along with comments and revisions provided by all informal workshop participants.

Ms. Katherine Kaye (SERDP Munitions Response Program Support Office) acted as the organizer for the informal workshop and her notes from the meeting provided the basis for much of the content contained in the report. The informal workshop was supported by SERDP Acting Director, Dr. Anne Andrews.

1. Introduction and Objectives of Informal Workshop

SERDP hosted an informal workshop on “Burial and Mobility Modeling of Munitions in the Underwater Environment” from 30 June – 1 July 2014, at the Holiday Inn Arlington in Arlington, Virginia. The objectives of the informal workshop were to allow SERDP project teams to 1) collaboratively share research progress with peers; 2) identify needs for integration of observations and modeling efforts; 3) comprehend the concerns of DoD site managers; 4) define a pathway forward; and 5) clearly state the product expected to culminate from all relevant project efforts. The strategy for achieving the informal workshop objectives was developed by the coordinating committee led by Dr. Joseph Calantoni (Naval Research Laboratory), Dr. Herbert Nelson (SERDP) and Dr. Michael Richardson (Institute for Defense Analyses). The report was compiled and written by the members of the coordinating committee along with comments and revisions provided by all informal workshop participants. The informal workshop agenda is included as Appendix A, and the list of attendees is included as Appendix B.

Research on the burial and mobility modeling of munitions in the underwater environment is a priority for SERDP/Environmental Security Technology Certification Program (ESTCP) (Final Report, 2007; White Paper, 2010). Quite often, underwater environments can be dynamic locations where munitions are more likely subject to mobility, burial, and re-exposure when compared to terrestrial environments. Additionally, there are a wide range of underwater environments that all have different and complex fluid and granular-fluid mechanics driving the phenomenology. In addition to the coastal ocean, the underwater environment also includes estuaries, lakes, and rivers. Each of these locations has different wave and circulation patterns that drive sediment erosion and deposition. Likewise, the bottom type can vary from soft clays and muds, to sandy sediments, large cobbles, and coral reefs. Heterogeneous bottom types (or mixtures) are also prevalent, complicating mobility modeling, as well as detection and classification sensors alike. Additionally, a wide range of boundary and forcing conditions exist across underwater environments. The need to assess and manage risk associated with each underwater site necessitates the development of robust predictive models. Predictive models require detailed measurements for verification and validation. One of the goals of the burial and mobility modeling aspect of the SERDP Munitions Response (MR) program is the development of predictive models to quantify both the short- and long-term behavior of the distribution of unexploded ordnance (UXO) present at each underwater site. These predictive models must be probabilistic in nature such that they not only make predictions, but also simultaneously estimate the uncertainty of the predictions to allow site managers to make the most informed decisions with regards to remediation and risk.

The lead Principal Investigator (PI) for each SERDP project that was represented at the informal workshop provided up to a 30-minute presentation that included 5-10 minutes for questions on the morning of 30 June 2014. The presentations were roughly grouped into two categories that included three presentations focused on burial and mobility modeling; and three presentations focused on field and laboratory measurements. The breakout discussions utilized a series of questions provided by the coordinating committee, and by Dr. Alan Brandt and Dr. Sarah Rennie (Johns Hopkins University Applied Research Laboratory). The report summarizes the results and discussion from the informal workshop, identifies areas and topics for future research, and may be used as a guide for future proposals.

2. Summary of Munitions Burial and Mobility Projects

The current portfolio of projects funded by the SERDP MR program focused on burial and mobility modeling of munitions in the underwater environment, which can be roughly broken down into two categories. One set of projects focus on theoretical and modeling studies, and the other set of projects focus on field and laboratory experiments. In the next two subsections a condensed summary of the six different projects that were briefed during the informal workshop is presented. The informal workshop represented the first opportunity for all the primary investigators of these related projects to meet, as well as share their progress and ideas with their peers, sponsors, and end users. In the last subsection, a brief summary of past SERDP & ESTCP projects focused on burial and mobility modeling of munitions in the underwater environment is presented.

2.1. Theoretical and Modeling Studies

MR-2227: Underwater Munitions Expert System to Predict Mobility and Burial – PI: Dr. Sarah Rennie, Johns Hopkins University, Applied Research Laboratory

The objective of this project is to develop a computer-based probabilistic expert system that synthesizes recent and new research to model munitions burial and mobility in a range of underwater environments. The Underwater Munitions Expert System (UnMES) will be a prototype software tool demonstrating the methodology for providing knowledge required to optimize the deployment of the likely constrained resources available for underwater munitions detection and classification. The expert system approach employs a Bayesian network whose probabilistic basis provides a means of accounting for the inherent uncertainties given unknown initial conditions and environmental forcing over long time intervals. The probabilistic construct of UnMES produces output, which feeds naturally into risk assessment models. With characterization of the probabilities of munitions concentration and degree of burial for sub-regions within the site, clearance efforts can be more efficiently planned and executed. An example Bayesian network, representing a partial model for migration and degree of burial at two cross-shore locations at a wave-driven coastal site, was designed and populated with available data. Gaps in existing process-based models and data were identified. In support of this project to develop an expert system to predict underwater munitions burial and mobility, several series of laboratory studies were performed utilizing a range of relevant UXO surrogates. The first series involved tests for initiation of mobility on a flat rigid surface with varying roughness. These tests were specifically designed to address the empty parameter space in the center of Figure 1 (right), where the relevant UXOs reside. The other test series studied scour burial under steady flow on a flat sand bed, and the combination of mobility and scour burial due to accelerating flow on sloped sand bed. These data have been shared with MR-2224 for refinement of the parameterized models.

MR-2224: Simple Parameterized Models for Predicting Mobility, Burial and Re-Exposure of Underwater Munitions – PI: Dr. Carl Friedrichs, Virginia Institute of Marine Science

The objectives of this project are to: 1) to compile existing quantitative data regarding the mobility, burial, and re-exposure of underwater UXO; 2) to utilize these data to further develop simple models for UXO mobility, burial, and re-exposure; and 3) to quickly provide these improved parameterized model formulations for use by others. A search has been conducted of the literature and of the engineering, scientific, and Department of Defense (DoD) communities for quantitative field and laboratory data on the mobility, burial, and re-exposure of objects that

are large relative to the surrounding sediment (including natural objects such as cobbles and rock fragments, as well as man-made objects such as UXO and other artifacts). These data were utilized to develop and constrain simple, rational, parameterized models for UXO mobility and burial (e.g., Figure 1). Progress has focused mostly on providing a clearer physics-based derivation of parameters for the initiation of motion of seabed objects and improved calibration of the formulation in close collaboration with MR-2227. The parameters developed are already being applied as process model components within MR-2227 as described above.

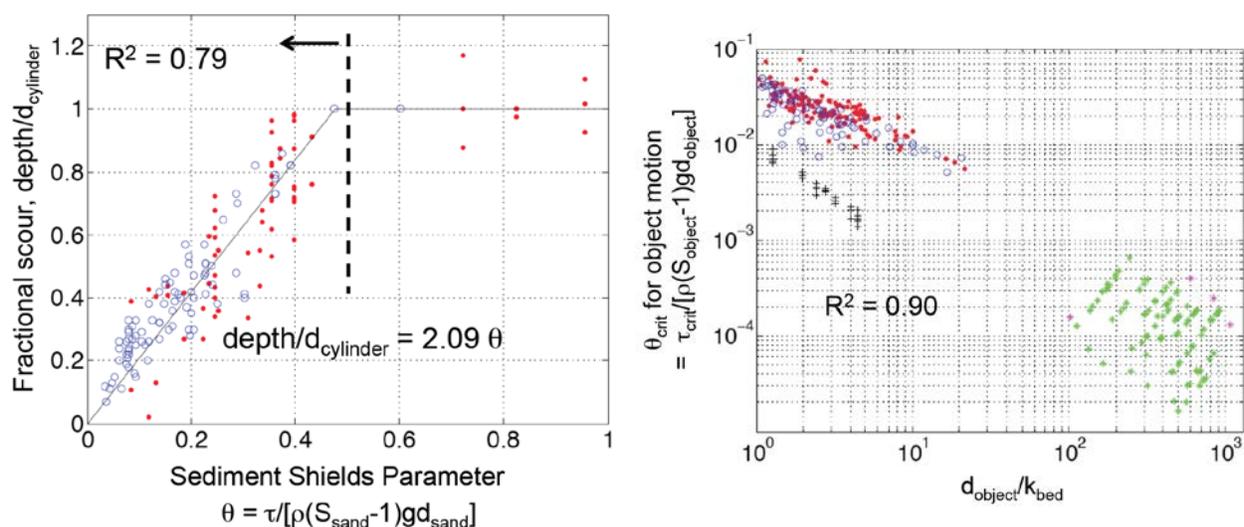


Figure 1. Scour (left) and initiation of motion (right) of UXO governed by sediment and object Shields parameters, respectively. (left) Blue symbols represent laboratory studies under oscillatory flow; red mark field data under natural conditions. (right) Red and magenta symbols represent field data for heterogeneous sediment and UXO-like cylinders in sand under waves, respectively. Blue, black, and green symbols represent laboratory data for natural sediments, glass spheres, and UXO-like cylinders on a flat bed, respectively. Lacking are (i) sufficient observations of movement of UXO-shaped objects on a mobile sand bed, (ii) better understanding of shape effects, and (iii) the effect of $\rho_{\text{object}}/\rho_{\text{sand}}$ (e.g., bed fluidization).

MR-2411: *A Wide Area Risk Assessment Framework for Underwater Military Munitions Response – PI: Dr. K. Todd Holland, Naval Research Laboratory*

The objective of this project is to develop a prototype statistical framework supporting Wide Area Assessment (WAA) and Remedial Investigation (RI) decisions relating to the risk of UXO and other military munitions concentrated in underwater environments. The framework will provide a consistent approach to accurately delineating contaminated areas at underwater munitions sites through the estimation of most probable concentrations. The approach is to adapt existing probabilistic technological solutions to develop a prototype decision support system to manage environmental uncertainty at underwater munitions response sites. Realistic evaluation of environmental attributes impacting underwater munitions assessment will include expected munitions type/condition, spatial distribution of initial contamination, time since initial contamination, state of burial, and associated environmental conditions that are available from databases or operational data servers. These parameters will include water depths in areas of interest, seafloor sediment types, hydrodynamic conditions, turbidity, and salinity. The design concept for the prototype Risk Assessment System (RAS) links output from a probabilistic

estimation framework to ArcGIS © to allow end users to specify inputs and view outputs in a single geospatial interface.

2.2. Field and Laboratory Experiments

MR-2320: *Long Time Series Measurements of Munitions Mobility in the Wave-Current Boundary Layer – PI: Dr. Joseph Calantoni, Naval Research Laboratory*

The objective of this project is to provide detailed time series measurements of the in situ boundary layer processes responsible for munitions mobility including transport, burial, and re-exposure. A set of field experiments is being performed to characterize the environment in which munitions are found while simultaneously recording the location of munitions relative to the seafloor at high spatial and temporal frequency. Instrumentation will provide high spatial and temporal resolution measurements for the relevant boundary layer processes (e.g., wave height and direction, current profiles, suspended sediment concentrations, as well as sediment erosion and deposition) while simultaneously monitoring the mobility of surrogate munitions. The year 1 field effort is complete and the mobility of surrogate munitions (ranging from 20 mm to 155 mm in diameter) was observed and quantified under moderate storm conditions in a sandy coastal environment. Perhaps more interestingly, the rapid burial of surrogate munitions was observed during the latter half of the storm event.

MR-2319: *Continuous Monitoring of Mobility, Burial and Re-Exposure of Underwater Munitions in Energetic Near-Shore Environments – PI: Dr. Peter Traykovski, Woods Hole Oceanographic Institution*

Field measurements of mobility, burial, and re-exposure of munitions in energetic near-shore environments with high potential for mobility have been conducted. The surrogate munitions type, size, and density were varied to enhance potential for migration processes. The researchers developed an autonomous four-transducer ultra-short baseline (USBL) transceiver system to continuously track objects during energetic conditions. The system acoustically measured range and bearing to surrogate munitions equipped with acoustic transponders. Hydrodynamic forcing parameters were measured using a combination of conventional acoustic Doppler velocimeters and more advanced pulse coherent profilers. During the year 1 (winter of 2013/14) experiment, tethered global positioning system (GPS) floats were used to track munitions mobility. In year 1, the measurements were located on Wasque Shoals, adjacent to the Muskeget Channel between Martha's Vineyard and Nantucket, Massachusetts. This location has strong tidal flows (1.5 m s^{-1}) and wave (1 to 3 m height) forcing. Bedforms consist of large-scale sand waves with wavelengths of approximately 100 m and heights of 3 m in 6 m water depth. Smaller-scale tidally reversing mega-ripples (1 to 5 m wavelength, 0.1 to 0.5 m height) were superimposed on the large-scale sand waves. The mega-ripples migrate with rates up to 1 wavelength per half tidal cycle. The large scale sand waves migrate at rates of one wavelength per 4 months, and a crest migrated past the study site during the observational period burying the instrumented frame and the most dense (3 g cm^{-3}) UXO surrogates. The burial process was imaged with a rotary sidescan sonar indicating the UXO transient (hours to days) burial under the migrating megaripples and long-term (months to years) burial under the large sand wave. Less dense ($\square \leq 2 \text{ g cm}^{-3}$) UXO surrogates migrated distances up to 20 m in front of the advancing sand wave and came to rest in the trough of the large-scale sand waves (Figure 2). The year 2 (fall of 2014) measurements are underway at a surf zone location on the south shore of Martha's Vineyard with 1 to 4 m waves and weak tidal currents. Bedforms at this site are typically wave orbital scale ripples with wavelengths of up to 1.5 m and heights up to 0.2 m. The bedforms migrate onshore in response

to waves with high velocity skewness. The UXO are tracked by the acoustic USBL system and very small surface floats. One set of instruments and UXO surrogates is located in the trough between the nearshore sand bar and the beach to examine potential for migration due to strong alongshore currents, and the second set of instruments and UXO is located farther offshore to examine potential for onshore wave skewness forced migration into the nearshore. Surveys of the surface float locations indicate larger migration rates at the surf zone site relative to the tidally forced site. Lower density UXO ($\rho \leq 2 \text{ g cm}^{-3}$) deployed at the offshore locations migrated 170 m onshore and came to rest 15 m from the shoreline at the base of the steep beach face. UXO with densities greater than 3 g cm^{-3} did not migrate, and were presumably buried.

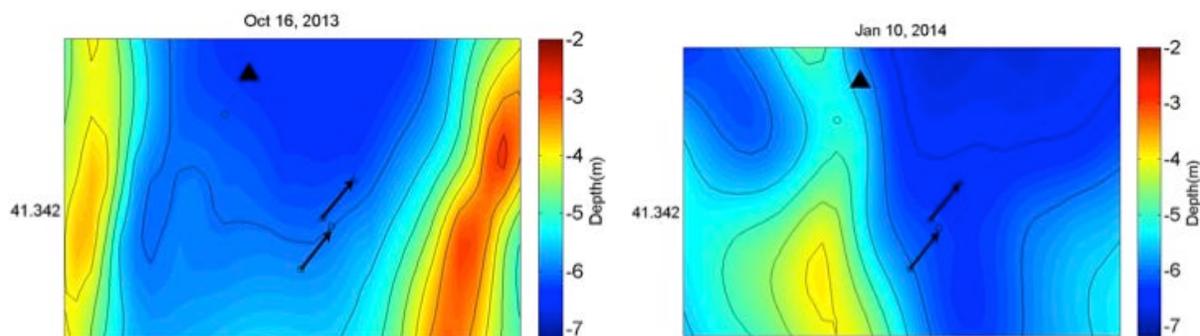


Figure 2. Migration of surrogate UXO in front of a migrating large-scale sand wave. On October 16, 2013 (left), the UXO were deployed in the trough of 100 m wavelength, 3 m high sand wave. By January 10, 2014 (right), the sand wave had migrated over the instrument frame (black triangle), burying the frame and a nearby high density UXO. Lower density UXO migrated downslope into the trough of the advancing sand wave.

MR-2410: *Large-Scale Laboratory Experiments of Incipient Motion, Transport, and Fate of Underwater Munitions under Waves, Currents, and Combined-Flows – PI: Dr. Marcelo Garcia, University of Illinois at Urbana-Champaign*

As the project represents a fiscal year (FY)14 new start, only plans were presented. The objective of this project is to quantify the incipient motion, transport, and fate of underwater munitions in coastal environments, comprised of mobile beds and/or hard bottoms (e.g., sandy and gravel/rock), under a range of relevant hydrodynamic conditions (e.g., waves, currents, combined flows). Through an extensive set of detailed large-scale laboratory experiments, this project seeks to develop a complete picture of the phenomena involved in the entrainment, transport, and fate of underwater munitions. The laboratory experiments will allow for detailed measurements over a controlled range of conditions, which are not practically possible to achieve in field experiments, and cannot be completely simulated with numerical models. The laboratory data will be a valuable complement to existing field experiments and will augment the data available to test, calibrate, and validate predictive numerical models. The advantage of these laboratory experiments is greater control of environmental conditions (both flow characteristics and substrate properties), as well as higher precision measurements than can be obtained in the field, where the flow conditions are constantly changing with time.

2.3. Past Projects

MR-201003: *Vortex Lattice UXO Mobility Model for Reef-Type Range Environments – PI: Dr. Gerald D'Spain, Scripps Institution of Oceanography*

This project leveraged previous ESTCP investments in the development of a UXO Mobility Model (UXO-MM, described below in MR-201234) to assess probable UXO fate and transport at the Waianae dump site, Hawaii, and at the Vieques Islands, Puerto Rico firing and bombing exercise ranges (with focus on the South Impact Area). The objective of this work was to develop modifications to the UXO-MM software to implement reef geomorphology in the model grid building scheme. The reef platform micro-bathymetry was constructed from spatial Fourier transforms of the light-detection and ranging (LIDAR) data using the reef platform at the Pacific Missile Range Facility (PMRF), Kauai as a geomorphic proxy of other island reef systems. After validating software revisions using the ESTCP-funded field data at PMRF, this work showed that the model predicted, through long-term, extreme-event simulations at Vieques Island, that the UXO eventually concentrate in the reef awa channels. Here, UXO are amenable to recovery by conventional sand dredging methods, while presenting a persistent danger of becoming transported to the beach during storms if not recovered. Concentration of UXO in the awa channels over time resulted from higher mobility on the reef platform due to two primary mechanisms: 1) higher ambient wave-induced velocity over the locally shallower reef platform; and 2) reduced rolling resistance of UXO on the hard substrate of the reef platform.

MR-201234: *Vortex Lattice UXO Mobility Model Integration – PI: Dr. Gerald D'Spain, Scripps Institution of Oceanography*

The objective of this project was to integrate an existing ballistics impact burial model with the Vortex Lattice UXO-MM in order to compute the initial state of the UXO population based on range firing records at various sites. The UXO-MM is a physics-based model that solves a classic boundary value problem using computational fluid dynamics methodologies. The UXO-MM applies long-term fluid forcing by wind, waves, and currents to the sediment budget of an underwater UXO site to predict changes in the initial burial state of the resident UXO population. It conducts a sequence of time-stepped computations of UXO exposure and subsequent mobility until local scour processes and broad-scale accretion induce reburial. The ballistic impact burial model embedded into the UXO-MM architecture is STRIKE35, a six-degree-of-freedom ballistics model that is a derivative of the Navy's well-proven mine impact burial model, 3D rigid body impact burial prediction model (IMPACT35).

3. State of the Art: Munitions Burial and Mobility Modeling

Munitions burial and mobility models are expected to have a significant role in the larger context of the MR program of SERDP & ESTCP. For example, burial and mobility models may be used to motivate the choice of acoustic detection and classification sensors at a particular remediation site by providing inputs required to estimate the probability of detection for a given sensor. Consequently, burial and mobility modeling will be a cornerstone in any RAS used to determine when to remediate, or if remediation is even necessary.

For the past two decades, the Office of Naval Research (ONR) has had a strong program focused on mine burial prediction (e.g., Wilkins & Richardson, 2007; Chu & Fan, 2007; Traykovski et al., 2007). Many field and laboratory measurements were performed and models developed. One

key product from the years of research was the development of the Mine Burial Expert System (MBES) as an operational model for making predictions (Rennie et al., 2007). The measurement techniques, modeling framework (including the MBES), and data acquired under the past mine burial program are being leveraged to the fullest extent possible during the execution of the SERDP & ESTCP efforts for burial and mobility modeling of munitions. Some of the researchers involved in the projects described in Section 2 have prior connections with, and in several cases were PIs under the previous ONR mine burial program. An important distinction and motivation for the work being performed under the MR program of SERDP is the focus on UXO, which are often much smaller and more mobile than their larger mine-like counterparts.

The sections below describe the state-of-the-art technology being utilized and improved for scour and impact modeling, mobility and migration modeling, as well as measurement technologies. For nearly all phenomenology, strong existing basic and applied research (6.1 and 6.2) from ancillary programs (e.g., ONR) may be leveraged by transferring knowledge and techniques from mine and mine-like objects to UXO of interest to SERDP & ESTCP. It was strongly agreed among the researchers that while the typical shapes for UXO may vary from their mine-like counterparts, much of the existing science and technology could be used directly. In some cases, existing theories and models just need a fresh verification and validation with typical UXO objects.

3.1. Scour and Impact Models

Existing models developed under the ONR mine burial program are being leveraged by SERDP & ESTCP projects for both scour and impact burial (Chu & Fan, 2007; Jenkins et al., 2007; Rennie et al., 2007). However, these models were developed for the typical large cylindrical mine. For both scour and impact verification and validation needs to be performed to determine if the existing models are adequate for a variety of UXO shapes and sizes. Scour models require environmental forcing conditions for remediation sites. Critical site characteristics for both scour and impact include sediment properties and the bulk density, sizes, and shapes of the range of munitions of interest. Under MR-2224, existing field and laboratory data for scour around objects was aggregated and parameterized in a manner derived from traditional models for sediment motion (e.g., Figure 1 – left).

Through discussion, it was determined that impact should not be relevant for the long-term fate of munitions unless the initial impact burial was below the sediment surface (e.g., impact in soft clays or muds). The one exceptional case would be for impact burial in stiff muddy sediments where the UXO might initially be partially buried. It was generally accepted that for all munitions the speed of impact on the bottom would typically be equivalent to the terminal velocity of the object in the water column. However, in very shallow water there will exist a range of munitions that impact the water surface at very high velocity and still have not reached terminal velocity when impacting the bottom. For example, the STRIKE35 model (Chu et al., 2011) has predicted water column trajectories for high velocity impacts at the water surface for a large, finned bomb, but has not been validated for typical UXO of interest to SERDP & ESTCP. STRIKE35 may be leveraged to estimate impact velocity on the bottom once a group of such high velocity munitions relevant to SERDP & ESTCP has been identified and tested. If unclassified, underwater impact data for munitions exist, these data need to be incorporated into the UnMES and ultimately any resulting RAS.

3.2. Mobility and Migration

Mobility and migration dominate the redistribution of munitions over long time intervals. The majority of research to date for mobility and migration of UXO has been focused on quantifying the conditions necessary to initiate motion with little work performed to understand either short-term displacements or long-term migration patterns. Of particular interest may be the relationship between long-term migration patterns for UXO and far field effects, such as winter/summer beach profile changes. Under MR-2224, existing field and laboratory data for the initiation of motion of objects was aggregated to elucidate a simple non-dimensional relationship between the critical stress on the object and the length scale of the object (e.g., Figure 1, right). It was determined that simple relationships of this type are extremely valuable when supported by a wide range of field and laboratory data. It was recommended that once validated for a relevant range of conditions, turbulence resolving, computational fluid dynamics models be used to generate probability tables for a variety of sizes, shapes and densities of UXO. Extending such computationally intensive simulations to extreme energetic conditions was of particular interest, but also may pose numerical challenges (e.g., performing Large Eddy Simulations at high Reynolds number).

The only existing model for mobility and migration is the UXO-MM described in Section 2.3. The UXO-MM is a physics-based model that solves the classic boundary value problem. The model results are sensitive to the initial conditions for the distribution of UXO per cubic meter of seafloor sediments, for example. Additionally, the UXO-MM is extremely data intensive with regards to boundary conditions and gridding requirements; and is extremely computationally intensive requiring long run times for individual site scenarios. Specific limitations on the predictive capability of the UXO-MM are discussed in Jenkins et al. (2011).

3.3. Measurement Technologies

The measurement technologies for quantifying the relevant environmental forcing conditions important for burial and mobility modeling including bathymetry, sediment characterization, sediment transport, waves, currents, and tides are in general very mature. Likewise, the capabilities and instrumentation found among the existing SERDP project teams previously described represent the state-of-the-art for measuring the relevant environmental forcing conditions in both the field and laboratory. However, lacking to-date are viable methods for simultaneously tracking the mobility of munitions over long temporal and spatial scales. High frequency sonars have proven to be valuable for tracking munitions mobility and burial over long time scales, but lack spatial range (Figure 3). During the year 1 field experiment of MR-2320, for example, a sector scanning sonar image was acquired every 12 minutes for 33 days from a fixed platform; however, only a small patch of the seafloor was imaged ($\sim 6 \text{ m}^2$). Similar sonar imaging technology was also used successfully during the previous ONR mine burial program and produced imagery of transient and long-term burial under small and large-scale migrating bedforms in MR-2319.

One technology under development as part of MR-2319 is the new USBL acoustic tracking array with UXO mounted transponders. A maximum tracking range of up to 2.5 km is anticipated. Other technologies that are being explored include embedding small, low-cost, inertial measurement units (IMU) into munitions. However, these technologies are not yet robust enough to allow for integration of the UXO trajectories over long time periods. They can be used to

provide accurate orientation data for UXO, such as if a mortar tends to bury nose down. Low-cost IMUs were used successfully in MR-2319 to identify small-scale rolling or “rocking” motions at the imitation of motion and “tumbling” motions during active migration. In very shallow water attempts will be made to couple image tracking of painted UXO from above (e.g., using fixed or portable towers) with embedded accelerometers to provide simultaneous orientation information in the surf and swash zones.

Before and after locations for UXO have been recorded, when the targets were either tethered at a fixed point on the seafloor or attached to a line with a buoy floating on the surface. In both cases, the data obtained may be strongly contaminated by the tether; however, in the latter case the degree of contamination depends on the buoyancy of the buoy relative to the weight of the object. An alternative method that was suggested would involve removing the tether and embedding a small acoustic release device that would send up a buoy (if possible) either on a timer or when triggered. When coupled with an onboard transponder, it is believed that instrumented UXO such as these may be useful to provide final locations resulting from extreme storm events.

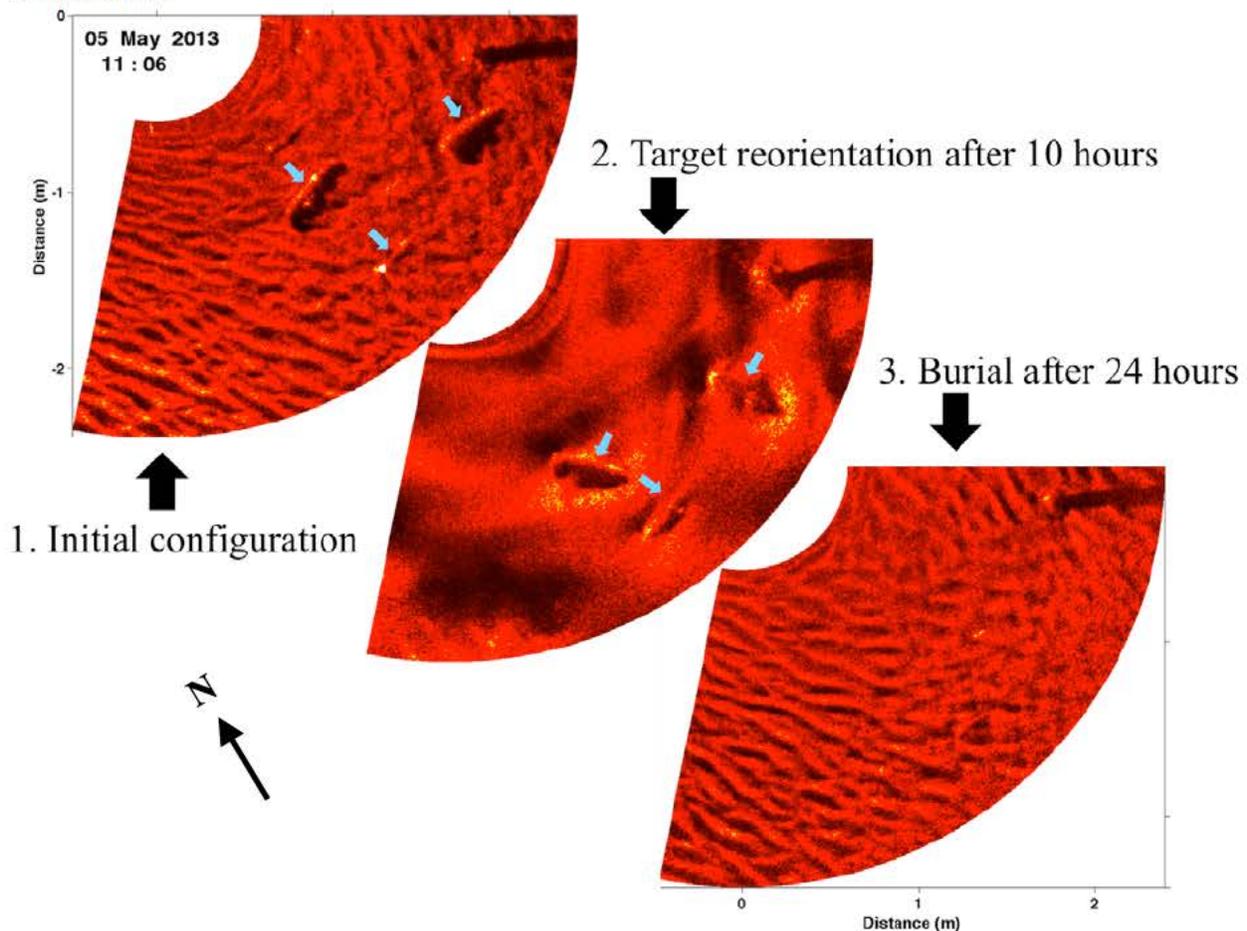


Figure 3. Sequence of sector scanning sonar images highlighting the movement and burial of two replica 155 mm shells and one replica 81 mm mortar (with fins). The initial positions of the three targets are identified with the white arrows (upper left). The same targets were still visible about 10 hours later in their new positions again indicated by white arrows (center). The final image (lower right) was taken 24 hours later.

4. Future Experiments

The future experiments planned under the existing projects and additional experiments, not currently planned but deemed necessary to the ultimate success of the program, were discussed. It was suggested that plans should be made to attempt to collect data for burial and mobility during major storm events (e.g., nor'easter or hurricane). Because most conventional instrumentation would not be expected to function or survive during a hurricane, initial and final locations of munitions might be quantified through some combination of electromagnetic (EM) and acoustic surveys perhaps coupled with acoustic releases that could be embedded inside the larger UXO of interest to facilitate locating the targets after the storm (as described above). Additionally, investigation of the burial and mobility of UXO in the swash zone was identified as a gap in the ongoing field studies (MR-2319 and MR-2320). The swash zone is the upper part of the beach that roughly defines the shoreline, where intense erosion occurs during storms. A lack of data for the burial and mobility of UXO in riverine environments was also noted.

A range of topics were discussed that should be considered to ensure that the benefit of future experiments in both the field and laboratory is maximized. The topics include 1) better guidance and consistency regarding the types of UXO to be used during experiments, 2) the dissemination of environmental characteristics for sites and the use of existing research models to estimate the “active layer”, 3) quantifying the importance of near field versus far field measurements for validating predictive models for mobility, 4) integration with laboratory measurements, and 5) the establishment of test beds for coastal ocean and riverine environments. The discussion below for each topic outlines the problem and suggests potential solutions.

4.1. Types of UXO

The munitions of interest have been loosely defined for the SERDP researchers involved in the informal workshop to include 20-155 mm diameter shells and projectiles with tapered shapes and fins such as mortars. Where possible, care has been taken to fabricate replica and surrogate munitions with similar overall size, shape, and weight to actual munitions. However, most experiments have been performed with simple cylindrical shapes of varying sizes and densities. It was generally accepted that most UXO are likely to have a specific gravity, $3 < S < 4$. It is also accepted that munitions with specific gravity (or density) greater than that of a water-saturated, sandy sediment bed, $S = 2$, are most likely to bury during large sediment transport events. A table of the bulk density for the range of UXO of interest is required. Of particular concern is the lack of knowledge of the remaining portion of fins, which may break off during deployment of relevant UXO.

The range and types of UXO of most interest in terrestrial environments have been clearly identified. However, strong guidance for the typical range and types of UXO of critical interest in the underwater environments is still lacking. There is an expectation that the inventory of interest will differ from terrestrial environments. These differences need to be clearly identified and inert certified munitions need to be made available to the researchers in the SERDP & ESTCP burial and mobility modeling program. It is agreed that the identification of the appropriate UXO will most effectively be accomplished by employing feedback from site managers and others outside of the group of PIs participating in the informal workshop.

4.2. Remediation Site Characteristics

The consensus among the researchers was that strong guidance and data for the characteristics of the remediation sites of interest are still lacking. The two main field efforts presented at the informal workshop were performed in coastal ocean environments. However, nearly half of the sites of interest to the Navy are represented by harbors and bays. Meanwhile, the majority of the sites of interest to the Army are represented by rivers and lakes. With regards to rivers, it was noted that there has been a history of programs, completed and ongoing, for both measurements and modeling within the Army (e.g., U.S. Army Engineer Research and Development Center [ERDC] in Vicksburg, Mississippi) and Navy (e.g., ONR and Naval Research Laboratory [NRL] funded efforts) that could be leveraged to propel the research forward rapidly for the purposes of munitions mobility modeling in this environment. The issue of obtaining site characteristic assessments for all Navy remediation sites is currently being addressed by a new effort led by Naval Facilities Engineering Command (NAVFAC).

When munitions are found onshore at a particular site, the origin of the UXO is typically unknown. Two possible options were discussed: 1) the UXO had always been onshore and was recently excavated due to some change in beach profile or sediment transport (i.e., beach churn); or 2) the UXO was washed ashore from some more remote offshore location due to gradients in the waves, currents, and sediment transport patterns. Choosing the appropriate option may be possible given a priori knowledge of the “active layer” at remediation sites. The “active layer” concept refers to an elevation envelope representing the minimum and maximum estimate that the sediment bed will move over some known timeframe (e.g., during a storm). While the estimation of the “active layer” will be an important variable for many site managers, the concept may not apply to all sites of interest (e.g., coral reefs and rocky coasts).

There was little confidence that any model would be adequate to predict munitions mobility during extreme storm events since, as of yet, no data exist for these conditions. Currently, for coastal ocean environments there are no operational models available to forecast/hindcast sediment erosion and deposition. However, there are well-developed research models such as COAWST (<http://woodshole.er.usgs.gov/operations/modeling/COAWST/>) and Delft3D (<http://oss.deltares.nl/web/delft3d/home>) that may be adequate to estimate the horizontal and vertical extent of the “active layer” at the remediation sites of interest. While these models lack maturity and rigorous validation, they represent our best opportunity to quickly quantify the potential for UXO burial and re-exposure from typical to extreme weather conditions. There are several models available that have been developed for the coastal ocean under ONR funding (e.g., NearCoM – <http://chinacat.coastal.udel.edu/programs/nearcom/>); and others available that have been developed for riverine environments under U.S. Army Corps of Engineers (USACE) funding (e.g., HEC-RAS – <http://www.hec.usace.army.mil/software/hec-ras/>).

4.3. Near Field Versus Far Field

Near field phenomenology occurs when the UXO directly affects the process (e.g., impact and scour burial). Far field phenomenology affects mobility, burial, and re-exposure independent of the UXO (e.g., erosion, sand ripple or large bedform migration). It is generally accepted that we have more data available to quantify the near field phenomenology than the far field for munitions. However, some data sets have been able to observe both. During the year 1 field experiment of MR-2320, for example, the conditions leading to the onset of motion for

munitions were first observed followed by the burial of the target field in a migrating bedform (Figure 4). Similarly in MR-2319, transient burial by migrating megaripples followed by long-term burial by large-scale sand wave migration was observed.

Separate models exist that may be utilized to deal with each effect independently. However, models that combine near field and far field phenomenology are rare. Many of these models for both cases, such as UXO-MM, are still considered research tools and have not undergone sufficient verification and validation for operational use. For example, typical far field models for bedform migration are computationally intensive and have a limited prediction horizon (up to several days). They also neglect anthropogenic effects. The repeated use of far field models at remediation sites will require boundary conditions that may need to be sampled at regular intervals such as bathymetry or cross-shore profiles for dynamic coastal environments. Waves, currents, and tides need to be forecasted/predicted or sampled continuously to provide boundary conditions for model runs. However, given the long durations of most UXO contaminations, accumulation of error in initial conditions will require that all of the environmental forcing parameters measured must be clearly linked to the probabilistic (expert system) model described in Section 2.1.

4.4. Integration with Laboratory Experiments

While some preliminary laboratory measurements have been completed under project MR-2227, more exhaustive measurements are beginning under project MR-2410. A matrix of munitions, substrate types and flow conditions will be simulated in the laboratory. The laboratory measurements are most effective at quantifying near field phenomenology such as scour burial and incipient motion of munitions over a range of substrates. It is encouraged that UXO replicas or surrogates used in laboratory measurements be consistent in size, shape, and density with UXO deployed during field experiments to facilitate direct comparisons of scientific findings for burial and mobility. It is important for field and laboratory researchers to work collaboratively in order to maximize the range of data immediately available for model development and validation.

A gap was identified in the integration of laboratory and field measurements with models. Presently, there is no planned effort to perform detailed, turbulence resolving simulations of measurements for incipient motion of munitions. It was agreed that a small subset of detailed simulations should be performed to solidify the connections among the different data sets and the probabilistic and theoretical modeling studies.

4.5. Establishment of Test Beds for Burial and Mobility Observations

Effort should be taken to establish test beds that represent many of the environmental characteristics common to the underwater sites of interest to the MR program of SERDP & ESTCP. The selection of a test bed for performing burial and mobility observations must consider the following important factors:

- Established infrastructure and technician support
- Documented history of in situ experimentation
- Vulnerability to extreme storm events (e.g., hurricanes or typhoons)
- Common environmental forcing conditions and characteristics among remediation sites

The establishment of test beds during the ongoing SERDP work described above in Section 2 will facilitate closer collaboration among funded field experimentation and modeling efforts. Initially, it is recommended that one coastal and one riverine test bed be chosen. Eventually, test beds for observing burial and mobility need to be integrated with test beds used for evaluation of sensor technologies to facilitate future demonstrations under the MR program of SERDP & ESTCP. Risk management and assessment at remediation sites will require the integration of all products from both detection and classification to burial and mobility modeling to make the most informed decisions.

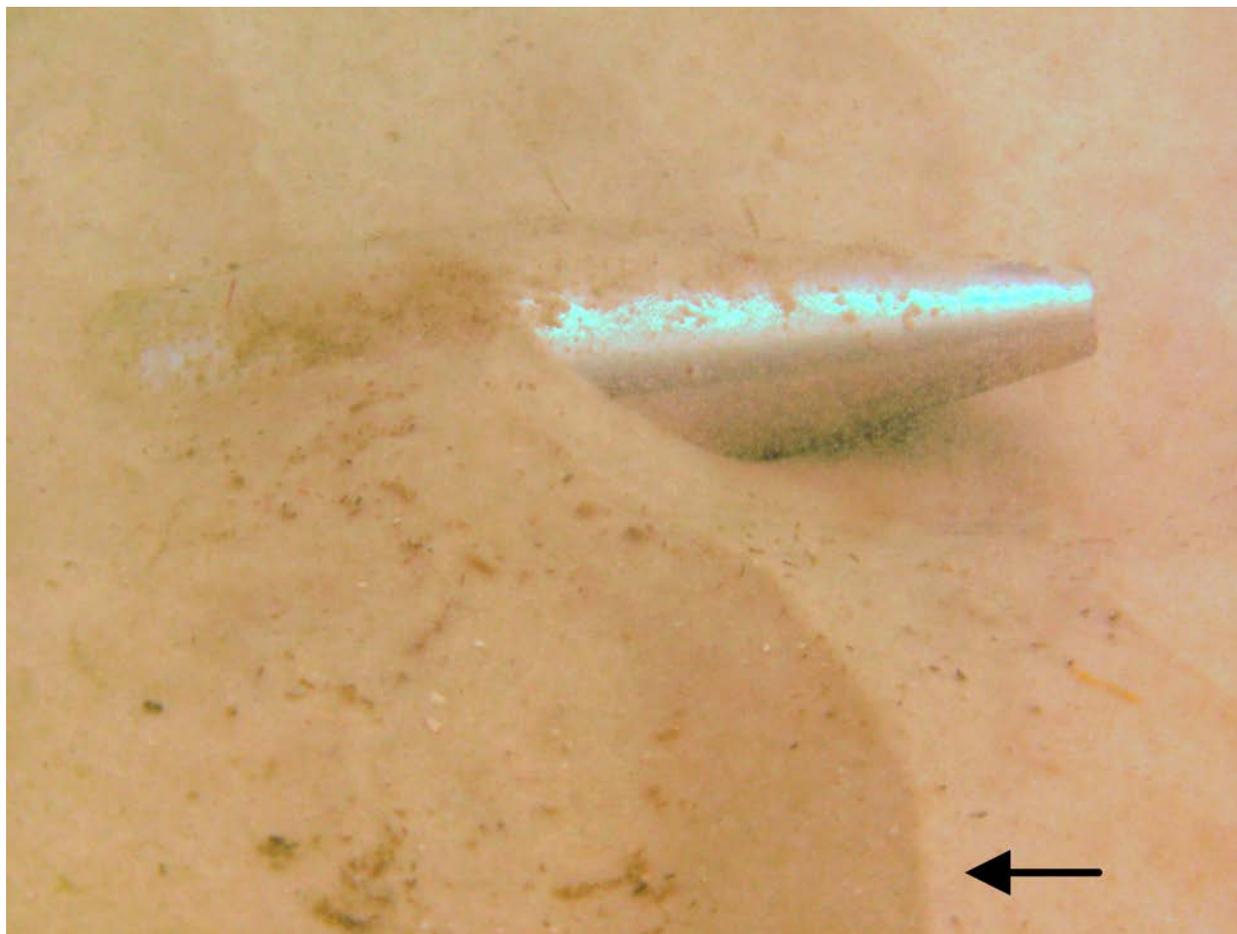


Figure 4. Diver photo of 155 mm replica fabricated from solid aluminum that was partially buried in the crest of a large sand ripple in 8 m water depth after the passage of a storm front in the northern Gulf of Mexico (e.g., far field phenomenology).

5. The Way Ahead and Proposed Timeline

How do we most effectively and efficiently manage the existing risk in the underwater environment? The eventual answer to this question is possibly the best summary for what are the needed products and sub-products of all the researchers and managers participating in the MR program of SERDP & ESTCP. Below we will try to clarify the timeline for some of the most

significant expected contributions of the burial and mobility modeling of munitions in the underwater environment projects to this end.

An important distinction to be made is that the MR program of SERDP & ESTCP is concerned with the management of fields of UXO. However, most often research is focused on individual UXO and their behavior in the environments of interest. The concept of fields of UXO puts the product of the research into a broader context. For example, it is still an open question whether fields of UXO would diffuse or aggregate as a function of the environmental forcing conditions of a particular remediation site. Experiments have yet to be proposed that involve a simultaneously large number of munitions to be deployed in a field relative to each other. Of particular interest, is the potential for large numbers of closely spaced UXO to interact with each other through mechanical contact, vortex generation, and scour burial.

The models being developed here, in particular, the expert system, need to be structured to accommodate planned program improvements as the scientific knowledge base increases. The physics must not be static. For example, re-training of the expert system needs to be part of the model workflow. Additionally, linkages between the expert system and the environmental forcing conditions at remediation sites need to be made stronger and more robust. The predictive models for the environmental forcing conditions will need to be linked directly to the expert system in a larger framework for eventual operational use.

The timeline for moving forward from emphasis on SERDP research to future ESTCP demonstrations in the underwater environment is roughly 3-5 years. Once the structure for predictive modeling of burial and mobility of munitions is in place, validation will occur through demonstration projects under ESTCP. However, demonstrations can only occur after the topics in the previous section have all been adequately addressed. The UXO of interest, with new embedded technologies, will be deployed at a test bed and monitored in connection with a proposed wide area risk assessment framework that links the environmental predictive models with the expert system in a geospatial interface. It is recommended that the group of SERDP & ESTCP funded researchers represented here meet annually to brief progress, share findings, and promote collaboration.

6. References

- Chu, P.C. and C. Fan, Mine-Impact Burial Model (IMPACT35) Verification and Improvement Using Sediment Bearing Factor Method, *IEEE Journal of Oceanic Engineering*, 32(1), 34-48, 2007.
- Chu, P.C., Bushnell, J.M., Fan, C., and K.P. Watson, Modeling of Underwater Bomb Trajectory for Mine Clearance, *Journal of Defense Modeling and Simulation: Applications, Methodology, Technology*, 8(1), 25-36, 2011.
- “Final Report: SERDP and ESTCP Workshop on Technology Needs for the Characterization, Management, and Remediation of Military Munitions in Underwater Environments” (2007), <https://www.serdp-estcp.org/content/download/8054/99435/file/SERDP-ESTCP-UW-Workshop.pdf>
- Jenkins, S.A., Friedrichs, C.T., Rennie, S.E., and J. Calantoni, Capabilities and Future Requirements of Predictive Models of Underwater UXO Burial, Exposure and Mobility, *Report of the Special Working Group of the SERDP-ESTCP Joint Partners Symposium*, 23 March 2011.
- Jenkins, S.A., Inman, D.L., Richardson, M.D., Wever, T.F., and J. Wasyl, Scour and Burial Mechanics of Objects in the Nearshore, *IEEE Journal of Oceanic Engineering*, 32(1), 78-90, 2007.
- Rennie, S.E., Brandt, A., and N. Plant, A Probabilistic Expert System Approach for Sea Mine Burial Prediction, *IEEE Journal of Oceanic Engineering*, 32(1), 260-272, 2007.
- Traykovski, P., Richardson, M.D., Mayer, L.A., and J.D. Irish, Mine Burial Experiments at the Martha’s Vineyard Coastal Observatory, *IEEE Journal of Oceanic Engineering*, 32(1), 150-166, 2007.
- “White Paper: Munitions in the Underwater Environment: State of the Science and Knowledge Gaps” (2010), https://www.serdp-estcp.org/content/download/8547/104693/file/Munitions%20in%20the%20Underwater%20Environment%20White%20Paper_FINAL.PDF
- Wilkins, R.H. and M.D. Richardson, Mine Burial Prediction: A Short History and Introduction, *IEEE Journal of Oceanic Engineering*, 32(1), 3-9, 2007.

Appendix A – Informal Workshop Agenda

Monday June 30, 2014		
0830	Introduction to Informal Workshop and Objectives	Anne Andrews, SERDP
0845	Introduction of Participants	Joe Calantoni, NRL
0850	MR-2227: Underwater Munitions Expert System to Predict Mobility and Burial	Sarah Rennie, Johns Hopkins University
0920	MR-2224: Simple Parameterized Models for Predicting Mobility, Burial and Re-exposure of Underwater Munitions	Carl Friedrichs, VIMS – presented by Calantoni
0945	MR-2411: A Wide Area Risk Assessment Framework for Underwater Military Munitions Response	Todd Holland, NRL – presented by Calantoni
1010	Break	
1030	MR-2320: Long Time Series Measurements of Munitions Mobility in the Wave-Current Boundary Layer	Joe Calantoni, NRL
1100	MR-2319: Continuous Monitoring of Mobility, Burial and Re-exposure of Underwater Munitions in Energetic Near-Shore Environments	Peter Traykovski, WHOI
1130	MR-2410: Large-Scale Laboratory Experiments of Incipient Motion, Transport, and Fate of Underwater Munitions under Waves, Currents, and Combined-Flows	Marcelo Garcia, University of Illinois at Urbana-Champaign
1200	Lunch	
1315	Goals and Expected Outcome of Informal Workshop – Joe Calantoni, NRL	
1330	Breakout Group Sessions: Group 1: Measurements; Group 2: Modeling -Identify major accomplishments/goals/gaps -What is the final product or expected outcome?	
1530	General Discussion Based on Breakout Group Reports	
1630	Adjourn for the day	

SERDP REPORT – INFORMAL WORKSHOP ON BURIAL AND MOBILITY MODELING

Tuesday July 1, 2014	
0830	Morning Networking Session
0845	Recap Day I
0900	Breakout Group Discussions: What is the role/relevance of mobility measurements/modeling in the larger SERDP & ESTCP mission? How do we integrate our results/products with others?
1015	Break
1030	General Discussion Based on Breakout Group Reports
1115	General Group Discussion: Develop Outline for Informal Workshop Report
1145	Lunch
1300	General Group Discussion: The Way Forward for Munitions Mobility Research
1400	Final Comments and Assignments for Writing Informal Workshop Report
1430	Adjourn

Appendix B – List of Attendees

- Dr. Anne Andrews (SERDP & ESTCP)
- Dr. Alan Brandt (Johns Hopkins University)
- Dr. Joseph Calantoni (Naval Research Laboratory)
- Dr. Shelley Cazares (Institute for Defense Analyses)
- Dr. Marcelo Garcia (University of Illinois at Urbana-Champaign)
- Mr. Bryan Harre (NAVFAC Engineering and Expeditionary Warfare Center [EXWC])
- Ms. Katherine Kaye (SERDP & ESTCP Support Office, HydroGeoLogic, Inc.)
- Dr. Robert Kirgan (Army Environmental Command)
- Dr. Blake Landry (University of Illinois)
- Dr. Herbert Nelson (SERDP & ESTCP)
- Dr. Jack Puleo (University of Delaware)
- Dr. Sarah Rennie (Johns Hopkins University)
- Dr. Michael Richardson (Institute for Defense Analyses)
- Dr. Alexandru Sheremet (University of Florida)
- Dr. Peter Traykovski (Woods Hole Oceanographic Institute)
- Dr. Arthur Trembanis (University of Delaware)