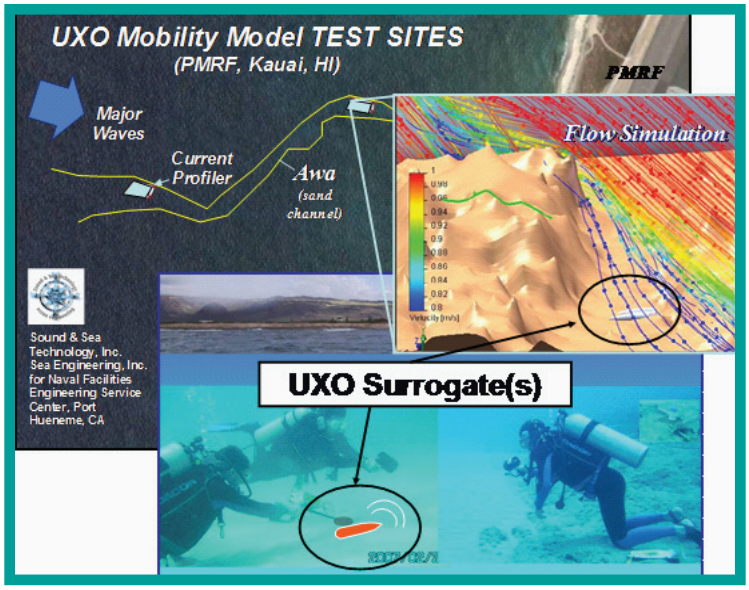
ESTCP
Cost and Performance Report

(MM-0417)



Predicting the Mobility and Burial of Underwater Munitions and Explosives of Concern Using the VORTEX Model

June 2008

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

COST & PERFORMANCE REPORT
Project: MM-0417

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ACRONYMS AND ABBREVIATIONS

ADCP	Acoustic Doppler Current Profiler
AGD	Applications Guidance Document
CNO	Chief of Naval Operations
CONUS	Continental United States
CPE	circular probable error
CRAB	Coastal Research Amphibious Buggy
DoD	U.S. Department of Defense
EPA	U.S. Environmental Protection Agency
ESRI	Environmental System Research Institute
ESTCP	Environmental Security Technology Certification Program
FRF	Field Research Facility
FRTR	Federal Remediation Technologies Roundtable
GPS	Global Positioning System
IM	Interaction Model
LARC	Lighter Amphibious Resupply Cargo
LIDAR	Light Detection and Ranging
MB	megabyte
MBBS	multibeam backscatter
MDT	Mugu Drifter Test
MM	Mobility Model
MMFT	Measurement Method Field Test
NAVFAC	Naval Facilities Engineering Command
NAVFAC ESC	Naval Facilities Engineering Service Center
NESDI	Navy Environmental Sustainability Development to Integration
NOAA	National Oceanographic and Atmospheric Administration
PMRF	Pacific Missile Range Facility
ROI	return on investment
SCM	Site Conceptual Model
SEI	Sea Engineering, Inc.
SERDP	Strategic Environmental Research and Development Program
SST	Sound & Sea Technology
USACE	U.S. Army Corps of Engineers
UXO	unexploded ordnance

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ACKNOWLEDGEMENTS

The Unexploded Ordnance (UXO) Mobility Model (MM) Demonstration/Validation program was funded by the Environmental Security Technology Certification Program (ESTCP). It was conducted by the Naval Facilities Engineering Command Engineering Service Center (NAVFAC ESC), with support from Sound & Sea Technology, CSST. Ms. Barbara Sugiyama and Ms. Alexandra DeVisser, with NAVFAC ESC, were the principal investigators for this effort. The SST program was led by Mr. Jeffrey Wilson. The UXO MM was developed by Dr. Scott Jenkins and Mr. Joe Wasyl of Scott A. Jenkins Consulting. The model was tested and evaluated by Mr. Dennis Garrood, Mrs. Chanda Daly, and Mr. Eugene Keam of SST. The field work was directed by Mr. William Daly and Mr. Ian McKissick of SST. On-site field demonstration support was provided by Mr. Carl Miller, Mr. Ray Townsend, and the staff of the U.S. Army Corps of Engineers (USACE) Field Research Facility (FRF) at Duck, NC. The supporting human Interaction Model (IM) that evaluates probability of human encounters with UXO was developed by Mr. Jeffrey Wilson of SST.

The original UXO MM was developed under the Chief of Naval Operations (CNO) Navy Environmental Sustainability Development to Integration (NESDI) program. The NESDI program is managed for CNO-N45 by the Naval Facilities Engineering Command (NAVFAC). The model upgrades and the field demonstration and validation efforts were funded by ESTCP, with this report prepared by the combined NAVFAC ESC/SST staff.

Technical material contained in this report has been approved for public release.

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

The U.S. Department of Defense (DoD) has responsibility for human safety and environmental stewardship for coastal ranges and for abandoned ordnance unintentionally left underwater as a result of historic military activities. In an effort to address these concerns, the Navy through its Navy Environmental Sustainability Development to Implementation (NESDI) Program funded a program to assess the environmental effects of underwater unexploded ordnance (UXO). The site conceptual model (SCM) developed under this program identified the inability to predict the mobility and burial of UXO underwater as a critical gap in capability. To meet this need, the Naval Facilities Engineering Command Engineering Service Center (NAVFAC ESC) initiated a project to modify the existing vortex lattice, model which is used to predict mine mobility and burial. The new software is called the UXO Mobility Model (MM). By using the MM, it is possible to predict the fate of UXO over the broad range of coastal diversity where UXO is known to exist.

As a supplement to the MM development and validation program, Sound and Sea Technology (SST) and NAVFAC ESC staff developed a human Interaction Model (IM). The IM was adapted from existing Navy models of the interaction of bottom fishing gear with seafloor cables. The IM estimates the probability of human interaction with seafloor UXO.

Identifying the areas and entombment depths likely to contain UXO reduces costs associated with fieldwork focused on physically locating or clearing UXO items. The ultimate goal is to include the MM output data in a risk evaluation model specifically configured to support munitions response programs. Guidelines for using the MM as part of the overall process of analyzing risk of human interaction with UXO are provided in the Applications Guidance Document (AGD) (Wilson et al., 2008a).

The Navy program developed the MM and completed short term, surf-zone validation for just one coastal type. The basic demonstration method was to place a series of surrogate 5-inch 38-caliber rounds at known locations off the coast and track their movement using acoustic pingers or metal detectors and diver tracking systems, while also recording the local current and wave conditions. The observed movement was then compared to the MM predictions. The MM was thereby first calibrated and then validated.

1.2 OBJECTIVES OF THE DEMONSTRATION

The primary objectives of the demonstration were to:

- Calibrate and validate the UXO MM for the two most common geomorphic coastal environments in which DoD UXO is known to exist (trailing edge/East Coast of the continental United States [CONUS] and biogenic reef/tropical islands).

- Perform the calibration and validation steps by matching observed migration patterns of instrumented surrogate UXO samples allowed to move freely under

the influence of the local seafloor conditions in the candidate environments against the movement patterns predicted by the MM.

- Provide potential users a validated MM and IM to assist in the overall evaluation of risks associated with UXO at DoD sites. By providing credible statistical predictions of UXO movement (or nonmovement), reduce costs and improve the quality of remediation.

1.3 DEMONSTRATION RESULTS

The first field demonstration, a trailing edge coast, was conducted at the U.S. Army Corps of Engineers (USACE) Engineering, Research & Development Center, Field Research Facility (FRF), Duck, NC. The demonstration was installed on June 22, 2005. Data were collected at various points over a 22-28 month period. Half the number of UXO surrogates deployed was recovered in April 2007 with the remainder left in place. This first effort was documented in a final field demonstration report (Wilson et al., 2008b).

The second Environmental Security Technology Certification Program (ESTCP) UXO field demonstration, a biogenic reef site, was conducted off the coast of the Pacific Missile Range Facility (PMRF) on the southwestern coast of Kauai, HI. The hardware was installed February 22, 2007, and the effort was completed, with all deployed items recovered, on May 31, 2007. The second field effort was documented in a final field demonstration report as well (Wilson et al., 2008c).

Both demonstrations were fully successful in that all the required data were obtained and the behavior of the surrogates matched the predictions from the MM closely enough to allow calibration and validation of the MM for those coastal environments. Details of the calibration are provided in the field test reports and in the Final Report for the program (Wilson et al., 2008b; 2008c; 2008d).

1.4 IMPLEMENTATION ISSUES

The demonstration program has already addressed various stakeholder or end-user decision-making factors concerning the technology. Before the MM validation was even complete, NAVFAC ESC and SST received several inquiries about possible application of the MM to near-term problems from UXO site managers with the USACE (several districts), the Naval Facilities Engineering Command (NAVFAC), and private contractors supporting the City of Hampton Roads, VA.

As a supplement to the formal documentation of the ESTCP program, the team prepared an AGD (Wilson et al., 2008a). The AGD is the report that the ESTCP guide refers to as a “decision support tool,” a top-level guide to using the MM in the context of comprehensive munitions response efforts. The AGD illustrates how the MM and supporting IM can impact major decisions about UXO. The MM predicts which areas can safely be considered to contain immobile (or fully entombed) UXO and which populations are at risk of moving into areas where they may come into contact with the public. The MM also aids planning for remediation

purposes by indicating how long after a survey UXO will remain where they are found and what areas will stay free of UXO after remediation efforts are complete.

1.5 COST AND PERFORMANCE

The UXO MM is a very cost-effective tool. The cost to use it varies from a few tens of thousands of dollars to a few hundred thousands of dollars, depending on the level of detail required and the area to be modeled. The primary cost is in the acquisition of input data. For basic Mode 1 preliminary studies with desktop data, there is no associated cost for acquiring new data. Where improved bathymetry or other environmental data are required, ocean survey technologies such as light detection and ranging (LIDAR) or multibeam backscatter (MBBS) provide ample detail for a few days of survey work. When more information is required on the actual initial distribution of UXO, those surveys are more expensive to conduct, though improvements in that technology are the subject of many other ESTCP and Strategic Environmental Research and Development Program (SERDP)-funded efforts.

Even when applying the highest levels of modeling, the cost of the MM is likely to be far less than the savings produced by eliminating areas from cleanup requirements and providing assistance to contractors for generating remediation proposals.

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2.0 INTRODUCTION

2.1 BACKGROUND

Sustainable range management and readiness are vital national security interests, yet are subject to increasingly restrictive regulatory oversight and public concern for safety. In addition to range sustainability interests, the DoD has additional responsibility for human safety and environmental stewardship for coastal ranges and for abandoned ordnance unintentionally left underwater as a result of historic military activities. The Navy through its NESDI Program funded a program to assess the environmental effects of underwater UXO. The SCM developed under this program identified the inability to predict the mobility and burial of UXO underwater as a critical gap in capability. To meet this need, the NAVFAC ESC initiated a project to modify the existing vortex lattice model, which is used to predict mine mobility and burial. The new software is called the UXO MM. With MM, it is possible to predict the fate of UXO over the broad range of coastal diversity where UXO is known to exist.

As a supplement to the MM development and validation program, SST and NAVFAC ESC staff developed a human IM. The IM was adapted from existing Navy models of the interaction of bottom fishing gear with seafloor cables. The IM estimates the probability of human interaction with seafloor UXO. Identifying the areas and entombment depths likely to contain UXO also reduces costs associated with fieldwork focused on physically locating or clearing UXO items. The ultimate goal is to include the MM output data in a risk evaluation model specifically configured to support munitions response programs. Guidelines for using the MM as part of the overall process of analyzing risk of human interaction with UXO are provided in the AGD (Wilson et al., 2008a).

The Navy program developed the MM and completed short-term, surf-zone validation for just one coastal type. The ESTCP UXO MM field test program consisted of two major field demonstrations. The first was at the USACE FRF, Duck, NC. The second was at the PMRF, Kauai, HI. The basic demonstration method was to place a series of surrogate 5-inch 38-caliber rounds at known locations off the coast and track their movement using acoustic pingers or metal detectors and diver tracking systems, while also recording the local current and wave conditions. The observed movement was then compared to the MM predictions. The MM was thereby first calibrated and then validated.

2.2 OBJECTIVES OF THE DEMONSTRATION

The primary objectives of the demonstration were to:

- Calibrate and validate the UXO MM for the two most common geomorphic coastal environments in which DoD UXO is known to exist (trailing Edge/East Coast of CONUS and biogenic reef/tropical islands).

- Perform the calibration and validation steps by matching observed migration patterns of instrumented surrogate UXO samples allowed to move freely under the influence of the local seafloor conditions in the candidate environments against the movement patterns predicted by the MM.

- Provide potential users a validated MM and IM to assist in the overall evaluation of risks associated with UXO at DoD sites. By providing credible statistical predictions of UXO movement (or nonmovement), reduce costs and improve the quality of remediation.

2.3 REGULATORY DRIVERS

The effort reported herein addresses the following DoD requirements:

> **Navy Requirements:** 1.I.2.b Improved Marine Sediment/Dredge Spoil Remediation and Decontamination, 1.I.1.g Improved Methods for Removal of UXO, and 1.III.2.n Improved Characterization and Monitoring Techniques for Sediments
>
> **Army Requirements:** A(1.6.a) UXO Screening, Detection, and Discrimination and A(1.6.b) Soil/Sediment UXO Neutralization/Removal/Remediation

These requirements all imply a need for a basic ability to know where UXO is located throughout its life cycle. Even the most optimistic predictions of technology for directly measuring UXO locations through on-site surveys lead to extremely high costs, both because of the amount of area and volume to be surveyed and the considerable evidence that the surveys would have to be repeated frequently to be of value. Therefore, a model to predict UXO movement is essential to any monitoring of UXO and assessment of environmental or explosive safety.

3.0 TECHNOLOGY

3.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

The vortex lattice MM is a three-dimensional, time-stepped, process-based model for the prediction of exhumation, migration, and subsequent burial of UXO by general bed erosion and local vortex scour. Details of the MM and the Fortran code are provided in the Final Report (Wilson et al., 2008d).

The MM is applicable to a wide variety of coastal, riverine, or estuary conditions, from the high water line to beyond the closure depth. The MM was validated for the three major coastal classifications (i.e., collision coastal/West Coast of CONUS, trailing edge/East Coast of CONUS, and biogenic reef/Hawaii). Field validation efforts used surrogate 5-inch 38-caliber projectiles, which is a common UXO size that behaves like larger "cobble" sized seafloor objects. Limited efforts also included 20 mm surrogates, which behave more like small-grain sediment the size of sand. The original Vortex Lattice MM is already validated for larger 500-lb bomb shapes.

3.2 PROCESS DESCRIPTION

For each time step, the MM produces a three-dimensional image of the UXO and the adjacent seabed. The MM accepts forcing from either measurements or forecasts of surface gravity waves, coastal currents, and river discharge or precipitation. The computational methodology for the migration/burial processes is based on the vortex lattice method, which calculates the vortex system shed by the UXO of arbitrary shape. The method of images is used to resolve the ground effects of the vortex system over the seabed, based on a formulation derived from Peace and Riley (1983). The induced velocity of the vortex system acting on the seabed causes both bedload and suspended load scour treated by the ideal granular sediment transport equations of Bagnold (1963) and updated by Bailard and Inman (1979). The reaction forces to the vortex induced velocity field cause migration of the UXO once the moment balance is exceeded. Migration, burial, or exposure by general bed accretion or erosion is accounted for by equilibrium profile changes (Inman et al., 1993) and by accretion/erosion waves (Bagnold, 1963; Inman, 1987). The following modifications to the MM were made:

- Algorithms for calculating the near-field effects on UXO were modified to address the complex tapered shapes.

- The overall algorithm for calculating the far-field effects that drive sediment movement was modified. The sediment movement determines when the UXO is and is not buried, which has a major impact on overall UXO migration. The algorithm for calculating the total shape and size of the critical volume of sediment that is active along a given beach was re-created using thermodynamic balance (Jenkins and Inman, 2002) as the basis rather than the past methods based on Dean's models.

- To support the critical volume analysis, an improved method of calculating the closure depth, the depth beyond which there is no net movement of sediment, was developed and incorporated in the MM.

3.2.1 Processes Represented and Applicable Coastal Regions

The MM is a process-based model that incorporates both regional (farfield) processes and local (nearfield) processes acting within several diameters of the UXO. Farfield processes are those that alter the seabed elevation over length scales that are large in comparison to the size of individual UXOs, usually in response to general erosion or accretion. Nearfield processes are due to the flow disturbance caused by the UXO and affect the seabed elevation by local scour as well as induce hydrodynamic forces that cause the UXO to move.

3.2.1.1 Farfield Processes, Exhumation, and Burial

Farfield processes provide the broad-scale forcing leading to the general bed erosion that exhumes buried UXO. Farfield processes can also cause general bed accretion, ensuring perpetual entombment of buried UXO or accelerating the subsequent burial of exhumed UXO. These processes involve changes in the elevation of the seabed with cross-shore distances of hundreds of meters that may extend along the coast for kilometers (Inman et al., 1993; Inman, 1987). Farfield time scales are typically seasonal with longer periods due to variations in climate. Farfield exhumation and burial mechanics are associated with large-scale littoral cell processes including changes in beach profile, deposition from rivers, sediment loss by turbidity currents, and bottom modification by ice push. These processes vary over a manifold of time scales, including diurnal oscillations associated with tides and sea breeze, inter-annual oscillations associated with summer/winter seasonal change, multi-annual variability and multi-decadal due to long-term climate variability. Because the farfield processes determine the elevation and slope of the seabed on which the nearfield processes operate, the farfield exerts a controlling influence on the nearfield. Hence farfield processes are built in at the top of the MM.

Farfield processes are controlled by the balance between the amount of sediment entering the farfield and the amount leaving. This sediment budget requires the identification of sediment sources and sinks, which will vary with the type of coastline. Some basic types of coastlines have been identified. The Geomorphic Coastal Classification module in Figure 1 selects the relative scaling and assigns the sediment sources and sinks to which a particular UXO site belongs. The classification includes three general tectonic types of coasts with their morphologic equivalents and two types associated with latitudinal extremes: 1) collision coasts with narrow shelves and steep coastal topography resulting from collisions between two or more tectonic plates; 2) trailing edge coasts that are on the stable, passive margins of continents with broad shelves and low inland relief; 3) marginal sea coasts that are semi-enclosed by island arcs and thereby fetch-limited; and 4) biogenic coasts that are formed by fringing coral reefs or mangroves, etc.

Although the relative importance of transport processes varies among coastal types, two processes are always important to UXO exhumation and burial. These are seasonal changes in the beach profile and fluxes of sediment into and out of the UXO environment by accretion/

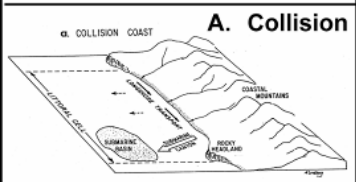
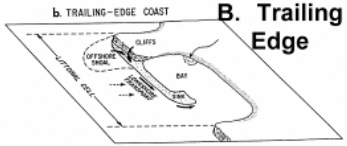
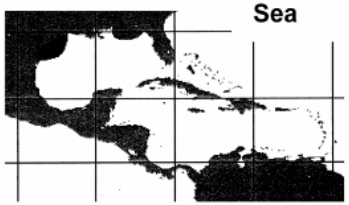
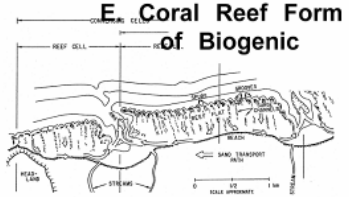
Geomorphic Type	Boundary Conditions					Model Parameters		
	Morphology (Example)	Sediment Source	Sediment Sink	Closure Depth	Littoral Cell Dimensions	Grid Cell	Grain Size	Bed Roughness, η_0
 A. Collision	Narrow-Shelf Mountainous Coastal Bluffs (Cailfornia)	Rivers & Bluff Erosion	Submarine Canyons	15 - 18 m	Longshore: 50 km Cross Shore: 1 - 5 km	Farfield: 70 - 90 m Nearfield: 1 - 4 cm	Beach: 0.2 - 0.3 mm Shelf: 0.06 - 0.10 mm	0.5 - 3 cm
 B. Trailing Edge	Wide-Shelf Plains (Duck, NC)	Headlands & Shelves	Roll-Over Shoals Spit-Extension	10 -13 m	Longshore: 100 km Cross Shore: 30 - 50 km	Farfield: 40 - 80 m Nearfield: 2 - 7 cm	Beach: 0.2 - 0.4 mm Shelf: 0.06 - 0.15 mm	0.8 - 5 cm
C. Marginal Sea 	a) Narrow-Shelf Mountainous (Korea) b) Wide-Shelf Plains (Corpus Christi) c) Deltaic tideless (Mississippi) d) Deltaic tidal (Bangladesh) Wide-Shelf	Rivers & Deltas	a) Canyons b) Beaches & Barriers c) Delta & Shelf d) Delta Islands, flats, canyons	Narrow shelf: 7 - 10 m Wide shelf: 4 - 7 m Delta: 3 m	Longshore: a) 5-10 km b) 100 km c) 5-200 km d) var Cross Shore: a) 1 - 5 km b) 50 km c) 20-80 km d) var	Farfield: 10 - 20 m Nearfield: 1 - 3 cm	Beach: 0.06 - 0.21 mm Shelf: 0.01 - 0.09 mm Delta: .005 - .05 mm	a-d) 0.1 - 1 cm d) sand waves
 E. Coral Reef Form of Biogenic	Coral Reef Island (Hawaii)	Carbonate Reef Material Volcanic Headlands	Pocket Beaches & Awa Channels to the Shelf	Reef Platform	Longshore: ~2 km Cross Shore: 0.5 km	Farfield: 100 - 150 m Nearfield: 1 - 20 cm	Beach: 0.2 - 0.4 mm Shelf: 0.03 - 0.1 mm	Reef Platform ~1 m Offshore 1 - 15 cm

Figure 1. Geomorphic coastal classifications used in UXO MM (Mode 1).

erosion waves. The field demonstrations were conducted in trailing edge and biogenic reef environments. They represent a substantial fraction of all the sites of interest and virtually all the sites with high-energy waves where UXO movement is likely to occur (Table 1.)

Table 1. UXO site coastal classifications.

Coastal Category	Coastline Subcategory	Bay/Estuarine Subcategory	Total
Collision	17%	30%	48%
Trailing edge	22%	9%	30%
Biogenic carbonate	9%	4%	13%
Marginal seas	9%	0%	9%

3.2.1.2 Nearfield Processes, Migration, Scour, and Burial

Nearfield processes occur over length scales on the order of the UXO dimensions and on time scales of a few seconds to hours and are primarily governed by local hydrodynamic forces and scour mechanics arising from the disturbance which the UXO creates in the flow. The UXO and adjacent seabed is subdivided into a set of panels (lattice). The vortex field induced by the UXO is constructed from an assemblage of horseshoe vortices, with a horseshoe vortex prescribed for each panel. This computational technique is known as the vortex lattice method and has been widely used in aerodynamics and naval architecture.

The strength of the vortices is derived from the pressure change over each panel associated with the local wave and current velocity. The release of trailing vortex filaments from each panel causes scour of the neighboring seabed. When viewed in any cross-wake plane, each pair of filaments induces a flow across the seabed that results in scour proportional to the cube of the vortex strength and inversely proportional to the cube of the sediment grain size. This sensitivity of scour to grain size selectively removes the finer grained fraction of the bed material and leaves behind the coarser grained fraction in the scour, depression. The coarse material that remains in the scour hole armors the bed against further scour, thereby slowing the rate of scour burial. Scour burial is a shape-dependent process that varies with the intensity of hydrodynamic forcing and with bed composition and slope.

Because most UXO is bodies of revolution, the burial mechanism proceeds by a series of scour and roll events on a fine sand bottom, whereby the UXO successively scours a depression and then rolls into that depression. In contrast, flat bottom mine-like objects (e.g., MANTA, ROCKAN, etc.) or UXO resting flat-side down bury by scour and slip sequences involving episodic shear failures (avalanches) of the slopes of the scoured depression (Jenkins and Inman, 2002). During these shear failures, the UXO is in a state of sliding friction with the bed and is easily moved by the hydrodynamic forces of waves and currents.

3.2.2 User Requirements

The MM is a Fortran program that will run on a variety of professional-grade laptop or desktop computers. The user must be capable of compiling and running Fortran programs and also needs a general understanding of coastal processes, basic hydrodynamics, and related

ocean engineering technologies. In order to conduct the complete risk analysis, the user must be able to run Environmental System Research Institute's (ESRI) ArcGIS spatial analysis tool and Microsoft's spreadsheet program, Excel, and be familiar with the overall processes described in the AGD (Wilson et al., 2008a). The detailed requirements for software, computer hardware and user skills are described in the User's Manual (Garrood et al., 2008).

3.2.3 Previous Testing of the MM

The NESDI program supported the UXO MM software development, a limited validation test at a single collision coastal site adjacent to Mugu Beach, CA (Wilson, 2004), and a series of Measurement Method Field Tests (MMFT) on the coast of Ocean Shores, WA (Wilson et al., 2005). The Mugu Drifter Test (MDT) used only small-diameter UXO (20 mm rounds and surrogates). It served as a surrogate for UXO sites belonging to the collision coastline sub-category, one of the eight coastal subcategories given in the Geomorphic Coastal Classification system. It validated the expected movement of small UXO in a large, open coastal movement area (the Santa Barbara cell), which tends to move small UXO offshore like sand.

The MMFT at Ocean Shores used only larger UXO (5-inch 38-caliber inert and surrogate rounds). MMFT was a short-term test intended primarily to validate the effectiveness of two measurement methods for tracking UXO movement: physical tethers and acoustic pingers. The tests were conducted for just one to three days each. The test provided a calibration for the part of the MM that addresses the high-energy breaking surf zone, again on a collision coastal beach.

3.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

There are no other known models that predict the full burial, unburial, movement, and reburial cycle of UXO in water. The advantages of having such a tool are as follows:

- Areas in which UXO is buried and will remain so can be positively identified—which can substantially reduce areas of required remediation.

- In areas of intermittent or sustained unburial, it is possible to predict the percent of the time that UXO is exposed to human contact or to other hazardous processes such as corrosion, damage, etc.

- Where UXO is exposed, it is possible to predict the rate and direction of net movement as a function of weather and other local conditions. These calculations help to determine the probability of UXO appearing in adjacent areas outside initial impact zones.

- After obtaining in situ survey of UXO, the MM allows munitions response managers to determine whether the UXO will remain where it was originally found and thereby guide the speed of remediation efforts.

The primary limitations of the MM, as with all computer models, are the quantity and quality of the input data. In general, the MM output statistics are driven by the statistics of (a) the

estimates of original UXO distributions (type, location, burial depth) and (b) the data on past weather conditions (waves, currents). Data on the sediment type and local bathymetry are also critical to the MM accuracy, but they tend to be more deterministic in nature.

To accommodate these variations in data quality, the MM can be run in three modes (1, 2, and 3), depending on the availability of input data. Mode 1 uses "default" data for the environment, given only a general description of the UXO distribution, coastal classification, coarse bathymetry, and wave data from distance references. Modes 2 and 3 use more specific input data, the latter being the model's most detailed configuration that includes the complete modeling of individual UXO items and employing full spatial sampling of the seafloor properties, in situ wave data, and high-resolution bathymetry or imagery (e.g., LIDAR, multibeam backscatter, side scan, etc.).

4.0 PERFORMANCE OBJECTIVES

The performance objectives shown in Table 2 provide the basis for evaluating the performance and costs of using the MM.

Table 2. UXO MM validation program objectives.

Performance Objective	Metric	Data Required	Success Criteria	Results
Qualitative Performance Objectives				
MM proves usable by engineers other than software creators.	Review by selected panel including Navy, Army, and support contractors concludes software is transferable to other users.	Results of attempted MM runs by users other than the software creators	Users other than the original developers can run the MM software successfully.	Yes. Both NAVFAC ESC and SST staff have been able to run the MM software. There is still value to be gained from the MM developer (Scott A. Jenkins Consulting) as new applications arise.
MM provides credible prediction of movement in support of test planning, ops.	Predictions check against general engineering theory and observations at similar sites.	Graphic presentations of predicted and measured movement of surrogates from both field demo sites	Differences between predicted values and measurements are consistent and can be reduced to within 20% or less by calibration.	At both the PMRF and FRF Duck sites, the MM predictions generally agree with complex movements observed for multiple items. All surrogates remained within planned range of measurements.
Quantitative Performance Objectives				
Field demonstration involves collecting sufficient quality data to allow validation of MM.	Tracking movement of surrogates with accuracy consistent with input data and MM computational resolution	Measured position of the surrogates versus time at the field tests (location and depth of burial)	> 50% of surrogates are tracked successfully at each site. Movements are measured within +/-10%.	At Hawaii, 73% of the 168 possible data points in the 6 measurements were successful. 100% of the final 3 measurement sets were successful. Measurements were accurate within 1-2 m (<9% of range).
				At FRF Duck, 92% of 120 data points in the 5 main measurements were successful. Measurements were accurate within 1-2 m (<7% of range). No movement of 20 mm was observed.
Match between predictions and measurements, with coefficients correctable to positive match	Model skill factor (ability to correctly predict surrogate movements and burial)	Measured position of the surrogates versus time at the field tests (location and depth of burial)	R > 0.8	MM validation for FRF Duck, $R_\xi = 0.87$ for movement and $R_h = 0.93$ for burial. For Hawaii, $R_\xi = 0.88$ for movement, $R_h = 0.90$ for burial.

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5.0 SITE DESCRIPTION

The USACE Engineering Research Division, FRF, is located along the northern Outer Banks in Duck, NC (Figure 2). The area in which the demonstration took place is situated just north of the 1840 ft long pier (Figure 3). The PMRF, Kauai, HI, site is located on the southwestern coast of Kauai, HI (Figure 4).

Figure 2. Duck, NC, is approximately 60 miles south of Norfolk, VA.

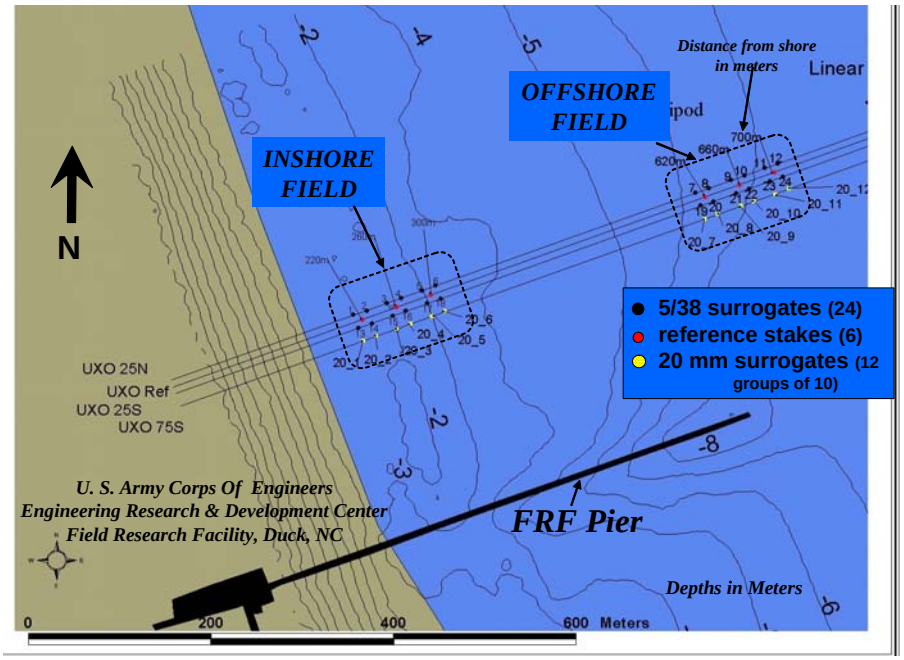

Figure 3. FRF Duck field demonstration configuration.

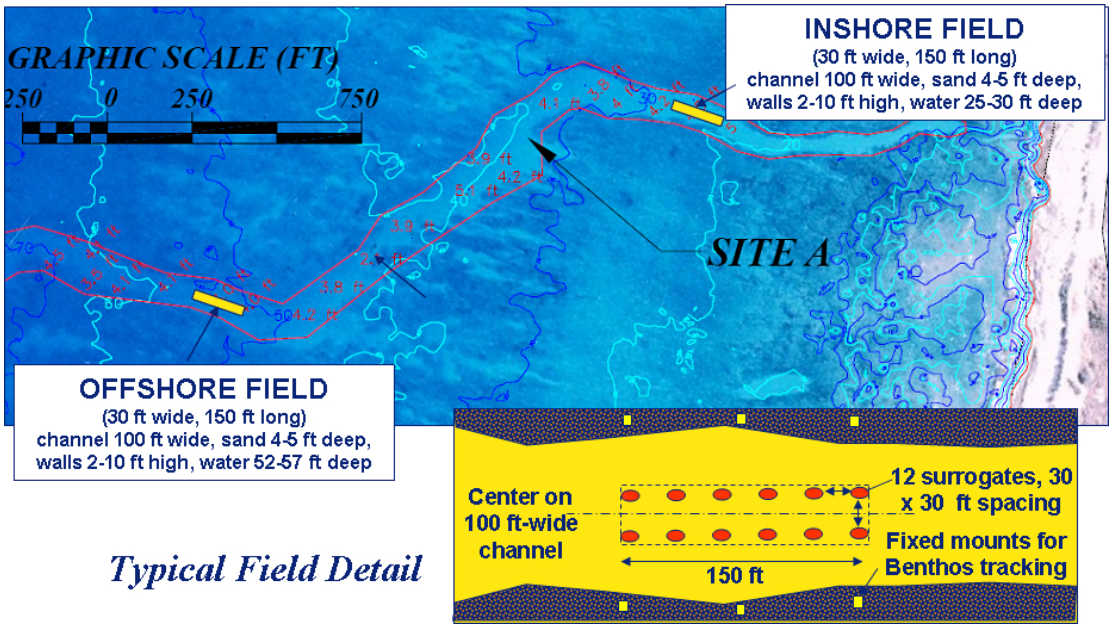

Figure 4. PMRF field demonstration configuration.

5.1 SITE SELECTION

The following criteria were used to select a demonstration site:

- Representative of a major coastal classification. The two most common types of known UXO sites are the trailing edge (i.e., shallow coast, as in East Coast of CONUS), and biogenic reef.

- Controlled access. Areas with limited public access are favored in order to minimize disturbance.

- High frequency of high-energy weather events. Areas which experience frequent storms are conducive to measuring surrogate movement.

- Environmental permits. The ability to meet environmental permitting requirements is necessary.

The two sites for the UXO ESTCP demonstration/validation program were selected primarily because each represents a broad class of coastal environments in which underwater UXO is found. The field demonstration at Duck, NC, validated the MM for a trailing edge coastal environment and the field demonstration in Hawaii validated the MM for a biogenic reef environment. The Navy UXO site percentages shown in Table 1 and the Navy test results greatly supported the ability to validate MM for 50% of all known UXO sites. More importantly, 50% of the UXO sites includes nearly all the sites of known high energy and expected high rates of UXO movement. In the "sheltered coastal bays/estuaries" subcategories, the energy is much lower and movement is primarily related to sediment transport; the human interaction risks are generally lower there as well.

The sites also were attractive because they are either under full military control (i.e., FRF Duck) or have very limited civilian access (i.e., PMRF, Kauai, HI). The Navy test program environmental reviews for the California and Washington state tests have all shown that there is no significant impact from the short-term testing process, which helped to expedite the permitting processes.

Choosing the FRF site clearly matched the requirements since it represents the trailing edge environment and, being just south of Cape Hatteras, it is normally exposed to hurricanes in the summer and nor'easter storms in the winter. It also is very well instrumented and has a long history of test operations similar to those planned for this program. Permits were easily obtained, and the FRF Duck staff members were extremely capable and helpful. Their Coastal Research Amphibious Buggy (CRAB) vehicle and Lighter Amphibious Resupply Cargo (LARC) vessel provided optimal support for installing, monitoring, and recovering the demonstration items over the many months of the effort.

The Hawaii site selection process took a lot longer since more than one possible site was identified. The PMRF site was eventually approved and it afforded the team with a location representative of many typical biogenic reefs, along with rugged bathymetry, wandering sand channels (awas), and heavy winter storm waves. Fortunately, LIDAR data were available; otherwise, the MM would not have been run in its most intensive mode, Mode 3, to properly account for the awa formations. All Hawaii field operations were conducted by Sea Engineering, Inc. (SEI), whose divers worked from small ocean craft.

5.2 DEMONSTRATION SITE HISTORY

FRF is an active research site since their personnel maintain a comprehensive measurement program even during severe storms when significant coastal change occurs. Their long-term monitoring program of the coastal ocean includes waves, tides, currents, local meteorology, and resultant beach response. Divers and small craft are used in various tests and the beach is profiled by the CRAB on a weekly basis. The site is used by USACE and a variety of educational institutions; the primary impact of FRF's busy operations schedule on the demonstration was the occasional schedule conflict with divers and equipment for monitoring.

PMRF also is heavily used as a test facility, though most of the activity takes place on land. The beach area is used by recreational surfers and fishing boats that do frequent the area, but none of those activities had any impact on the demonstration. SEI divers were able to work whenever the weather allowed, which was most of the time.

5.3 SITE GEOLOGY

The FRF site is a classic trailing edge coastal geomorphic environment, as defined in Wilson et al. (2008c). The site is characterized by a shallow, relatively flat seafloor extending several miles offshore and is covered by frequently shifting sands.

The PMRF site is categorized as a typical biogenic reef. The area is composed of hard rock and coral, with awa (sand channels) cutting through it.

5.4 MUNITIONS CONTAMINATION

For diver safety reasons, these sites were chosen because they are environmentally similar to many UXO sites but have no known underwater ordnance located there.

6.0 DEMONSTRATION DESIGN

6.1 CONCEPTUAL EXPERIMENTAL DESIGN

The two field demonstrations conducted are described in detail in Wilson et al. (2008b; 2008c). The demonstration hardware, general positioning of the samples, and monitoring methods were essentially the same for both sites. At each site, 24 instrumented surrogate 5-inch 38-caliber projectiles (Figure 5) were installed and their movement monitored. The Inshore Field of 12 was placed in the normal area of breaking waves (the surf zone). The Offshore Field of 12 was placed at or near the closure depth, where wave effects reached seafloor only during major storms. At FRF Duck, several groups of uninstrumented 20 mm surrogates were also placed alongside the two fields.

Figure 5. Surrogate 5-inch 38-caliber projectiles used in the MM field demonstrations.

The primary difference between the sites was the environment. At FRF, the bottom was composed entirely of sand, and the beach slope was shallow in slope with a moving inshore berm and sand waves that propagated parallel to the beach. The Inshore Field was in approximately 6-10 feet of water and the Offshore Field was in 20-30 feet of water. At PMRF, the bottom consisted of hard coral reef with an awa (sand channel) meandering through it. The surrogates were placed on the shallow sandy bottom of the awa, with the Inshore Field in approximately 20-30 feet of water and the Offshore Field in 50-60 feet of water. Figure 3 and Figure 4 show the two site configurations relative to shore.

At FRF Duck, the surrogates were placed directly from the CRAB vehicle (Figure 6). The lowering line was so straight that the CRAB Global Positioning System (GPS) position was used as the “installed” location for each surrogate. The site was monitored by current profilers and wave monitors that were part of FRF. The beach was profiled weekly. At PMRF, SEI installed an Acoustic Doppler Current Profiler (ADCP) at the Offshore Site to directly monitor the incoming waves.

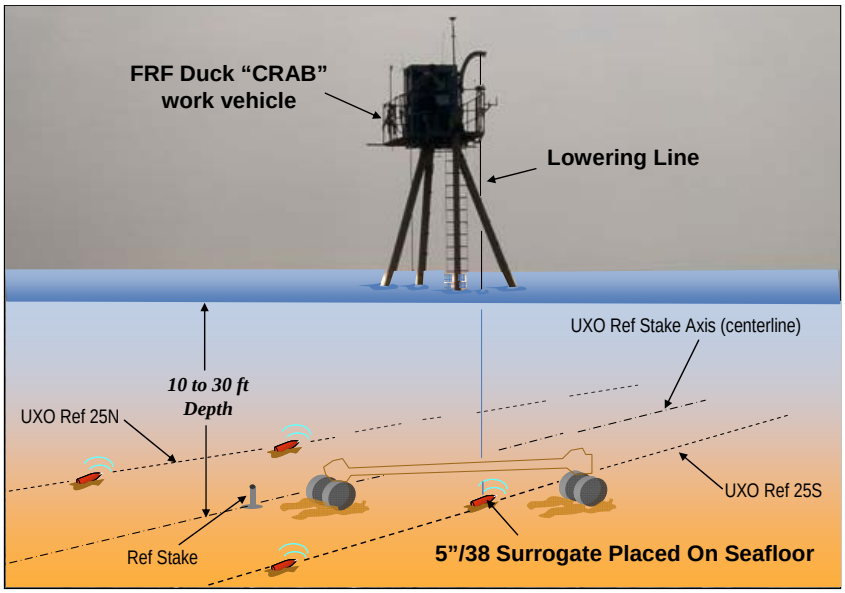

Figure 6. FRF's CRAB acted as a platform for UXO surrogate deployment.

At both sites, divers collected several grab samples of the surface sediments that were then tested for grain size distribution, material characteristics, etc. The measurement process for monitoring the location of the surrogates is shown schematically in Figure 7. The surrogates each had pingers mounted in the tip. Divers located the pingers with handheld acoustic receivers, which were supplemented by using metal detectors for finding the final location. The divers then used the received signals from two or more Benthos acoustic tracking transponders to fix the position of each surrogate within the field. The Benthos transponders were mounted on driven stakes at the FRF site, and on marked points on the sides of the awa in the PMRF demonstration. The acoustic tracking system had a resolution of approximately 1-2 m, which is just slightly greater than the length of the surrogates. The system was calibrated with tape measurements, which all fell within a few inches of the center of the circular probable error (CPE) for the acoustic measurements.

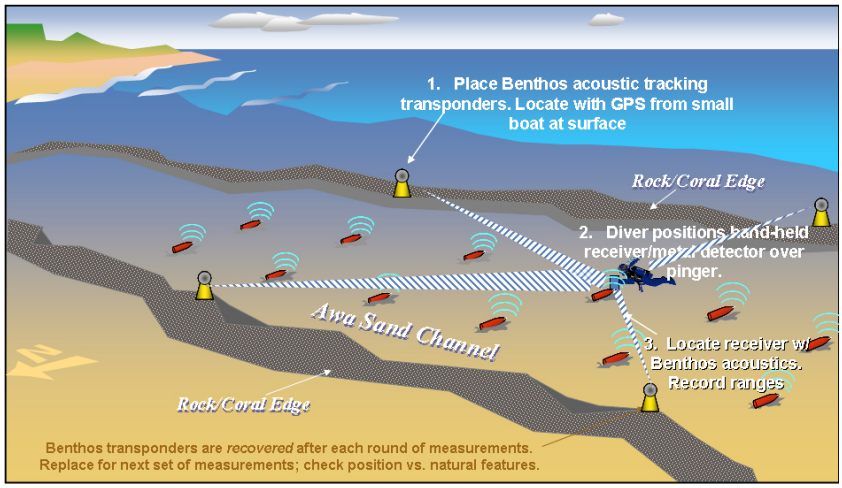

Figure 7. UXO MM Field Test surrogate location monitoring method.

6.2 SITE PREPARATIONS

The primary pre-demonstration effort was the Navy program that developed the MM itself and conducted the initial short-term validation tests at Point Mugu, CA, and Ocean Shores, WA. In addition, there were site visits and preliminary MM analyses performed to aid in the planning of the field tests.

6.3 SYSTEM SPECIFICATIONS

The main hardware for the UXO field demonstrations was the surrogate 5-inch 38-caliber projectiles. They were cast from plastic with a steel core so they represented the correct shape and weight. They were equipped with small Sonotronics acoustic pingers in the nose to facilitate locating them even when buried. Sonotronics underwater acoustic receivers were used to guide divers to the location of the surrogates during each round of measurements. When the surrogates were buried, handheld metal detectors were used to refine the diver's position within less than 1 m. The diver's location in the test field was then determined by ranges from two or more Benthos acoustic transponders located at fixed points in or near the field.

The surrogates are shown in Figure 5. For further details regarding the test hardware, refer to the two separate Field Demonstration Reports (Wilson et al., 2008b; 2008c).

6.4 DATA COLLECTION

6.4.1 FRF Field Demonstration Operations

The first field demonstration, at a trailing edge coast, was conducted at the USACE Engineering, Research & Development Center, FRF, Duck, NC. The demonstration was installed on June 22, 2005, and data were collected at various points over a 22-28 month period. The offshore field UXO surrogates were recovered in April 2007. Weather, FRF operations schedule conflicts, and equipment difficulties thwarted plans to recover the inshore field surrogates throughout the remainder of 2007; specific retrieval actions are planned for FY08. The effort was documented in detail by Wilson et al. (2008b).

6.4.2 PMRF Field Demonstration Operations

The second ESTCP UXO field demonstration, at a biogenic reef site, was conducted off the coast of the PMRF on the southwestern coast of Kauai, HI. The demonstration was installed February 22, 2007, and the effort was completed and the hardware recovered on June 27, 2007; this work is documented in a separate report by Wilson et al. (2008c).

Both demonstrations were fully successful in that all the required data were obtained and the behavior of the test items matched the predictions from the MM closely enough to allow calibration and validation of the MM for those coastal environments. Details of the calibration are provided in the field demonstration reports and in the Final Report (Wilson et al., 2008d).

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7.0 UXO MOBILITY MODEL CALIBRATION AND VALIDATION PROCESS

The process by which software like the MM is adjusted so that it provides an accurate prediction of UXO behavior involves two steps. The first step is calibration. In the calibration step, the results of a given set of data are compared against the MM predictions and the MM is adjusted so that the MM predictions match up to the field data as closely as possible. In comparing the data sets, the difference between each recorded data point and the corresponding predicted value for that surrogate is calculated. For each surrogate at each measurement, there is a predicted and measured value of location with respect to the previous position (x, y), depth (z), and orientation (α). Standard computational algorithms are then applied to calculate the average difference, the mean difference, and the standard deviation of all the differences measured.

The second step is validation, during which the MM is used to predict the behavior of a second set of field demonstration data. In the best case, the information serves as a second set of data from the same demonstration conditions; therefore, this is the method that was used for MM validation. The process was repeated to validate that the "as-adjusted" MM does work for the second set of data.

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8.0 PERFORMANCE ASSESSMENT

8.1 PERFORMANCE DATA

The detailed performance data for the two field demonstrations and the resultant calibration of the MM are provided in the two Field Demonstration Reports and the Final Report (Wilson et al., 2008b; 2008c; 2008d). The two demonstrations each successfully involved installing and monitoring the movement of 24 x 5-inch 38-caliber surrogate projectiles. The field demonstration data (observed movements) and the predicted movements from the MM simulations are shown together in Figure 8 and Figure 9. Figure 8 shows the results for all surrogates at PMRF test sites, February 13 –June 27, 2007. Figure 9 shows the results for all 5-inch 38-caliber surrogates, Rounds 1-4 at FRF, Duck, NC (June 2005 – February 2006).

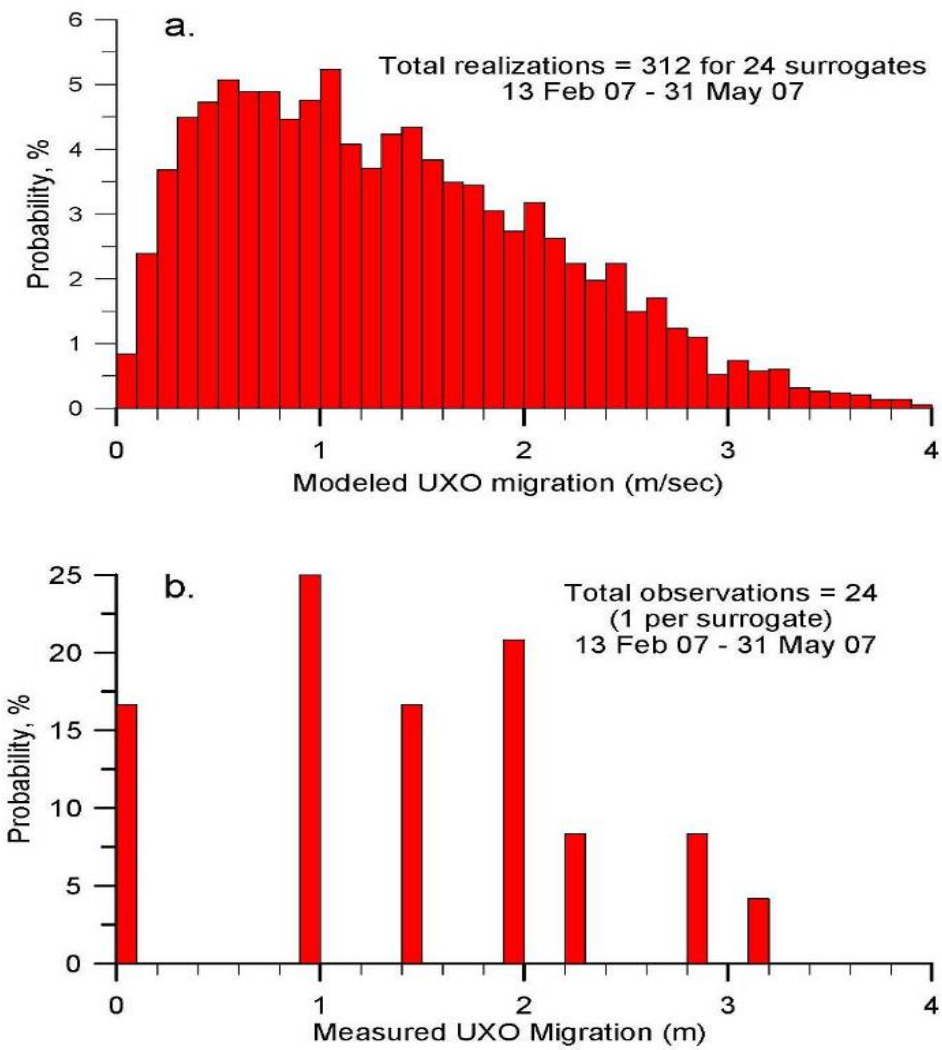

Figure 8. Statistics of MM predictions versus measured movement (PMRF).

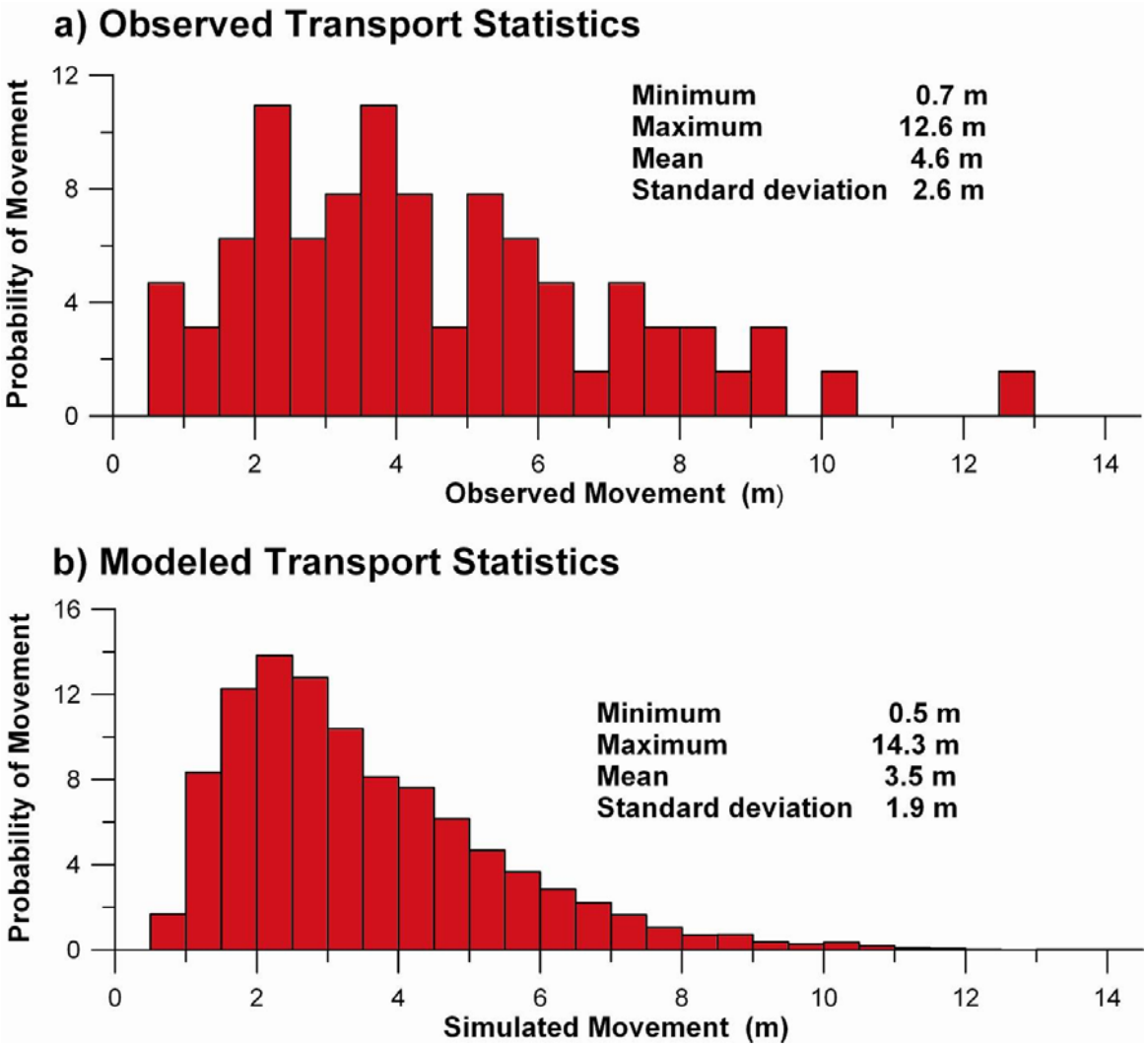

Figure 9. Statistics of MM predictions versus measured movement (FRF).

8.2 PERFORMANCE CRITERIA

The primary metric for success of each field demonstration was collection of data on the movement of all or most of the UXO surrogates and documentation of the environmental conditions that caused those movements. The primary metric for success of the UXO MM validation effort is that the observed movement matches the predicted movement well enough to allow calibration and validation of the MM (Table 3).

Table 3. UXO MM validation performance criteria.

Performance Criteria	Criteria Description	Primary or Secondary
MM proves usable by engineers other than software creators.	MM software studied and exercised by NAVFAC ESC and SST staff.	Primary
Field demonstrations collect sufficient quality data to allow validation of MM.	Movements measured and data recovered from at least 50% of large surrogates and 10 % of the 20 mm surrogates.	Primary

Table 3. UXO MM validation performance criteria (continued).

Performance Criteria	Criteria Description	Primary or Secondary
MM validation shows good match between predictions and measurements, with coefficients correctable to positive match.	Either R or r-squared >0.8 at each site	Primary
MM provides credible predictions of movements in support of test planning.	MM used for each site to predict movement in planning tests. Resultant movement stays within bounds of test.	Secondary

Specifically, the UXO MM itself was validated by the standard criteria used for software simulation validation. There are two commonly used metrics for validating MM performance in a quantitative manner. These are the skill factor "R" and the coefficient of determination "r-squared." The predictive skill factor R of the MM solutions for migration distance, h, is measured by the following estimator adapted from the mean squared error

$$R_{\xi} = 1 - \frac{1}{N\hat{\sigma}_i}\left\{\sum_{1}^{i=N}\left[\hat{\xi}(i) - \xi(i)\right]^2\right\}^{1/2} \tag{1}$$

where $\hat{h}(i)$ is the measured migration distance for i = 1, 2...9 temporal observations, h(i) is the predicted migration distance for time, i, and σ_i is the standard deviation of all observations over the period of record. The coefficient of determination, r^2, is used as a measure of predictive skill for the migration parameters (distance and direction) and is calculated from the usual form

$$r^2 = \frac{SSe}{SSe - SSr} \tag{2}$$

where SSe is the residual sum of squares given by the sum of the squares of the difference between the predicted and observed values, and SSr is the regression sum of squares given by the sum of the differences between the average of all observed values and the predicted value at each time, i.

Both are based on the mean-squared variation between measured migration distance and predicted migration distance. For the MM to be of merit, it must at least be capable of achieving a value greater than 0.5 for either R or r-squared. If the MM can do better than R > 0.8 or r-squared > 0.8, then it is considered to be a highly predictive model. A perfect model achieves R = r-squared = 1.0.

8.3 DATA ASSESSMENT

As is normal for at-sea operations, there were a few erratic or missed data points in the monitoring process. At FRF, some of the points were missed because surrogates were buried too deep at that time, or because weather closed in. At PMRF, on one occasion the measurements were offset by one number because a diver mistakenly took a fix on some other buried metal

object. However, 70 to 90% of all data were consistent so outlying or missing data points did not obscure the overall accuracy of the validation process.

From visual comparison of the shapes of the distribution functions for measured versus predicted movement at both PMRF and FRF—and from the fact that the r-squared comparison is 0.87 to 0.93 for all the data sets—it is clear that data collected in these tests were credible and that the MM provides predictions that are adequate for engineering analysis of UXO sites. The results of the MM are limited only by the statistics of the weather data and the original estimates of UXO distributions.

8.4 TECHNOLOGY COMPARISON

There is no alternative technology at the present time. No other comprehensive software model has been identified that directly models the unburial, migration, and reburial of UXO throughout its life cycle. The only other alternative is to simply not use the MM at all. That would imply either greater assumed risk (where there is no possibility of knowing whether or not the remediation will continue to be effective), or greater cost (the case in which a much larger area is restored)—or both.

9.0 COST ASSESSMENT

9.1 COST MODEL

Per the Federal Remediation Technologies Roundtable (FRTR) *Guide to Documenting and Managing Cost and Performance Information for Remediation Projects* (U.S. Environmental Protection Agency [EPA] 542B 98-007, Oct 98), "The total cost for an application should not include other project phases/activities, such as preliminary assessment/site investigation, remedial investigation/feasibility study, remedial design, or post-closure surveillance and long-term monitoring." Since the UXO MM is a basic tool to support all the "other project phases/activities," the cost structure of this section will not include most of the items in the standard format that pertain to the actual remediation process.

The operational costs of using the MM and associated IM are substantially less than the costs that were required to develop and validate the two models. The primary cost elements for using the MM, in generally descending order, are listed as follows:

- Data acquisition (e.g., climatology, bathymetry, seafloor conditions, human use activities, UXO history, and distribution). The costs can be minimal if the site is already well documented, though it can be as much as several hundred thousand dollars for each small site if in situ surveys are required.
- Data formatting and processing for use (i.e., gridding bathymetry, deriving UXO population values, etc.) can incur as much as a few months of labor.
- MM computer operations, which are typically on the order of less than a few weeks of labor.
- Report development.
- Customer liaison.

Since the MM is applied in steps (Mode 1, 2, 3 as required), the total cost of using the MM is controlled by the level of detail required and by the site-specific results obtained as the analysis proceeds. The actual costs of the MM development and validation are provided here for reference. Then example estimates of costs for various levels of site analysis are provided.

9.1.1 Development and Validation Costs

The Navy program that developed the UXO MM and provided the initial limited validation started in December 2002 and concluded in December 2005. The entire ESTCP UXO MM validation program started in June 2004 and concluded in June 2008. The program spanned 5 years and the total expenditure was approximately $1,795,750. The ESTCP investment was approximately $1,278,000.

Table 4 summarizes the program costs. The investment was divided between the MM development work (28%) and the field validation effort (72%).

Table 4. UXO MM program cost summary.

	Navy	ESTCP	Total
MM Development			$498,375
FY02-FY04	$143,375		
FY05-FY08		$355,000	
MM Validation			$1,297,375
Point Mugu Test	$119,188		
MMFT	$255,188		
FRF Duck, NC, Demonstration		$404,320	
PMRF Kauai, HI, Demonstration		$433,320	
Example Application Analysis		$85,360	
Totals	**$517,750**	**$1,278,000**	**$1,795,750**

9.1.2 Costs to Apply MM at Full-Scale Sites

The costs to apply the MM at full-scale sites are separated into three phases of analysis. The detailed process of applying the MM to a full-scale site is described in Wilson et al. (2008a).

9.1.2.1 Mode 1 Screening Analysis

The first phase uses only Mode 1 of the MM. The inputs are all existing data available from a "desktop" study. Default values are used for many of the MM inputs, based on the general coastal type. The primary purpose of the Mode 1 analysis is to determine areas that are not at risk of human exposure to UXO. Table 5 shows an example cost estimate for a basic Mode 1 screening analysis of a typical UXO site. Note that "site" in this context means a relatively small, contiguous area of UXO with dimensions in the order of a few kilometers, such as a small bay, a firing range, etc. Estimates for larger sites, such as an entire island, a major coastline, etc. are developed as multiples of single sites. The assumptions made in this cost estimate are as follows:

- UXO site manager liaison provided via NAVFAC.
- Analysis performed by support contractors (engineers, computer analysts).
- UXO site managers have Mode 1 level data available, including:
  - General estimate of history of UXO type and distribution
  - Basic bathymetry (National Oceanographic and Atmospheric Administration [NOAA] charts or past local surveys)
  - Defined areas of responsibility (boundaries)
  - Summary of type and location of human use (fishing, recreation, dredge, etc.)
- Initial analysis performed without travel (no site visits).
- Baseline site is a single section of coastline (small bay, offshore from a firing range, etc.).
- Mode 1 phase lasts about 3-6 months.

Table 5. Nominal cost of Mode 1 screening analysis of a single UXO site.

Mode 1 Screening Analysis	
Initial contact, problem definition, liaison	$20,000
Preliminary screening (set up ARC GIC, plot areas of use, define closure depth)	$20,000
Mode 1 analysis of UXO movement at selected points in risk areas (no model modifications)	$30,000
Preliminary analysis of risk of human interaction	$8000
Initial report and recommendations	$8000
Program management	$10,000
Mode 1 Total	**$96,000**

9.1.2.2 Mode 2 Detailed Analysis

The Mode 2 analysis is only conducted on those parts of the site that are not clearly shown to be low risk by the Mode 1 analysis. Mode 2 requires input data for the local environmental conditions that are not normally available for UXO sites. The costs to apply the MM at full-scale sites varies considerably with the size and location of the site (area to be modeled, cost of data to be collected), complexity of the bathymetry, level of human use, etc. Table 6 provides an example cost estimate of a Mode 2 detailed analysis.

Table 6. Estimated cost of Mode 2 detailed analysis.

Mode 2 Detailed Analysis	
Detailed Mode 2 phase program plan	$10,000
Bathymetry survey (LIDAR or MBBS)	$200,000
On-site sediment sampling and ADCP (four seasons)	$95,000
Human use surveys (fishing, boating, diving, etc.)	$30,000
Update Mode 1 ARC GIS and data sets	$15,000
Mode 2 Analysis of UXO movement at selected points in risk areas	$50,000
Updated analysis of risk of human interaction	$12,000
Mode 2 report	$12,000
Program management	$35,000
Total	**$459,000**

9.1.2.3 Mode 3 Enhanced Analysis

Mode 3 adds the final input detail of enhanced estimates of the UXO initial distribution. Since that is the most expensive (and potentially dangerous) data to collect, it is only added to the process when the desktop data on UXO distributions are not credible (because of age, inconsistencies, etc.) and either (a) there is clear evidence of substantial risk of human interaction or (b) large-scale UXO movements are predicted that need more accurate estimates. Table 7 shows an example estimate of the costs of this additional Mode 3 enhanced analysis phase. The assumptions for a Mode 3 cost estimate are as follows:

- Mode 1 and 2 previously completed
- Mode 3 only used for cases of high risk, or if UXO data are questionable
- UXO site manager liaison provided via NAVFAC
- Analysis performed by support contractors (engineers, computer analysts)

- Mixture of means used to develop UXO distribution baseline:
  - Impact analysis (historical firing records plus physics of impact)
  - Analysis of previous bottom imagery to locate UXO exposed on the surface
  - New visual searches of seafloor (i.e., ROV, towed fish, divers)
  - New acoustic surveys (i.e., imagery, sub-bottom)
  - Magnetometer surveys
- Costs vary considerably with size and location of site, and type of UXO
- Mode 3 phase is takes approximately 12 months in duration beyond Mode 2 phase (6 months survey, 6 months analysis).

Table 7. Mode 3 enhanced analysis cost estimate.

Mode 3 Enhanced Analysis	
Detailed Mode 3 phase program plan	$5000
Impact analysis (historical firing records plus physics of impact)	$8000
Analysis of previous bottom imagery (for surface UXO)	$10,000
New visual searches of seafloor (remotely operated vehicle [ROV], towed fish, divers)	$200,000
New acoustic surveys (imagery, sub-bottom)	$200,000
Magnetometer surveys	$50,000
Run Mode 3 simulations (updates Mode 2 results at key points). Estimate half-life of UXO survey data versus remediation schedule.	$30,000
Updated analysis of risk of human interaction	$12,000
Mode 3 report	$12,000
Program management	$50,000
Total	**$577,000**

9.2 COST DRIVERS

Note there are essentially no required annual costs for this MM. The software does not require updates since it is written in Fortran. Both the commercial ABSOFT and the freeware GNU compilers have been used, and the computer resource required is a standard, professional-grade laptop or desktop unit; see the User's Manual (Garrood et al., 2008) for details.

As with any software model that predicts a hardware system response to environmental forcing functions, there are two primary costs in using the MM:

1. Collecting data on the initial hardware configuration
2. Collecting historical data from which to predict the environmental forcing functions.

The cost of actually running the MM itself is very low (typically a few days of engineering labor). The MM runs on a typical high-end engineering desktop computer, so there is no computer time cost. A simulation of UXO migration and burial for a 60-day period using the coarsest time step of 6 hours produces 136 megabyte (MB) of output for a migration burial solution. For the full complement of solutions at 1-hour time steps with shifted gridding for small caliber munitions, the storage memory requirement is estimated to be roughly 540 MB using the

present equation solver based on vortex lattice panels. On a 500 MHz desktop PC, run time is presently 5 min/time step. On a more advanced platform such as an SGI Octane with approximately 2 GB and 8 CPUs, the run time is approximately 1 hour for a 60-day simulation or 15 sec/time step.

In the case of the UXO MM, collecting data to establish the initial configuration of the hardware (distribution of UXO) is likely the most expensive task. That is because at most sites there are only limited records of the UXO distribution, particularly in water. Also, much of the UXO has been in place for many seasonal cycles and is likely not where it originally landed, or in the original state of burial. Therefore at least some limited in-water surveys would be beneficial to provide a credible baseline to start the MM. Given the limited state of the art of UXO location technology, the size of the areas to be surveyed, and the generally high day rate costs of at-sea operations, it is likely that several tens of thousands of dollars would be required for even a minimal sampling survey. A more credible survey could cost several hundred thousand dollars. Fortunately, the MM itself can be used as a what-if advisor to help focus the survey. The MM can be applied to the various sub-environments of a given area of interest to determine in what areas UXO would be subject to unburial and movement if it does exist there. Only those areas would then need to be surveyed.

The second cost item is the collection of data to define the environmental parameters. Fortunately, most sites already have a historical data base for the primary environmental forcing function—weather. The added costs that might be incurred would be in collection of data on the seafloor sediment types and local sediment sources (e.g., rivers, etc.). Typically a few tens of thousands of dollars per site would provide the key data required to support the MM.

The primary cost drivers in using the MM all relate to data collection efforts. The costs for a site could be as little as $\approx$ \$96,000 for a basic Mode 1 screening to as much as \$1 million or more for a full Mode 2-3 analysis of a complex site with high risk conditions.

9.3 COST BENEFIT

There are no other available computer models to which the MM can be compared to determine competitiveness. The most instructive comparison is the cost of applying the MM versus the potential savings in remediation efforts.

In any event, the cost of using the MM to define areas of high risk will be small compared to alternative approaches such as sweeping the total area of possible UXO contamination, which can easily cost many tens of millions of dollars per site. As of this writing, the MM is also the only tool that allows credible analysis of sites to be conducted to verify that risk either is already at an acceptably low level, and therefore does not require clean up costs, or to set the depth and area of cleanup so that it covers the entire risk area and avoids the need to sweep the area again later if adjacent UXO migrate into the swept area after cleanup. Also, analysis at the Mode 1 level reduces the need for Mode 2 data collection, and, in turn, Mode 2 reduces need for Mode 3 to be conducted.

The return on investment (ROI) from using the MM is shown in the Final Report to be on the order of 1000 or more. In the worst case (Mode 3 analysis), the break-even point, or ROI = 0, occurs when MM usage saves just \$3 million, which is 0.00928 x worst case costs (less than

0.1%); this is only 0.06 km^2, or an area of seafloor approximately 245 x 245 m^2 (one football field per site).

Clearly, the cost to use the MM will virtually always be much less than the savings it produces in reduced area requiring survey and remediation.

10.0 IMPLEMENTATION ISSUES

10.1 COST OBSERVATIONS

The key factors that affect costs for the UXO MM are the availability of site data (versus the cost of conducting new surveys), the total size of the site, and the complexity of the environment (bottom roughness and variability, UXO population variability, number of different human uses, etc.). The basic differences in sites that create the basic geomorphic coastal classifications are described in the Final Report. They include bottom types, including such data as slope and sediments, and general wave action. The primary way to reduce costs is to make maximum use of available site data and follow the three-step process to reduce the area of study as much as possible for each level of analysis.

10.2 PERFORMANCE OBSERVATIONS

The UXO MM met all performance objectives, that is, it correctly describes the behavior of the assigned range of UXO in response to given inputs taken from real site data. It is validated for the primary coastal classifications of interest. It has been run by several different engineers at two different contractors and at the NAVFAC ESC.

10.3 SCALE-UP

There are no technical issues in moving up from the field test demonstrations to full-scale sites. Analyses of large sites are simply a series of analyses of individual example UXO at selected points in the actual site. The analysis of a large site would require more time, with the schedule measured in terms of weeks of labor rather than in hours.

10.4 OTHER SIGNIFICANT OBSERVATIONS

As of this writing, no additional factors are identified that can affect the implementation of this technology. As a wealth of MM data is assembled from efforts similar to this, factors may arise that may be used to advance the MM process; therefore, modifications can be made at that time.

10.5 END-USER ISSUES

The primary end users for this technology include the operators and managers of the 23 identified Navy UXO sites, as well as the dozens of other Army UXO sites. The MM also will be used by higher level administrative organizations such as Navy Regional Commands and Systems Commands in the development of environmental programs, decisions regarding investment in new UXO cleanup technology, etc. The Army has similar requirements. No Air Force or Coast Guard requirements have been identified at this time.

There are no procurement issues associated with this software. It is government-owned and can be copied for government use. It is likely that contractors bidding on UXO surveys and cleanup contracts will be given the output from the MM by NAVFAC ESC personnel. There is no known commercial application for the software beyond supporting military UXO planning and risk mitigation.

10.6 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

The application of the UXO MM itself requires no environmental permits, as there is no field activity in the modeling process. The acquisition of survey data would require standard permits for operation of aircraft or vessels with multibeam sonars, but those are standard commercial operations with very low environmental impact. Collection of bottom samples by divers, use of ADCP instruments, etc. for site monitoring would fall in the same general category.

The UXO MM has been validated by this ESTCP program, and it has no competitor technology to support munitions response operations.

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APPENDIX A

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