Technical Report CERC-93-7
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Waterways Experiment Station

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Cooperative Laboratory and Field Study to Investigate Effects of Wave and Current Action on Dual-Rocket Distributed Explosive Array Deployment

by Jimmy E. Fowler, William Birkemeier,
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Coastal Engineering Research Center

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Prepared for Department of the Navy, Indian Head Division

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Final report

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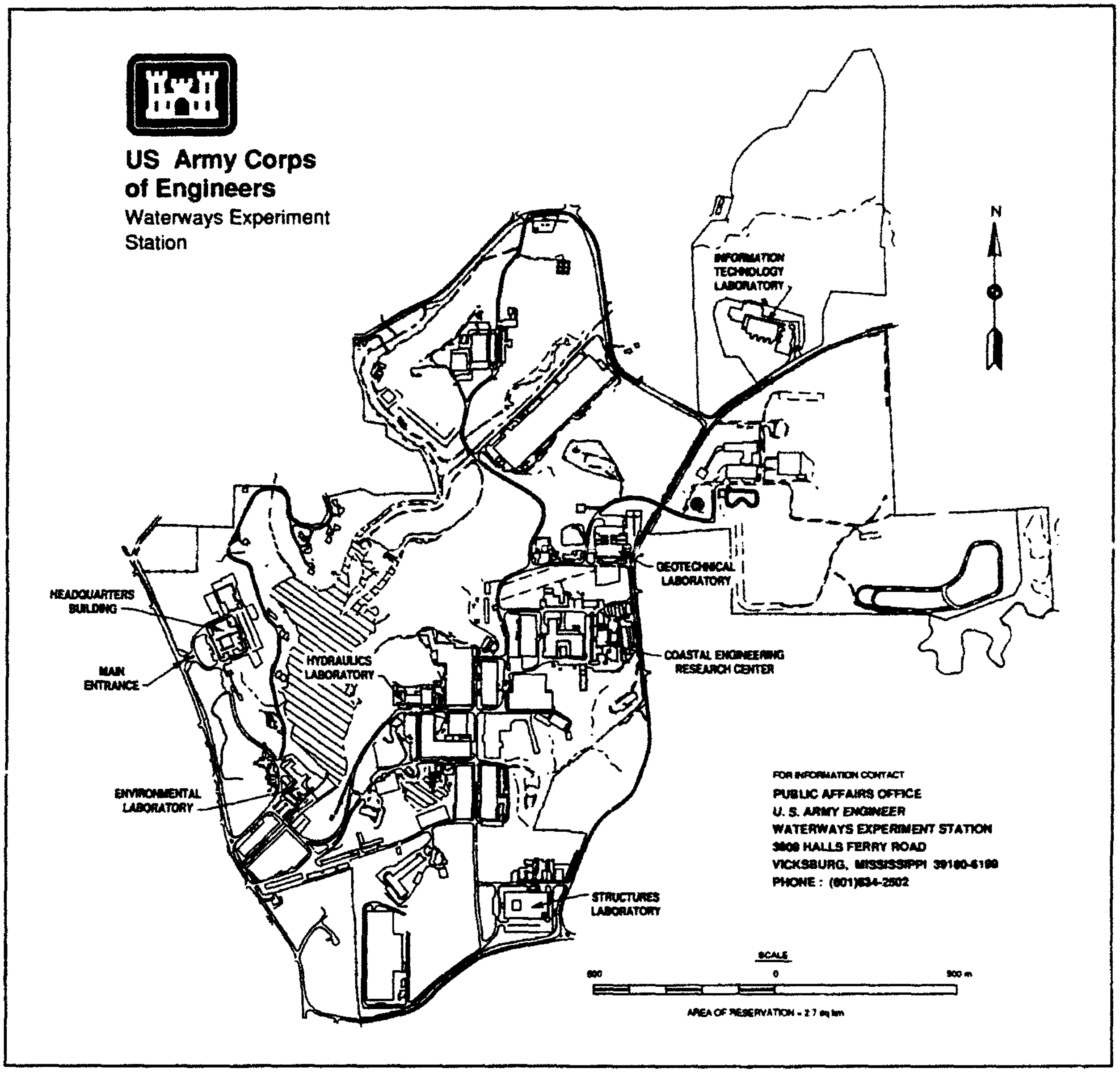

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PREFACE

This report was prepared by the US Army Engineer Waterways Experiment Station (WES), Coastal Engineering Research Center (CERC), and is the result of work funded by and performed for the Department of the Navy, Indian Head Division, Naval Surface Warfare Center (IHDIVNAVSURFWARCEN), Indian Head, MD. This research was authorized by Headquarters, US Army Corps of Engineers and was conducted by Dr. Jimmy E. Fowler, Wave Dynamics Division, CERC; and Messrs. William A. Birkemeier and Eugene W. Bichner, both of CERC's Field Research Facility Group, and Mr. David Krivich, IHDIVNAVSURFWARCEN. The work was carried out under the general supervision of Dr. James R. Houston, Director, CERC; Mr. Charles C. Calhoun, Jr., Assisstant Director, CERC; Mr. C. E. Chatham, Chief, Wave Dynamics Division; Mr. D. G. Markle, Chief, Wave Processes Branch; and Mr. Thomas Richardson, Chief, Engineering Development Division.

This report was prepared by Dr. Fowler, Mr. Birkemeier, Mr. Krivich, and Ms. Denson, with assistance from contract student Ms. Judy H. Roughton, CERC. The authors acknowledge the contributions to this report of the following: Mr. L. A. Barnes, Mr. J. E. Evans, Mr. L. R. Tolliver, Ms. B. E. Stephens, Engineering Technicians, CERC; and Mr. R. R. Sweeney, Contract Student, CERC. Assisting in the field work from the Field Research Facility were Messrs. C. F. Baron, K. K. Hathaway, P. R. Hodges, M. W. Leffler, B. L. Scarborough, C. R. Townsend III, and Guan Hong-Lee, Contract Student.

Director of WES during preparation and publication of this report was Dr. Robert W. Whalin. Commander was COL Leonard G. Hassell, EN.

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CONVERSION FACTORS, NON-SI TO SI
UNITS OF MEASUREMENT

US customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	metres
feet per second	0.3048	metres per second
inches	2.54	centimetres
ounces	32.1507	kilograms
pounds (mass)	0.4535929	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre

COOPERATIVE LABORATORY AND FIELD STUDY TO INVESTIGATE EFFECTS OF WAVE ACTION AND CURRENTS ON THE DUAL ROCKET DISTRIBUTED EXPLOSIVE ARRAY DEPLOYMENT

PART I: BACKGROUND INFORMATION

Background

1. Engineers and scientists associated with the Shallow Water Mine Countermeasures Program (SWMCM) are currently developing countermine systems to neutralize advanced and hardened mine threats in the surf zone regions. One such system currently being developed consists of a distributed explosive array constructed from detonation cord and kevlar, dual rockets for deployment, and an appropriate water craft such as the Navy's Landing Craft, Air Cushion (LCAC)) to be used for positioning and as a launching platform. Figure 1 is an artist's rendition of the proposed distributed explosive array system being deployed from an LCAC. Prior to the study reported herein, the dual rocket deployment technique had been successfully tested in field tests, but little information existed concerning the effects of its deployment in a coastal environment and specific concerns included pertinent operational effects on:

a. Array orientation and expansion retainment during descent
b. Array descent rate in fresh or salt water
c. Embedment characteristics of array after reaching bottom.

To study the effects of waves and currents on the array, Coastal Engineering Research Center (CERC) engineers and scientists participated with IHDIVNAVSURFWARCEN personnel in a two-phased research effort. The initial phase was conducted during May - June 1992, and consisted of a series of scaled laboratory wave flume tests conducted in CERC's test facilities located at the U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. The Second phase was a series of field deployments conducted during August 1992, at CERC's Field Research Facility (FRF) in Duck, NC.

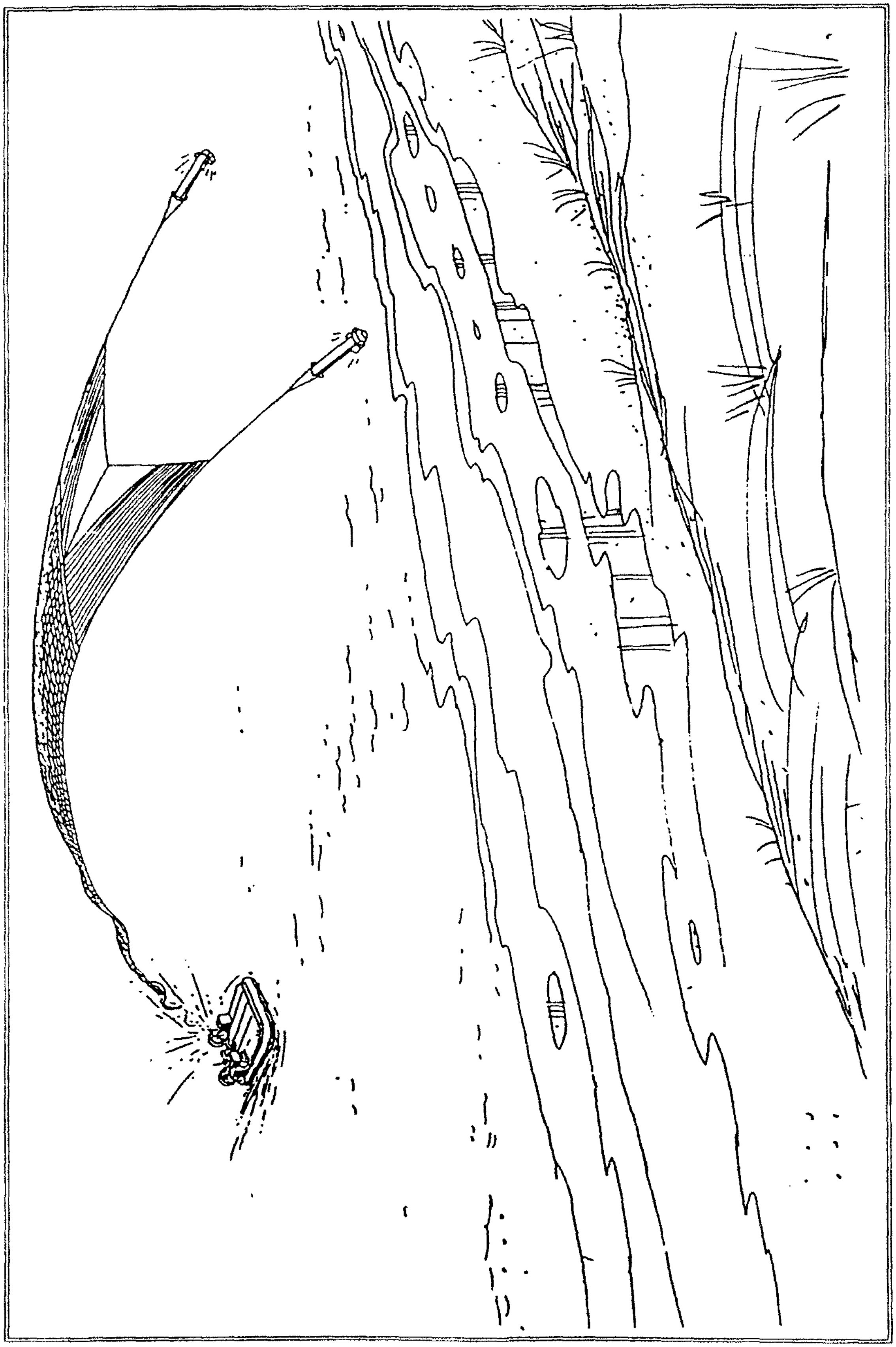

Figure 1. Artist's Rendition of Proposed Deployment Method

Purpose

2. The purpose of this project was to investigate effects of energetic sea state conditions on the proposed deployment of the distributed explosive array system.

Organization of Report

3. A summary and general discussion of facilities, materials, procedures used, and results obtained in the laboratory tests are presented in Part II. A description of the materials, methods, procedures and results obtained from the field tests are contained in Part III. Part IV is a summary of study results and also contains recommendations regarding future studies and array deployment considerations.

PART II: LABORATORY STUDY

Laboratory Facilities

4. All laboratory tests were conducted in the CERC'S 6-ft-wide[1] wave flume during the period May - June 1992. The flume is constructed of concrete and has glass viewing windows in the test section (Figure 2) which is located 246 feet from the wave generator. The flume has dimensions and capacities shown in Figure 3. The wave machine used in the 6-ft flume is hydraulically operated and is constructed such that it may be used in either the flapper, piston, or combined flapper and piston mode and can generate 1.68 ft wave heights at maximum operating conditions. For both regular and irregular wave generation, the wave generator was controlled using CERC software and a Micro-Vax I microcomputer. During operation of the wave generator, feedback from the piston motion and wave gages was actively monitored using a multi-channel oscilloscope as well as by digital recordings. Wave data were collected using both resistance and capacitance wave rods. An Automated Data Acquisition and Control System (ADACS) designed and constructed at WES (Turner and Durham, 1980) was used to

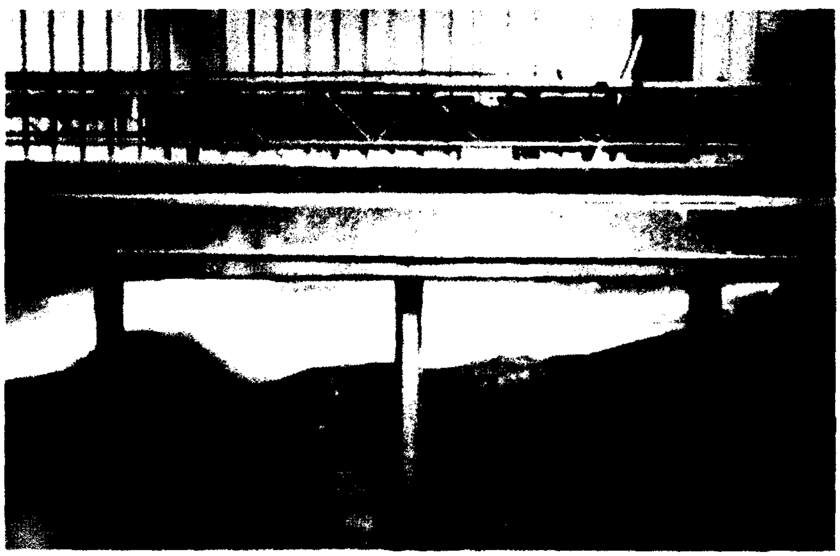

Figure 2. Photograph of Test Section of 6-ft-wide flume facility

[1] A table of factors for converting Non-SI units of measurements to SI units is presented on page 6.

calibrate the wave rods and ensure correct measurements of wave heights. Figure 4 is a schematic of the ADACS used with the 6-ft-wide flume. Wave data were collected at a rate of 20 hz and analyzed using both frequency and time domain techniques.

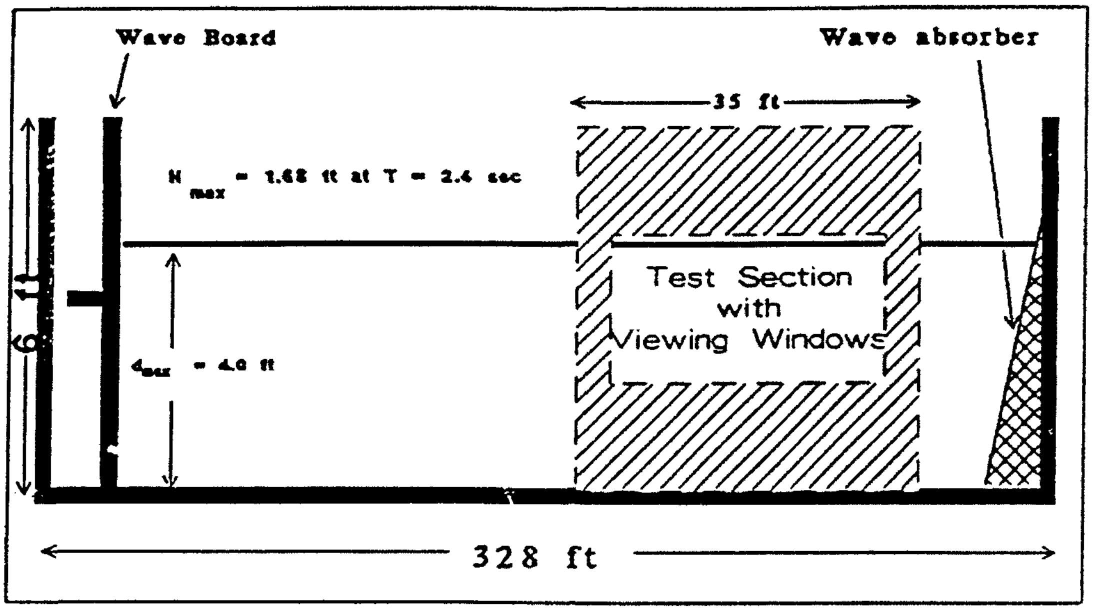

Figure 3. Characteristics of 6-ft-wide flume facility

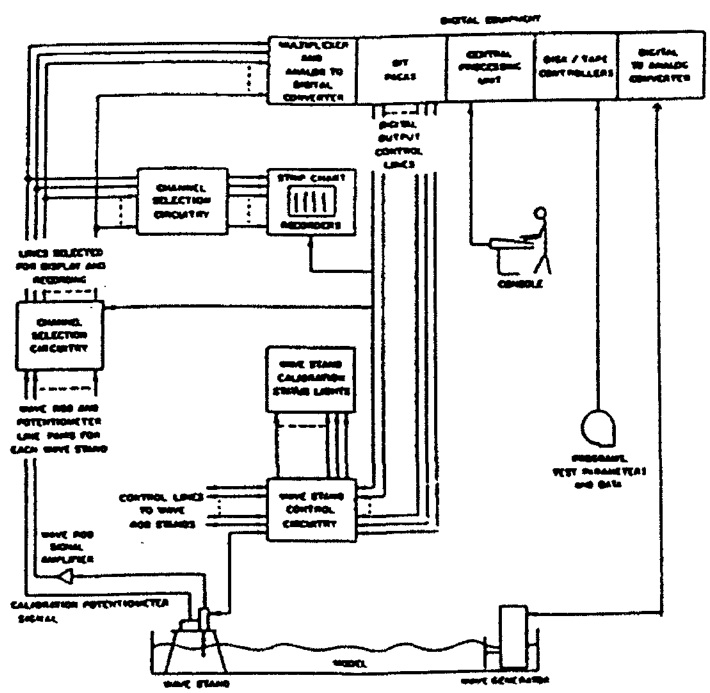

Figure 4. Schematic of ADACS for 6-ft-wide flume

Model Scaling Criteria

5. Studies by Hughes and Fowler (1990) indicated that movable-bed models designed using guidance based on preserving sediment fall speed similarity produces good results for energetic situations such as occurs in the surf zone. Fall speed scaling guidance requires that the following criteria should be met:

<u>Fall Speed Scaling Guidance for Wave Dominated Transport Regimes</u>

1) Fall Speed Parameter ($H/\omega T$) similarity;
2) Time and Hydraulics scales based on Froude ($Fr = V/(gl)^{½}$ modeling requirements;
3) Model is undistorted ($N_l = N_x = N_y = N_z$); and
4) Use fine sand (D = 0.08mm lower limit) as model sediment at largest possible scale ratio.

For the above:

H = wave height

ω = sediment fall speed

T = wave period,

V = an appropriate velocity

g = gravitational acceleration

l = Characteristic length

N = Scale ratio

D = mean sediment diameter

Subscripts l, x, y, and z are characteristic length, length in x direction, length in y direction, and length in z direction respectively.

6. The scaling guidance above was used to scale the model setup and test conditions and can be used to convert model values to corresponding prototype values. Using item number 1 above, similarity between model and prototype fall speed parameters is achieved when

$$\left[\frac{H}{\omega T}\right]_{model} = \left[\frac{H}{\omega T}\right]_{prototype} \tag{1}$$

For an undistorted model, $N_H = N_l$, which reduces Equation 1 to

$$N_t = \sqrt{N_l} \quad or \quad N_t^2 = N_l \tag{2}$$

For the above, N_H, N_l, and N_t are the model to prototype ratios for wave height, arbitrary length, and time, respectively. The Froude scaling relationship for time is given by

$$N_t = \sqrt{N_l} \quad or \quad = N_t^2 = N_l \tag{3}$$

Equations 1, 2, and 3 can be combined to yield a unique scaling guidance which satisfies the first two scaling criteria:

$$N_\omega = \sqrt{N_l} = N_t \tag{4}$$

where N_ω is the model to prototype ratio for sediment fall speed. The scaling relationship in Equation 4 can be used to convert model values to corresponding prototype conditions *once a prototype sediment diameter (and corresponding fall velocity) is known*. Figure 5 can be used to obtain fall speeds for various sand sizes. Froude scaling criterion for time can be used to determine prototype wave period and elapsed time.

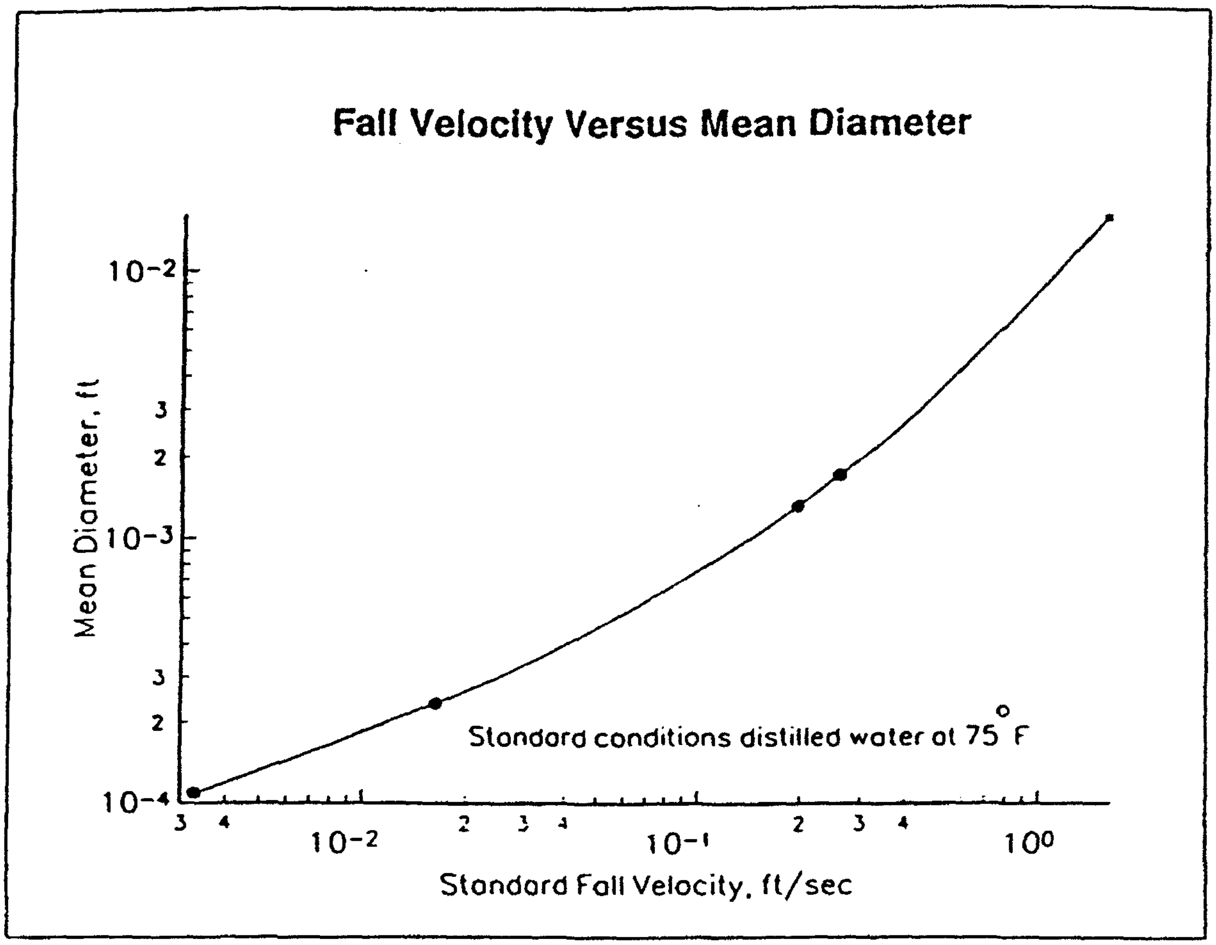

Figure 5. Fall Speed Versus Sand Size (after Seabergh, 1983)

Model Sediment Characteristics

7. Fine quartz sand obtained from the Ottawa Sand Company in Ottawa, Illinois, having mean diameter of 0.00043 ft (0.13 mm) with a specific gravity of 2.65 and a fall speed of 0.0542 ft/sec (1.64 cm/sec) was used in all tests.

8. As noted in paragraph 6, model lengths were scaled by the fall speed parameter as:

$$N_L = (N_\omega)^2 \tag{5}$$

The initial design step is to select an arbitrary prototype sediment (sand) mean diameter which is reasonable or representative of the prototype area. For this study, a value of D = 0.0011 ft (0.33 mm) was selected. From Figure 5, we obtain ω_p = 0.147 ft/sec (4.47 cm/sec). As noted in paragraph 7, the model sand has mean diameter = 0.00043 ft and ω_m = 0.0536 ft/sec (1.64 cm/sec). Substituting this information into Equation 5 gives

$$N_L = (N_\omega)^2 = \left(\frac{0.0536}{0.147}\right)^2 = \left(\frac{1}{2.74}\right)^2 = \frac{1}{7.5} \tag{6}$$

Therefore, selected length scale is 1:7.5 and appropriate lengths of the array can be determined by the following equation:

$$L_{model} = \left(\frac{1}{7.5}\right) L_{prototype} \tag{7}$$

To accommodate the width constraint associated with the flume, dimensions of the model array were selected to be 4 ft X 40 ft. Linear spacing of longitudinal and lateral components of the prototype array were given as 7 in X 5.0 ft. Dividing by the selected length scales, this leads to comparable spacing of the model array as follows:

$$\begin{aligned} \textit{Model Spacing} &= \frac{7.0\ in}{7.5}\ \textit{by}\ \frac{5.0\ ft}{7.5} \\ &= 1.0\ in\ \textit{by}\ 8.0\ in \end{aligned} \tag{8}$$

Figure 6 is a schematic of the proposed array given in prototype dimensions.

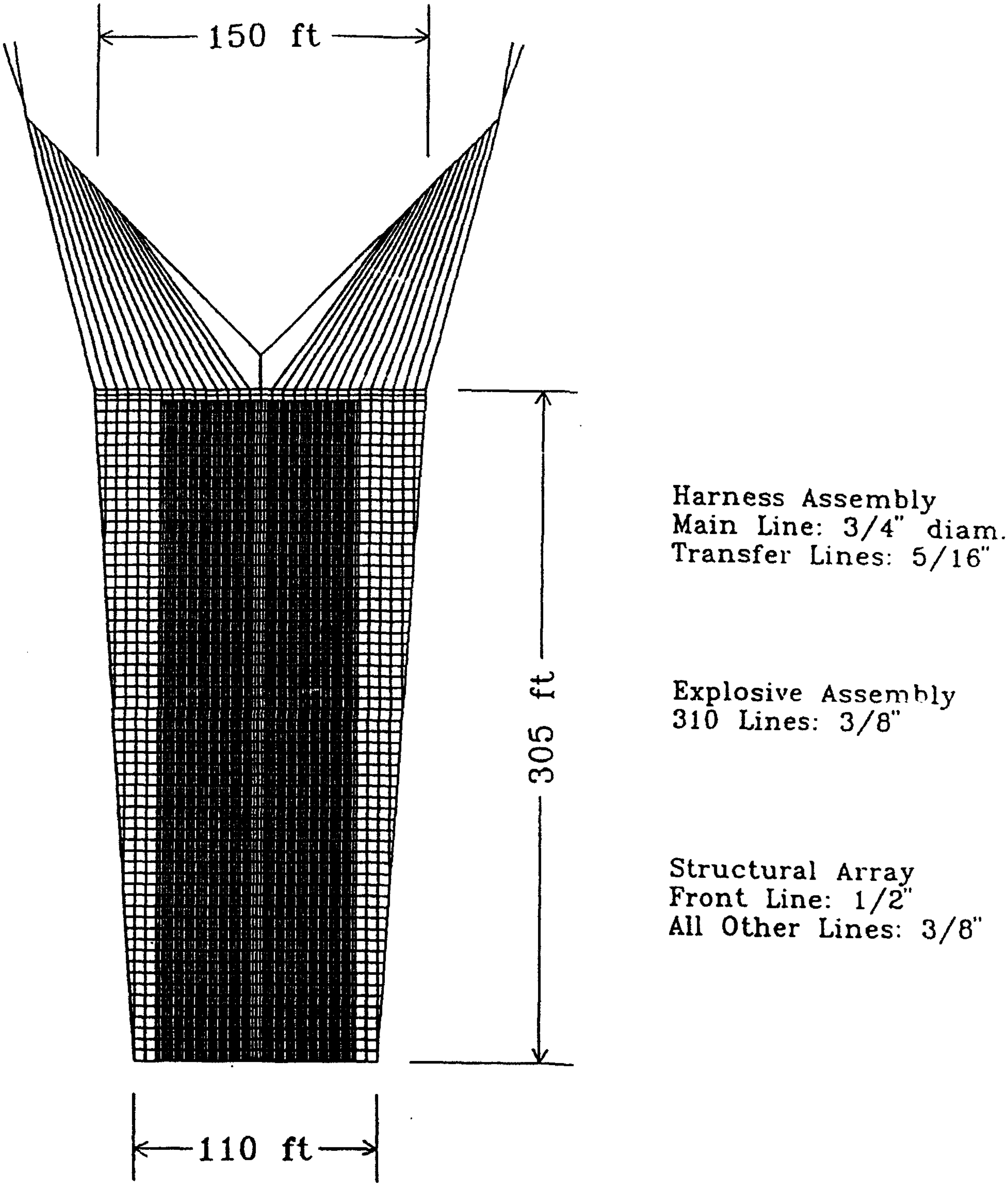

Figure 6. Schematic of Proposed Array with Prototype Scale Dimensions

Specifications for detonation cord (200 grains explosive per linear foot, diameter = 0.375 in. and specific gravity = 1.3) to be used in the prototype array were provided by IHDIVNAVSURFWARCEN personnel. Calculation of the scaled diameter of the model array is straightforward and is determined from Equation 7 as

$$\begin{aligned} Diameter_{model} &= \left(\frac{1}{7.5}\right) Diameter_{prototype} \\ &= \left(\frac{1}{7.5}\right)(0.375\ in) \\ &= 0.05\ in \end{aligned} \tag{9}$$

Scaling Considerations for Hydraulics and Buoyancy Effects

9. As stated in paragraph 5, hydraulics and time are scaled according to the well-known Froude criteria:

$$\begin{aligned} time_{model} &= (N_l)^{0.5}\ time_{prototype} \\ &= \left(\frac{1}{2.74}\right) time_{prototype} \end{aligned} \tag{10}$$

$$\begin{aligned} Length_{model} &= (N_l)\ Length_{prototype} \\ &= \left(\frac{1}{7.5}\right) Length_{prototype} \end{aligned} \tag{11}$$

Wave period, wave height, water depth, horizontal distance, elapsed time, and forces associated with hydraulics were scaled by the above. To correct for buoyancy differences between fresh (laboratory) and salt water (most prototype situations) and correctly scale specific gravity of the model array, the following adjustments are required:

It is desired to simulate

$$\begin{gathered} Effective\ Weight\ of\ Array = Weight\ of\ Array - Buoyancy\ force \\ or \\ (W_e)_a = W_a - F_b \end{gathered} \tag{12}$$

Weight of array, W_a, and buoyancy force, F_b are given by the following:

$$W = \gamma_a (L)^3 \tag{13}$$

$$F_b = \gamma_w (L)^3 \tag{14}$$

where

γ_a = specific weight of array, lb_f/ft^3

γ_w = specific weight of water, lb_f/ft^3

L = arbitrary length, ft

Now, effective weight, $(W_e)_a$, of the array can be expressed as

$$(W_e)_a = (\gamma_a - \gamma_w)(L)^3 \tag{15}$$

From Froude scaling relationships, for physical hydraulic models, force is scaled as

$$\frac{F_{model}}{F_{prototype}} = \left(\frac{\rho_{model}}{\rho_{prototype}}\right)\left(\frac{L_{model}}{L_{prototype}}\right)^3 \tag{16}$$

where ρ is the fluid density. Values of ρ for salt and fresh water are 1.99 slugs/ft^3 and 1.94 slugs/ft^3, respectively, so that

$$\frac{F_{model}}{F_{prototype}} = 0.975\left(\frac{L_{model}}{L_{prototype}}\right)^3 \tag{17}$$

Since $(W_e)_a$ is the force to be modeled, we combine Equations 15 and 17 to obtain

$$\frac{(W_e)_{model}}{(W_e)_{prototype}} = \frac{\left[(\gamma_a - \gamma_w)\, L^3\right]_{model}}{\left[(\gamma_a - \gamma_w)\, L^3\right]_{prototype}} = 0.975\left[\frac{(L^3)_{model}}{(L^3)_{prototype}}\right] \tag{18}$$

which yields

$$(\gamma_a - \gamma_w)_{model} = (0.975)(\gamma_a - \gamma_w)_{prototype} \tag{19}$$

Since the specific gravities of the prototype array and prototype water are 1.3 and 1.026, respectively, we can express these quantities as

$$(\gamma_a)_{prototype} = 1.3(\gamma_w)_{model} \tag{20}$$

and

$$(\gamma_w)_{prototype} = 1.026(\gamma_w)_{model} \tag{21}$$

Substituting these two equations into Equation 19 yields

$$(\gamma_a)_{model} = (0.975)[1.3(\gamma_w)_{model} - 1.026(\gamma_w)_{model}] + (\gamma_w)_{model}$$

$$= (1.268 - 1.00 + 1)(\gamma_w)_{model}$$

$$= 1.268(\gamma_w)_{model}$$

This indicates that the model array should be constructed from material with specific gravity of 1.268 if prototype specific gravity is 1.30, to account for effects of buoyancy differences between salt and fresh water.

Selection of Materials for Model Arrays

10. From the previous paragraphs regarding scaling requirements for the model array, the exact scaled array would have the following characteristics:

Specific gravity	1.268
Diameter of simulated detonation cord	0.05 in.
Spacing of array components	1 in by 8 in.

Unfortunately, no material was found which exactly satisfied these requirements. Because of this, three model arrays were assembled as follows:

Table 1. Materials Used in Model Array Construction.

Array ID	Material(s) Used	Specific gravity	Diameter, in	Spacing
I	Polyester	1.38	0.12	1in x 8in
II	No. 18 Nylon	1.15	0.083	1in x 8in
III	Polyester and No. 18 Nylon	1.38 and 1.15	0.12 and 0.083	1in x 8in
IV (Prototype Scale)	Polypropylene lateral members Polyester longitudinal members	1.1 1.38	0.375 0.375	7in X 5ft

The best match was determined to be a combination of commercially available polyester and nylon, in which the combination of the two yield a combined specific gravity closer to that required to simulate the net effective weight. Polyester strands were used to model the detonation cord, and nylon was used to simulate the lateral spacing lines.

Modifications to Arrays to Assess Operational Improvements

11. To assess requirements for stabilizing the deployed array in an energetic wave environment, some modifications to the array were also tested. Modifications were designed to

a. Assist the array in its orderly descent to the bottom.

b. Assist the array in maintaining its initial orientation and expansion.

Specifically, the scaled arrays tested were constructed at 1:7.5 undistorted model to prototype ratio and as shown in Table 2 included the following:

Table 2. Modifications to Arrays.

Modification	Array ID	Remarks
1) Unweighted array	I, II, and III	Three separate model arrays, as described in Table 1, were tested without modifications, to evaluate model arrays and provide baseline data for comparison against modification tests.
2) Weights at selected points on array	III	Lead weights ranging from 1-4 oz (model values) were connected to each seaward corner
3) Weight distributed within array	III	Stiff multi-strand wire was threaded into the array in the deepest section to simulate optimum weight defined in point weight tests

Details of various tests are described in following sections and Appendix A.

Sea States and Irregular Wave Parameters

12. The Navy would like to deploy the distributed explosive array system during sea state 3 conditions (see Table 3) and lower, therefore model test conditions were selected to cover wave parameters up to and including sea state 3. As can be seen from Table 3, individual sea states are described by ranges of both wave height and wave period. Irregular waves, which are most representative of water waves most commonly found in nature, were used for all model tests. *No currents were used in the two-dimensional laboratory study.* Tables 4, 5, and 6 provide summaries of the modeled wave conditions in terms of H_{mo} (essentially equal to significant wave height ($H_{1/3}$) in deep water) and T_p. Conditions listed in Table 5 were used to simulate the longer wave period range of the sea states, while those in Table 4 list those conditions which simulated the shorter wave period ranges for all sea states. Table 6 contains conditions modeled at prototype scale.

13. Water waves in nature are typically represented by statistical wave height parameters or energy-based parameters. These statistical parameters are representative of the wave climate during a period of time in which the wave process is assumed stationary. Typical statistical wave height parameters include: H_{avg} (mean wave height of all waves), H_{rms} (root-mean-square wave height), and $H_{1/3}$ (average of the highest 1/3 of all waves). The primary energy-based wave height designator is H_{mo}, which is directly related to energy contained in the wave spectrum. H_{mo} is approximately equal to $H_{1/3}$ for deep water waves but can be significantly different for shallow water waves (Thompson and Vincent (1984); Hughes and Borgman (1987)).

Table 3. Deepwater Sea State Conditions from Pierson-Moskowitz Scale

Sea State	Deep Water Significant Wave Heights (ft) $(H_{1/3})_o$	Deep Water Significant Wave Periods (sec) $(T_{1/3})_o$	Deep Water Average Wave Lengths (ft) L_o
0	0.1 - 0.2	0.3 - 1.3	1.3 - 2.0
1	0.5 - 1.2	0.8 - 3.8	6.6 - 15.8
2	1.5 - 3.0	1.3 - 6.0	19.7 - 39.4
3	3.5 - 5.0	2.0 - 7.7	46.0 - 65.7
4	6.0 - 7.5	2.7 - 9.4	78.8 - 98.5

Table 4. Short Period Model Wave Conditions Tested.

Test Condition	Zeroth Moment Wave Height H_{mo} Model Feet	Wave Period T_p Model seconds	Sea State Simulated
1	0.133	1.07	1
2	0.200	1.23	2 Low
3	0.267	1.43	2 Medium
4	0.400	1.72	2 High
5	0.467	1.88	3 Low
6	0.529	2.01	3 Medium
7	0.667	2.24	3 High

Table 5. Long Period Model Wave Conditions Tested.

Test Condition	Zeroth Moment Wave Height H_{mo} Model Feet	Wave Period T_p Model Seconds	Sea State Simulated
8	0.133	2.01	1
9	0.200	2.23	2 Low
10	0.267	2.43	2 Medium
11	0.400	2.72	2 High
12	0.467	2.88	3 Low
13	0.529	3.01	3 Medium
14	0.667	3.22	3 High

Table 6. Prototype Scale Wave Conditions Tested.

Test Condition	Zeroth Moment Wave Height H_{mo} Model Feet	Wave Period T_p Model Seconds	Sea State Simulated
15	1.000	5.4	1
16	1.200	5.5	2 Low
17	1.267	2.43	2 Low

Experiment Procedures

14. Procedures used for all tests were designed to simulate effects of wave action (effects of current were not studied in the 2-D model tests reported herein) on deployment and operational aspects of the array. All tests were done in the 6-ft wide wave flume described in paragraph 4 on a sand beach initially smoothed to a 1V-on-15H slope. Prior to testing of the arrays each of the model wave conditions listed in Tables 4 and 5 were verified as described in paragraph 4 to ensure that the desired sea state conditions were properly reproduced. Procedures for array deployment varied from dropping the array (in one of the configurations listed in Table 2) into the water to placing the array on the sand bottom in its maximum expansion prior to turning on the wave maker. After the array was deployed, still photography, video cameras, and visual observations were used to document the effects of various waves on the array. On the average, waves were run for 400 model seconds, which is equivalent to 1,095 prototype seconds (18.5 min) per test. Since this is greater than the notional time required for deployment and detonation of the explosive system, this modeled test duration was felt to be very adequate. Additional details, notes and descriptions for each test are given in Appendix A.

Shakedown Tests

15. Initial, or "shakedown," tests were conducted during 7-9 May 1992 and involved 20 different tests on 3 different arrays. Two of the three arrays (Arrays I and II) were 1:7.5 scale representations of the prototype array and the third array (provided by IHDIVNAVSURFWARCEN) was constructed at full (prototype) scale. Of the twenty shakedown tests, seventeen used the scaled arrays and the remaining three used the prototype array. The shakedown tests were conducted to establish test procedures and evaluate performance of the model Arrays I and II. Results of these tests indicated that Arrays I and II were unsatisfactory with regard to specific gravity scaling. Array I, which was constructed completely from nylon, having a specific gravity of 1.15, proved much too light and even floated for approximately 30 min before becoming saturated

and finally sinking to the bottom. Array II (constructed entirely from polyester having specific gravity of 1.38) did not experience floating problems and actually performed extremely well, but it was felt that results obtained using this array might be too good since it was constructed using material with a specific gravity somewhat greater than scaling laws dictated. Following shakedown tests, a third scaled array was constructed (Array III), using a combination of the nylon and polyester materials to obtain a net specific gravity which was closer to the required value for similitude. All subsequent scaled tests were conducted using this array (Array III). Shakedown tests correspond to Test Numbers 1-SS1 through 3-SS3H-D in Table A-1 of Appendix A.

Results With Unweighted Array III Tests

16. A second test series containing twenty-four different tests was conducted during the period 20-23 May 1992. As stated in paragraph 15, a third scaled array (Array III) was constructed using a combination of nylon and polyester twine to more closely simulate the fall speed and density of the prototype array. Tests on this unweighted array indicated that once placed on the bottom, the array was reasonably stable during sea states 1 and the low to middle energy ranges of 2, with considerable movement of the array during sea state 3 (see Figures 7 and 8) and limited movement during high sea state 2 conditions. *Based solely on wave effects, sea state 3 seems to be a limiting condition for use of the array without additional weighting/anchoring.* The unweighted Array III tests correspond to Test Numbers 4-SS1 through 4-SS3H and 10-SS1LP through 10-SS3HLP Table A-1.

Results With Weighted Array III Tests

17. Tests were conducted to determine the benefits of adding weights (provided by lead sinkers and multistrand wire) to the corners/back edge of the array. During these tests, various quantities of weight (1 - 4 model oz per corner) were added to the seaward corners of the array (note: to obtain prototype scale weights, multiply model values by 422). The weights were varied to determine minimum weight requirements for

maintaining initial expansion of the array under the more energetic wave conditions tested. Tests showed that adding additional weight did enhance stability of the array and that 2 oz per corner was sufficient to maintain reasonable expansion of the array for all cases (including sea state 3) when the simulated rocket motor's landing points were

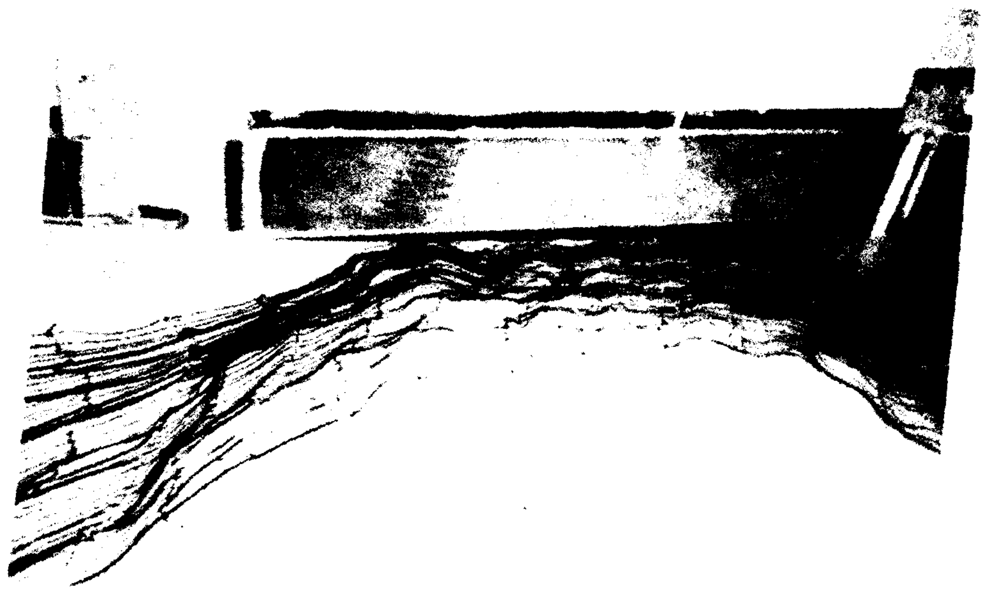

Figure 7. Photograph of Failed Model Array Deployment Tests.

Figure 8. Additional Photograph of Failed Model Array Deployment Test.

positioned shoreward of the maximum wave runup. Following the point weight tests, tests were conducted using 4 oz of multistrand wire distributed evenly across the seaward 10 ft of the model array. The additional weight appeared to enhance stability of the array during the more energetic wave conditions, but not as effectively as the point weights of similar total weight. Again, laboratory results are based solely on effects of wave action - no accounting was made for effects of longshore currents. The weighted Array III tests correspond to Test Numbers 5-SS3M-D through 6AR-SS3H and 12-SS2LLP through 13-SS3HLP in Table A-1.

Results of Prototype Scale Array Lab Tests

18. A number of tests were conducted using the prototype scale array (Array IV) for limited prototype scale wave conditions simulating sea state 1 and lower ranges of sea state 2. During initial prototype scale tests conducted during the period of 8-9 May 1992, a 40 ft x 4 ft section of Array IV was used. Some movement was observed at the seaward end in a water depth of 1.5 ft, during sea state 1. This movement appeared to be caused by the buoyancy of the polypropylene lateral members and shortness of the array. Tests conducted with the 40-ft-long section of Array IV placed totally in the deeper water (4 ft) nearer to the wave maker, showed very good stability under the influence of sea state 1 wave action alone. Following these initial tests, the prototype array was tested for sea state 1 and the lower range of sea state 2. During these tests, however, the length of the array was doubled to 80 ft so that the seaward edge of the array was located in approximately 3.5 ft of water. In this case, only the last seaward 3-4 ft of the net experienced noticeable movement, again probably due to the effects of the polypropylene laterals. The prototype scale array tests correspond to Test Numbers 3-SS0 through 3-SS1-DW, 9-SS1PR through 9-SS2LP, 11-SS1LP through 11-SS2LP and 14-SS2MLP in Table A-1.

Results of Simulated Drop Tests

19. Ten laboratory flume tests included attempts to simulate deployment of the arrays, during both calm and energetic sea conditions. In general, wave action alone for conditions below sea state 3 does not seem to have a great impact on descent of the array through the water. For mid and high ranges of sea state 3, the array was somewhat hindered in its descent to the bottom, particularly in the region with breaking waves. The scaled array tests which included deployment simulations (drops) correspond to Test Numbers 3-SS1-D through 3-SS0-D, and 5-SS3M-D in Table A-1.

Results of Embedment Tests

20. A single test series was conducted to examine embedment characteristics of the array in the sand if the array is allowed to reside on the bottom for an extended period of time after initial deployment. The tests were run using Array II, which was the densest of the arrays, to ensure maximum potential for embedment. After running waves for approximately 2500 model sec (6850 sec prototype) total elapsed time, no evidence of embedment was observed.

PART III: FIELD TESTS

Overview of Field Tests

21. The field tests were designed to evaluate the performance of a simulated explosive array under actual wave and current conditions and to determine our ability to deploy, monitor, and retrieve the array. The tests were conducted over a 5-day period from August 17 to August 21 1992. In order to simulate as closely as possible the deployment characteristics of a rocket-deployed array, a helicopter was used to deploy and retrieve the array. Seven deployments, or *drops*, were made during the 5 days and each one was monitored with video cameras, bottom surveys, and environment measurements. Specific field test objectives were:

a) Assess the performance of an array under differing mild wave conditions and bottom configurations;

b) Evaluate the settling characteristics of an array including how tightly it lays on the bottom;

c) Evaluate modifications to the array design to improve its performance

d) Develop techniques to monitor the expansion of an array during and immediately after deployment;

e) Demonstrate the ability to deploy and retrieve a simulated explosive array.

Because of monitoring and logistic concerns, the tests were scheduled during August, a time of expected mild wave and current conditions. In actuality, the conditions during the week were never mild. Offshore wave heights ranged from 2 to 3 ft, and the strong longshore currents reached up to 2 ft per sec.

22. The discussion which follows addresses both the performance of the simulated explosive array along with an assessment of the lessons learned in deploying and monitoring the drops.

Field Test Location

23. The field tests were conducted at the Field Research Facility (FRF) located on the Atlantic Ocean in Duck, NC. The facility is shown in Figure 9. This site was selected because the research pier and the observation tower offered good camera

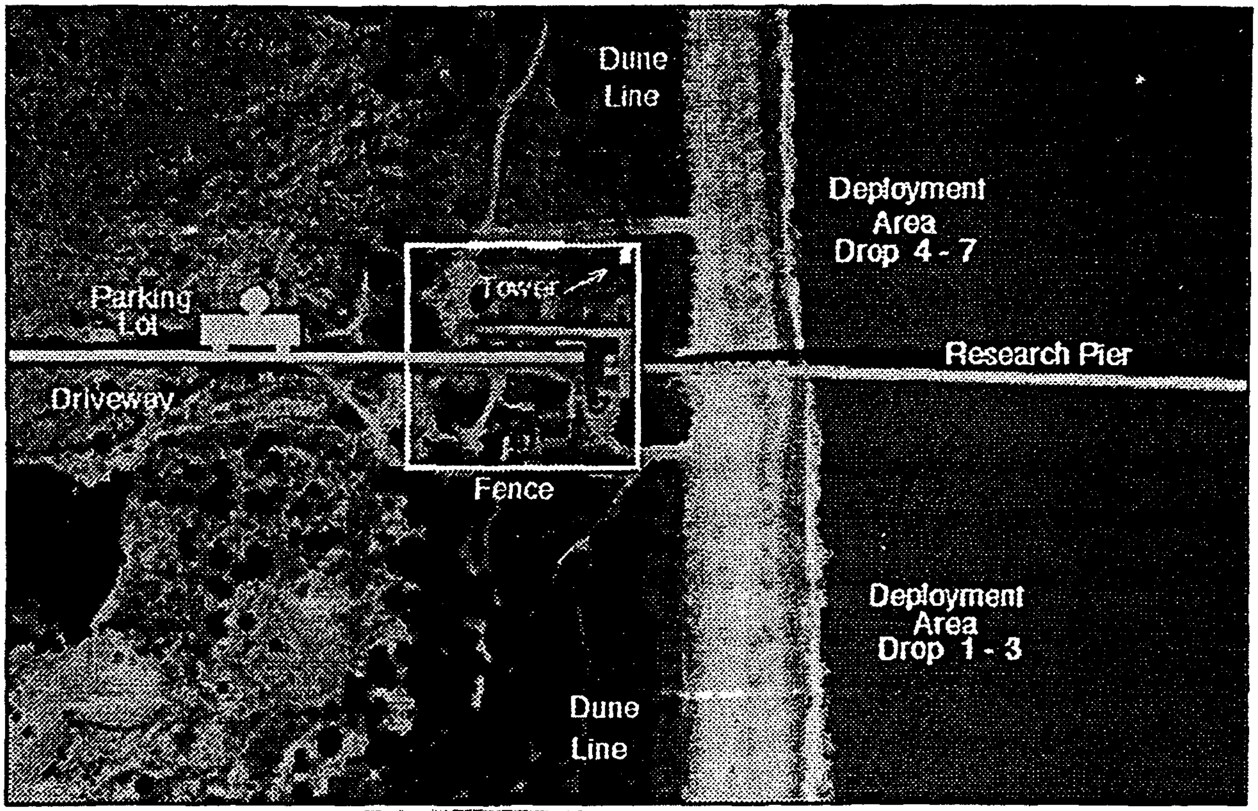

Figure 9. The Field Research Facility and Location of the Deployment Zones

positions, instruments were available to measure the wave and current conditions, and the FRF is suitably equipped to handle the array. Specific FRF equipment required in the tests included a four wheel drive forklift (Figure 10), the Coastal Research Amphibious Buggy (CRAB), and an instrumented sled. The CRAB is a unique 35-ft tall self propelled tripod capable of operating in waves out to the 30-ft depth contour. The sled is a heavily weighted mobile instrumented frame used to support two current meters and a pressure sensing wave gage (Figure 11). It was pulled offshore by the CRAB and used to obtain measurements of currents and waves across the surf zone near the drop site. The CRAB was also used to survey the shape of the bottom across the deployment zone and to accurately place marker buoys.

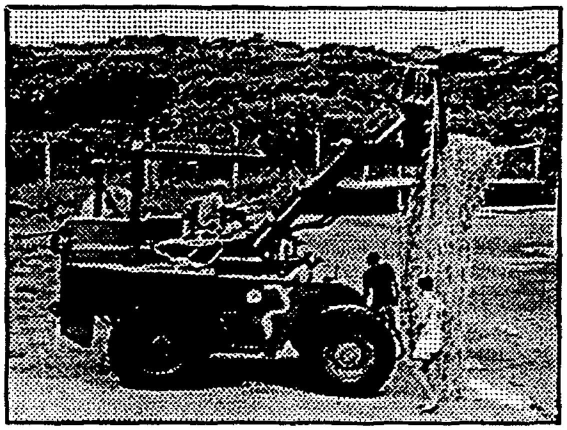

Figure 10. Forklift Moving Array to the Beach

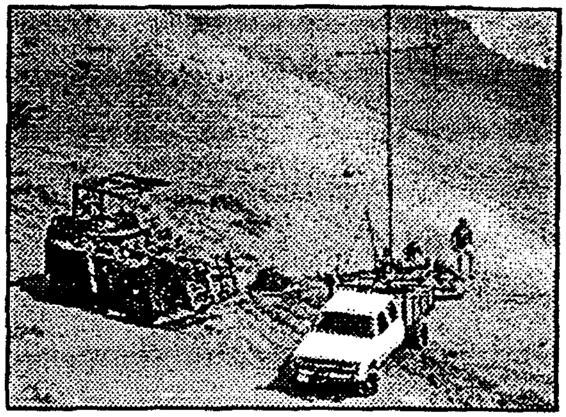

Figure 11. Instrumented Sled Being Readied for Deployment

24. One attribute of the FRF is the long-term knowledge of the variation in the beach and nearshore bottom under changing conditions. At the FRF, the region of greatest variation extends from about the +0 ft elevation contour on the beach seaward to a depth of approximately -13 ft, a distance of 500 ft, equal to the prototype array length. Within this zone, the profile often is characterized by a steep bar/trough feature which is highly mobile in the cross-shore. The natural variation of the bottom in this zone has significant implications to the performance of the explosive array. Figure 12 shows the variation in this zone over a

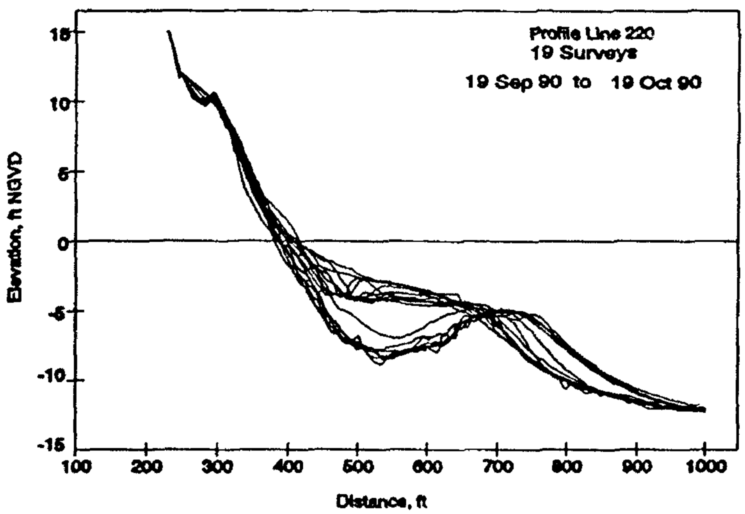

Figure 12. Variation in Nearshore Profile Activity During a One-Month Period

short, three week period. While these surveys were collected during an active time period when the beach is responding to early autumn storms, changes of this magnitude can occur during single storm events. Mines placed on a sandy bottom in this region will scour in and may be deeply buried as the bar develops and moves onshore or offshore. Although the bottom is less active offshore, seaward of this zòne, heavy mines will still scour into the bottom under the action of waves and currents. Once buried, mines will stay buried unless a deep trough develops, temporarily excavating the mines. While these data are specific to the FRF, they can be expected to occur on any sandy beach affected by waves. Obviously, an awareness of this variation must be accounted for in any shallow water mine countermeasure program. Moreover, for a distributed explosive array to be effective, it must be able to settle uniformly against the bottom. This includes settling into the trough, where buried mines are most likely to reappear, and where the longshore current is strongest.

Test Array Configuration and Rigging

25. The test array was provided by the Naval Surface Warfare Center, Indian Head Division. It was constructed of six 25×50 ft, panels. These were combined to make an array with dimensions of 25×300 ft, approximately 27% of the area of the prototype array (see Figure 6). This small size was designed to extend from the beach to the crest of the bar and to facilitate deployment and removal. The lines simulating the detonation cord of each panel were constructed of 3/8" polyester rope. The transfer lines were simulated with 3/8" polypropylene rope. A loop constructed with a nicopress fitting was used to terminate each of the lines. These loops were used to connect the panels; the nicopress fittings added weight to the perimeter of each panel. The polyester lines ran the length of the array and were spaced every 7" across the array. This resulted in a weave which was the same as the design of the prototype weave. Materials were selected to simulate the specific gravity of the prototype array. In a drop test using a 6×6 ft panel, a fall velocity of 0.5 ft/s was estimated. This relatively slow fall speed reflects the slight negative buoyancy relative to sea water.

26. During Drops 5 through 7, *lead-core* line (a lead weighted rope) was added to the second and third panels from the shoreline. A total of 200 lbs of line was added by fastening 50-ft lengths of lead-core line to every other longitudinal line. The lead-core line was attached with cable ties and was an attempt to improve the settling characteristics of the array.

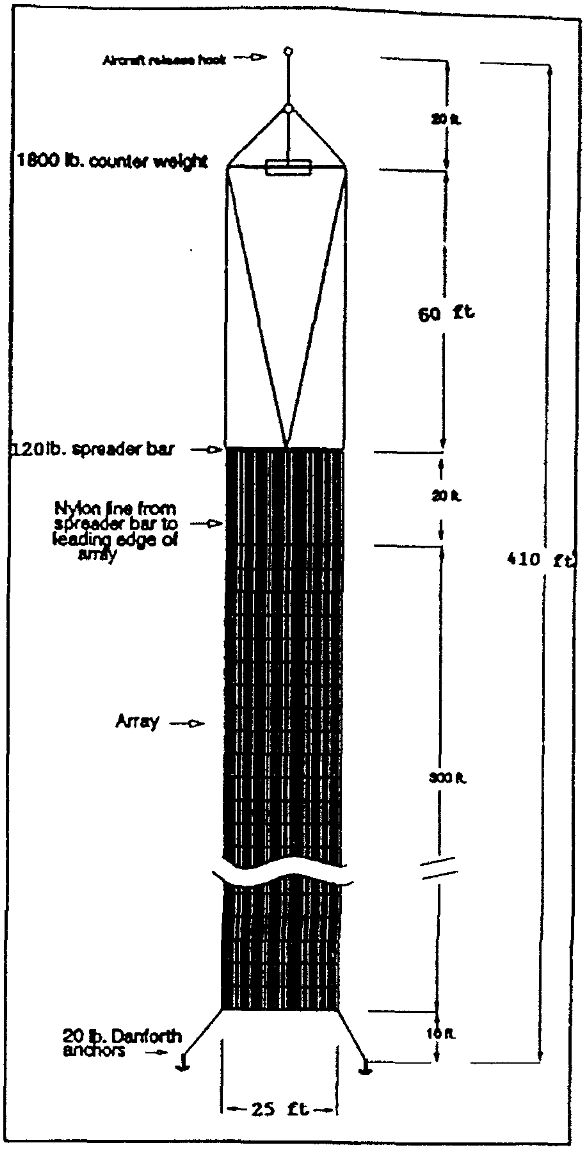

Figure 13. Test Array Design With Anchoring and Release Lines

27. The shoreward end of the array was attached to two 20-lb Danforth anchors by 10-ft nylon ropes. At the seaward end, each longitudinal line was connected by a 20-ft nylon rope to a 25-ft long steel *spreader* bar which kept the array spread under the helicopter. The spreader bar was connected by four 60-ft chains to another 25 ft bar and release mechanism which was suspended 20 ft below the helicopter. The release mechanism included a 1800-lb weight that damped the motion of the helicopter during release. Upon release, the spreader bar and chains remain attached to the array. Figure 13 shows the entire 410-ft long array with anchoring and release attachments. Figure 14 shows the top of the array attached to the helicopter.

28. Since a critical aspect of the field tests was observing the expansion of the array immediately following deployment, a series of small buoys were attached at the corners of each panel. In order to be effective, the buoys had to be attached to the array in such a way that they didn't interfere with the deployment of the array and didn't

release until hitting the water. A number of different deployment schemes were tried, and the most effective technique was to use 6"×4" white oval buoys attached to the array with *net cord*. The length of the cord was adjusted to approximately twice the expected water depth and a large fishing tackle *snap swivel* was used for easy attachment and removal from the array. The buoy line was first hand coiled and then bound to the buoy and to the edge of the array with a large rubber band. The rubber band was passed around (not over) the buoy and one end of the rubber band was pulled through the other end and secured with a sugar cube. Once in the water the sugar rapidly dissolved releasing the buoy. The buoys were attached after the array was folded and ready for deployment. Care was taken to insure that the buoys all lay to the outside of the array and that they would not interfere with the array as it was lifted. During Drops 2 thru 7, double-wide sheets of computer paper where used to separate the bouys from each other and the array. Two additional bouys marked the spreader bar.

Figure 14. Top Part of the Array Suspended Below the Helicopter Just Before Release

29. Different size buoys and different colors were tried in order to improve the visibility of the buoys. Of the colors used, white worked the best. However, none of the buoys worked under the breaking wave conditions which existed late in the week.

Cameras and Video Tape

30. Video cameras were the primary method of monitoring the drops. A combination of S-VHS and VHS tape formats was used. Each drop was recorded from three or four positions, including the observation tower (S-VHS), the pier (VHS), the

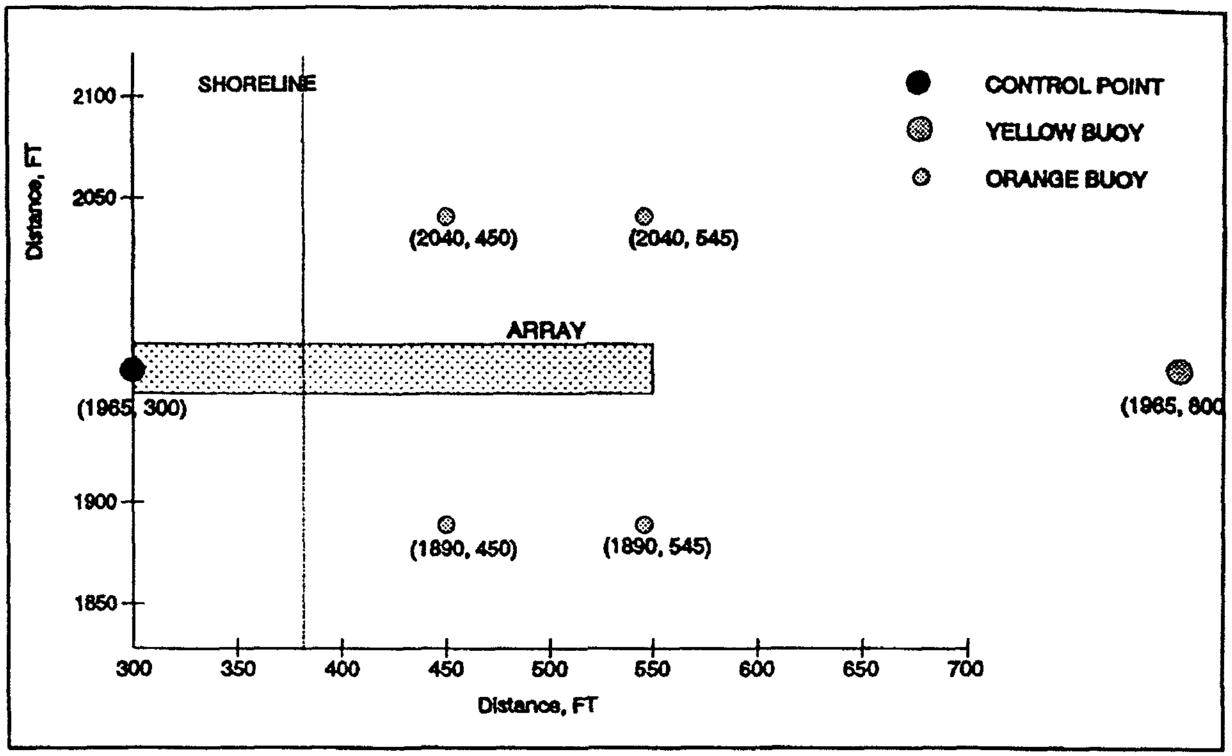

Figure 15. Diagram of Control Points and Buoys (for Drops 4-7)

CRAB (S-VHS, Drops 1-3), and from behind the dune (VHS). In order to estimate the movement of the array, a series of four large orange buoys were placed by the CRAB in a square around the drop zone. An additional yellow buoy marked the centerline of the drop, and a control point on the beach marked the landward end of the array. Figure 15 is a schematic of the layout. In theory, changes in the array could be measured by observing its movement relative to the control markers. While this worked for some of the drops, typically the array moved so rapidly alongshore that the control buoys had to be widely spaced. Consequently at a camera setting wide enough to see the control buoys, the small buoys marking the array perimeter were nearly invisible. To see them, the camera was zoomed and then panned along the length of the array. While this technique precluded the measurement of movement from the video tapes, it did document the general shape of the array. Another problem resulted from the inshore reference buoys moving alongshore with the current. This problem could not be eliminated by adding more anchor weight since the weight required might have hampered the retrieval of the array had it become entangled with the buoys.

31. The quality of the camera work improved through the week as the tape from each drop was reviewed and discussed. These discussions resulted in moving the location for Drops 4-7 to just north of the FRF's 125 ft observation tower. The height of the tower provided a much better vantage point for the two S-VHS cameras. One of the cameras was remotely operated and could be controlled from the FRF building by the test directors. A second camera on the tower was used for close zooms of the array as it was deployed, and a third camera on the pier provided an alternate view angle. We also used a camera located on the dune close to the array. However, this angle was generally too low and too close to be useful.

32. Another consideration which affected video tape quality included conducting the deployments in the afternoon when the sun was behind the cameras, significantly improving the visibility of the array and the marker buoys. A minor problem resulted from the use of cameras with auto-adjusting irises. These are tricked by the changing level of white due to wave breaking. The result was a video image which varied rapidly from dark to light as the image varied with the white of the breaking waves. This added to the difficulty of identifying the small perimeter buoys.

Deployment Sequence

33. Although considerable thought went into the deployment plan prior to the arrival at the FRF, the procedure evolved during the week. In this section, details of the plan that ultimately was adopted are described.

34. At the start of each day, access to the FRF oceanfront was restricted by posting signs and fencing off the beach at the north and south property limits. At the same time, a crew of 8 people helped to move the array to the beach using the forklift. A crew of 3 people used the CRAB to deploy the large buoys marking the drop zone.

They also used the CRAB to survey the bottom across the drop zone. At the same time the instrumented sled was readied to be moved by the forklift to the beach. The video camera crew used this time to load tapes, and to position the cameras.

35. On the beach, the array was carefully folded into a 25×25 ft pile (Figure 16). Location on the beach was important, there had to be enough level beach seaward of the reefed array for the helicopter to land. The anchors were attached to the shore end of the array, extended, and buried. The spreader bar was set on the beach just seaward of the array. The forklift then set the counterweight/release mechanism just seaward of the array and the chains were attached. The perimeter buoys were coiled and attached to the array in such a way as to prevent them from interfering with the array. When everything was confirmed ready (array, sled, and video cameras) by radio to the test directors, the helicopter was called in and the beach cleared of array handlers. The helicopter landed as shown in Figure 17 and one of the helicopter crew members attached the array to the helicopter.

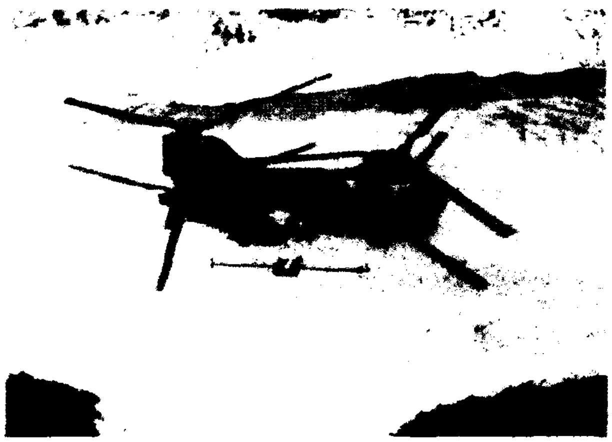

Figure 16. Array Layout Prior to Deployment

36. Helicopter procedures were fully detailed in a flight test plan provided to the Naval Surface Warfare Center, Indian Head Division, by the Naval Air Warfare Center Aircraft Division, Patuxent River, MD. We were fortunate to have a skilled 4-person helicopter crew since the lifting and deployment of the array required precise piloting control and communications. If they flew too high, the array would not be fully extended seaward when released; if too low it would be dragged through the water, quite unlike a rocket deployed array. Correct tension was also a concern. The amount of tension that the helicopter applied to the array was limited by the allowable swing of the counterweight under the helicopter and the altitude of the helicopter. If too much

tension was applied, the array would recoil toward the beach, rotating and collapsing about itself, as was the case during Drop 1.

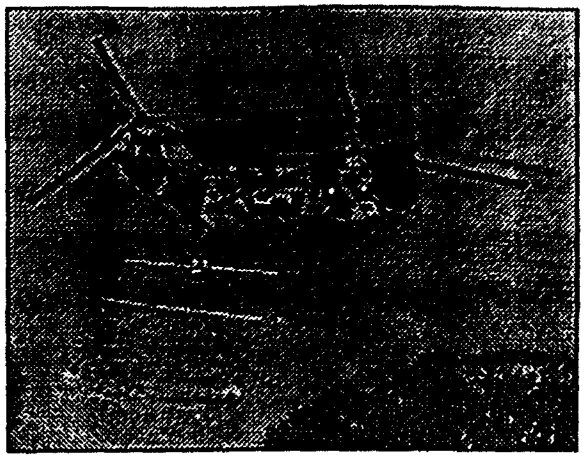

Figure 17. Helicopter Ready to Lift Array

37. During the best drops, the helicopter maintained a low altitude, keeping some of the array in the water. Once fully extended, the helicopter applied only enough tension to fully extend the array laterally and to straighten it out. Then on radio command from the test directors, the release mechanism was pulled by the helicopter crew and the array was deployed. The helicopter then returned to its landing area to drop off the counterweight.

38. Once deployed, the ground crew returned to the landward end of the array to check the anchor lines and to make observations, particularly of marker buoy and array performance. Movement of the array was recorded by the video cameras.

39. The retrieval process began with the beach crew releasing the array from the anchors and securing the landward end of the array with a single long line. This line was held by one person located as far away from the end of the array as possible to avoid the prop wash of the helicopter. The helicopter then landed over the landward end of the array and one of the crew members connected it. As the helicopter took off, the array was lifted out of the water and flown to an open stretch of beach. Instead of simply lowering the array into a pile, the helicopter pilot was able to spread out the entire array before releasing it and returning to the landing area. The array handlers then began the retrieval process, first removing the perimeter buoys and then reefing the array onto the forklift.

40. During and before the deployment of the array, the forklift also was used to

pull the instrumented sled shoreward, stopping at specific offshore locations in order to record the local wave heights and currents. Because the sled was located some distance from the drop site, visual estimates were also made of the longshore current in the drop zone by measuring the movement of floating markers. This was particularly important for some of the later drops when it appeared that the sled was in or near a rip current and that longshore velocities measured by the sled were not representative of conditions around the array.

Drop Discussion

41. Each of the drops had slightly different objectives and successes. In the following paragraphs, each of the drops is discussed in detail. The seven drops can be separated into two groups, drops made either north or south of the research pier.

a) Drops 1 through 3 were conducted on the south side of the pier to take advantage of the wide beach which provided adequate room to locate the array and the helicopter. Drop 1 was a test of the helicopter deployment procedure and was not designed to collect data. Following this drop, the procedure was modified to reduce the tension applied to the array prior to release and to keep the helicopter at a lower altitude. This drop was also a first test of the video camera angles and techniques. Because it was not a data drop, Drop 1 is not discussed further. Drops 2 and 3 were conducted to refine the observations and the release procedure. During these drops the primary video camera was located on the CRAB which was driven onto the dune. Since this did not provide a high enough view angle, it was decided to move the drop zone to the north side of the pier.

b) Drops 4 through 7 were conducted seaward of the observation tower. These were generally the best drops. Drops 5 through 7 differed from all earlier drops in that lead core line was attached to two of the array panels in an attempt to improve its stability.

Wave and Current Conditions

42. Table 6 lists the process measurements which were made. The first column gives the Drop number, the date and the exact time of the drop in Eastern Standard Time. The second column lists the wave height (H_{mo}), wave period (T_p), and direction (relative to true north) as measured by a wave gage in 25 ft water depth. Wave directions are given relative to true north and are the directions from which the waves are approaching. For reference, shore normal waves at the FRF arrive from 70 deg. The 25 ft wave gage provides general wave conditions for each drop.

43. The movable sled was instrumented with a pressure gage to measure wave height and water depth, and three current meters located at 1.3, 3.4, and 5.3 ft above the bottom. These are respectively referred to in Table 6 as B (bottom), M (middle), and T (Top). Since most of the required measurements were in water shallower than 5 ft, the top current meter was used only at the deepest point during Drop 2. Position and orientation of the sled were determined by surveying prisms located on the sled mast. The sled was not deployed during Drop 1, and a leak in one of the underwater housings caused Drop 4 to be missed. Under the *Sled Position* heading in Table 6 are the start time, location, and depth of each stop the sled made during the different drops. The depth column is the mean depth as measured by the pressure gage, and the coordinates are relative to the FRF coordinate system.

44. Under *Sled Measurements* are the H_{mo} and T_p as measured by the pressure gage, along with the current speed and direction for each of the current meter positions. Current directions are given in terms of the direction toward which the current is flowing. Since the general orientation of the shoreline at the FRF is 340 degrees (N 20 deg W), a direction measurement of around 320 degrees indicates a current flowing predominately northward with a slight onshore component. Similarly, a direction of 30, 60, or 80 degrees indicates a current moving offshore and it is likely that the sled was in a rip current. This was particularly true during Drop 6 when the sled, located north of

Table 7. Wave and Current Conditions Measured by the Sled

Drop # Date Time	8m Wave gage (H,T,dir)	Time (EST)	Sled Position: Longshore (ft)	Sled Position: Cross-Shore (ft)	Sled Position: Depth (ft)	Sled Measurements: Hmo (ft)	Sled Measurements: Tp (s)	Sled Measurements: CM (B,T,M)	Sled Measurements: Speed (ft/s)	Sled Measurements: Direction (TN)
Drop 2 18-Aug-92 10:16	2.3 ft 7.5 s 89 deg	10:14	894	585	6.4	2.76	7.5	M	0.04	277
								T	0.18	149
		10:23	890	552	4.7	2.03	7.5	M	0.41	68
		11:03	872	480	2.9	1.9	7.8	M	1.27	351
Drop 3 18-Aug-92 15:34	2.4 ft 7.3 s 95 deg	13:49	922	770	7.7	3.18	8.3	B	0.23	59
								M	0.09	99
		14:18	871	625	5.3	3.12	7.8	B	1.18	31
								M	1.19	37
		14:57	860	580	3.0	2.43	8.3	B	2.20	39
								M	1.75	35
Drop 4 19-Aug-92 11:25	2.5 ft 8.5 s 100 deg	no sled data								
Drop 5 19-Aug-92 17:08	2.2 ft 7.8 s 100 deg	16:38	2264	590	4.9	2.36	8.8	B	0.66	302
								M	0.69	318
		16:55	2290	494	5.6	1.9	8.8	B	0.89	308
								M	1.01	324
		17:23	2305	438	2.9	1.74	8	B	0.95	312
								M	0.93	327
Drop 6 21-Aug-92 9:24	3.1ft 4.9 s 58 deg	9:15	2359	656	8.8	3.41	4.7	B	0.84	66
								M	0.85	88
		9:49	2397	561	8.1	3.48	4.7	B	0.39	83
								M	0.34	79
		9:58	2404	442	7.3	2.53	4.9	B	0.95	57
								M	1.01	36
Drop 7 21-Aug-92 13:38	2.6 ft 5.0 s 61 deg	13:32	2251	636	10.3	3.22	5.1	B	0.24	306
								M	0.51	316
		13:46	2270	530	10.0	3.51	5.1	B	0.57	263
								M	0.71	274
		14:01	2298	439	6.8	2.79	5.1	B	1.00	183
								M	1.24	202

the drop zone, was observed to be in a rip. To augment sled measurements, the movement of tossed floats was timed in the drop zone. When not in a rip, the sled measured currents across the surf zone which reflected increasing longshore current speed closer to the beach. This is shown for Drop 7 in Figure 18.

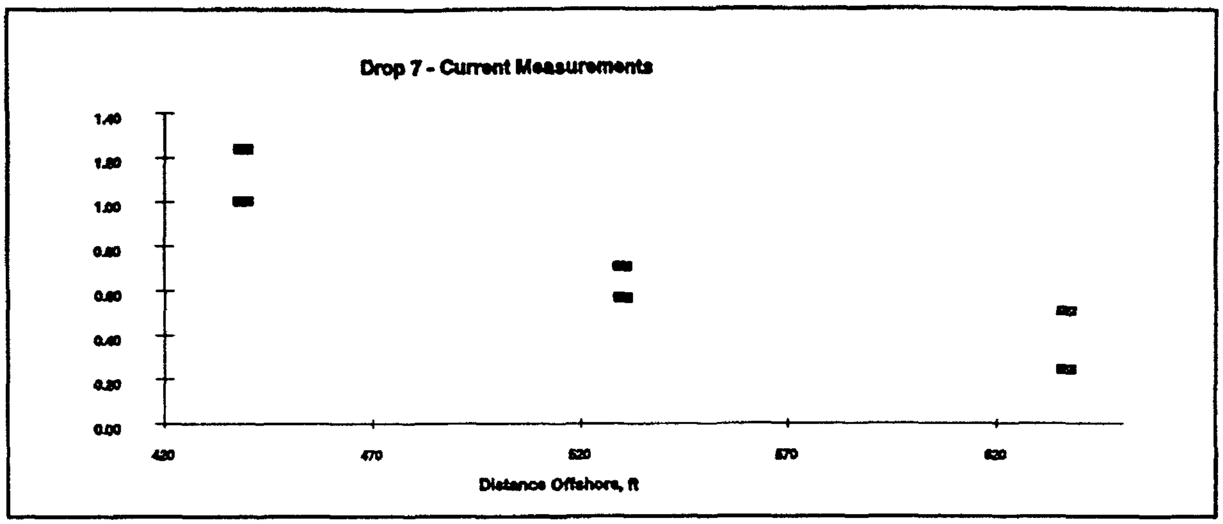

Figure 18. Distibution of Current Velocity by Offshore Distance. The Two Squares at Each Location Indicate the Two Current Meters

45. Although the drops were planned for mild wave conditions, Drops 2 to 5 were characterized by sea state 2 waves (2-2.5 ft high) approaching the drop zone at an angle of 20 degrees to shore normal. These waves produced strong longshore currents of up to 2.2 ft/s which had a profound impact on the array. Conditions during Drops 6 and 7 approached sea state 3 (see Table 3) with 3.1 ft waves arriving from the NE. Because of the influence of the pier, the general flow of the longshore current was still toward the north.

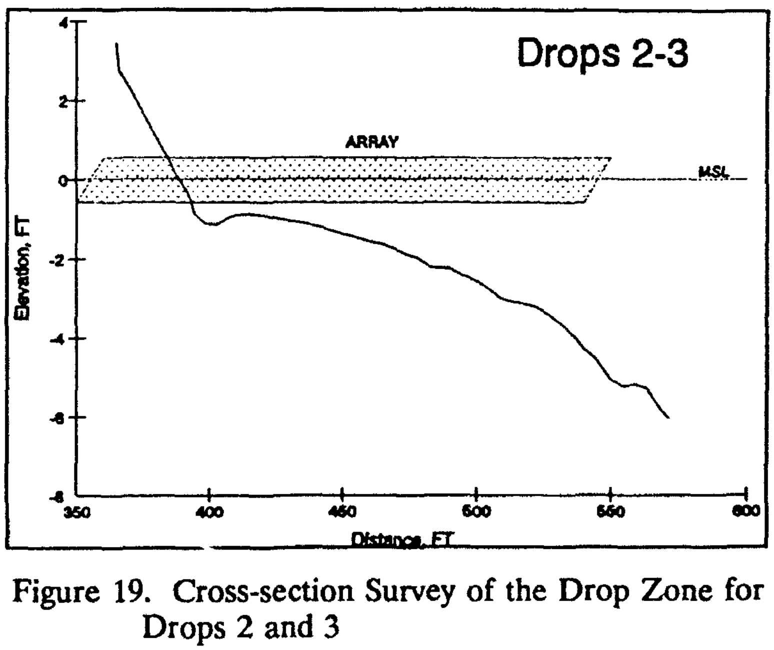

Figure 19. Cross-section Survey of the Drop Zone for Drops 2 and 3

Drops 2-3

46. The bottom profile and approximate initial location of the array relative to the shoreline is shown in Figure 19. The profile cross-section indicates a large wide nearshore terrace with a trough close to the shoreline position. Nearshore currents were estimated at 2 ft/s, toward the north since they were driven by the southerly approaching waves.

47. As can be seen in Figure 20, Drop 2 was perfectly handled by the helicopter. The array was fully extended and expanded from the shore just before release. However, because of a high anchoring position on the beach, only about 1/2 of the array was in the water. Since the perimeter buoys did not release well, the video coverage was inadequate. The video tapes do show the rapid movement of the SE control buoy toward the beach into the drop zone. Observations made from the beach indicated that the array immediately moved northward under the influence of the strong current.

48. Drop 3 was a repeat of Drop 2 except that video taping techniques were changed as was the perimeter buoy rigging. The helicopter tensioned the array so it was straight prior to release. However, within seconds of the drop, the array deformed into a wide curve. This can be seen in Figure 21 taken 1 minute after the drop. Note that the white circles with the X in the center indicate the location of the control buoys. Small white ovals mark the visible perimeter buoys. More buoys are visible in the original video tape. The one minute time interval reflects the minimum time between water impact of the array and detonating it. The current in the drop zone was estimated at 2 ft/s. The drop went well with more of the array in the water than in Drop 2, and much improved perimeter buoy release. In fact many of the buoys released too soon, as the array was being lifted. With the low afternoon sun angle, the perimeter buoys showed well on the video tape. Unfortunately, the array and the control buoys were moved quickly out of the fixed camera angle.

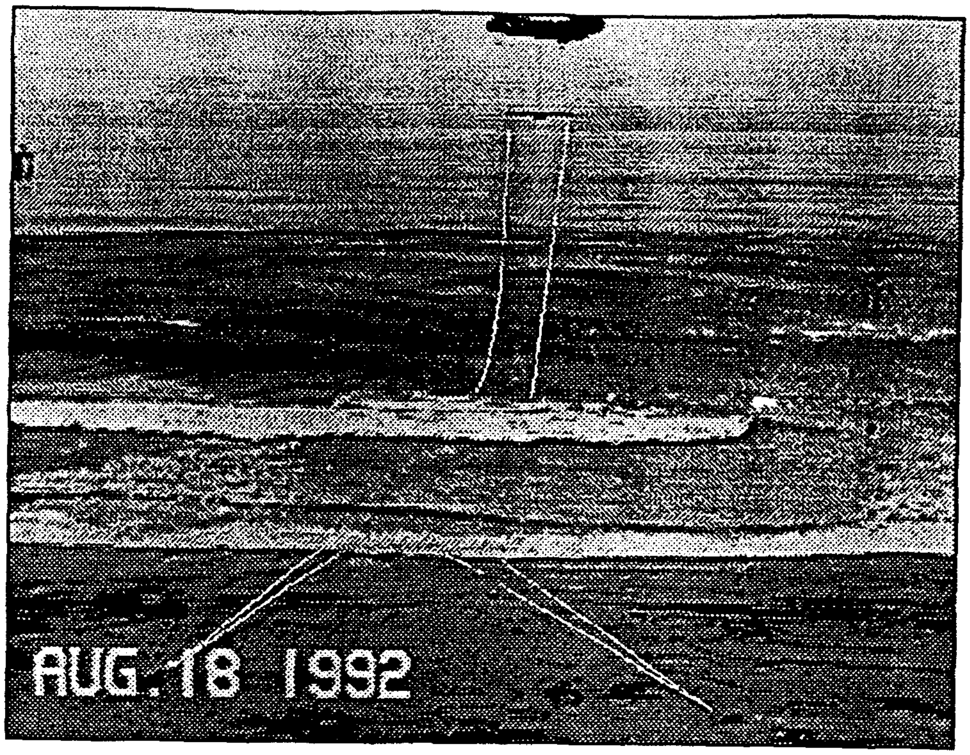

Figure 20. Helicopter and Array Just Prior to Drop 2

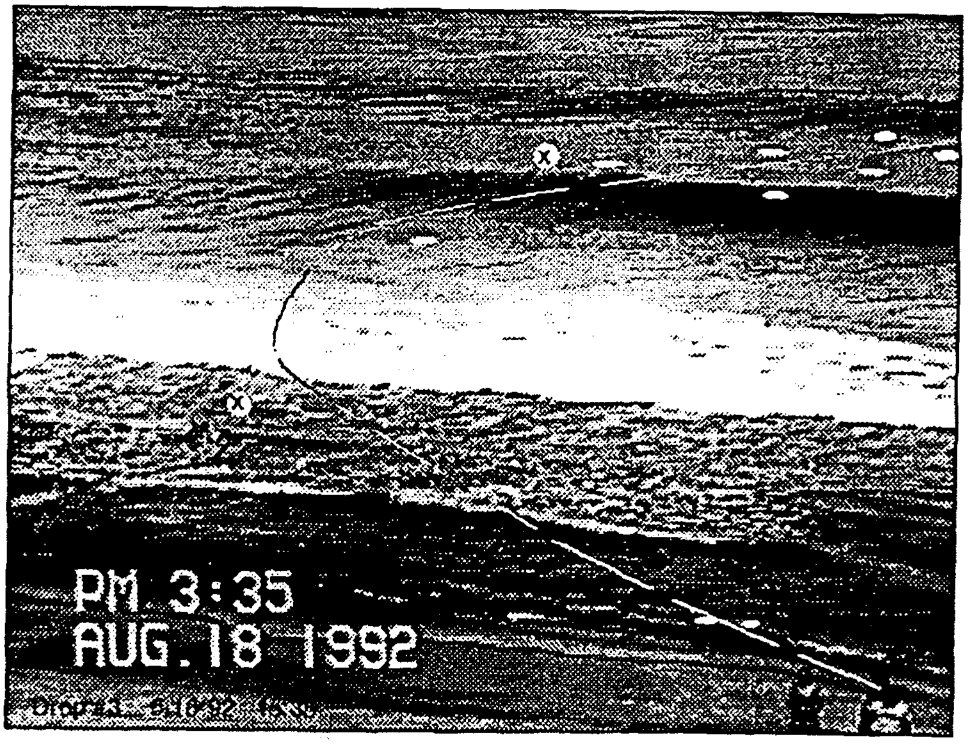

Figure 21. Drop 3 One Minute After Deployment

Drops 4-7

49. These drops were conducted just north of the FRF observation tower and over the profile shown in Figure 22. As on the south side of the pier, the profile in the drop zone was relatively wide with a small trough feature close to the beach.

50. Drop 4 was an excellent drop as shown in Figure 23 with nearly full and straight initial extension of the array. The wave conditions were good for video taping with wave breaking only close to shore. The camera angle from the tower was sufficient to observe the movement of the array during the first few seconds after deployment. Water visibility was also excellent allowing the array to be observed as it sank. Within 6 sec after the release, the inshore section of the array had already moved almost the full width of the array (approx. 25 ft). A full 16 seconds elapsed before the seaward end of the array sank out of view.

51. Figure 23 taken one minute later shows that the array had already moved to the left a distance of approximately 50-70 ft eventually reaching an equilibrium shape between the beach anchors and the spreader bar.

52. The lead core line was added to the second and third panel from the landward end prior to Drop 5. This was in the zone of most movement

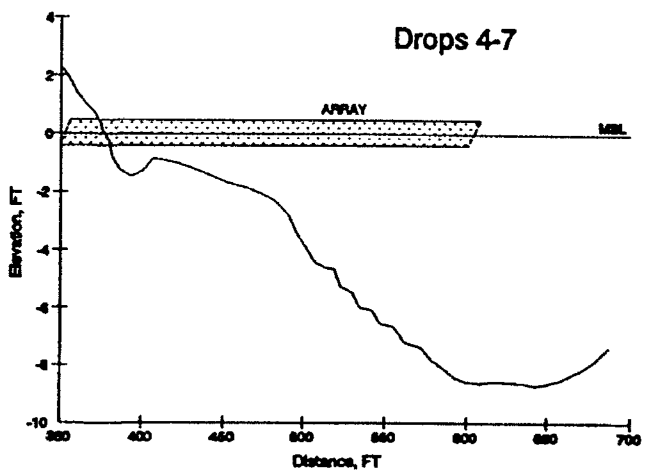

Figure 22. Cross-section Profile for Drops 4-7

during Drop 4 and it was hoped that this section of the array would sink faster and adhere to the bottom better. During the lifting process, one or more of the perimeter buoys became entangled in the array about 2/3 out. This caused a large snarl to develop which interferred with the expansion. In addition, the array was released early and was never properly extended by the helicopter. This can be seen in Figure 25 which clearly shows the control and perimeter buoys and the initial shape of the array at the time of release. For reference, the control buoys are approximately 150 ft apart (longshore). One minute later, the array had migrated further to the left (Figure 26) reaching the control buoys. More importantly, the array appeared to roll, losing its sideways expansion. The added weight did not appear to improve the performance of the array in the current and wave conditions experienced during the drop.

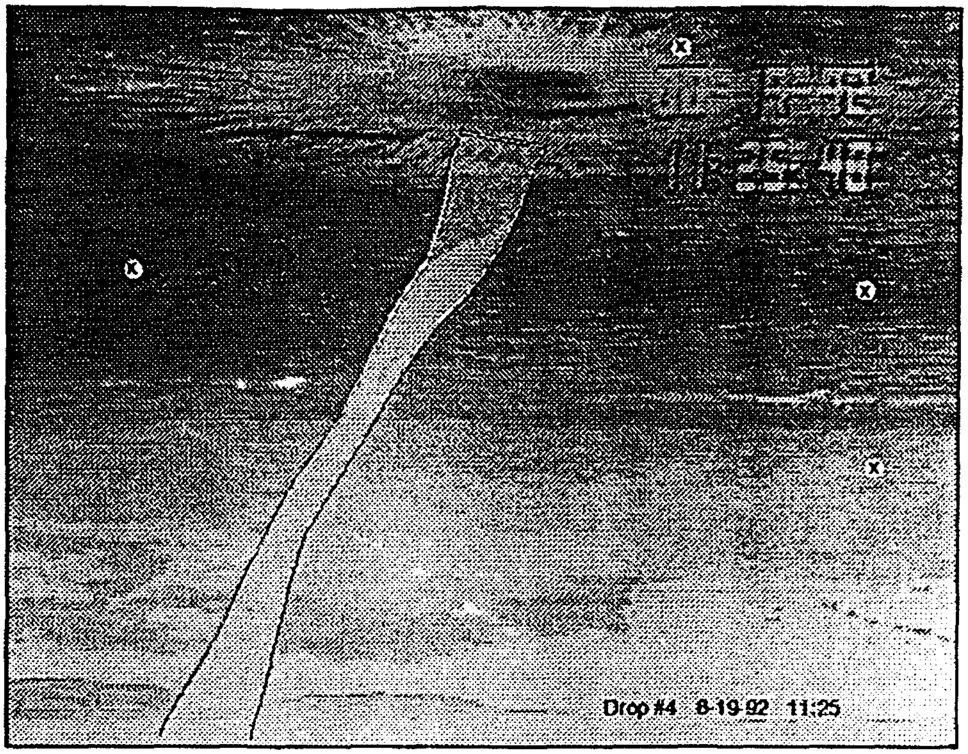

Figure 23. Drop 4 From the Tower Just as the Spreader Bar Hits the Water

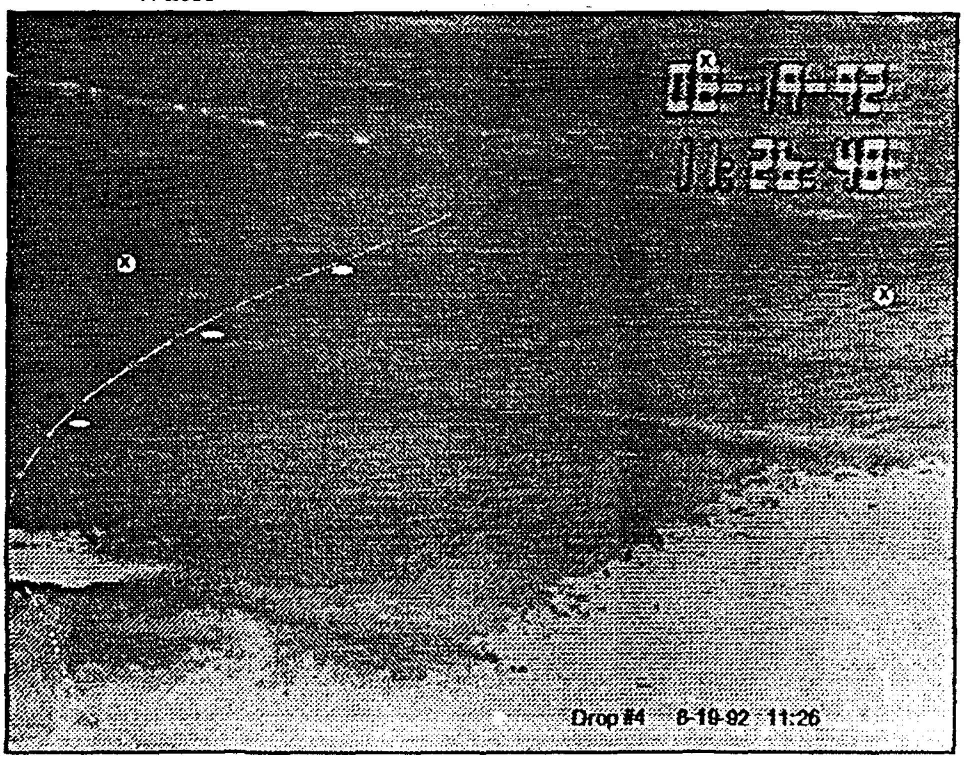

Figure 24. Position of the Array, One Minute into Drop 4

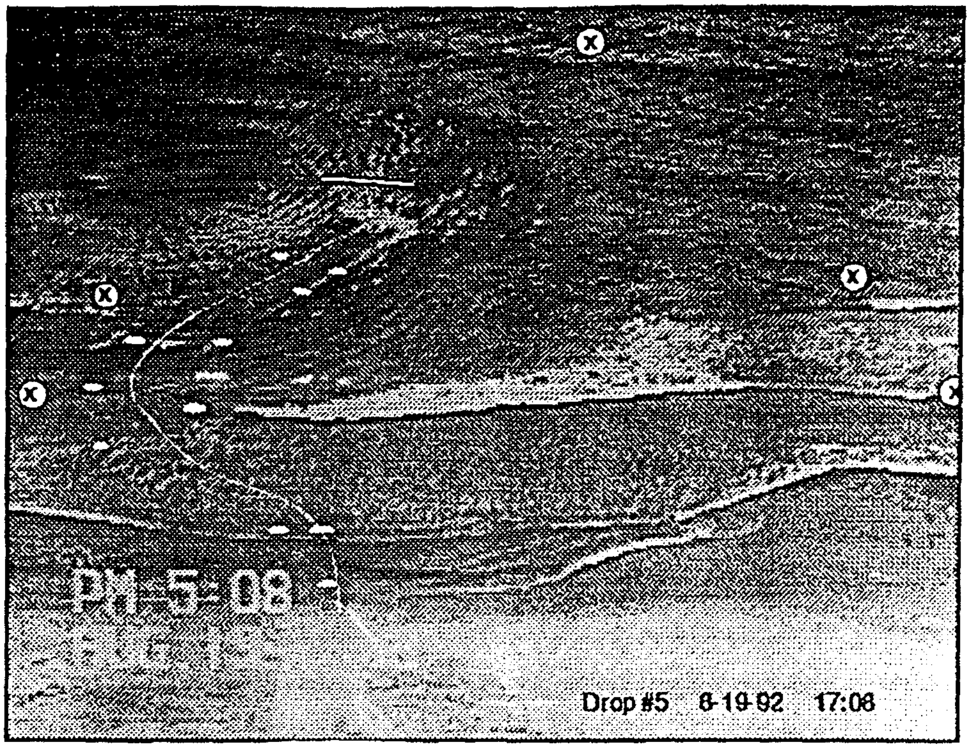

Figure 25. Drop 5 as the Spreader Bar Enters the Water

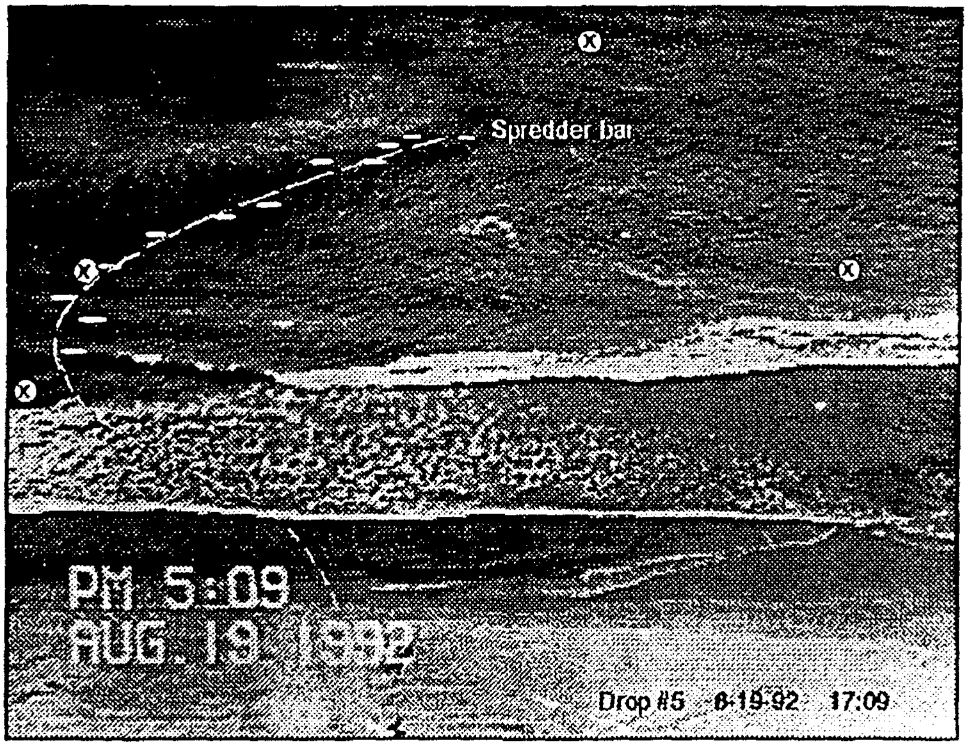

Figure 26. Drop 5 After One Minute. The Array has Already Reached the Northern Control Markers

53. Wave conditions for Drop 6 were significantly different, larger wave heights and shorter periods than for any of the earlier drops (see Table 6). This significantly affected our ability to monitor the drop. Figure 27 shows the spreader bar entering the water surrounded by rough seas. Again, the array was not tensioned properly and even as it entered the water it was already moving to the north. The perimeter buoys deployed well but because of the sun angle and the rough seas, they could only be identified from the zoomed camera view shown in Figure 27. This image, taken one minute after the drop reflects the observed 1.5 ft/s current moving to the north. It was impossible to determine if the lead core line improved the performance.

54. Waves were breaking across the inner part of the drop zone during Drop 7 shown in Figure 29. This obscured the white perimeter buoys close to shore. Although lateral expansion was good, the release occurred slightly before the array was fully stretched seaward. Close to shore the array moved northward and the panels with lead core line appeared to bunch up and roll. Most of the perimeter buoys were visible seaward of the breaking waves. The final shape of the array is clearly evident in Figure 30, taken one minute after deployment. It was estimated visually that deformation equaled 25 to 40 ft.

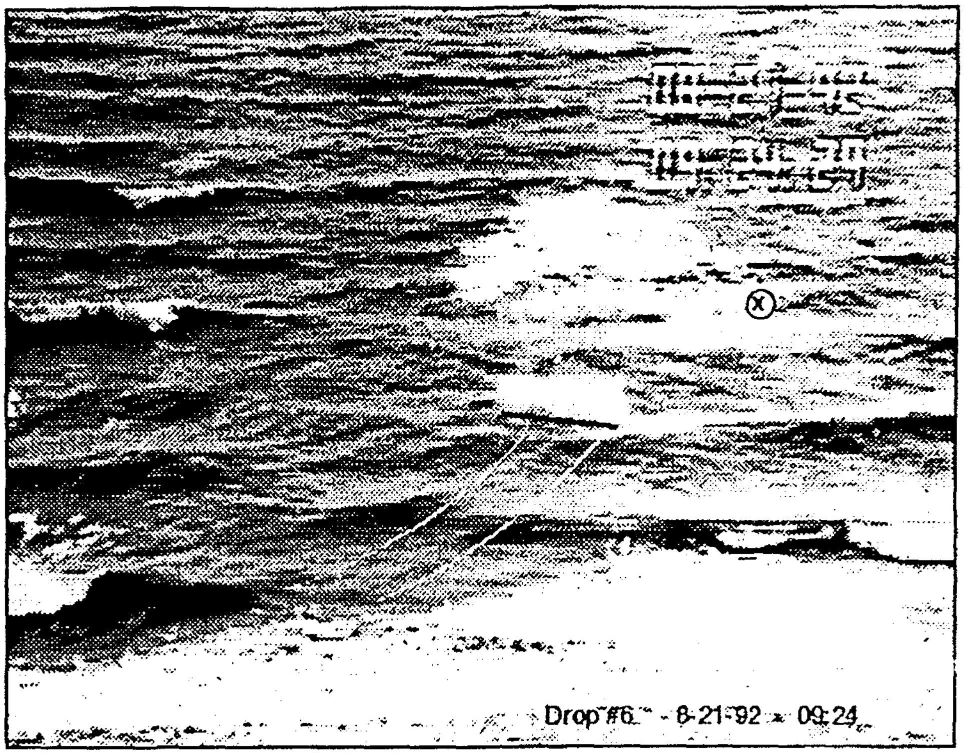

Figure 27. Drop 6 as Spreader Bar Hits the Water. Note Wave Action

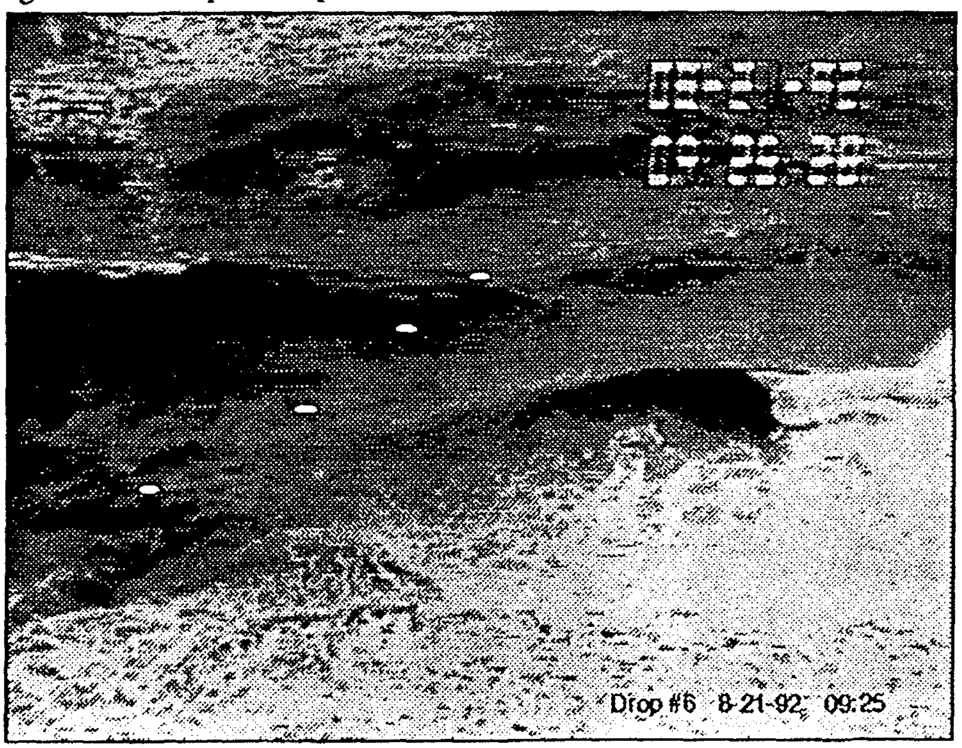

Figure 28. Zoomed View of Drop 6 After One Minute
Perimeter Buoys Show Movement of the Array
to the North

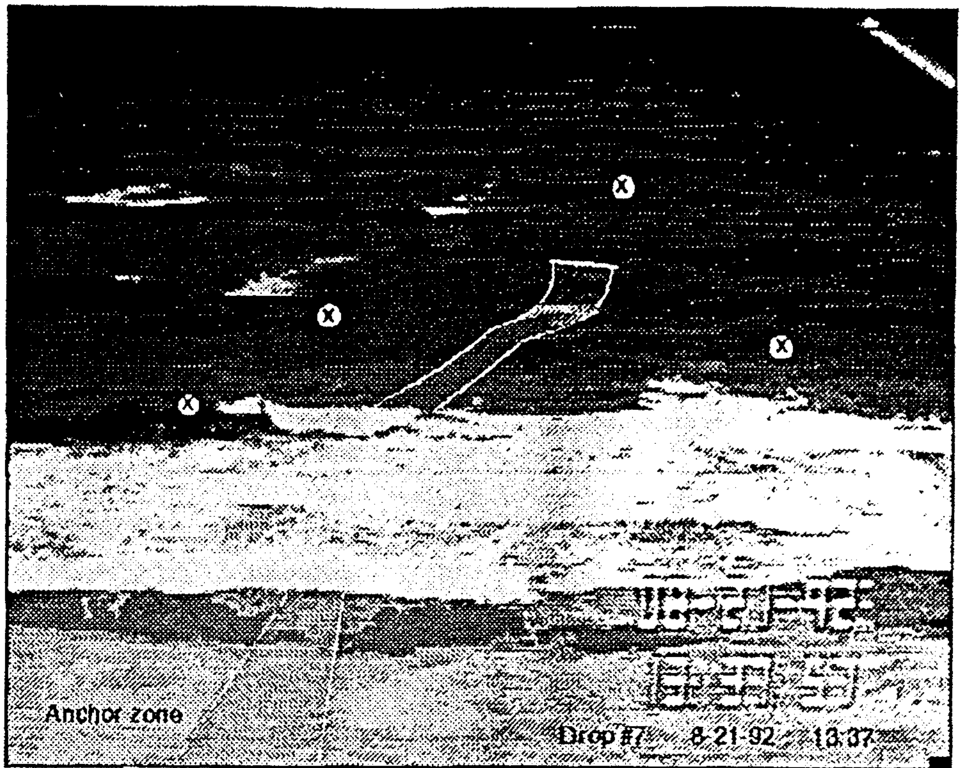

Figure 29. Drop 7 as Spreader Bar Hits the Water

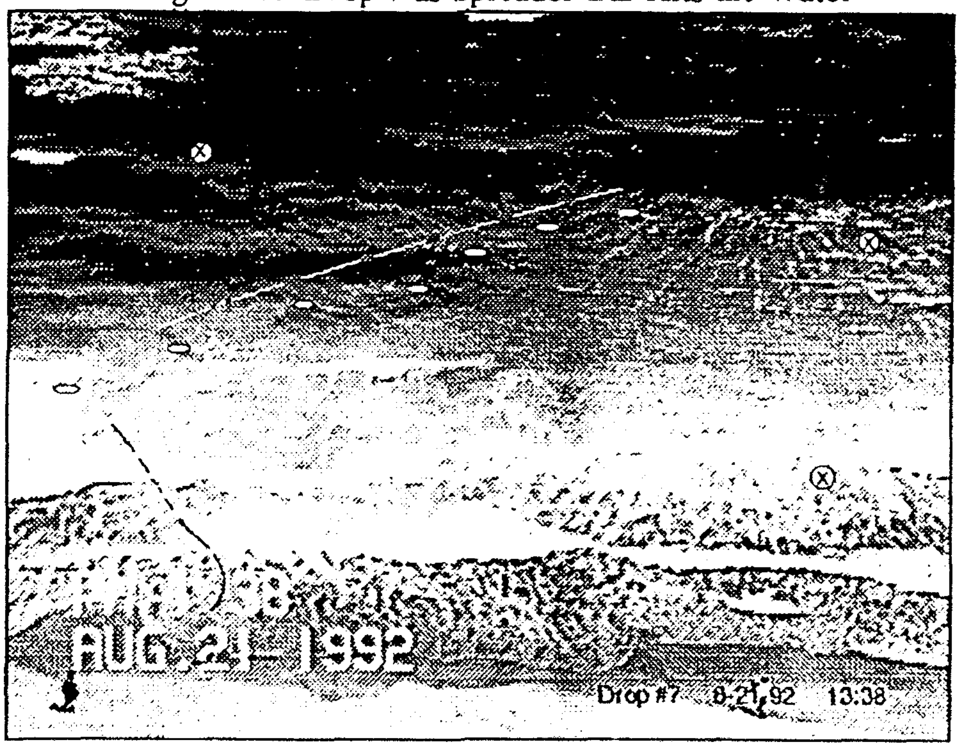

Figure 30. Drop 7 After One Minute Showing Array Extension to the North

Results of the Field Tests

55. The primary product of the field tests is the set of original video tapes which documents the different drops. Table 8 summarizes the video tapes taken during the week. All have been copied to VHS format for ease of distribution.

Table 8. Summary of Video Tape Coverage

Video Tape ID, Camera Person	Camera Location	Included Coverage	Tape Time
A - Bill Parillo	Beach	Array preparations	0:00:00
	Beach	Drop 1	0:05:00
	Beach	Drop 2	0:25:00
	Beach	Drop 3	0:43:25
	Helicopter	Drop 4	0:56:06
	Helicopter	Drop 5	1:00:50
	Helicopter	Drop 6	1:08:11
	Helicopter	Drop 7	1:13:28
B - Clifford Baron	Beach	Array preparations	0:00:00
	Pier	Drop 1	0:20:00
	CRAB on dune	Drop 2	0:35:00
	CRAB on dune	Drop 3	1:18:40
C - Clifford Baron	Pier	Drop 4	0:00:00
		Drop 5	0:14:15
		Drop 6	0:39:40
		Drop 7	0:53:31
D - William Birkemeier	Tower (camcorder)	Drop 4	0:00:00
Michael Leffler		Drop 5	0:22:40
Michael Leffler		Drop 6	0:39:12
Michael Leffler		Drop 7	0:59:46
E - Jim Fowler	FRF compound	Array preparation	0:00:00
	Beach	Drop 1	0:15:16
	Pier	Drop 2	0:38:13
	Dune	Drop 3	1:11:46
F - Jim Fowler	Dune	Drop 4 (scratched lens)	0:00:00
G - Judy Roughton	Tower	Drop 1	0:00:00
		Drop 2	0:24:00
		Drop 3	1:13:02
		Drop 4	1:31:46
H - Judy Roughton	Tower	Drop 5	0:00:00
		Drop 6	0:34:51
		Drop 7	1:09:00

56. Probably the most profound aspect of the field tests, the one with greatest importance to the system design is the influence of waves and currents on the array. Being nearly neutrally buoyant and without anchoring, once the array hits the water it moves at or near the velocity of the flow. For the 2 ft/s currents observed during the tests, this could equate to upwards of 120 ft of longshore movement during the first minute. This kind of movement was not observed only because the spreader bar acted like an offshore anchor. Had the spreader bar not been used, then it is highly likely that the entire array would have eventually migrated to the shoreline, held only by the land anchor. The addition of the of the lead core line did little to change the overall performance and may have actually interfered with lateral expansion. It is likely that if the weight necessary to stabilize the array was added, it would be too heavy to logistically launch and handle (note, the 70-100 lb anchors used on the control buoys were inadequate to keep them in place). It should be noted that although the system requirements are based on sea state, longshore currents result from a combination of wave and energy and wave angle. *Consequently, it is possible to have strong longshore currents under mild wave conditions.*

57. The influence of the high waves and currents had other effects on the conduct of the tests. Many of the monitoring plans were designed around milder conditions when the array would be expected to stay in place and swimmers and divers could be deployed to observe how well the array maintained its expansion. In fact, we were unable to determine any impact that the waves had on the settling or expansion characteristics of the array. This is unfortunate since the laboratory tests indicated problems adhering to the bottom under higher wave conditions.

58. In retrospect, the field conditions experienced were probably fortuitous. Key objectives of the field test were satisfied. We demonstrated that a helicopter can deploy and retrieve the array under the design conditions, in itself a significant achievement. Most importantly however, the importance of currents to the performance of the system was identified early enough to revise the design or deployment plan.

Suggestions for Future Field Experiments

59. A future series of experiments would benefit from some of the lessons learned during these tests. One obvious shortcoming of the helicopter deployment is that, while it works, it doesn't correctly simulate a rocket deployment. In fact, the array enters the water first in the shallow landward end, exactly opposite to a rocket launched array. This contributed to the poor expansion of the array since the shoreward end was in the zone of strongest currents the longest. An ideal test would use rockets to launch the array and a helicopter to retrieve it. Similarly, a wider array would better mimic the prototype array and be easier to observe. The spreader bar should be eliminated in order to more closely mimic the lack of offshore anchoring.

60. More control information was needed in the video images, and these could have been points marked on the beach, or additional buoys. Control markers should be permanently anchored for accurate measurements. The perimeter buoys eventually worked well but could only be seen in calm water. Buoy sizes should be tested at the operational camera view points before the actual tests. Clear water, which is uncommon at the FRF except in July and early August, would have helped. Afternoon deployments, with the sun behind the cameras, are a must for quality video tape.

PART IV: DISCUSSION AND SUMMARY

Limitations for Deployment

61. Based on experience gained in the laboratory study reported herein, *which considered effects of wave action only, sea state 3 seems to be a limiting condition for use of the array without additional weights or anchors.* Laboratory tests conducted to determine the benefits of adding weights (in the form of lead sinkers and multistrand wire) to the corners/back edge of the array showed great success in all cases (including sea state 3). Greatest success for minimizing effects of wave action was obtained when the simulated rocket motor landing points were positioned shoreward of the maximum wave runup.

62. Field tests conducted at Duck reinforced laboratory findings which concluded that sea state 3 is a limiting condition for practical unmodified deployments. In addition, the field tests provided an eye-opening insight into the effects of longshore current on the proposed system. Although no calm or very mild sea state conditions were experienced during the field tests, the consensus of opinion of the study participants is that the effects of current are major and must be considered in design of all arrays to be used in a shallow water coastal environment. Unfortunately all deployments during the field study were conducted at or above the mid range of sea state 2. Therefore, few conclusions can be drawn from the field test concerning deployments during wave/current conditions of lower sea state 2 and lower.

Discussion and Recommendations

63. Based on observations and data from the laboratory and field tests, several items will need to be addressed before distributed explosive arrays can be successfully deployed and functional in a wave/current environment. Among the more prominent are:

a. What can be done to minimize the effects of longshore currents?

b. In order to optimize deployment timing, a better understanding is needed as to when the array needs to be detonated for maximum effect.

c. Can point weights be added to the array and successfully launched by dual rocket motors?

d. How does the cleared lane get marked so that follow-on traffic successfully avoids mines/obstacles which are not cleared.

Items a, b, and c must be addressed by further study (either in a laboratory or field environment) before successful deployments of a distributed explosive array in a wave/current setting will be possible. Item d) is not included here, but could also be successfully addressed in laboratory or field studies. Several ideas for improving performance in a wave/current environment have been put forth;

a. If battlefield conditions allow, a deployment technique which uses anchors at each of the array corners (the rocket motors would suffice at the shoreward corners) might contribute significantly to the stability of the deployed array and increase expansion of the array. When the distributed explosive array is installed while not under hostile fire, consideration should be given to using the LCAC to position (expand) the array.

b. When longshore current direction is consistent, a modification to the array, which includes additional weighted lines or point weights positioned along the updrift edge of the array, might allow the current to assist in "expanding" the array. Although this could be successfully simulated in a physical model or at the FRF, it is not known what effects such modifications would have on the rocket deployment methods.

c. For situations where longshore currents are strong and hostile fire is not a consideration, a deployment of the array with the longest dimension parallel to the shoreline might actually take advantage of the current.

Additional Comments

64. The proposed distributed explosive array is over six times wider than the array tested at the FRF. If its expansion could be maintained, this size would be an improvement over the test array. Even if it deformed in the current, the area covered would still be on the order of 100+ ft, wide enough to be useful. It would however be important to accurately identify the covered area. Wide arrays, even if they deformed as observed during the field tests could still be overlapped to provide adequate cleared zones.

65. Although rip currents are ephemeral features not consistently found on the world's beaches, they offer clear advantages for array usage. First, the offshore flowing current would help extend the array seaward from the rocket anchors while reducing the longshore deformation. Moreover, rip current channels provide the deepest water access to the beachface and if currents are not overwhelming, are ideal for an amphibious landing. Unfortunately, identifying the location of rip currents is difficult. The identification of rip channels and other nearshore features using remote sensing is a subject of ongoing ONR studies being conducted at the FRF and elsewhere.

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APPENDIX A: NOTATION

D	sediment particle diameter
d	depth
d_{max}	maximum depth
d_w	depth of water at vertical wall
F_b	Force due to buoyancy of array
Fr	Froude number, $V/(gL)^{½}$
H	wave height
$H_{1/3}$	significant wave height, or average of highest 1/3 of all waves
H_{avg}	mean height of all waves
H_{rms}	root mean squared wave height
H_{max}	maximum wave height
H_{mo}	zeroth moment wave height
H_o	deep water wave height
l	characteristic length
L_o	deep water wave length
N	scale ratio
SWL	still water level
t	time
V	velocity
W_a	weight of array
$(W_e)_a$	effective weight of array
x	horizontal distance
z	distance above bed

Greek Letter symbols

ω	Sediment fall speed
γ_a	specific weight of array
γ_w	specific weight of water
ν	kinematic viscosity $= \mu/\rho$

Subscripts

b	bed
l	characteristic length
m	Model
max	maximum
mo	Zeroth moment
p	Prototype
s	significant
t	time
T	wave period
x	distance in x direction
y	distance in y direction
z	distance in z direction
ω	fall speed

APPENDIX B

DETAILS, NOTES, AND OBSERVATIONS

FROM ALL TESTS

Table B-1. Details, Notes and Observations for All Laboratory Tests.

Test Number	Date	Test Condition Tables 4 and 5	Sea State Simulated	Array Used	Remarks
1-SS1	5-8-92	1	1	II	Polyester array behaved at all depths; 400 sec. of waves at 1.0 sec. period; white array is difficult to see
1-SS2L	5-8-92	2	2L	II	Same as 1-SS1
1-SS2M	5-8-92	3	2M	II	Same essentially; some minor movement to-and-fro; no displacement
1-SS3L	5-8-92	5	3L	II	Movement - completely dragged into surf zone
1-SS3M	5-8-92	6	3M	II	1st actually comp to between 2H - 3L
1-SS3H	5-8-92	7	3H	II	Moved considerably; probably a limiting case
2-SS1	5-8-92	1	1	I	Not much movement; some near shoreline
2-SS2L	5-8-92	2	2L	I	Not much movement; more near shoreline; still feasible development
2-SS2M	5-8-92	3	2M	I	Still fairly well behaved; in 10' (prototype) depth some waves moved the array and lifted it off bottom momentarily
2-SS2H	5-8-92	4	2H	I	Completely balled up in surf zone - Probably upper limit of deployability for this case
3-SS1-D	5-9-92	1	1	II	Conducted to observe array behavior during descent to bottom under mild waves; Array dropped and settled nicely; however a couple of small portions were not flat on the sand due to the way the net fell; not due to wave action
3-SS1-D	5-9-92	1	1	II	Net was dry; hung on water very shortly, then sank evenly and maintained expansion; lateral at 20' dist. from pt zero had bend in it.
3-SS2L-D	5-9-92	2	2L	II	Net is now wet from first test; net went right to the bottom; did not appear to be affected by waves at all
3-SS2M-D	5-9-92	3	2M	II	Tension net made it snap back; looked messy on bottom - but not from waves

Table B-1 (continued). Details, Notes and Observations for All Laboratory Tests.

Test Number	Date	Test Condition Tables 4 and 5	Sea State Simulated	Array Used	Remarks
3-SS2H-D	5-9-92	4	2H	II	Good drop; well behaved - no problem; right to the bottom
3-SS3L-D	5-9-92	5	3L	II	First time that the net rolled with the waves during drop (15 - 25 model ft from 0) before fully settling; instability at 0 to 10' model dist.
3-SS3M-D	5-9-92	6	3M	II	Did not seem to roll with the waves; settled very good
3-SS3H-D	5-9-92	7	3H	II	Moved with the waves; finally settled; motor washed over and dragged past zero mark; balled up between 5 to 17ft model dist.
3-SS0-DPR	5-9-92	-	0	IV	Dropped and settled evenly; slow but good sinking on deeper end; (poly gave some buoyancy)
3-SS1-PR	5-9-92	15	1	IV	poor lateral stability; bunched slightly lengthwise; (lost ~ 4'on seaward end); held on beach; overall expansion not bad
3-SS1-DWPR	5-9-92	15	1	IV	Deep water test; maintained expansion; very little shifting of array
4-SS1	5-20-92	1	1	III	Well behaved; virtually no movement all locations maintained shape
4-SS2L	5-20-92	2	2L	III	Same comments as above SS1
4-SS2M	5-20-92	3	2M	III	Same comments as above SS1
4-SS2H	5-20-92	4	2H	III	Some slight movement detected during bigger waves, however, kept overall shape very well
4-SS3L	5-20-92	5	3L	III	Much more movement but only slight disruption of the original spread. Did drag the array back into the water and this initiates majority of deformation

Table B-1 (continued). Details, Notes and Observations for All Laboratory Tests.

Test Number	Date	Test Condition Tables 4 and 5	Sea State Simulated	Array Used	Remarks
4-SS3M	5-20-92	6	3M	III	Considerably more movement and deformation, particularly in wave breaking region. Collapsed array towards middle - maybe this is a characteristic of the flume.
4-SS3H	5-20-92	7	3H	III	This is a limiting condition. Array significantly deformed in all regions; waves breaking completely lifted the array to the top of the column and moved to-and-fro.
5-SS3M-D	5-20-92	6	3M	III	3oz. Weights at front ends; 4oz. Weights at rear ends; Rear weighted ends did not move; tended to be scoured and dug deeper. Drop was not perfect so there was slack in the middle; consequently the center shifted to a greater degree than the pervious SS3M.
5A-SS3L	5-20-92	5	3L	III	4oz. weights in rear; Very little motion until wave runup pulled the onshore weights downward and resulted in slack in the array
5A-SS3M	5-20-92	6	3M	III	Well behaved - no significant deformation; 4oz. in rear
5A-SS3H	5-20-92	7	3H	III	Considerable movement - forward weights were dragged into the surf; rear weights also moved slightly; 4oz. in rear
5B-SS3L	5-20-92	5	3L	III	4oz. weights Forward R.M.'s moved above reach of runup (located 10' shoreward of zero; Did not move - well behaved maintained shape - very little slack in the entire array
5B-SS3H	5-20-92	7	3H	III	4oz. weights; Forward R.M. 10' above zero; Virtually no movement well behaved

Table B-1 (continued). Details, Notes and Observations for All Laboratory Tests.

Test Number	Date	Test Condition Tables 4 and 5	Sea State Simulated	Array Used	Remarks
6A-SS3L	5-21-92	5	3L	III	1oz. weight at rear; Front at +10.0ft. preplaced; No movement at rear; collapsed slightly in center; front well behaved
6A-SS3H	5-21-92	7	3H	III	1oz. weight at rear; Front preplaced at 10.0 shoreward of 0; Rear weights moved landward slightly - slack in array allowed deformation
6A-SS3H	5-21-92	7	3H	III	2oz. weights in rear; only slight deformation in the array; rear weights did not move
6AR-SS3H	5-21-92	7	3H	III	Repeat of 6A with SS3H; 1oz. weights in rear; Same results as previous 6A; rear weights moved 6 - 12 inches
7-SS2M	5-21-92	3	2M	II	Test done to see if array would bury; No sediment coverage
7-SS2H	5-21-92	4	2H	II	Same results as 7-SS2M
7-SS3L	5-21-92	5	3L	II	Same results as 7-SS2M
7-SS3M	5-21-92	6	3M	II	Same results as 7-SS2M
7-SS3H	5-21-92	7	3H	II	Same results as 7-SS2M
8-SS3L	5-21-92	5	3L	III	4oz. wire distributed in back section; well behaved; Forward weights +10.0 ft at most locations Wire end showed little if any motion
8-SS3M	5-21-92	6	3M	III	Forward weights +10.0ft. 4oz. wire distributed in back section; Same comments as 3L; Not much overall movement
8-SS3H	5-21-92	7	3H	III	Wire eq. to 4oz.; Wire moved slightly forward; allowed slight deformation; Nearly same as 6B which was 2.0 oz. sinker tests
9-SS1PR	5-22-92	15	1PR	IV	80ft. prototype array; Well behaved to approx. 38" depth trailing end moved and bunched up slightly - probably a function more of being the end of the array than anything else Weights on front; each corner

Table B-1 (continued). Details, Notes and Observations for All Laboratory Tests.

Test Number	Date	Test Condition Tables 4 and 5	Sea State Simulated	Array Used	Remarks
9-SS2LP-PR	5-22-92	16	2LP	IV	Prototype array; weights on front; each corner Moved a little more than SS1PR; still fairly well behaved none the less
10-SS1LP	6-10-92	8	1LP	III	No seaward weighting 2-RM's, Array on bottom initially; Long Period Waves; well behaved
10-SS2LP	6-10-92	9	2LP	III	Same results as 10-SS1LP
10-SS2MLP	6-10-92	10	2MLP	III	No seaward weighting; 2-RM's Array on bottom initially; Long Period Waves; Distorted from 0 to 10'; Well behaved on seaward end
10-SS2HLP	6-10-92	11	2HLP	III	No seaward weighting; 2-RM's Array on bottom initially; Long Period Waves; Very distorted; broke loose in shallow region; 0 - 10' seaward end moved at least 15'
10-SS2H	6-10-92	4	2H	III	No seaward weighting 2RM's Array on bottom initially Long Period Waves Regular period for comparison to last test. Some distortion (nothing as severe as before)
10-SS3HLP	6-10-92	14	3HLP	III	No seaward weighting; 2RM's; Array on bottom initially; Long Period Waves; Very distorted, twisted
11-SS1LPPR	6-10-92	15	1LP	IV	Prototype array with RM's; Well behaved, no distortion in deep or shallow ends; RM's got wet but did not move array; Array scours but never embeds
11-S2LPR	6-10-92	16	2LPR	IV	Prototype array with RM's; Well behaved, no distortion
12-SS2LLP	6-11-92	9	2LLP	III	4oz. wire rope distributed over last 12' of array; Array on bottom; RM's on beach; Well behaved, no movement
12-SS2MLP	6-11-92	10	2MLP	III	4oz. wire rope distributed over last 12' of array; Array on bottom; RM's on beach; Well behaved, some movement; no distortion

Table B-1 (continued). Details, Notes and Observations for All Laboratory Tests.

Test Number	Date	Test Condition Tables 4 and 5	Sea State Simulated	Array Used	Remarks
12-SS2HLP	6-11-92	11	2HLP	III	4oz. wire rope distributed over last 12' of array;. Array on bottom; RM's on beach; Shifted a little - kept good expansion; seaward end moved up a little
12-SS3LLP	6-11-92	12	3LP	III	4oz. wire rope distributed over last 12' of array; Array on bottom; RM's on beach; Distorted; seaward end moved up
13-SS3LLP	6-11-92	12	3LLP	III	4oz. wire rope, 4oz. sinker (2oz. each corner); Well behaved
13-SS3MLP	6-11-92	13	3MLP	III	Same results as 13-SS3LLP
13-SS3HLP	6-11-92	14	3HLP	III	4oz. wire rope; 4oz. sinker (2oz. each corner); RM's dragged down from beach a little; Distorted
14-SS2LLPR	6-11-92	16	2LLP	IV	Repeat of 11-S2LPR; Prototype array with RM's
14-SS2LP	6-12-92	17	2LP	IV	Prototype array with RM's and seaward end weights; Very well behaved; RM's on beach did not move; Array contoured to bottom and troughs; Seaward weights moved very little

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13. ABSTRACT *(Maximum 200 words)*

A series of 2-D (flume) laboratory and field tests were conducted to examine effects of waves and currents on a simulated dual-rocket distribution explosive array deployment (DRDEAD) system. The DRDEAD system consists of a large array of explosive material which can be deployed by rockets launched from Navy vessels across the surf zone in a mine-clearing operation. The U.S. Army Engineer Waterways Experiment Station (WES) Coastal Engineering Research Center's mid-scale 2-D facility was used to examine various wave conditions, methods of deployment, and anchoring systems for a simulated (inert) DRDEAD. Waves simulating sea state 3 conditions and lower (i.e., calm seas to 5-ft prototype waves) were used in the laboratory study. Laboratory tests indicated that sea state 3 will be a limiting condition for deployment of the array without additional weights or anchors. Field tests to assess effects of wave and current were conducted during the summer of 1992 at CERC's Field Research Facility (FRF) in Duck, North Carolina. Results of the field tests supported laboratory findings, but also indicated that longshore currents are likely to have equal or greater effects on the DRDEAD system and must be considered in the final design

14. SUBJECT TERMS
See reverse.

15. NUMBER OF PAGES
71

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

14. (Concluded).

Array embedment
Buoys
Coastal Engineering Research Center
DRDEAD
Dual-rocket distributed explosive array deployment
Duck, North Carolina
Explosive array
Explosive array deployment
Fall speed
Field tests
IHDIVNAVSURFWARCEN
Indian Head Division
Laboratory tests
LCAC
Landing craft, air cushion
Longshore currents
Scaled model
Shallow Water Mine Countermeasures Program
SWMCM
Waterways Experiment Station
Waves