ERDC/SL TR-00-4

US Army Corps of Engineers®
Engineer Research and Development Center

Analysis of Water Shock Data and Bubble Screen Effectiveness on the Blast Effect Mitigation Test Series, Wilmington Harbor, North Carolina

Denis D. Rickman

August 2000

Structures Laboratory

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Final report

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Prepared for U.S. Army Engineer District, Wilmington
P.O. Box 1890
Wilmington, NC 28402-1890

Engineer Research and Development Center Cataloging-in-Publication Data

Analysis of water shock data and bubble screen effectiveness on the blast effect mitigation test series, Wilmington Harbor, North Carolina / by Denis D. Rickman ; prepared for U.S. Army Engineer District, Wilmington.
100 p. : ill. ; 28 cm. – (ERDC/SL ; TR-00-4)
Includes bibliographic references.
1. Underwater explosions – Testing. 2. Shock waves. 3. Air curtains. 4. Wilmington, (N.C.) – Harbor. I. Rickman, Denis D. II. United States. Army. Corps of Engineers. Wilmington District. III. Engineer Research and Development Center (U.S.) IV. Structures Laboratory (U.S.) V. Series: ERDC/SL TR ; 00-4.
TA7 E8 no.ERDC/SL TR-00-4

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Preface

This research was sponsored by the U.S. Army Engineer District, Wilmington (CESAW), under MIPR No. W81LJ881988562. Mr. James T. Hargrove (CESAW-TS-ED) was the Technical Point of Contact.

The Geomechanics and Explosion Effects Division (GEED), Structures Laboratory (SL), Waterways Experiment Station (WES), U. S. Army Engineer Research and Development Center (ERDC), Vicksburg, MS, conducted the research.

Mr. D. D. Rickman, GEED, was the WES Project Scientist and was responsible for data analysis. Successful fielding of the WES instrumentation was made possible in large part by the efforts of Messrs. James W. Johnson and George Cronia, Instrumentation Services & Development Division, WES, ERDC.

During this investigation, Mr. A. E. Jackson was Acting Chief, GEED, and Dr. Michael J. O'Connor was Acting Director, SL, and Dr. Bryant Mather was Director Emeritus, SL.

At the time of publication of this report, the Director of ERDC was Dr. James R. Houston, and Commander was COL James S. Weller, EN.

1 Introduction

General

The U.S. Army Corps of Engineers, Wilmington District (CESAW), has been tasked with deepening the existing shipping channel for the Port of Wilmington, NC. Because well cemented rock will be encountered, in places, in the deepening or widening of Wilmington harbor, blasting will be required to fracture rock for removal. Experience has shown that the water shock produced by underwater blasting operations can produce significant fish kills and pose a threat to other aquatic life. Several endangered species inhabit the Cape Fear River in and near the shipping channel. Because of this, minimizing the biological effects of the blasting is of great interest.

Several water shock parameters have been associated, to varying degrees, with damage to aquatic life forms. Munday, et al (1986) provides an excellent overview of prior studies in this area. Peak water shock pressure is the parameter most commonly related to fish injury. However, Yelverton (1975) cites peak impulse as the most reliable parameter for predicting lethal ranges from underwater explosions. Peak energy flux density and the rate of pressure change have also been used as lethality predictors.

One commonly accepted means of reducing the level of peak shock introduced into the water is the placement of air curtains or bubble screens around the underwater explosive source. Bubble screens are generated by pumping air into a perforated manifold that is anchored on the bottom of the body of water. Research conducted by Strange and Miller (1961) and others has shown that the placement of bubble screens around underwater explosive sources can significantly reduce the levels of peak shock propagated into the water beyond. However, this research dealt only with explosives positioned entirely in the water (the "free-water" case). The effectiveness of bubble screens in reducing the peak water shock from explosives contained in a medium underlying the water is not well defined. This stems from the fact that the water shock pulse produced by a buried explosion is quite different from that produced by an explosion in free-water, and that very little data are available for the buried case. At this point, it is advantageous to examine more closely the character of explosively-induced water shock waves and how they are affected by bubble screens.

An explosion in free-water produces a water shock wave that propagates radially outward from the explosive/water interface. The shock wave is a wave of compression with a very fast rise (a few microseconds at most) to peak pressure. The sharp rise is a result of the intimate contact between the water and the surface of the explosive, which allows direct transfer of the explosive energy into the water. Since water is essentially incompressible, the peak shock level decreases almost entirely by the geometric expansion of the shock wave. An explosion in a medium underlying a body of water also produces a water shock wave. In this case, however, the explosive is not in immediate contact with the water and the amount of energy transferred into the water is greatly reduced. The amount of this reduction is dependent upon the depth at which the explosive is located in the medium and, to a lesser extent, the composition of the medium.

For the case of explosive detonated in a stemmed borehole in massive rock (i.e., a typical underwater rock blasting scenario), the explosive is not in direct contact with the water. Thus, the shock wave produced by the detonation must first travel through the overlying rock or stemming material before reaching the water. Also, a large portion of the explosive energy is expended in fracturing and/or displacing the surrounding rock. Because of this, the peak shock pressure imparted into the water is greatly reduced. The rise to peak pressure in the water shock wave is also somewhat slower than for the free-water case.

Engineer Technical Letter No. 1110-8-11, "Underwater Blast Monitoring" states that the approximate peak water shock pressure, P, from a detonation in free-water is

$$P=21{,}600(\lambda)^{-1.13}$$

Where λ is the scaled range ($ft/W^{1/3}$) and W is the TNT-equivalent explosive weight. Langefors and Kihlstrom (1963) cite a study in which the peak water shock pressure produced by explosives in boreholes was reduced to "10-14 percent" of the expected peak for the same charge weight in free-water. In the cited case, the ratio of explosive weight to volume of fractured rock was 1.25 lb/yd^3, as compared to approximately 1.4 lb/yd^3 for the planned Wilmington Harbor blasting operation. Based on this, the explosive in the boreholes in the Wilmington Harbor case is estimated to produce a peak water shock equivalent to 20 percent of that for the free-water case. The free-water equivalent explosive weight is attained by calculating the difference in charge weight required to achieve the observed reduction in peak water shock. If explosives located in a borehole produce a peak water shock equal to 20 percent of that produced by the same explosive weight in free-water, we can write the following relation

$$P_b = 21{,}600(\lambda_b)^{-1.13} = (0.2)P_f = 4{,}320\ (\lambda_f)^{-1.13}$$

Where P_b is the peak water shock from an explosive charge located in a borehole and P_f is the peak water shock from the same charge located in free-water. λ_b and λ_f are, respectively, the scaled ranges for the borehole and free-water cases. Since $\lambda_b = (r/W_b)^{1/3}$ and $\lambda_f = (r/W_f)^{1/3}$, it follows that

$$(r/W_b)^{1/3} = 4.155\ (r/W_f)^{1/3} \text{ and,}$$

$$W_b = 0.014\ (W_f)$$

Where the W terms are the charge weights in a borehole and in free-water and r is the radial distance from the charge. Thus, a given weight of explosives in a borehole produces peak water shock pressures equivalent to a charge only 0.014 times as large in free-water. For example, in the case of the typical 52-lb charges in boreholes planned for the Wilmington Harbor Case the equivalent free-water charge would be 0.728 lb (52-lb x 0.014).

The characteristics of the water shock wave are important when considering the effectiveness of bubble screens. A bubble screen functions as a compressible, low-density zone within the relatively high-density, incompressible body of water. In general, a water shock wave passing through a screen of bubbles is modified from its usual sharp rise to peak pressure and exponential decay as it compresses the air/water mixture. The amount of modification is dependent upon the air content of the bubble screen (air/water ratio and resultant density), the screen thickness, and the rise-time of the shock wave incident upon the screen. Because of dispersion effects, the peak pressure is reduced while the length of the pulse is increased. In fact, Strange and Miller noted that water shock wave duration was increased by up to a factor of three after passage through a bubble screen. Obviously, dispersion effects increase with increasing air content (compressibility) and thickness of the bubble screen, and decrease with increasing rise-time to peak of the incident water shock. Notably, the initial arrival of the shock wave at a particular location behind the screen is essentially unchanged, but the rise from ambient pressure to the observed peak is considerably increased from the free-water case. Data collected by Strange and Miller also indicate that the total impulse associated with the transmitted shock wave is essentially unaffected. This observation is consistent with conservation laws.

Based upon the factors stated above, it was believed that bubble screens might be useful in reducing the area in which potentially harmful levels of water shock would be produced during the deepening of the shipping channel, albeit to a lesser extent than for free-water explosions. A study conducted by Munday, et al indicated that bubble screens were effective in reducing peak water shock pressures during an underwater rock blasting project. However, the quality of the instrumentation used in the study was inadequate to measure accurately the water shock pressures and no systematic research has been done to quantify the effectiveness of bubble screens in reducing the peak water shock from underwater rock blasting. Since the deployment of bubble screens was estimated to add roughly $30,000,000 to the overall cost of the Wilmington Harbor Deepening project, CESAW decided to perform the Blast Effect Mitigation (BEM) Tests (HQUSACE, 1998). The BEM tests were designed to evaluate the effectiveness of bubble screens during trials of production blasting of underwater rock in the Cape Fear River.

A private contractor conducted the BEM Tests. The contractor's responsibilities included all drilling and blasting operations, deployment of bubble screens, and measurement of water shock pressures. The contractor was further required to derive impulse and energy-flux density values from the measured water shock data. The dynamic data would be used to determine the effectiveness of the bubble screens and correlated to the results of a caged fish study conducted during the test series.

The U.S. Army Engineer Research and Development Center (ERDC) is the center of expertise for the Corps of Engineers in the area of explosion effects. Because of this, CESAW tasked ERDC to recommend water shock measurement locations and contract specifications for water shock measurement/recording systems fielded on the BEM Tests. ERDC was further tasked with fielding companion water shock measurements as a check of the contractor's instrumentation system, and providing an independent review and analysis of all water shock data recorded during the tests. ERDC was also asked to analyze the effectiveness of the bubble screens in reducing water shock.

Scope

This document details the work done by ERDC in support of CESAW on the BEM Tests. Test designs are provided along with specifications of the bubble screen and water shock measurement systems. All water shock data collected on the BEM Tests are presented in tabular form. Where possible, impulse and energy-flux density values were computed from the measured water shock wave forms. The data were also analyzed to provide an assessment of the effectiveness of the bubble screens in reducing water shock parameters.

2 Experiment Plan

Test Configuration

The BEM Tests were conducted in a section of the Cape Fear River, NC. The average depth of the river in this area was approximately 30 ft. Details regarding the BEM Test location, the geology of the river bottom rock, the configuration of the explosive charges, and the bubble screen are provided in Appendix A. For each test, a number of boreholes were drilled into the rock layer underlying the river bottom. The boreholes were spaced at 8 ft intervals and a total of 13 to 32 boreholes were drilled for each test. Figure 1 illustrates the planned borehole arrays.

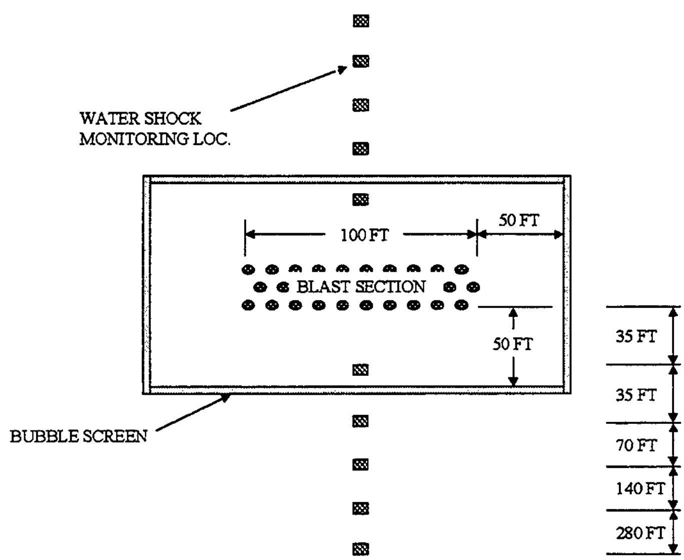

Figure 1. Plan view of typical BEM Test

The boreholes were drilled to a depth of 10-12 ft into competent rock, then each was loaded with 30 to 60 lb of gelatin dynamite and two, 1-lb booster charges. Each borehole was to be sufficiently stemmed so as to prevent high-pressure detonation gasses from escaping the blast holes. The explosives in each borehole were also to be sequentially initiated in order to eliminate the possibility of simultaneous detonations.

Bubble Screens

A bubble screen was placed to completely surround the charge array on selected tests. When deployed, the bubble screen was positioned at a distance of 50- to 70-feet from the outer edge of the charge array on all sides. The screen consisted of a perforated polyvinylchloride manifold and was intended to provide a continuous air bubble curtain around the charge arrays. The screen was designed to deliver approximately 16 ft^3/min of oil-free air per linear foot of manifold (Figure 2). In order to ensure that the maximum level of water shock attenuation was attained, the

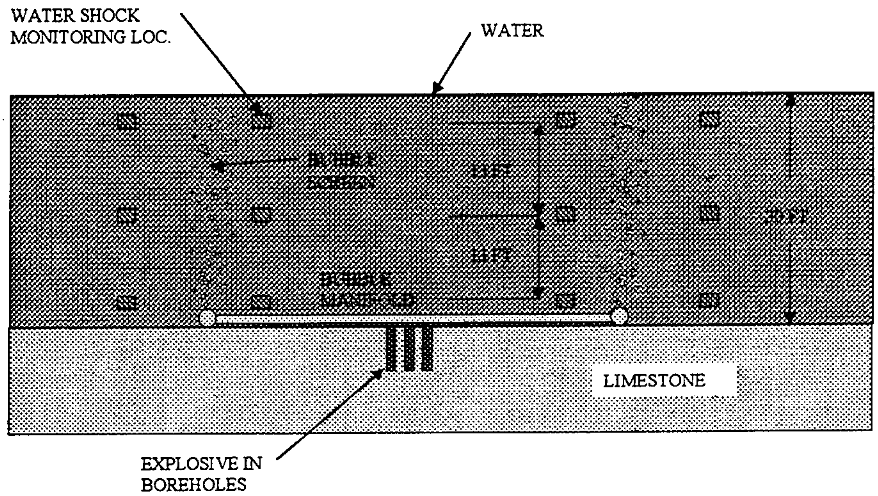

Figure 2. Cross section of typical BEM Test

screen was operated without pause for 5 minutes before, during, and 5 minutes after charge detonation.

Water Shock Instrumentation

The instrumentation configuration for a typical test is illustrated in Figures 1 and 2. Water shock measurements were placed approximately 3 ft above the river bottom, at mid-depth, and 3 ft below the surface at each of five ranges: 35, 70, 140, 280, and 560 ft from the edge of the charge array. Identical measurement arrays were placed on the upstream and downstream sides of the blast area. The measurements at the 35-ft range were located inside the bubble screen (when deployed) and were intended to provide a measure of the unmodified water shock waves and allow direct comparison of water shock values from tests with and without bubble screens. The remaining measurement ranges were selected to span the region in which potentially harmful water shock might be generated. Measurements were also located at various depths to quantify the effects of the riverbottom/water and water/air interfaces on the measured water shock. There were a total of 30 water shock measurement locations on each test.

A private contractor was responsible for fielding the water shock measurements on the BEM Tests. However, CESAW tasked ERDC to field a set of 5 additional water shock measurements on Tests 1A and 3 as a check of the contractor's instrumentation system. Consequently, a total of 35 water shock measurements were fielded on Tests 1A and 3.

All water shock pressures were measured with PCB tourmaline crystal (piezoelectric) pressure transducers (PCB, Inc., 1989) with maximum ranges of 5000 to 20000 psi. Coaxial cables were connected to the transducers to transmit the output signal to the recording devices. All signal cables were waterproofed and protected in either stainless steel tubing or polymer tubing, depending on the severity of the expected water shock environment at the measurement location.

Data Recording and Processing

All measurements fielded by ERDC were digitally recorded on Pacific Instruments Model 9830 transient data recorders. The data recorders were configured to provide a total recording duration of approximately 1.2 seconds at a maximum sampling rate of 500 kHz. All water shock measurements fielded by the contractor were recorded on Nicolet Model 440 Digital Recording Oscilloscopes. The oscilloscopes provided a total recording duration of approximately 0.525 seconds at a data sampling rate of 500 kHz.

All water shock pressure records were evaluated at ERDC for operational validity and data quality. Valid records were filtered as necessary to remove high-frequency electrical noise transients and were baseline-shifted to remove long-duration electrical offsets. These corrected water shock wave forms were then numerically integrated to obtain corresponding impulse records.

By definition, the impulse, I, of unit area of the water shock front up to a time, t, after shock arrival is given by:

$$I(t) = \int_0^t P(t)\,dt$$

Where P is the water shock pressure. The time period over which the integration is performed is usually an arbitrary value that is of sufficient duration to include all significant features of the pressure-time curve. As stated by Swisdak (1978), the integration time period is usually taken to be 5θ, where θ is the time constant or maximum time after peak pressure to which the shock wave decays exponentially. For the multiple discrete explosions featured in the Blast Effects Mitigation Tests, a logical time period for calculation of *peak* impulse is the positive pressure phase of the highest-amplitude pressure pulse. At the 35 and 70-ft ranges, this is typically the initial shock pulse; at greater ranges, the peak pressure often occurs at a random point in the shock wave train, as dictated by complex interactions of multiple shock waves with the reflecting boundaries (i.e., the river bottom and water surface).

Another quantity of interest with respect to fish injury/mortality is the energy flux density (EFD). EFD represents the energy transferred across a unit area of a fixed surface normal to the direction of water shock propagation. The method for calculating the EFD is given by Cole (1948) as:

$$EFD = \frac{1}{\rho c}\int_0^t P^2 dt + \frac{1}{\rho R}\int_0^t P[\int_0^{t'} Pdt]dt'$$

Where ρ is the density of undisturbed seawater (63.98 lb/ft^3), c is the sound speed in undisturbed water (4967 ft/sec), P is the water shock pressure, t is time during the initial water outflow, t' is time during water afterflow, and R is the radial distance from the source. The ρc term is usually referred to as the acoustic impedance; its reciprocal can be thought of as the transmission factor.

The first term of the expression for the EFD accounts for the outward-directed compressive flow of water required to fill the rarefaction left behind the water shock front, which transports water under compression away from the explosive source. The second term represents the effect of the excess particle velocity or afterflow. The afterflow produces kinetic energy which becomes converted to a pressure wave when the outward flow of water is reversed.

At pressures below a few thousand psi, the effect of the afterflow becomes negligible and the EFD can be approximated (to within less than 1% error) by the equation below:

$$EFD = \frac{1}{\rho c}\int_0^t P^2 dt$$

In this form, the afterflow term has been eliminated from the prior EFD expression. To obtain the EFD in ft-lb/in^2, the equation may be re-written as:

$$EFD = 0.01461\int_0^t P^2 dt$$

For the purpose of this study, the EFD calculation was made over the same time period as for the impulse.

3 Results

Overview

The BEM Tests were conducted during the period December 1998 through January 1999. A total of 9 tests were originally planned. However, because of severe instrumentation problems, the contractor was required to repeat Test 1. Test 5 was also repeated due to the loss of a large number of fish cages. The repeated tests were designated Test 1A and Test 5A. Table 1 lists the number of boreholes, explosive weight per borehole, and total explosive weight for each test (Gray and Reese, 1999). Also indicated are those tests on which a bubble screen was deployed.

Table 1
Charge details for BEM Tests 1-9

Test No.	No. of Boreholes	Max. Charge Weight Per Borehole, lb	Min. Time Delay Between Detonations	Total Charge Weight, lb
1	13	52	42	676
1A	13	52	42	666
2*	26	52	42	1292
3	32	52	42	1534
4*	32	252	42	1664
5	32	626	42	1694
5A	32	62	42	1644
6*	32	62	42	1584
7	32	62	42	1634
8*	32	62	42	1644
9	32	62	42	1664

*Test with bubble screen

Data Return

As stated above, severe instrumentation recording problems were experienced by the contractor on Test 1; no valid water shock data were obtained on the test. In addition, with the exception of a few comparison pressure wave forms measured by ERDC and the contractor, little usable data were obtained on Test 1a. For all other tests, the water shock measurements were evaluated to determine whether they provided usable data. The peak water shock, impulse and energy flux density values measured on each test are presented in Appendix B. In many cases, the measured wave forms had considerable electrical noise superimposed upon the actual data or had a significant baseline offset, but were corrected by filtering and/or other data processing methods. A large number of measurements featured wave forms that were not consistent with the known character of the data. This included wave forms with extremely long positive pressure phases (10's or 100's of msec instead of 1 msec or less), anomalously large baseline offsets, and/or obvious gage/cable/electrical failures. "Questionable" measurements exhibited either unusually slow rise-times to peak pressure or extremely low amplitude relative to other measurements. "No data" indicates that no discernable signal was recorded. This typically means that the sensor was off-line during the test, probably due to a bad electrical connection.

Figure 3 compares water shock pressure measurements obtained at the 35-ft range on Test 1a by ERDC and the contractor. Although the measurements were not made at the same depth, they do indicate that the contractor's sensor/recording system configuration was capable of capturing the same high-frequency transients measured by the ERDC system. Based upon this information, the contractor's instrumentation system was deemed capable of obtaining high-frequency water shock data on BEM Tests 2-9.

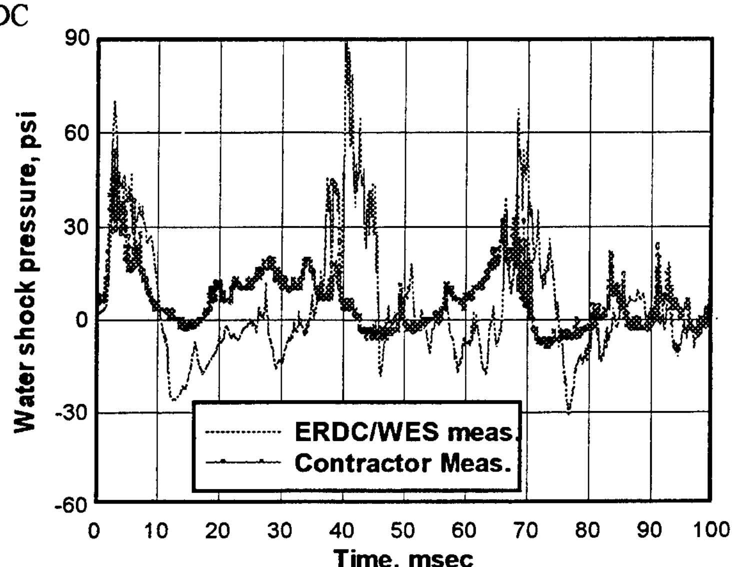

Figure 3. Comparison of WES and contractor-measured water shock wave forms at the 35-ft range, Test 1a

Distinct differences were apparent in the water shock measurements obtained on the north and south sides of the charge array. Figure 4 compares the measurements at the 35-ft range on Test 3. The measurement on the south side has a much lower peak and a slower rise, even though it is located near the bottom. The south measurement should have a higher peak than the north measurement, which was near the surface. The only apparent reasons for this disparity are (1) error in gage location or (2) poor frequency response of the south measurement. The south measurement does contain high-frequency components and was configured just as the north measurement, so frequency response was probably not the cause. However, the slow, exponential rise to peak does make the south measurement appear somewhat questionable and it is possible that the measured amplitudes are inaccurate. Most of the measurements on the south side exhibit similar characteristics and as a whole, those measurements are questionable.

Gage location was also a likely source of error. Relative locations of the measurements are such that the south gage near the bottom at the 35-ft horizontal range should be more or less 35 ft from the edge of the charge array. However, the north gage near the surface at the 35-ft horizontal range is actually almost 35 ft above the charge as well, so the straight-line distance to the charge array center should be

$$\sqrt{\{(35)^2 + (35)^2\}} = 49.5\,ft$$

The peak shock pressure measured by the south gage actually arrived 0.34 msec *later* than the peak shock measured by the north gage. This indicates that the north gage was closer to the charge array (or deeper) than planned, or, that the south gage was further away (or shallower) than planned. The direction of the prevailing current supports the notion that the gages were moved laterally in the directions stated above.

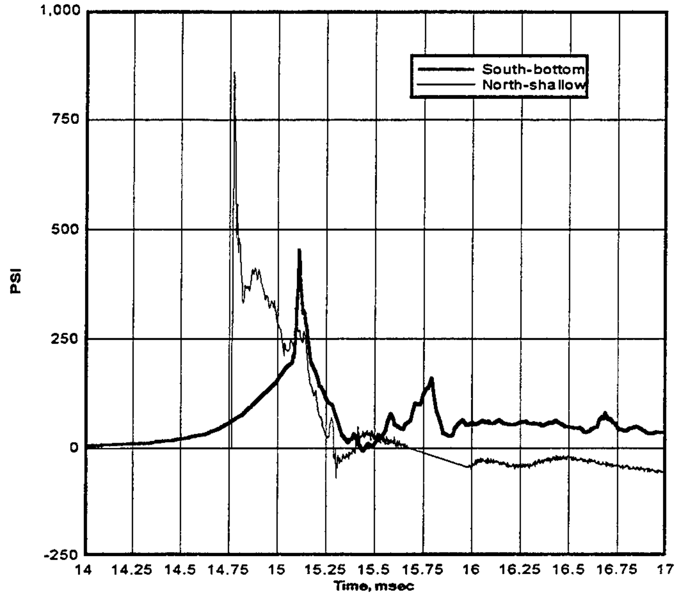

Figure 4. Comparison of water shock wave forms at the 35-ft range, Test 3

Additional analysis of the Test 3 data collected on the north and south gage arrays provides further evidence that the actual gage locations were somewhat affected by the river currents and/or placement errors. Shock waves travel at a constant velocity of approximately 4967 ft/sec in sea water. Assuming that the first gage locations were truly at a horizontal distance of 35 ft, the relative amount of time required for the peak water shock pressure to reach each successive gage location can be used to calculate the distance between the locations. This exercise was carried out for both the north and south measurement arrays. The results are shown graphically in Figure 5. It appears that the gage locations on the south array are slightly further away from the charge array than planned, while the locations on the north array are significantly closer than

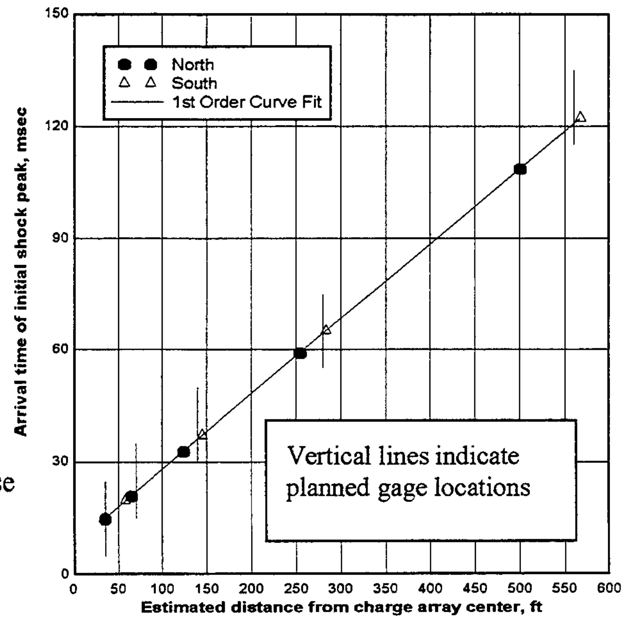

Figure 5. Estimated gage locations (from shock arrival data), Test 3

planned. These "corrected" locations are assumed to be the actual measurement locations, and the shock attenuation curves presented in this report were adjusted accordingly since the contractor did not provide as-built locations for the measurements.

For Tests 2, 3, 4, 5, 5a, 7, and 9, adequate measurements were obtained to allow the construction of curves describing peak water shock pressure versus distance for the upstream case. However, these curves for Tests 3, 4, 5, 5a, and 7 are somewhat questionable due to the severe electrical noise superimposed on many of the measurements, and the fact that, in many cases, only one valid measurement was obtained at a given range. No curves were developed for the downstream case due to the questionable nature of most of the downstream data measured at the positions closest to the blast arrays. Generally, sufficient water shock data were obtained at the 140-, 280- and 560-ft ranges to provide correlation to the caged fish study on both the upstream and downstream sides. At the 35- and 70-ft ranges, only sporadic direct comparisons to the fish study will be possible. Insufficient measurements were obtained on Tests 1a, 6, and 8 to allow any type of systematic analysis, and, in most cases, no credible data were obtained for correlation to the caged fish study.

Water Shock Pressure

The peak water shock pressures measured on the BEM Tests are presented in Appendix C. In order to evaluate the effectiveness of the bubble screens, direct comparisons must be made between the water shock data from those tests on which bubble screens were fielded (even-numbered tests) and those on which they were not (odd-numbered tests). Test-to-test variations in the amount of explosive per borehole, stemming material overlying the explosive, and the depth of the explosive in individual boreholes can significantly affect the resulting water shock. ERDC developed comparisons in which the curves describing the peak water shock pressure from tests with and without bubble screens are normalized to equate the peak pressure measured at the point closest to the blast arrays (inside the bubble screen position). The comparisons are provided in Figure 6. This comparison shows considerable scatter, especially for the five cases in which no bubble

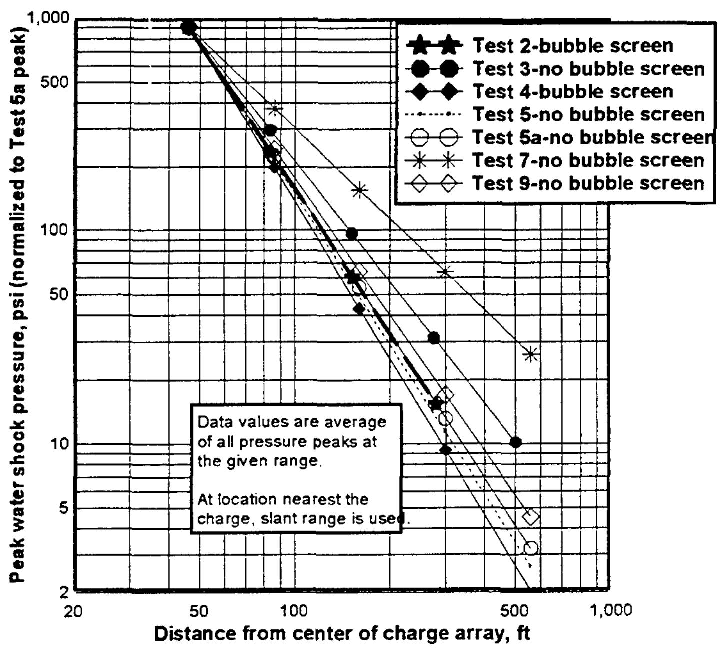

Figure 6. Normalized, average peak water shock pressure versus distance, Tests 2-9

which no bubble screens were used. This scatter is due to a combination of measurement uncertainty and the complex interaction of river currents and shock reflections from the changeable river bottom topography on the propagated water shock. Although only Tests 2 and 4 provided useful water shock data for the case in which bubble screens were deployed, the attenuation rates for these tests are on the high end of the range of water shock attenuation rates seen for the no bubble screen case. Unfortunately, because of the inconsistency of the curves for the tests with no bubble screen, this comparison methodology does not provide a clear quantification of the effectiveness of the bubble screens in reducing peak water shock pressure. Furthermore, the data from Tests 2 and 4 do not indicate an increase in the rate of attenuation of peak water shock pressures upon crossing the bubble screen location. This implies that the screens were not effective in reducing peak water shock pressures.

Since the foregoing analysis was not felt to be entirely conclusive, we decided to further investigate the peak water shock data. The average peak water shock pressures measured on the upstream side on Tests 2-9 are plotted versus distance from the center of the charge array in Figure 7. It is important to note that in this case, the actual measured values are plotted. Also plotted are the predicted values for a single 52-lb charge in a borehole, assuming a borehole/free-water charge weight equivalence of 0.014 (scaled, based upon the data cited by Langefors and Kihlstrom).

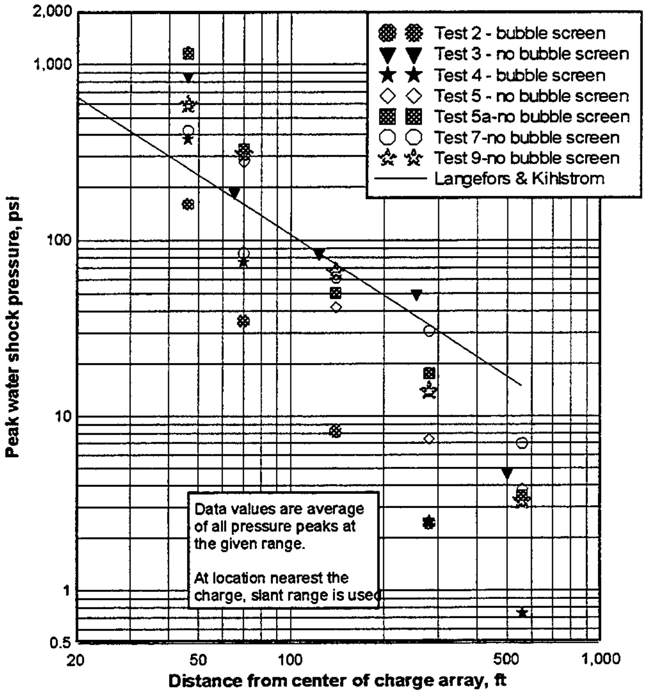

Figure 7. Peak water shock pressures measured on Tests 2-9

In all cases, the peak measured pressures attenuated more rapidly than the predicted values from the free-water curve. The reason for this phenomenon is not immediately clear, although local riverbed topography and/or strong currents (the data were from the upstream side) may have contributed. It is also evident that the actual peak water shock pressures from the tests with bubble screens were typically much lower than those from tests without the screens.

This is further illustrated in Figure 8, which compares the water shock wave forms at the 35-ft range as measured on Tests 2 and 3. On Test 3 (no bubble screen), peak water shock pressures were much higher, and the associated shock rise-times were faster than those observed on Test 2. Thus, the explosive energy was much better coupled into the water on Test 3 than on Test 2. This may suggest that in the case of Test 3, the first charge that was detonated (and possibly others) was either not entirely contained in the borehole, or was not stemmed, causing the detonation gases to be released immediately into the water. Conversely, the charges on Test 2 may have been very well-stemmed, thus releasing the detonation gases much more slowly into the water and creating a pressure pulse that is more of a "surge" than a true shock.

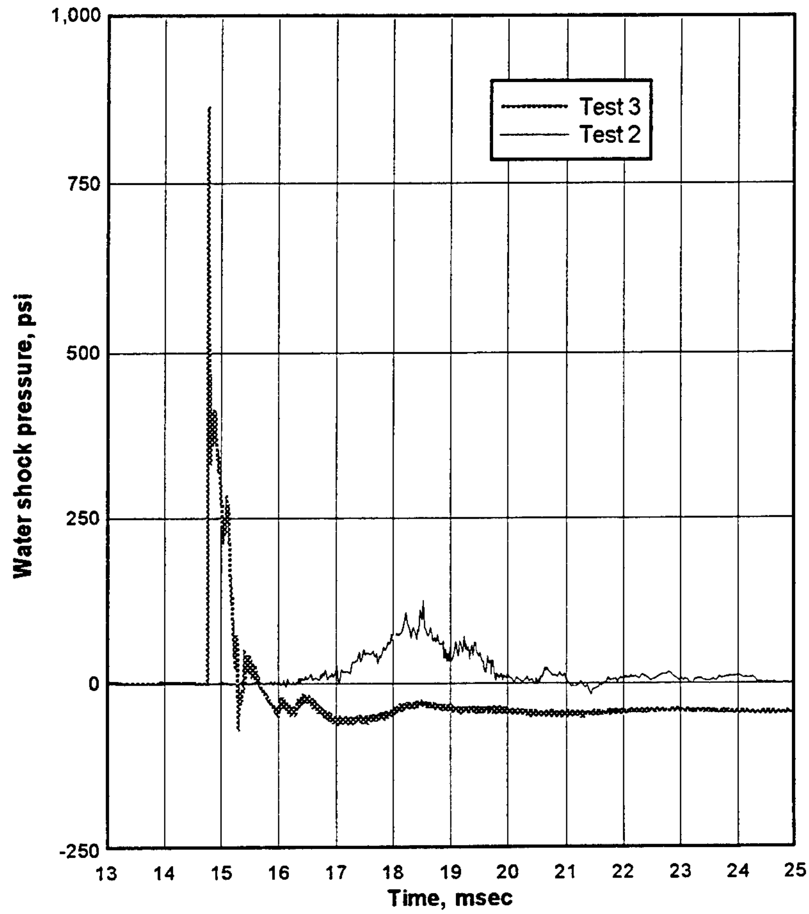

Figure 8. Water shock pressures measured at the 35-ft range, shallow depth, Tests 2 and 3

A second factor may have been the weight of explosive in the first borehole fired on each test. In Test 3, 42-lb of explosive were loaded in borehole 1; 32 lb of explosive were loaded in borehole 1 on Test 2. The smaller initial charge on Test 2 may have been stemmed with more overburden than the initial charge on Test 3. This, in combination with the smaller charge weight may have caused the scaled depth-of-burial for the initial Test 2 charge to be much greater than that for Test 3.

A third possibility for the differences in water shock pressure seen on Tests 2 and 3 may be an unanticipated shock attenuation function of the bubble screen. Ideally, the bubble screen was tended to produce a vertical "wall" of bubbles which would serve as a low-density zone in the water, thus reducing the peak value of the transmitted water shock wave. Naturally, one would look for a sharp reduction in the peak pressure attenuation rate when comparing the measurement station in front of the screen (35-ft range) to that immediately behind the screen (70-ft range). As stated previously, this does not occur. One possible reason for this apparent lack of effectiveness was the presence of strong river currents, which could significantly distort the bubble screen. If the current sufficiently transported the bubble-filled water downstream, it is possible that the water in and near the area of the charge array was significantly aerated. If so, this would serve as a low-density region and would reduce the peak transmitted water shock to some degree. It should be recalled, however, that only two water shock data sets were available for the bubble screen case. Further data is required before a conclusive analysis can be conducted of the effectiveness of bubble screens in reducing the peak water shock pressure from underwater rock blasting.

Water Shock Impulse

Impulse plots were generated by numerical integration of the water shock pressure records, as described in Section 2.4. Appendix D contains plots of peak impulse for each of the BEM Tests. The peak water shock impulse at the near-surface locations on each test is plotted versus distance from the edge of the charge array in Figure 9. Overall, the peak impulse values were more tightly grouped than the peak water shock values. In general, the tests with the bubble screen exhibited impulses that were reasonably close to the values from the tests without bubble screens. For example, at the measurement location immediately behind the bubble screen (70-ft range), the peak impulse on Tests 2 and 4 were in the mid-range of values measured on the test series. This is consistent with the theory that the total impulse delivered by a given charge at a particular range is conserved, whether or not the presence of a bubble screen or other factors might tend to reduce the amplitude of the peak water shock. Since peak impulse is the water shock parameter most frequently related to mortality of marine life, the data indicate that the bubble screen deployed on the BEM Tests did not significantly reduce the potential for harm to the endangered fish and mammal species in the Cape Fear River.

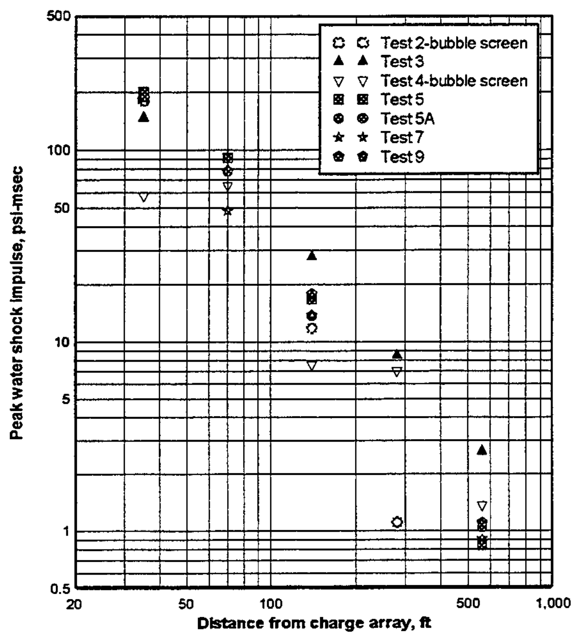

Figure 9. Water shock impulse at the shallow depth, Tests 2-9

Energy Flux Density

Energy flux density (EFD) plots were generated for each valid water shock pressure record by the method presented in Section 2.4. Appendix E contains plots of peak EFD for each of the BEM Tests. Peak EFD at the near-surface locations on each test is plotted versus distance from the edge of the charge array in Figure 10. Values for the tests with a bubble screen were generally much lower than for the tests without a bubble screen. The data indicate that bubble screens may be effective in reducing EFD. However, since the EFD is a measure of the energy contained in the water shock pressure wave, it is dependent upon the square of the measured pressure wave form. Thus, variations in the amplitude of the pressure wave are greatly magnified in terms of the derived EFD. Variability in the input water shock due to inconsistencies in charge weight per borehole and the amount of stemming may contribute significantly to the perceived influence of the bubble screen.

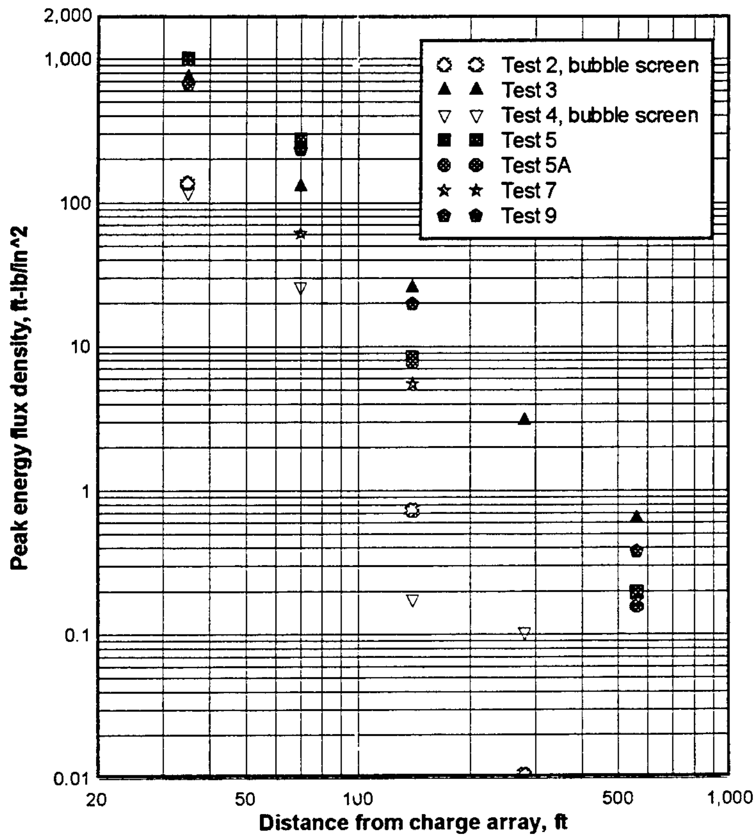

Figure 10. Peak energy flux density at the shallow depth, Tests 2-9

4 Conclusions and Recommendations

Conclusions

Conclusions from the ERDC analysis of the BEM Test water shock data are synopsized as follows:

a. For Tests 2, 3, 4, 5, 5a, 7, and 9, adequate measurements were obtained to allow the construction of curves describing peak water shock parameters versus distance for the upstream case. However, these curves for Tests 3, 4, 5, 5a, and 7 are somewhat questionable due to the severe electrical noise superimposed on many of the measurements, and the fact that, in many cases, only one valid measurement was obtained at a given range. No curves were developed for the downstream case due to the questionable nature of most of the downstream data measured at the positions closest to the blast arrays. Generally, sufficient water shock data were obtained at the 140-, 280- and 560-ft ranges to provide direct correlation to the caged fish study on both the upstream and downstream sides. At the 35- and 70-ft ranges, only sporadic direct comparisons to the fish study will be possible.

b. Insufficient measurements were obtained on Tests 6 and 8 to allow any type of systematic analysis, and, in most cases, no credible data were obtained for correlation to the caged fish study.

c. In order to evaluate the effectiveness of the bubble screens, direct comparisons must be made between the water shock data from those tests on which bubble screens were fielded and those on which they were not. ERDC developed comparisons in which the curves describing the peak water shock pressure from tests with and without bubble screens were normalized to equate the peak pressure measured at the point closest to the blast arrays (inside the bubble screen position). This comparison shows considerable scatter, especially for the five cases in which no bubble screens were used. This scatter is due to a combination of measurement uncertainty and the complex interaction of river currents and shock reflections from the changeable riverbottom topography on the propagated water shock. And, unfortunately, only Tests 2 and 4 provided useful water shock data for the case in which bubble screens were deployed. Because of this, and the inconsistency of the curves for the no bubble screen case, we are unable to accurately quantify the effectiveness of the bubble screens in reducing peak water shock pressure. The actual measured peak water shock values were generally lower on Tests 2 and 4 than on the other tests. However, the data from Tests 2 and 4 do not indicate an increase in the rate of attenuation of peak water shock pressures upon crossing the bubble screen location. This implies that the screens did not function as intended. It may well be the case, however, that the bubble screens sufficiently aerated the water in and near the test site to decrease the water density and lower the measured water shock pressures and the associated EFD values. Peak water shock impulse, which is the parameter most often correlated to marine life mortality, was not significantly affected by the presence of the bubble screen.

Recommendations

CESAW requested that WES provide recommendations for water shock pressure limits at a range of 140 ft from the center of the blast arrays during the production blasting phase of the project. These limits must be set low enough to avoid adverse effects on aquatic life in the blasting area, but must also allow the contractor a reasonable range of pressures that will accommodate operational variables such as charge hole stemming and riverbed topography. Based upon the available data, we recommend that the median peak water shock pressure not exceed 85 psi at a range of 140 ft from the center of the blast array during any five sequential blasts. We also recommend that the absolute maximum water shock pressure at the 140-ft range not exceed 140 psi. These limits are intended for near-surface locations, since water shock monitoring instrumentation will likely be placed within 3 ft of the water surface.

Data return from the BEM Tests was rather poor. This, coupled with the many variables associated with changeable river conditions, irregular depth of explosive charges in boreholes, and uncertainties in charge stemming, served to reduce the usefulness of the test results in terms of establishing or refining predictive methodologies for water shock from general underwater rock blasting operations. It is recommended that a series of controlled experiments be conducted to better define the water shock produced by underwater rock blasting and the effectiveness of bubble screens in reducing the water shock.

The proposed experiments would investigate the water shock produced by standard rock-blasting explosives contained in boreholes in well-defined rock or concrete below a water layer. The experiments could be conducted at ½-to ¼-scale and would consist of a number of water shock measurements at various ranges from the explosive charge array. The depth of explosive in the boreholes and amount of stemming would be precisely known, and both single borehole charges and multiple borehole charges fired at discrete time intervals would be investigated. These charge parameters could be varied as desired to span the range of typical blasting techniques. Other variables to be investigated would be the depth and (possibly) speed of current of the water layer. Initial experiments would examine the water shock environment produced by the charges without the use of shock-mitigation methods. Once the water shock parameters were well established, the effectiveness of bubble screens and other blast mitigating techniques could be determined through further experimentation.

This research would yield well-documented curves for use in determining the peak water shock parameters expected from underwater rock blasting operations. This information could then be used to determine the extent of detrimental effects on aquatic life and the relative benefits of using bubble screens or other blast mitigation methods without the cost of conducting an on-site operational test.

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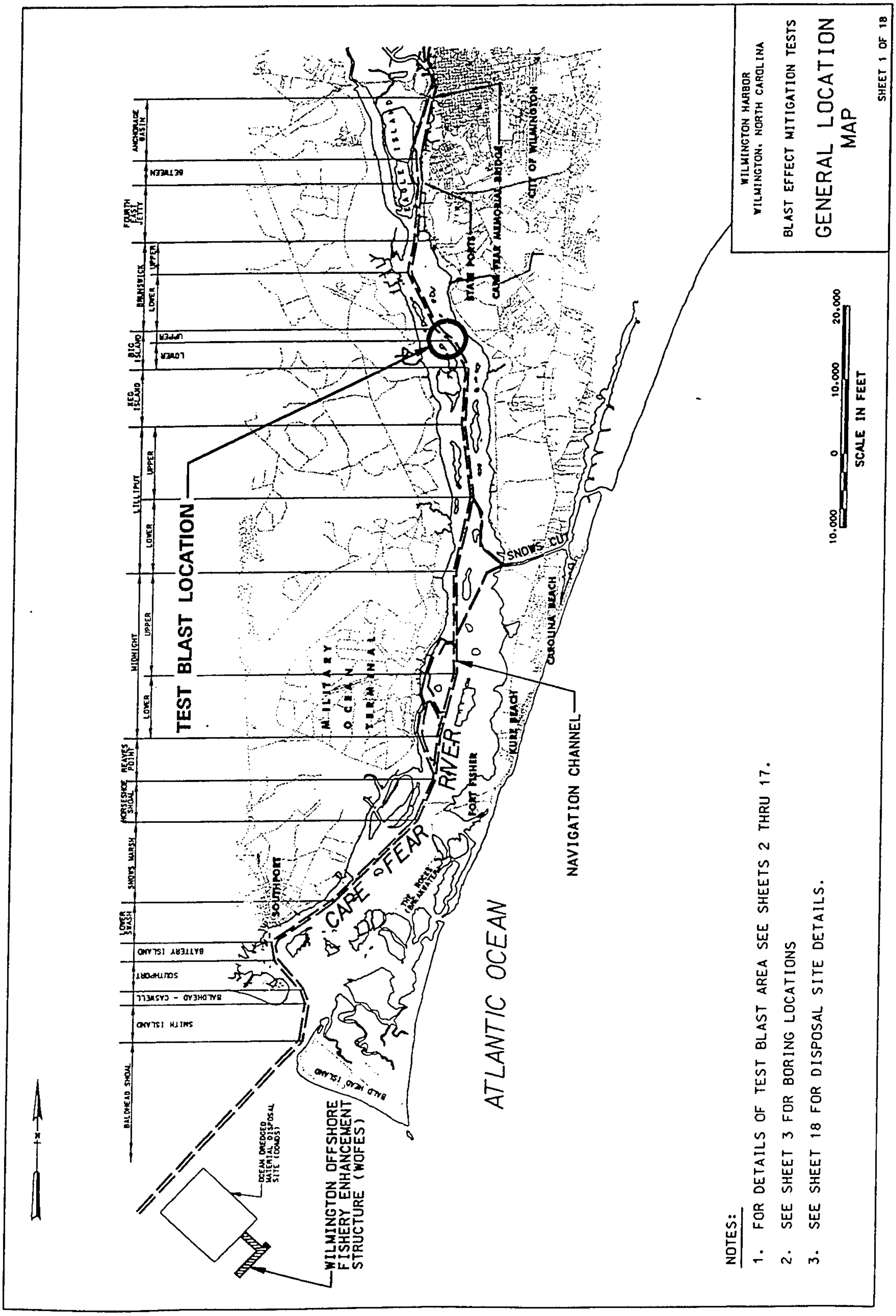
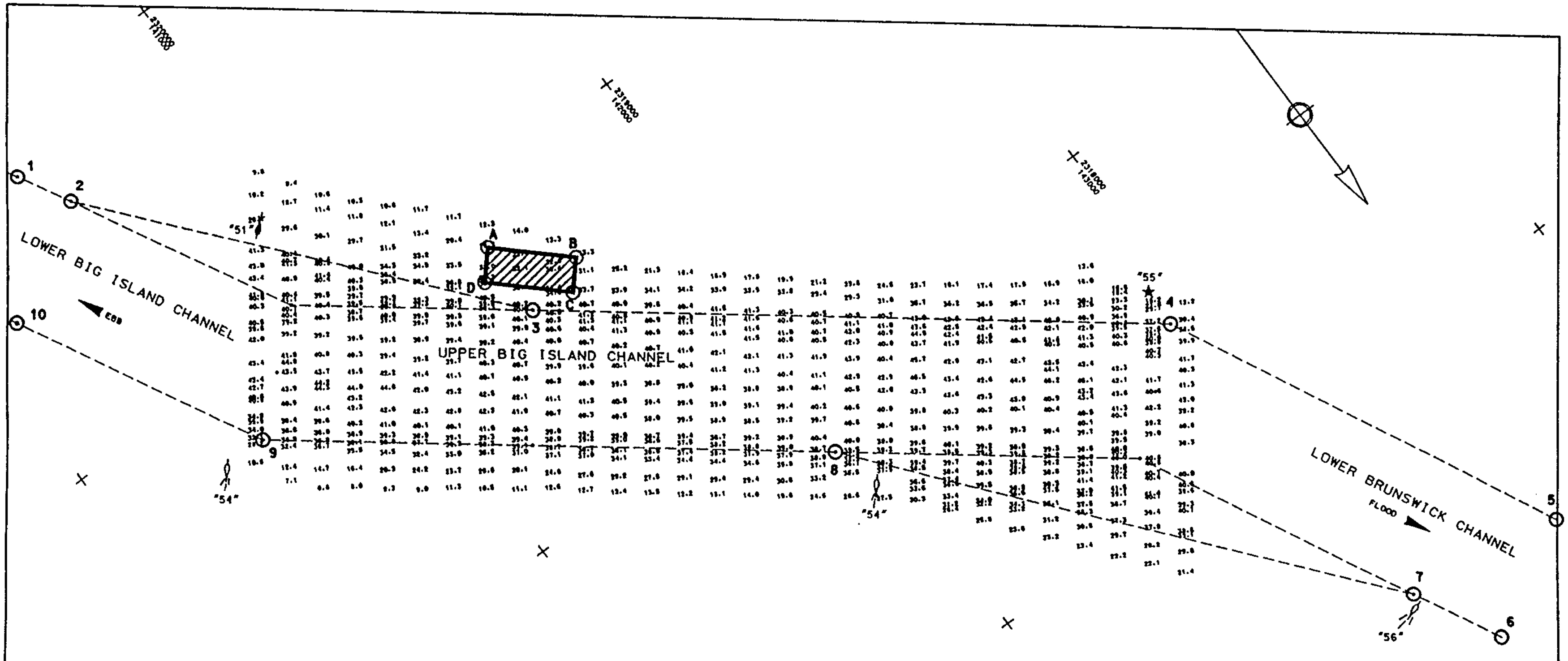
Appendix A
BEM Test Detail Drawings


WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA
BLAST EFFECT MITIGATION TESTS
GENERAL LOCATION MAP
SHEET 1 OF 18
10,000 0 10,000 20,000
SCALE IN FEET
TEST BLAST LOCATION
NAVIGATION CHANNEL
ATLANTIC OCEAN
CAPE FEAR RIVER
MILITARY OCEAN TERMINAL
SNOWS CUT
CAROLINA BEACH
KURE BEACH
FORT FISHER
SOUTHPORT
BALD HEAD ISLAND
STATE PORTS
CAPE FEAR MEMORIAL BRIDGE
CITY OF WILMINGTON
EAGLE ISLAND
WILMINGTON OFFSHORE FISHERY ENHANCEMENT STRUCTURE (WOFES)
OCEAN DREDGED MATERIAL DISPOSAL SITE (ODMDS)
BALDHEAD SHOAL
SMITH ISLAND
BALDHEAD - CASWELL
SOUTHPORT
BATTERY ISLAND
LOWER SWASH
SNOWS MARSH
HORSESHOE SHOAL
REAVES POINT
MIDNIGHT
LOWER
UPPER
LILLIPUT
LOWER
UPPER
KEG ISLAND
BIG ISLAND
LOWER
UPPER
BRUNSWICK
LOWER
UPPER
FOURTH EAST JETTY
BETWEEN
ANCHORAGE BASIN
NOTES:
1. FOR DETAILS OF TEST BLAST AREA SEE SHEETS 2 THRU 17.
2. SEE SHEET 3 FOR BORING LOCATIONS
3. SEE SHEET 18 FOR DISPOSAL SITE DETAILS.



CHANNEL PRISM COORDINATES

1	E 2,320,615.2	N 141,167.4
2	E 2,320,528.5	N 141,324.7
3	E 2,319,592.6	N 142,410.3
4	E 2,318,070.0	N 143,570.2
5	E 2,317,476.7	N 144,717.8
6	E 2,317,832.1	N 144,901.5
7	E 2,317,965.8	N 144,642.8
8	E 2,319,108.8	N 143,281.8
9	E 2,320,484.8	N 142,233.5
10	E 2,320,881.6	N 141,512.7

NAVIGATION AIDS (ACCURACY +/- 10 FEET)

LT. BUOY # 51	E 2,320,142	N 141,747
LT. BUOY # 52	E 2,320,605	N 142,217
LT. BUOY # 54	E 2,319,047	N 143,410
BCN #55	E 2,318,065	N 143,456
LT. BUOY # 56	E 2,317,963	N 144,672

TEST BLAST AREA COORDINATES

A	E 2,319,589	N 142,183
B	E 2,319,392	N 142,363
C	E 2,319,660	N 142,260
D	E 2,319,463	N 142,440

NOTES:

1. HORIZONTAL DATUM NAD 1983.
2. TIDE GAGE LOCATED AT BCN #55.
3. SOUNDINGS ARE EXPRESSED IN FEET AND TENTHS AND REFER TO NOS MEAN LOWER LOW WATER (MLLW). THE DECIMAL POINT OF EACH SOUNDING REPRESENTS THE APPROXIMATE LOCATION OF THE SOUNDING.
4. PROJECT SURVEYED 9 MARCH 1998 WITH DISTRICT SURVEY VESSEL "GILLETTE" USING D.G.P.S. HORIZONTAL POSITIONING EQUIPMENT AND 200 KHZ SOUNDING EQUIPMENT.
5. PRIOR TO COMMENCEMENT OF WORK UNDER THIS CONTRACT THE OVERBURDEN WITHIN THE TEST BLAST AREA WILL BE REMOVED BY OTHERS TO ELEVATION -38 FEET MLLW OR TO TOP OF ROCK, WHICHEVER IS HIGHER. THE TEST BLAST AREA WILL BE SURVEYED BY THE GOVERNMENT PRIOR TO COMMENCEMENT OF WORK UNDER THIS CONTRACT, AND A NEW MAP WILL BE PROVIDED TO THE CONTRACTOR.
6. THE WILMINGTON OFFSHORE FISHERIES ENHANCEMENT STRUCTURE (WOFES, SEE SHEET 18) IS THE GOVERNMENT FURNISHED DISPOSAL AREA AVAILABLE FOR DISPOSAL OF EXCAVATED MATERIAL.
7. SEE SHEET 3 FOR BORING LOCATIONS.

LEGEND

TEST BLAST AREA (AREA SHALL BE EXCAVATED TO 45' BELOW MLLW WITH 1H:1V SIDE SLOPES)

"55" "54" "51" NAVIGATION AIDS

300 150 0 300 600

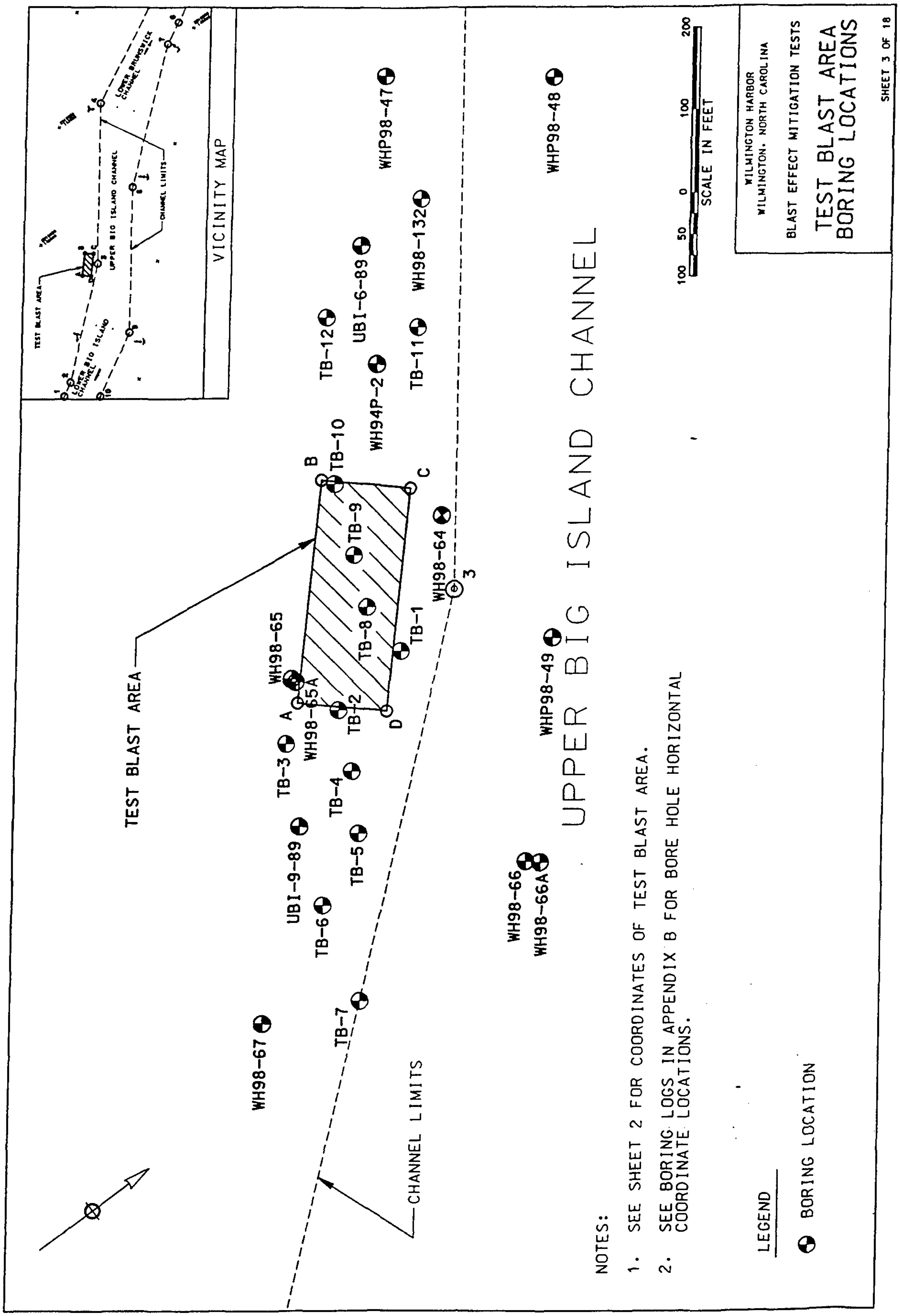
SCALE IN FEET

WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA

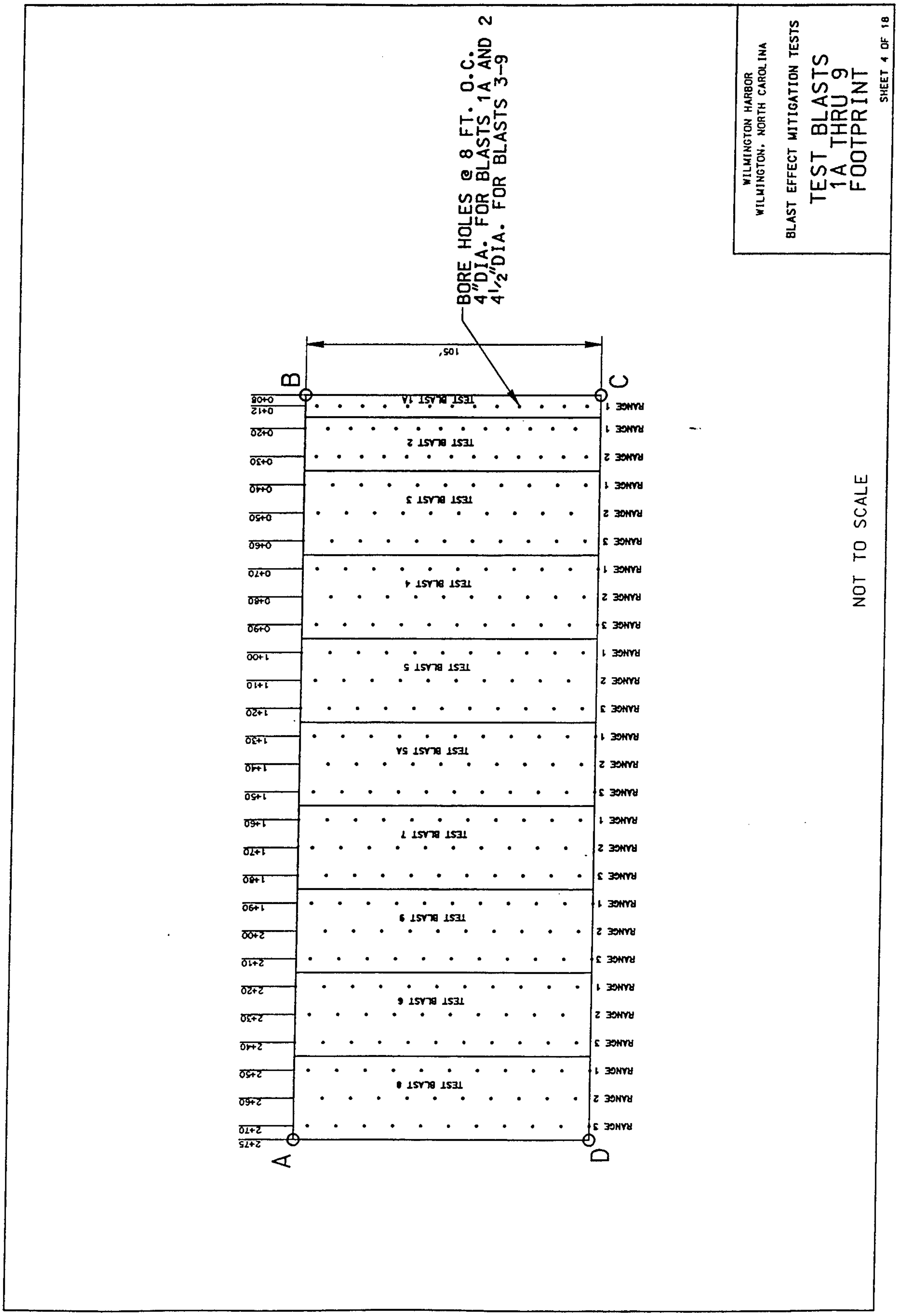
BLAST EFFECT MITIGATION TESTS

TEST BLAST AREA SITE PLAN

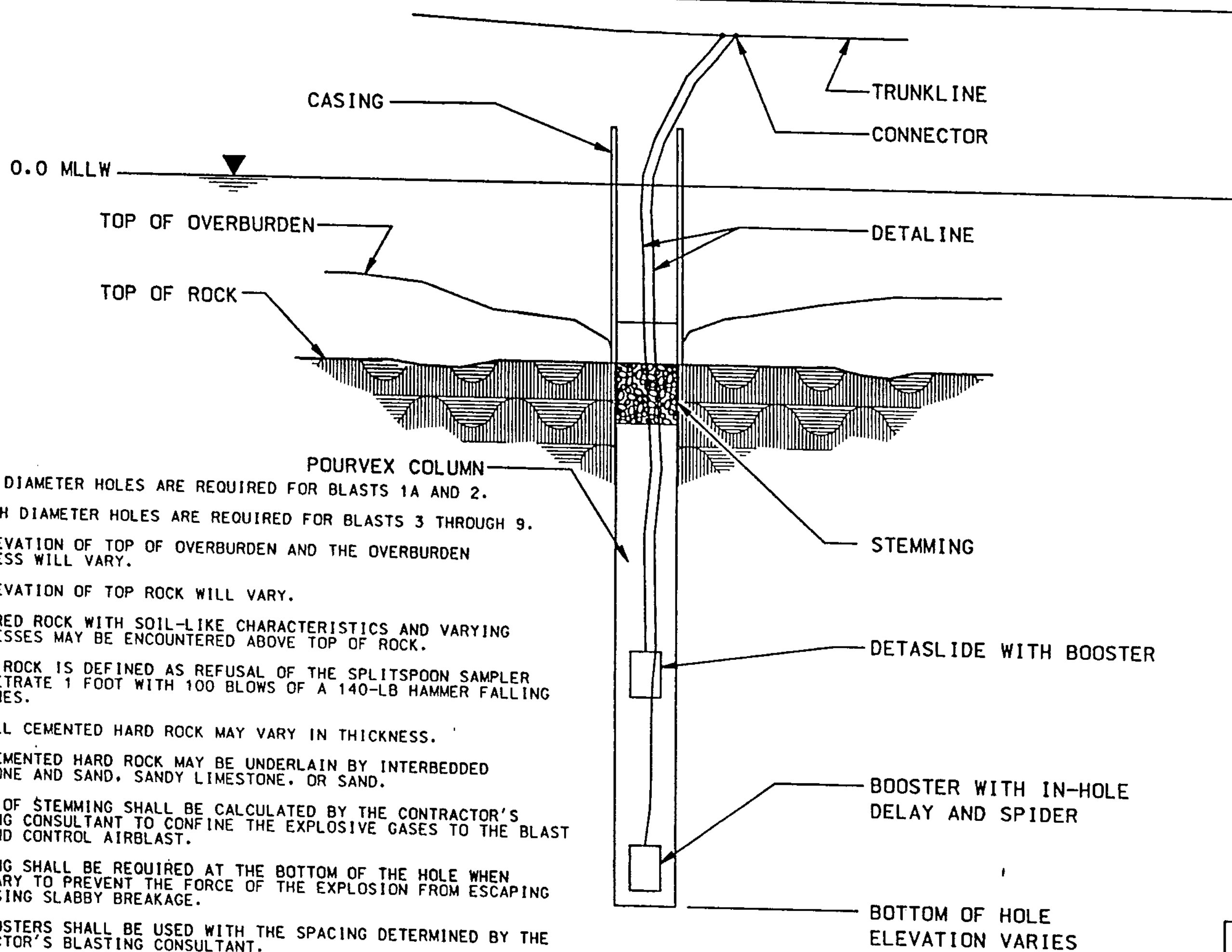
SHEET 2 OF 18



VICINITY MAP
TEST BLAST AREA
UPPER BIG ISLAND CHANNEL
LOWER BIG ISLAND CHANNEL
LOWER BRUNSWICK CHANNEL
CHANNEL LIMITS
TEST BLAST AREA
CHANNEL LIMITS
UPPER BIG ISLAND CHANNEL
A
B
C
D
3
TB-1
TB-2
TB-3
TB-4
TB-5
TB-6
TB-7
TB-8
TB-9
TB-10
TB-11
TB-12
WH98-64
WH98-65
WH98-65A
WH98-66
WH98-66A
WH98-67
WHP98-47
WHP98-48
WHP98-49
WH98-132
WH94P-2
UBI-6-89
UBI-9-89
NOTES:
1. SEE SHEET 2 FOR COORDINATES OF TEST BLAST AREA.
2. SEE BORING LOGS IN APPENDIX B FOR BORE HOLE HORIZONTAL COORDINATE LOCATIONS.
LEGEND
BORING LOCATION
100 50 0 100 200
SCALE IN FEET
WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA
BLAST EFFECT MITIGATION TESTS
TEST BLAST AREA
BORING LOCATIONS
SHEET 3 OF 18



WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA
BLAST EFFECT MITIGATION TESTS
TEST BLASTS 1A THRU 9 FOOTPRINT
SHEET 4 OF 18
BORE HOLES @ 8 FT. O.C.
4"DIA. FOR BLASTS 1A AND 2
4½"DIA. FOR BLASTS 3-9
105'
A
B
C
D
TEST BLAST 1A
TEST BLAST 2
TEST BLAST 3
TEST BLAST 4
TEST BLAST 5
TEST BLAST 5A
TEST BLAST 7
TEST BLAST 9
TEST BLAST 6
TEST BLAST 8
RANGE 1
RANGE 2
RANGE 3
NOT TO SCALE



NOTES:

1. 4 INCH DIAMETER HOLES ARE REQUIRED FOR BLASTS 1A AND 2.
2. 4½ INCH DIAMETER HOLES ARE REQUIRED FOR BLASTS 3 THROUGH 9.
3. THE ELEVATION OF TOP OF OVERBURDEN AND THE OVERBURDEN THICKNESS WILL VARY.
4. THE ELEVATION OF TOP ROCK WILL VARY.
5. WEATHERED ROCK WITH SOIL-LIKE CHARACTERISTICS AND VARYING THICKNESSES MAY BE ENCOUNTERED ABOVE TOP OF ROCK.
6. TOP OF ROCK IS DEFINED AS REFUSAL OF THE SPLITSPOON SAMPLER TO PENETRATE 1 FOOT WITH 100 BLOWS OF A 140-LB HAMMER FALLING 30 INCHES.
7. THE WELL CEMENTED HARD ROCK MAY VARY IN THICKNESS.
8. WELL CEMENTED HARD ROCK MAY BE UNDERLAIN BY INTERBEDDED LIMESTONE AND SAND, SANDY LIMESTONE, OR SAND.
9. AMOUNT OF STEMMING SHALL BE CALCULATED BY THE CONTRACTOR'S BLASTING CONSULTANT TO CONFINE THE EXPLOSIVE GASES TO THE BLAST HOLE AND CONTROL AIRBLAST.
10. STEMMING SHALL BE REQUIRED AT THE BOTTOM OF THE HOLE WHEN NECESSARY TO PREVENT THE FORCE OF THE EXPLOSION FROM ESCAPING OR CAUSING SLABBY BREAKAGE.
11. TWO BOOSTERS SHALL BE USED WITH THE SPACING DETERMINED BY THE CONTRACTOR'S BLASTING CONSULTANT.
12. THE EXPLOSIVE SHALL BE LOADED THROUGH CASING. 4 INCH DIAMETER HOLES SHALL BE LOADED AT 7 POUNDS PER FOOT. 4½ INCH DIAMETER HOLES SHALL BE LOADED AT 9 POUNDS PER FOOT.

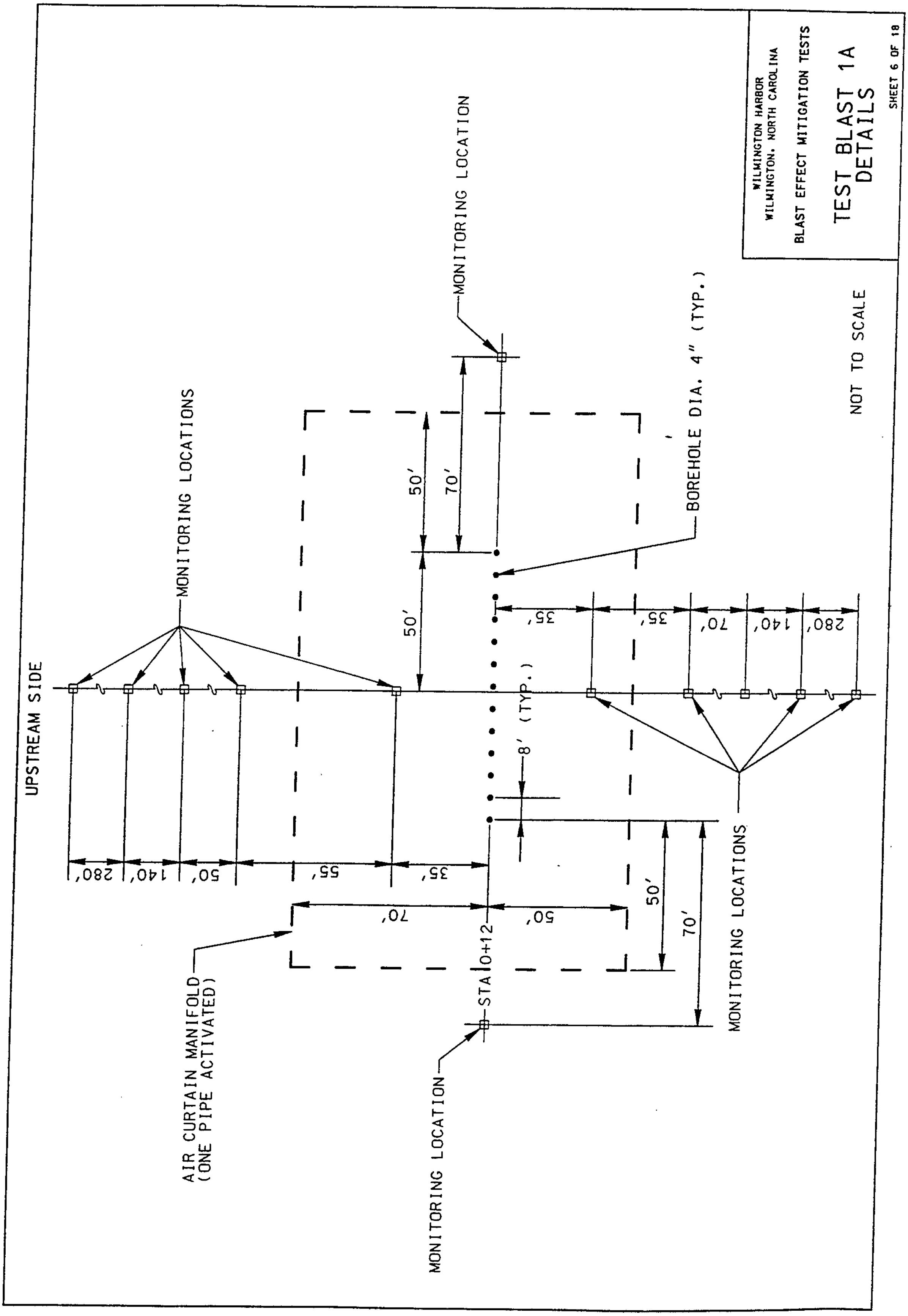
NOT TO SCALE

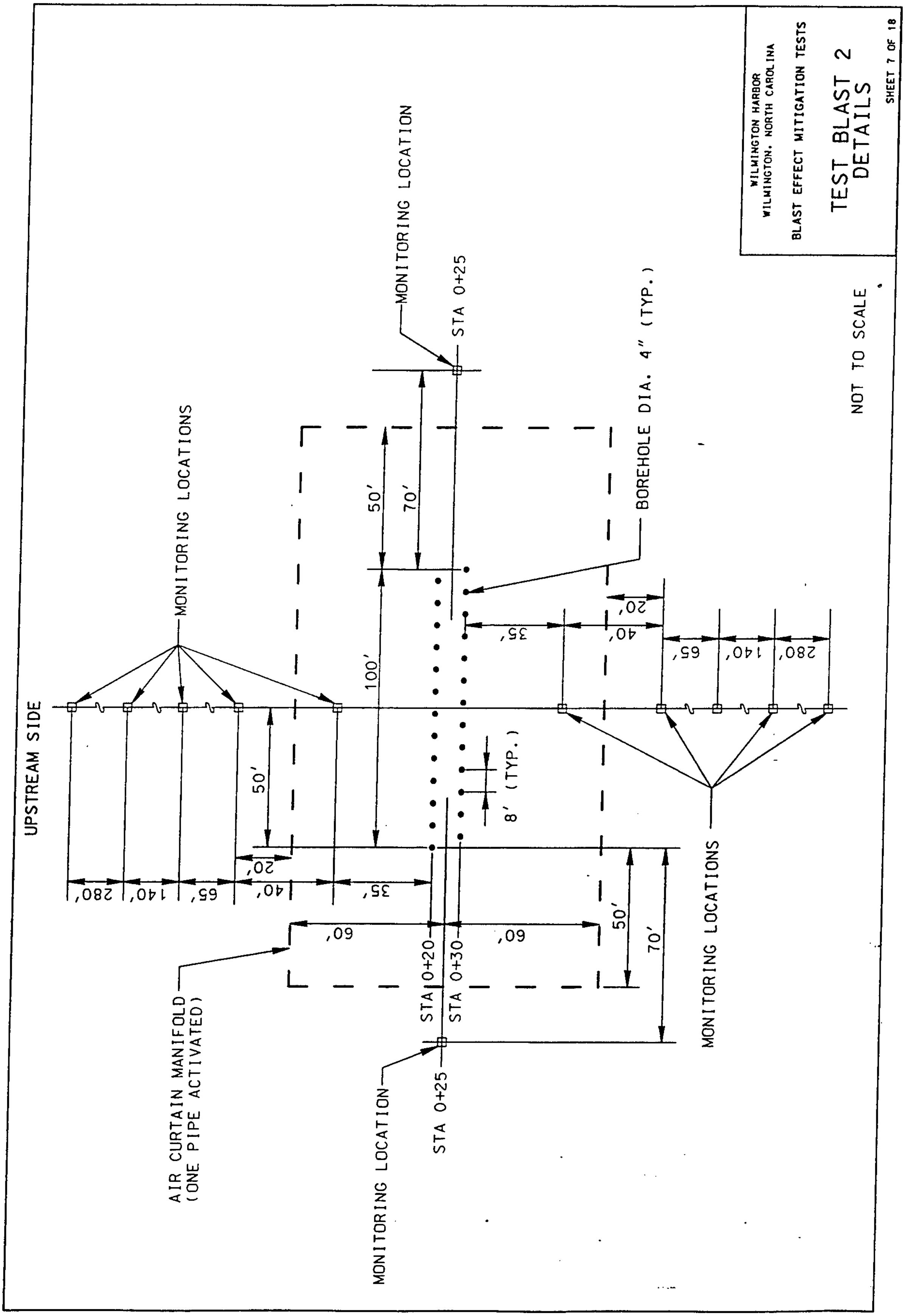
WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA

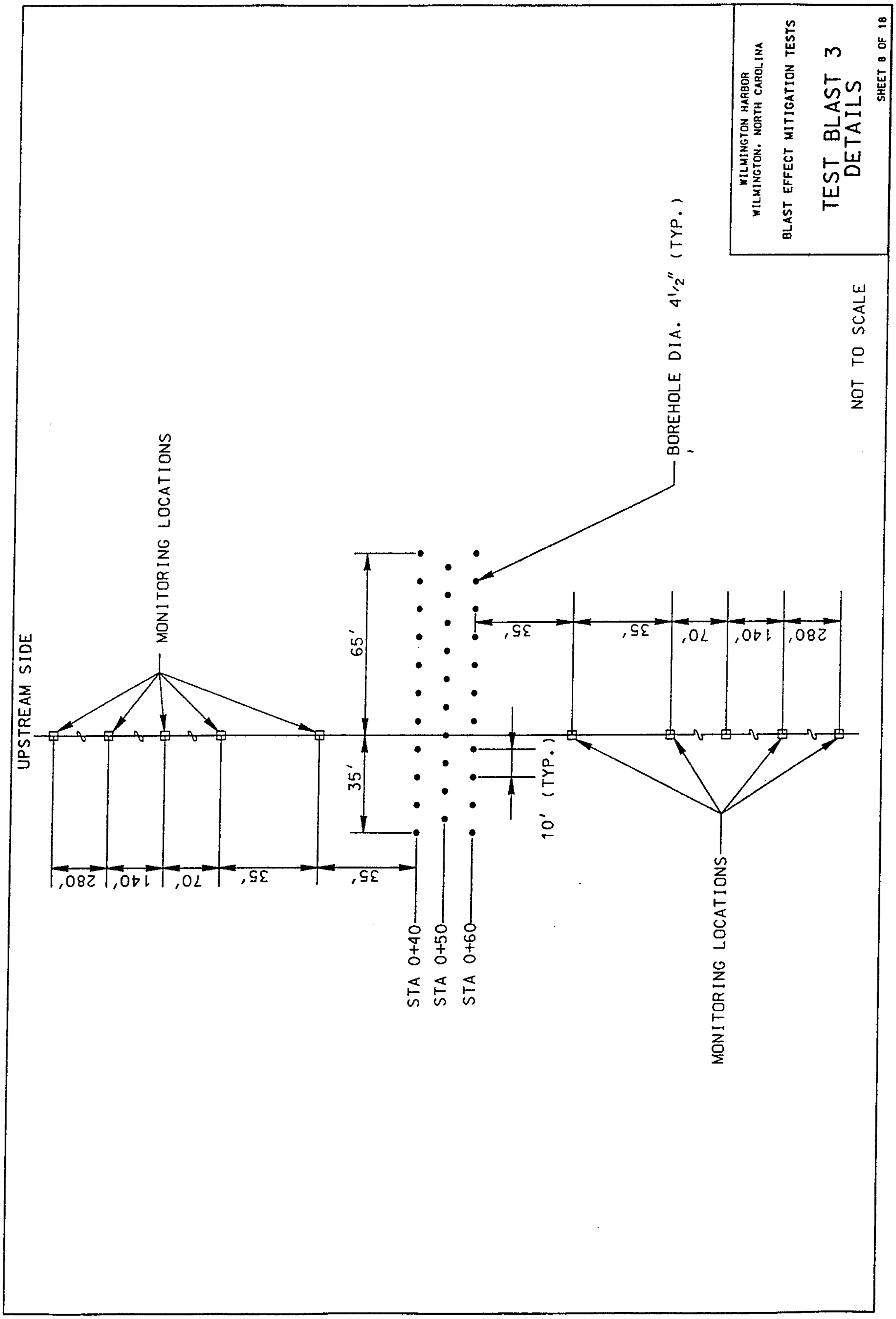
BLAST EFFECT MITIGATION TESTS

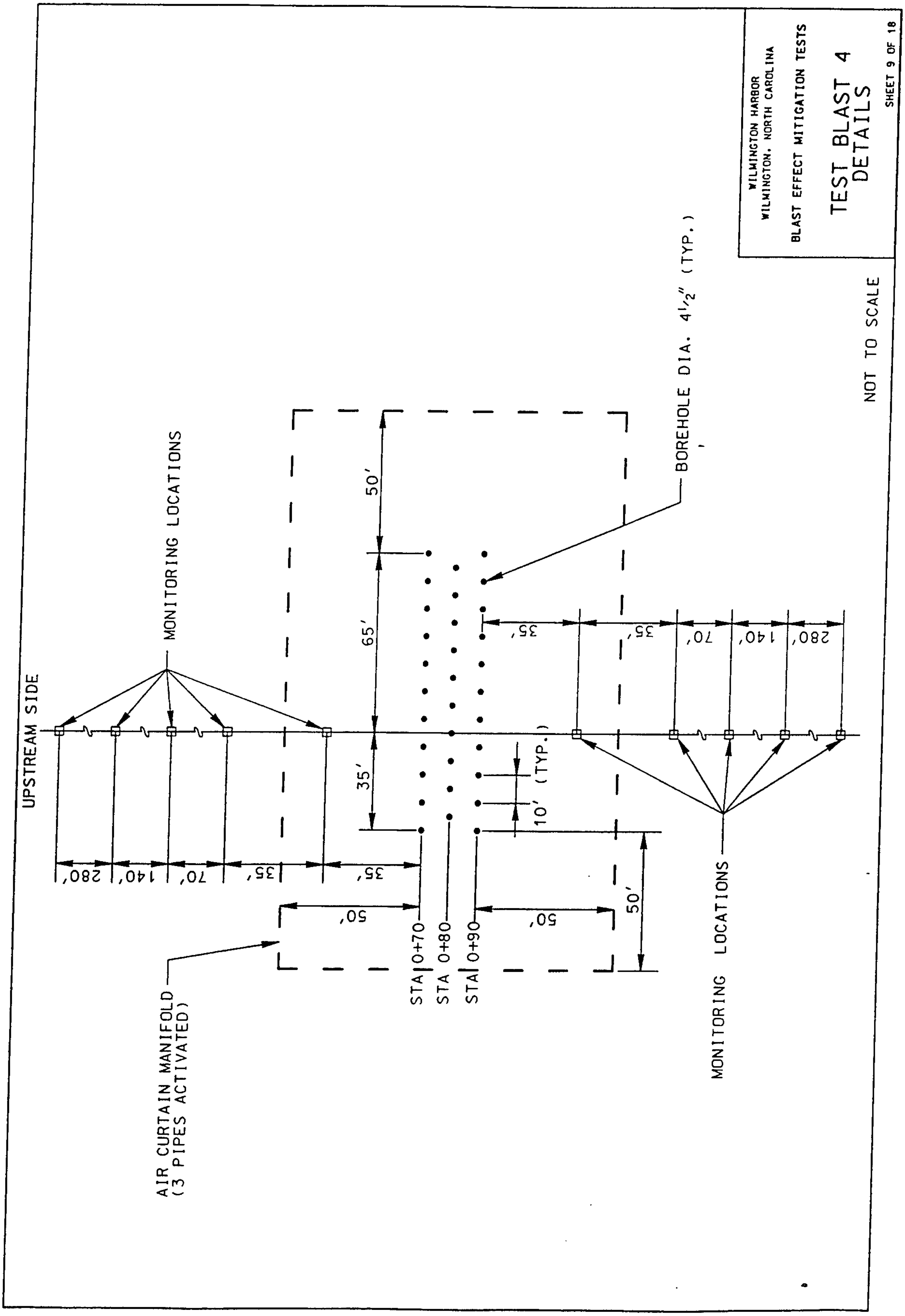
TYPICAL
BLAST HOLE

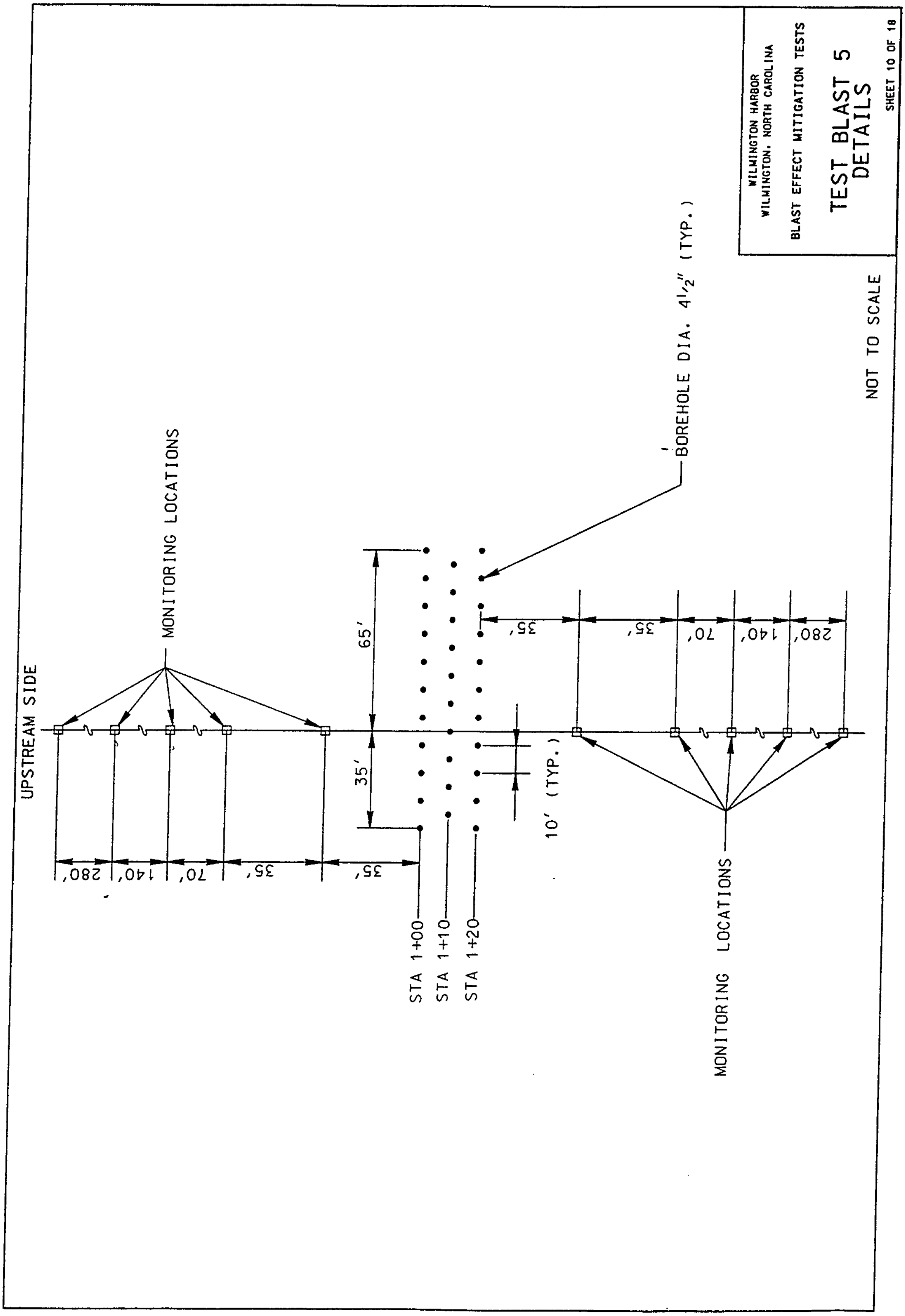
SHEET 5 OF 18

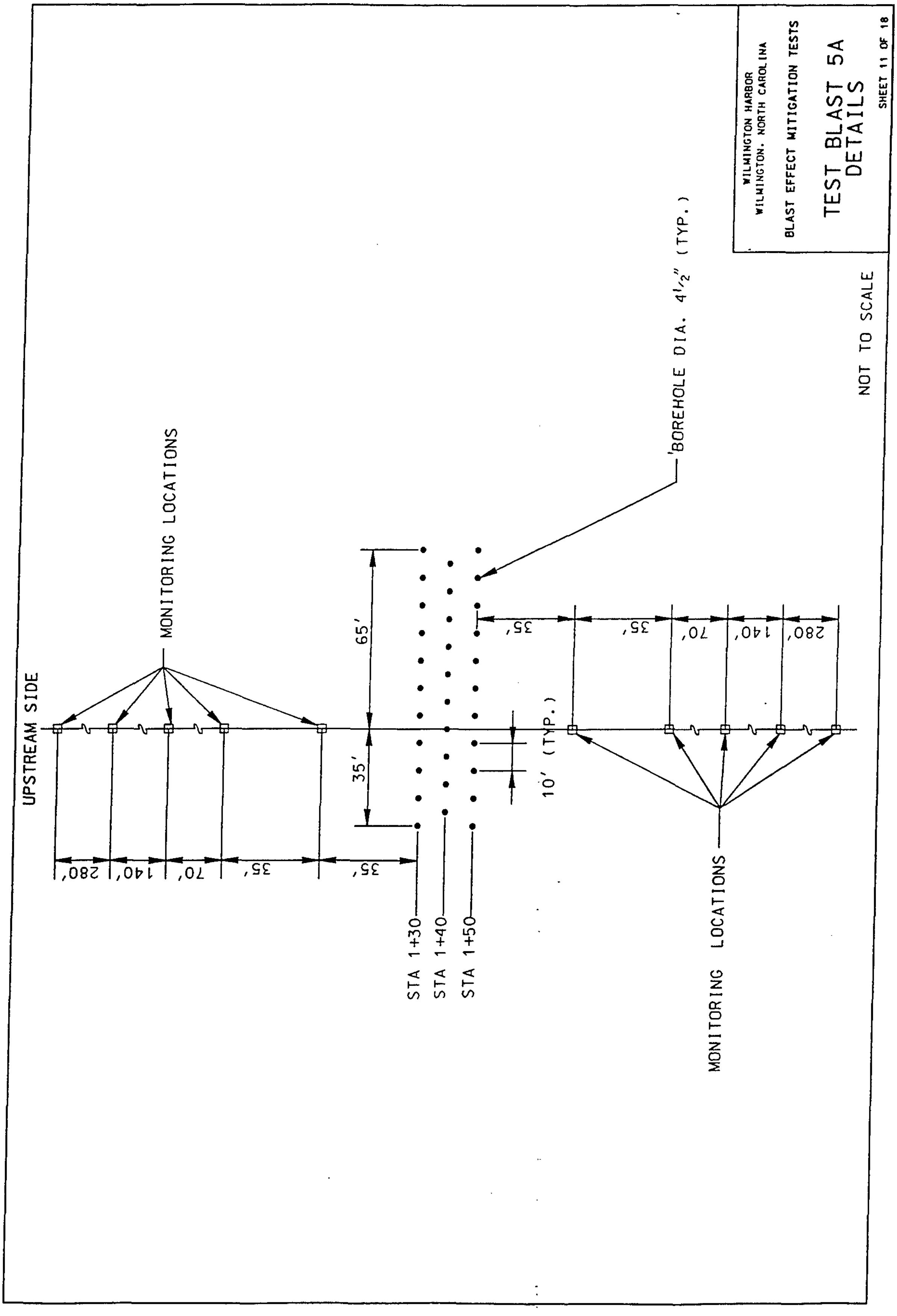

WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA
BLAST EFFECT MITIGATION TESTS
TEST BLAST 1A
DETAILS
SHEET 6 OF 18
NOT TO SCALE
MONITORING LOCATION
MONITORING LOCATIONS
BOREHOLE DIA. 4" (TYP.)
UPSTREAM SIDE
8' (TYP.)
AIR CURTAIN MANIFOLD
(ONE PIPE ACTIVATED)
STA 0+12
50'
70'
35'
55'
140'
280'

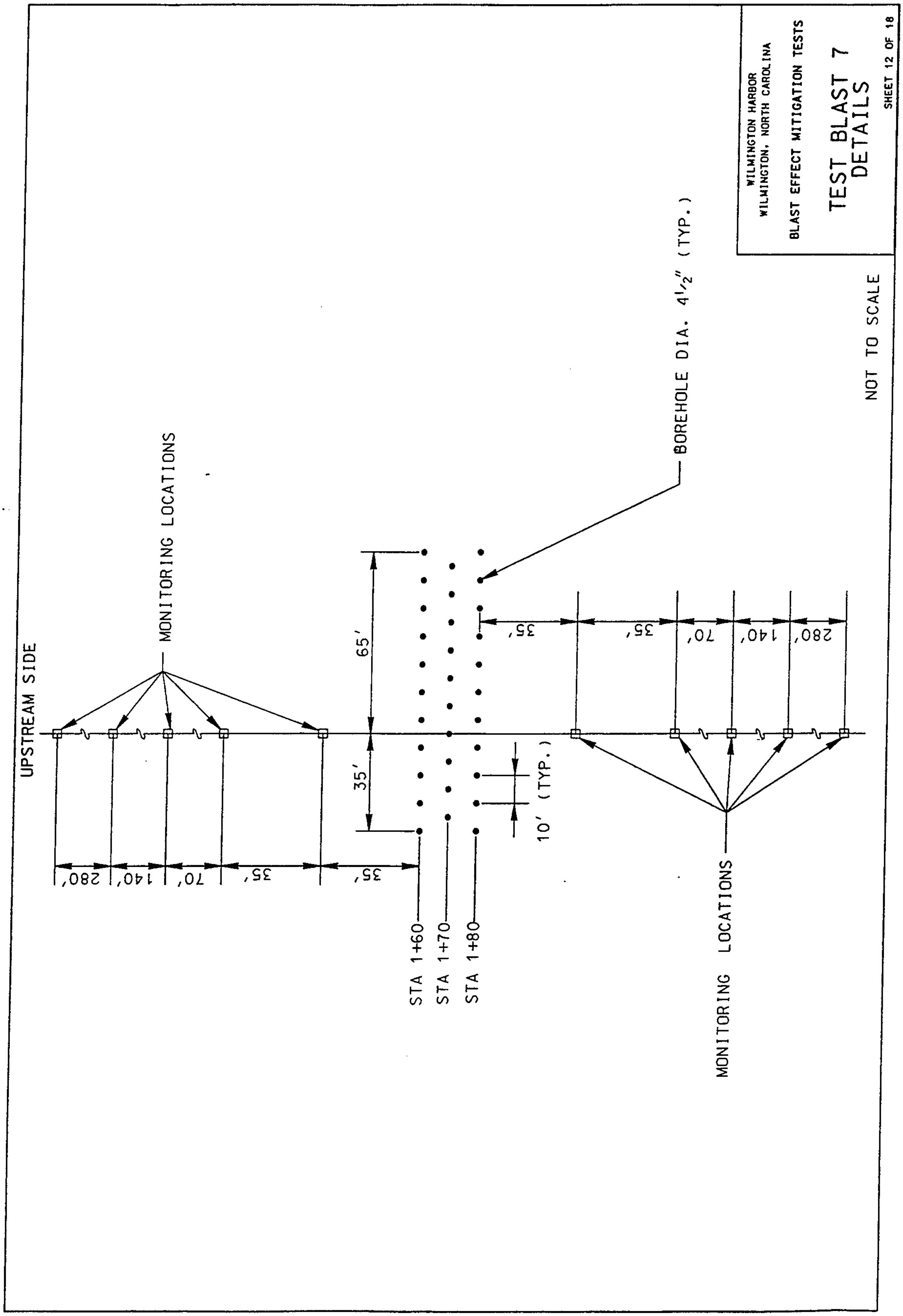

WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA
BLAST EFFECT MITIGATION TESTS
TEST BLAST 2
DETAILS
SHEET 7 OF 18
NOT TO SCALE
MONITORING LOCATION
STA 0+25
BOREHOLE DIA. 4" (TYP.)
MONITORING LOCATIONS
UPSTREAM SIDE
8' (TYP.)
AIR CURTAIN MANIFOLD
(ONE PIPE ACTIVATED)
STA 0+20
STA 0+30
MONITORING LOCATION
STA 0+25
MONITORING LOCATIONS
50'
70'
100'
50'
20'
35'
40'
65'
140'
280'
60'
60'
50'
70'

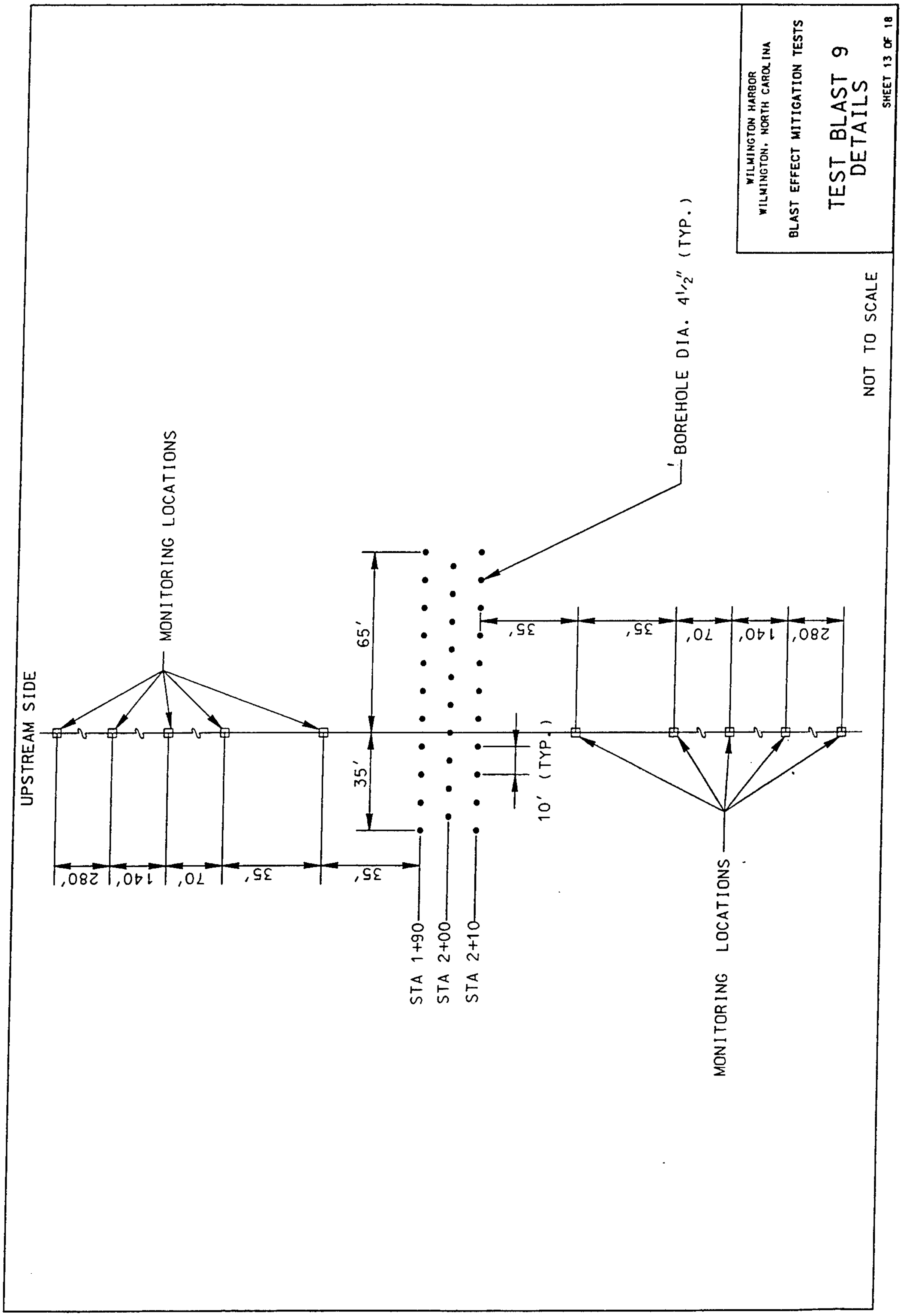

WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA
BLAST EFFECT MITIGATION TESTS
TEST BLAST 3
DETAILS
SHEET 8 OF 18
NOT TO SCALE
BOREHOLE DIA. 4½" (TYP.)
UPSTREAM SIDE
MONITORING LOCATIONS
MONITORING LOCATIONS
65'
35'
10' (TYP.)
280'
140'
70'
35'
35'
35'
35'
70'
140'
280'
STA 0+40
STA 0+50
STA 0+60

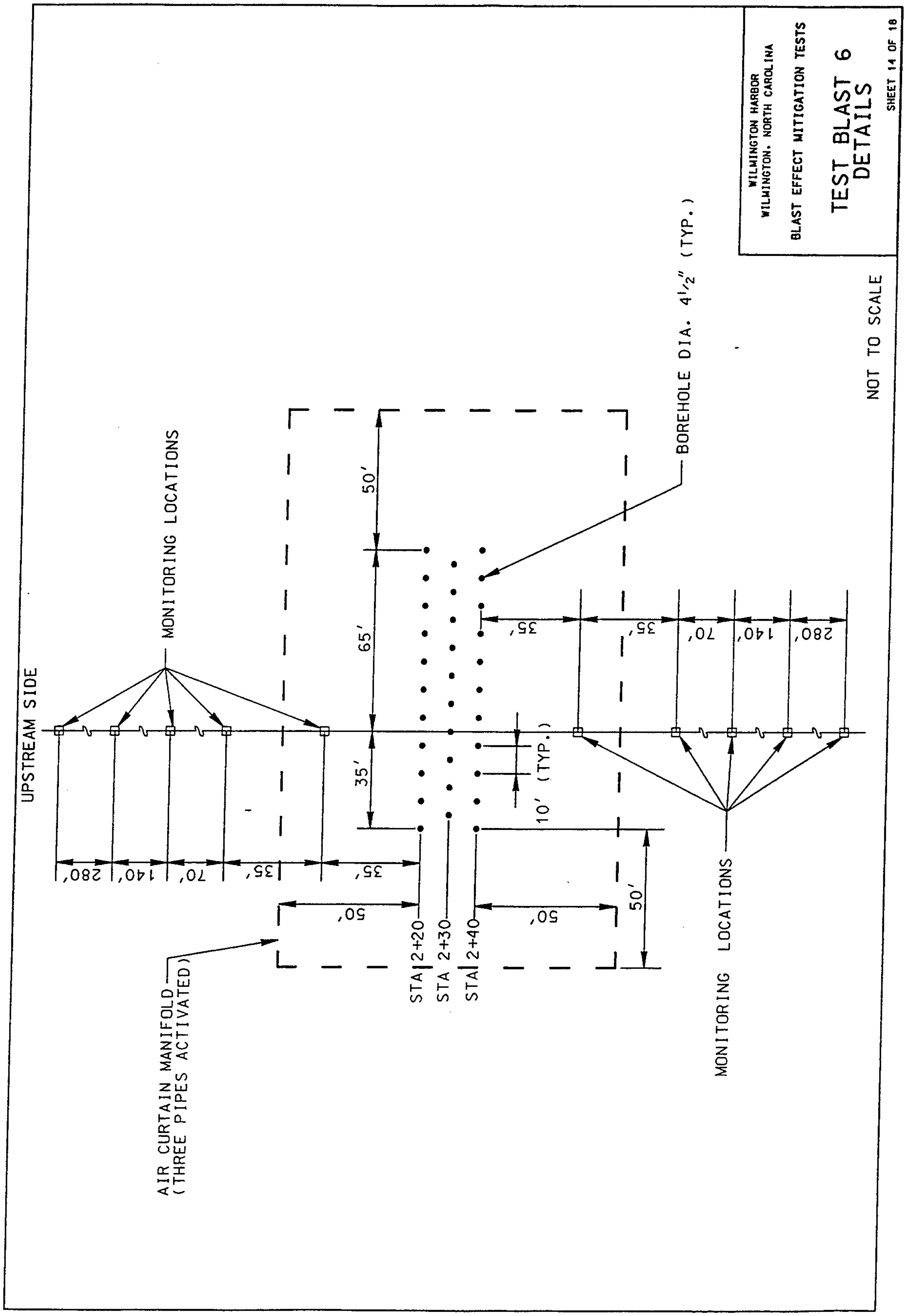

WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA
BLAST EFFECT MITIGATION TESTS
TEST BLAST 4
DETAILS
SHEET 9 OF 18
NOT TO SCALE
UPSTREAM SIDE
MONITORING LOCATIONS
BOREHOLE DIA. 4 1/2" (TYP.)
MONITORING LOCATIONS
AIR CURTAIN MANIFOLD
(3 PIPES ACTIVATED)
STA 0+70
STA 0+80
STA 0+90
50'
65'
35'
10' (TYP.)
280'
140'
70'
35'
35'
50'
50'
50'
35'
35'
70'
140'
280'

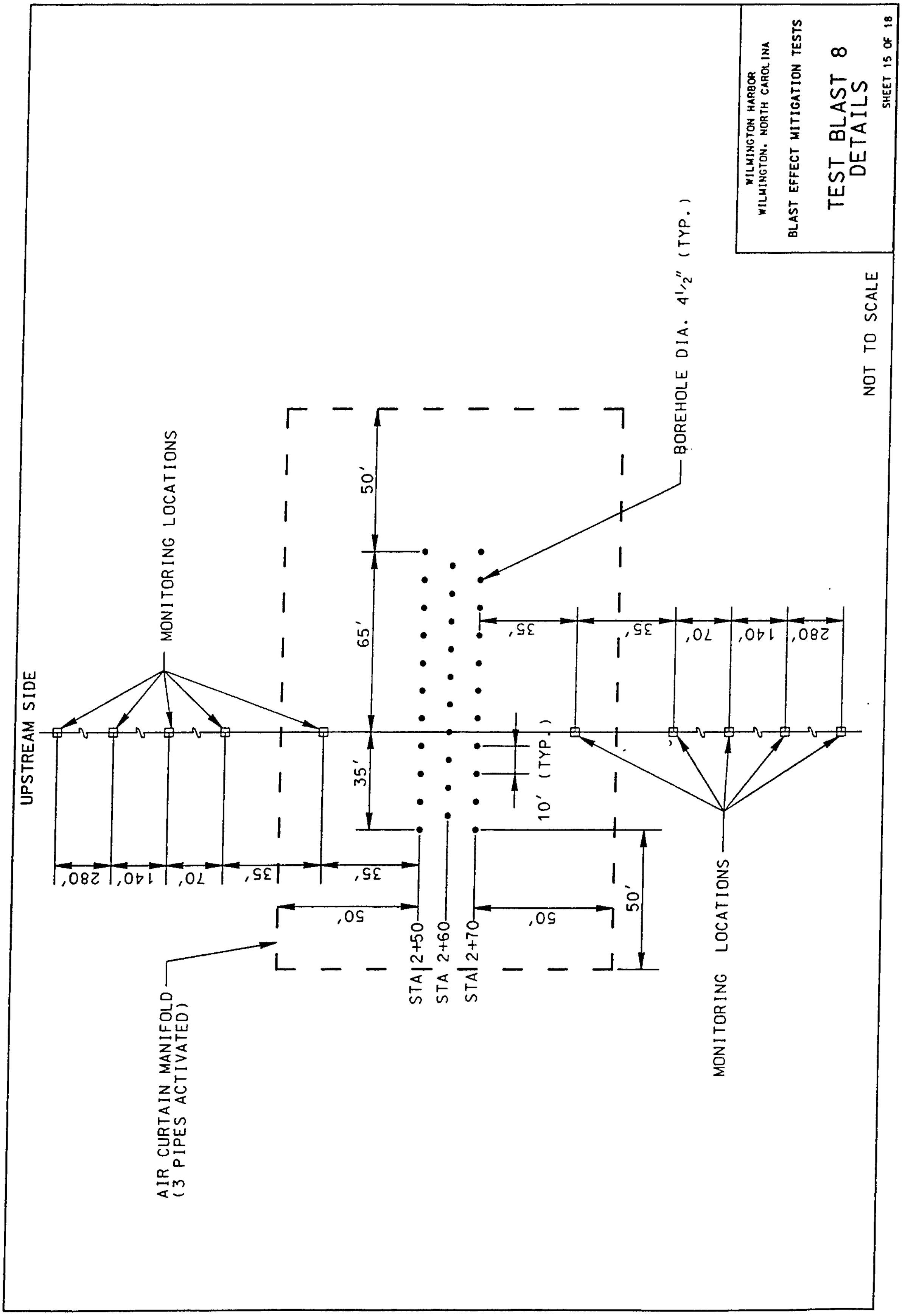

WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA
BLAST EFFECT MITIGATION TESTS
TEST BLAST 5
DETAILS
SHEET 10 OF 18
NOT TO SCALE
BOREHOLE DIA. 4½" (TYP.)
MONITORING LOCATIONS
UPSTREAM SIDE
65'
35'
10' (TYP.)
35'
35'
70'
140'
280'
STA 1+00
STA 1+10
STA 1+20
MONITORING LOCATIONS
280'
140'
70'
35'
35'


WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA
BLAST EFFECT MITIGATION TESTS
TEST BLAST 5A
DETAILS
SHEET 11 OF 18
NOT TO SCALE
UPSTREAM SIDE
MONITORING LOCATIONS
BOREHOLE DIA. 4½" (TYP.)
65'
35'
10' (TYP.)
280'
140'
70'
35'
35'
35'
35'
70'
140'
280'
STA 1+30
STA 1+40
STA 1+50
MONITORING LOCATIONS

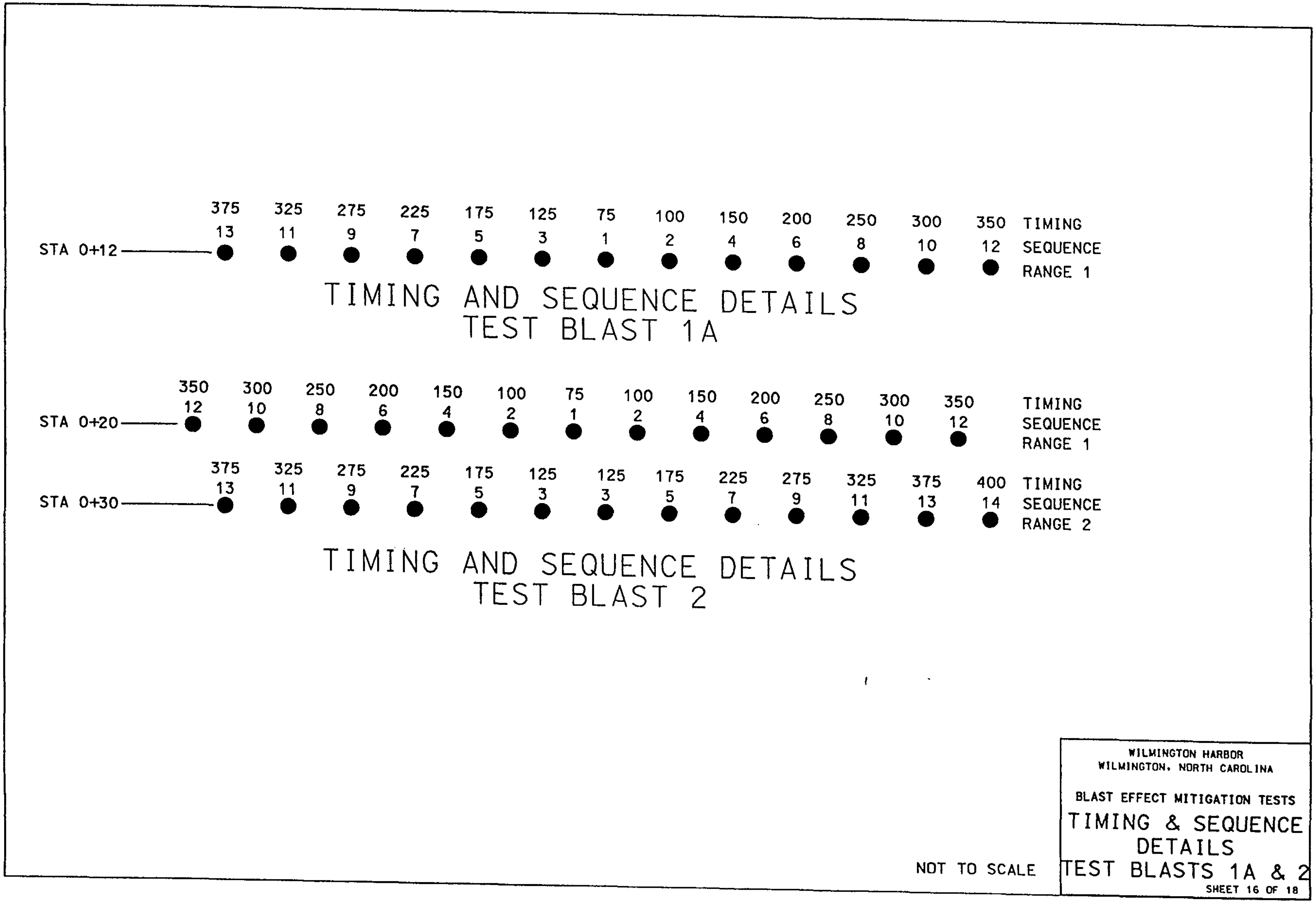

WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA
BLAST EFFECT MITIGATION TESTS
TEST BLAST 7
DETAILS
SHEET 12 OF 18
NOT TO SCALE
UPSTREAM SIDE
MONITORING LOCATIONS
BOREHOLE DIA. 4½" (TYP.)
65'
35'
10' (TYP.)
280'
140'
70'
35'
35'
35'
35'
70'
140'
280'
STA 1+60
STA 1+70
STA 1+80
MONITORING LOCATIONS

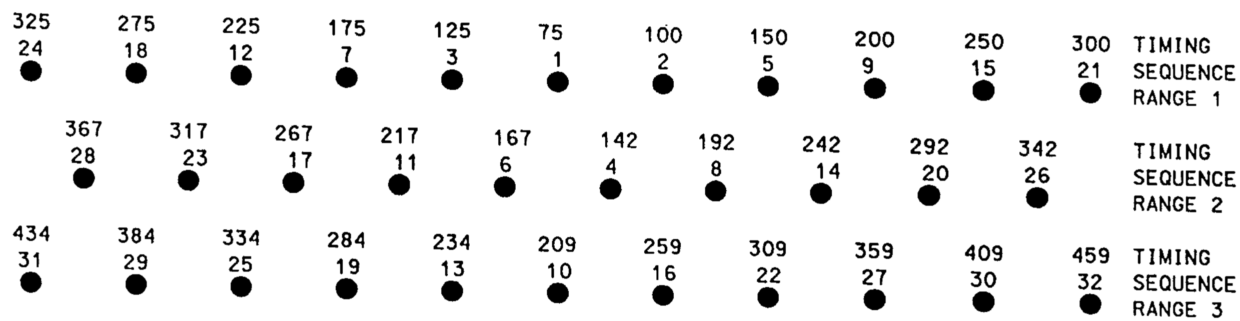

WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA
BLAST EFFECT MITIGATION TESTS
TEST BLAST 9
DETAILS
SHEET 13 OF 18
NOT TO SCALE
BOREHOLE DIA. 4½" (TYP.)
MONITORING LOCATIONS
UPSTREAM SIDE
65'
35'
10' (TYP.)
35'
35'
70'
140'
280'
STA 1+90
STA 2+00
STA 2+10
MONITORING LOCATIONS


WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA
BLAST EFFECT MITIGATION TESTS
TEST BLAST 6
DETAILS
SHEET 14 OF 18
NOT TO SCALE
UPSTREAM SIDE
MONITORING LOCATIONS
BOREHOLE DIA. 4½" (TYP.)
AIR CURTAIN MANIFOLD
(THREE PIPES ACTIVATED)
STA 2+20
STA 2+30
STA 2+40
50'
65'
35'
10' (TYP.)
280'
140'
70'
35'
35'
50'
50'
50'
35'
35'
70'
140'
280'
MONITORING LOCATIONS



WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA
BLAST EFFECT MITIGATION TESTS
TEST BLAST 8
DETAILS
SHEET 15 OF 18
NOT TO SCALE
UPSTREAM SIDE
MONITORING LOCATIONS
BOREHOLE DIA. 4½" (TYP.)
50'
65'
35'
10' (TYP.)
280'
140'
70'
35'
STA 2+50
STA 2+60
STA 2+70
AIR CURTAIN MANIFOLD
(3 PIPES ACTIVATED)


STA 0+12
375 13
325 11
275 9
225 7
175 5
125 3
75 1
100 2
150 4
200 6
250 8
300 10
350 12
TIMING
SEQUENCE
RANGE 1
TIMING AND SEQUENCE DETAILS
TEST BLAST 1A
STA 0+20
350 12
300 10
250 8
200 6
150 4
100 2
75 1
100 2
150 4
200 6
250 8
300 10
350 12
TIMING
SEQUENCE
RANGE 1
STA 0+30
375 13
325 11
275 9
225 7
175 5
125 3
125 3
175 5
225 7
275 9
325 11
375 13
400 14
TIMING
SEQUENCE
RANGE 2
TIMING AND SEQUENCE DETAILS
TEST BLAST 2
NOT TO SCALE
WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA
BLAST EFFECT MITIGATION TESTS
TIMING & SEQUENCE
DETAILS
TEST BLASTS 1A & 2
SHEET 16 OF 18



TIMING AND SEQUENCE DETAILS
TEST BLASTS 3 THRU 9

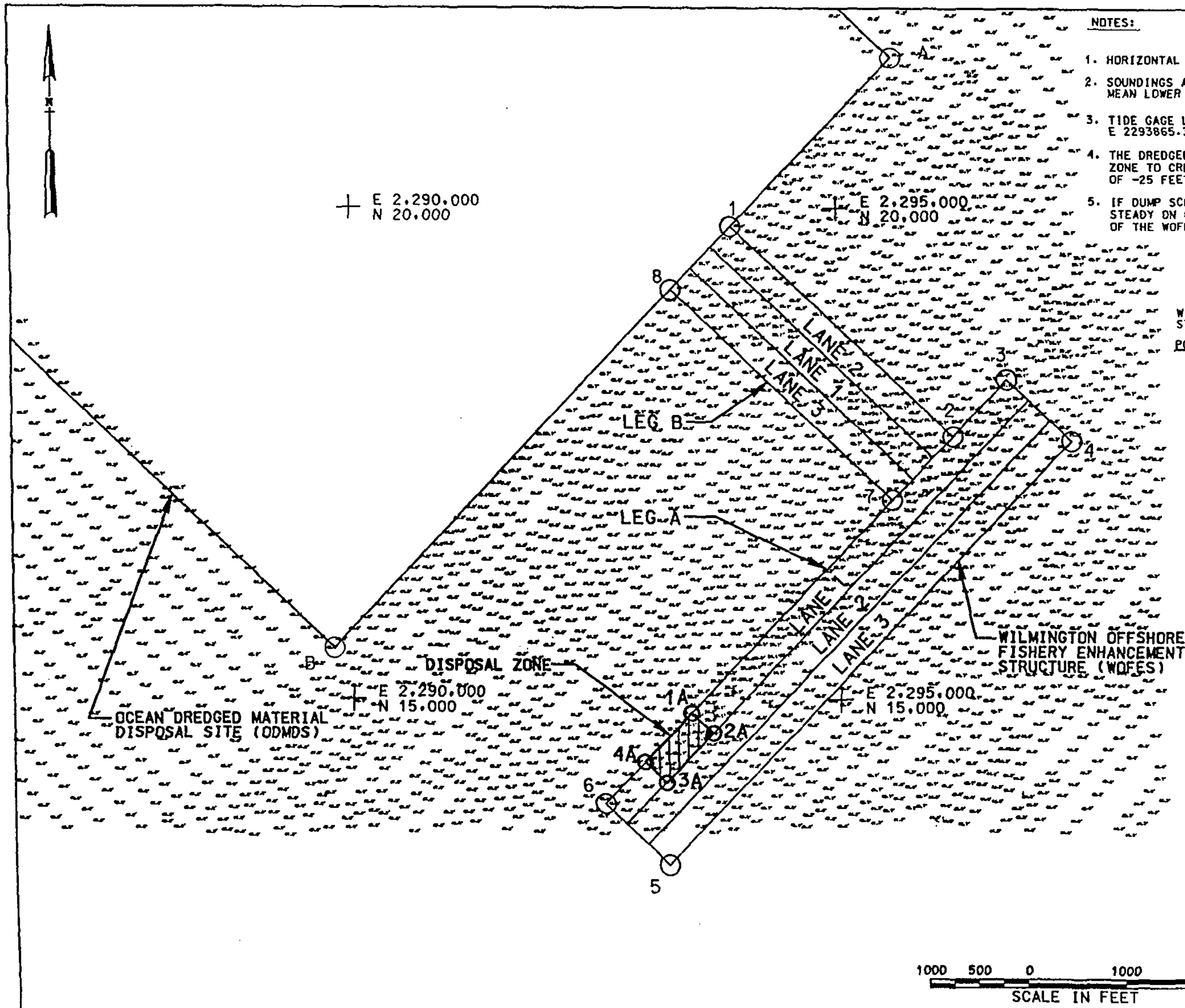
NOT TO SCALE

WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA

BLAST EFFECT MITIGATION TESTS

TIMING & SEQUENCE DETAILS
TEST BLASTS 3-9

SHEET 17 OF 18



NOTES:

1. HORIZONTAL DATUM NAD 1983.
2. SOUNDINGS ARE EXPRESSED IN FEET AND TENTHS AND REFER TO MEAN LOWER LOW WATER (MLLW).
3. TIDE GAGE LOCATED ON OFFSHORE PLATFORM (HAZEN GAGE) AT E 2293865.30 N 40285.34.
4. THE DREDGED MATERIAL SHALL BE DUMPED IN THE DISPOSAL ZONE TO CREATE A LINEAR BERM WITH A MAXIMUM ELEVATION OF -25 FEET MLLW.
5. IF DUMP SCOWS ARE USED, THE CONTRACTOR SHALL REMAIN STEADY ON COURSE WITH THE LONG AXIS OF LANE 1 OF LEG A OF THE WOFES.

WILMINGTON OFFSHORE FISHERY ENHANCEMENT STRUCTURE (WOFES) CORNER COORDINATES

POINT NO.	EASTING	NORTHING
1	2293922.4	19807.1
2	2296172.0	17674.1
3	2296725.3	18251.9
4	2297378.4	17632.6
5	2293228.5	13299.2
6	2292578.5	13921.7
7	2295549.5	17024.1
8	2293299.9	19157.1

DISPOSAL ZONE CORNER COORDINATES

POINT NO.	EASTING	NORTHING
1A	2293474.5	14857.3
2A	2293692.2	14650.9
3A	2293210.6	14143.0
4A	2292990.4	14351.8

OCEAN DREDGED MATERIAL DISPOSAL SITE (ODMDS) CORNER COORDINATES.

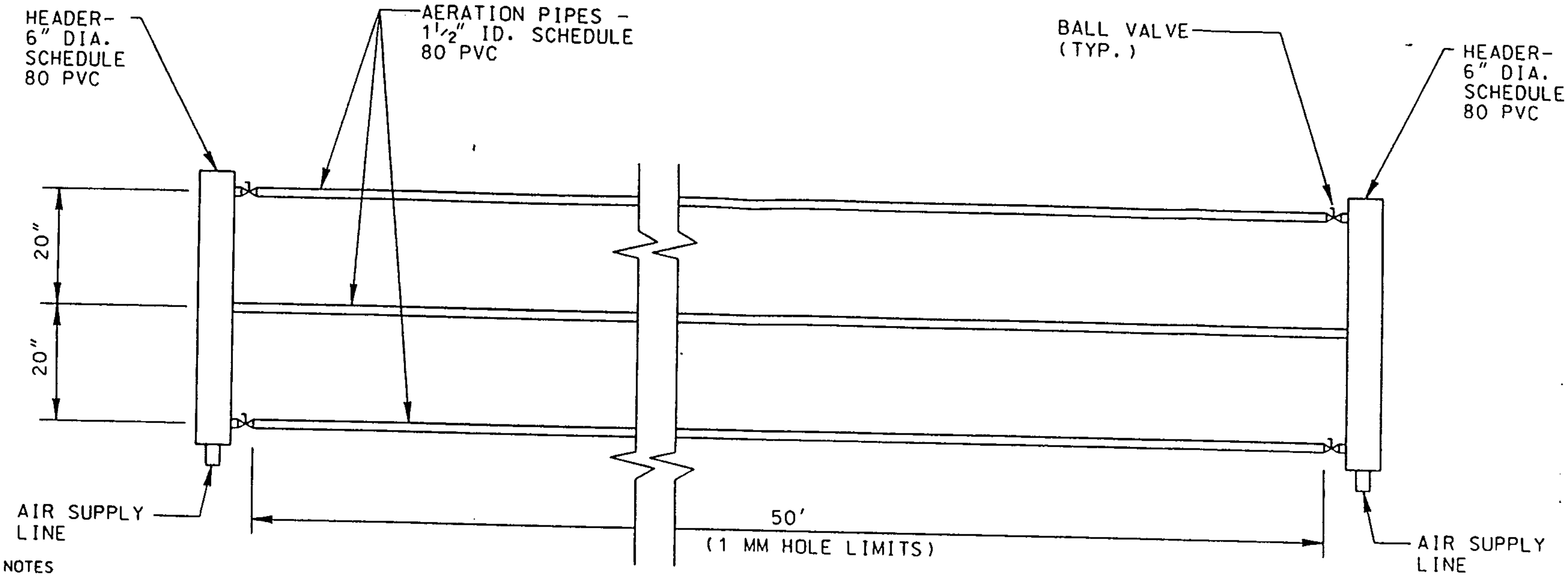
POINT NO.	EASTING	NORTHING
A	2295573	21531
B	2289807	15510

WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA

BLAST EFFECT MITIGATION TESTS

DISPOSAL AREA
WOFES

SHEET 18 OF 18



NOTES

1. EACH MANIFOLD SHALL HAVE 3 AERATION PIPES SPACED AT 20-INCHES ON CENTER.
2. EACH AERATION PIPE SHALL HAVE A 1 MM HOLE ON OPOSITE SIDES SUCH THAT THE HOLES HORIZONTALLY OPPOSE EACH OTHER WHEN THE MANIFOLD IS LAYING ON THE RIVER BOTTOM IN ITS OPERATIONAL POSITION.
3. THE 1 MM AERATION HOLES SHALL BE SPACED 1-INCH ON CENTER ALONG THE LENGTH OF THE AERATION PIPES.
4. VALVING SHALL BE PROVIDED TO ALLOW OPERATION OF ONLY ONE AERATION LINE ON EACH MANIFOLD FOR SOME OF THE BLASTS.
5. THE MANIFOLD SYSTEM SHALL DELIVER APPROXIMATELY 16 CFM OF OIL-FREE AIR PER LINER FOOT OF MANIFOLD TO THE RIVER BOTTOM. AIR SHALL BE UNIFORMLY DISTRIBUTED ALONG THE LENGTH AND WIDTH OF EACH MANIFOLD.
6. CONTRACTOR SHALL PROVIDE MEASURING DEVISES AS REQUIRED TO VARIFY THAT REQUIRED AIR VOLUME IS BEING DISPERSED INTO THE WATER.
7. THE SKETCH ABOVE IS A SCHEMATIC OF ONE POSSIBLE MANIFOLD SYSTEM WITH AERATION PIPES OF 50 FEET EACH. BASED ON THE PIPE MATERIAL AND SIZES SHOWN, REQUIREMENTS ABOVE, AND THE SITE CONDITIONS AN OIL-FREE AIR SUPPLY OF 800 CFM AT 90 PSI MAY BE SUFFICIENT FOR EACH MANIFOLD REQUIRED. AIR SUPPLY VOLUME WILL DEPEND ON THE FINAL MANIFOLD DESIGN.
8. CONTRACTOR SHALL PROVIDE RIGID FRAME BASED ON MANIFOLD LAYOUT AND MATERIAL AS REQUIRED TO SUPPORT AND PROTECT THE MANIFOLD DURING DEPLOYMENT, ALIGNMENT, OPERATION, RETRIEVAL AND STORAGE.
9. RESTRAINTS ALONG THE MANIFOLD AND OR FRAME AS REQUIRED TO RESIST BUOYANT, CURRENT AND BLAST FORCES MAY BE REQUIRED.
10. CONTRACTOR SHALL SUBMIT HIS MANIFOLD DESIGN ALONG WITH PLANS AND SPECIFICATIONS TO THE CONTRACTING OFFICER FOR APPROVAL PRIOR TO PROCEEDING WITH CONSTRUCTION.
11. CONTRACTOR SHALL PROVIDE A METHOD OF ASSURING MANIFOLD OVERLAP TO ENSURE CONTINOUS AIR DISCHARGE ALONG THE LINE OF MANIFOLDS. THIS MAY BE ACCOMPLISHED BY ADDITION OF ALIGNMENT RINGS AND GUIDE LINES ATTACHED TO EACH MANIFOLD.

WILMINGTON HARBOR
WILMINGTON, NORTH CAROLINA

BLAST EFFECT MITIGATION TESTS

AIR CURTAIN
MANIFOLD SECTION
SCHEMATIC

SHEET 1 OF 1

Hole No. TB-1

DRILLING LOG	DIVISION SOUTH ATLANTIC	INSTALLATION WILMINGTON DISTRICT	SHEET 1 OF 2 SHEETS
1. PROJECT BLAST EFFECT MITIGATION TESTS		10. SIZE AND TYPE OF BIT 2-7/8" Side Discharge Drag NQ2 core	
2. LOCATION (Coordinates or Station) (Upper Big Island) NC Lombert (NAD83): E. 2319613 N. 142316		11. DATUM FOR ELEVATION SHOWN (TBM or MSL) Mean Lower Low Water	
3. DRILLING AGENCY S. & M.E., Inc. (Raleigh, NC Office)		12. MANUFACTURER'S DESIGNATION OF DRILL CME 55 (Barge Mounted)	
4. HOLE NO. (As shown on drawing title and file number) TB-1		13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED 6; UNDISTURBED 0	
5. NAME OF DRILLER Mike Moseley		14. TOTAL NUMBER CORE BOXES 1	
6. DIRECTION OF HOLE [X] VERTICAL [ ] INCLINED ____ DEG. FROM VERT.		15. ELEVATION GROUND WATER N/A	
		16. DATE HOLE: STARTED 25 Jun 98; COMPLETED 25 Jun 98	
7. THICKNESS OF OVERBURDEN 39.3' (34.2' of Water)		17. ELEVATION TOP OF HOLE 0.0 MLLW	
8. DEPTH DRILLED INTO ROCK 11.4'		18. TOTAL CORE RECOVERY FOR BORING 84.6 %	
9. TOTAL DEPTH OF HOLE 50.7'		19. SIGNATURE OF INSPECTOR Greg Hippert, ZAPATA ENGINEERING	

ELEVATION MLLW	DEPTH (feet)	LEGEND	CLASSIFICATION OF MATERIALS (Description)	% CORE RECOVERY	BOX OR SAMPLE NO.	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant)
0.0	0 – 34	Water	0.0' to 34.2', Water RIVER BOTTOM @ 34.2'			Field log transcribed and/or annotated by Tong C. How, geologist, 9 Aug 98. NOTE: CHANGED SCALE @ 34.0' and 39.0' Weight of Rods indicates the overburden material was penetrated without blows from the hammer. BLOWS/FOOT
-34.2	34.2 – 35.2		No recovery. 35.2'			34.2' to 34.8' Weight of Rods — WR 34.2' to 35.2' Hole cleaned out
	35.2 – 36.7		GW, tan, gray, slightly silty, fine to coarse, sandy gravel (weathered limestone)		Jar 1	Drive 1: 35.2' to 36.7' Rec 0.5' Blows: 4-2-8 — 10
	36.7 – 37.0					36.7' to 37.0' Hole cleaned out
	37.0 – 38.5		37.0' Gray		Jar 2	Drive 2: 37.0' to 38.5' Rec 1.2' Blows: 14-12-12 — 24
	38.5 – 39.3		TOP OF ROCK @ 39.3'		Jar 3	Drive 3: 38.5' to 39.3' Blows: 18-100/0.3' At 39.3' began coring w/ NQ2 diamond core bit Splitspoon refusal @ 39.3' — 100/0.3'
-39.3	39.3 – 40		CASTLE HAYNE, Unit B Limestone: Hard, slightly weathered, aphanitic to fine grained light gray, fossiliferous (large), pitted to vuggy. 39.3' to 39.5' & 39.8' Fragmented	87	BOX 1 of 1	PULL1: 39.3' to 44.0' RAN 4.7' GAIN 0.0' REC 4.1' UL 0.0' LOSS 0.6' Hyd Press: 550 psi Drl Wat Ret: 100% Drilling Time: 16 min
-40.0	40		CONTINUED ON SHEET 2 NOTE: Soils field classified in accordance with the Unified Soil Classification System.			BLOWS/FOOT: NUMBER REQUIRED TO DRIVE 1⅜" ID SPLITSPOON WITH 140 LB. HAMMER FALLING 30 INCHES

ENG FORM 1836 PREVIOUS EDITIONS ARE OBSOLETE. PROJECT Blast Effect Mitigation Tests HOLE NO. TB-1

Hole No. TB-2

DRILLING LOG	DIVISION SOUTH ATLANTIC	INSTALLATION WILMINGTON DISTRICT	SHEET 1 of 3 SHEETS
1. PROJECT BLAST EFFECT MITIGATION TESTS		10. SIZE AND TYPE OF BIT 2-7/8" Side Discharge Drag	
2. LOCATION (Coordinates or Station) (Upper Big Island) NC Lambert (NAD83): E. 2319625 N. 142216		11. DATUM FOR ELEVATION SHOWN (TBM or MSL) Mean Lower Low Water	
3. DRILLING AGENCY S. & M.E., Inc. (Raleigh, NC Office)		12. MANUFACTURER'S DESIGNATION OF DRILL CME 55 (Barge Mounted)	
4. HOLE NO. (As shown on drawing title and file number) TB-2		13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED 5; UNDISTURBED 0	
5. NAME OF DRILLER Mike Moseley		14. TOTAL NUMBER CORE BOXES 1	
6. DIRECTION OF HOLE [X] VERTICAL [ ] INCLINED ____ DEG. FROM VERT.		15. ELEVATION GROUND WATER N/A	
7. THICKNESS OF OVERBURDEN 39.5' (28.3' of Water)		16. DATE HOLE: STARTED 25 Jun 98; COMPLETED 25 Jun 98	
8. DEPTH DRILLED INTO ROCK 10.5'		17. ELEVATION TOP OF HOLE 0.0 MLLW	
9. TOTAL DEPTH OF HOLE 50.0'		18. TOTAL CORE RECOVERY FOR BORING 55.2 %	
		19. SIGNATURE OF INSPECTOR Greg Hippert, ZAPATA ENGINEERING	

ELEVATION MLLW a	DEPTH (feet) b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
0.0	0	Water	0.0' to 28.3' Water RIVER BOTTOM @ 28.3'			Field log transcribed and/or annotated by Tang C. How, geologist, 10 Aug 98. NOTE: CHANGED SCALE @ 28.0' Weight of Hammer indicates the overburden material was penetrated without blows from the hammer but from the weight of the rods and hammer. BLOWS/FOOT
	28					
-28.3	28.3		No recovery 29.8'			Weight of Rods indicates the overburden material was penetrated without blows from the hammer and only from the weight of the rods. 28.3' to 29.8' Weight of Rods 0
	29					
	30		SP, Tan, gray, fine to medium sand		Jar 1	Drive 1: 29.8' to 31.3' Blows: 1- 1/1.0' Rec 0.6' 1
	31		32.0'			31.3' to 32.0' Weight of Rods
	32		SW, Gray, tan, fine to coarse sand		Jar 2	Drive 2: 32.0' to 33.5' Blows: None, Weight of Hammer Rec 0.5' 0
	33					
	34					33.5' to 35.5' Weight of Rods
-35.0	35		CONTINUED ON SHEET 2 NOTE: Soils field classified in accordance with the Unified Soil Classification System.			BLOWS/FOOT: NUMBER REQUIRED TO DRIVE 1⅜" ID SPLITSPOON WITH 140 LB. HAMMER FALLING 30 INCHES

ENG FORM 1836 MAR 71 PREVIOUS EDITIONS ARE OBSOLETE. PROJECT Blast Effect Mitigation Tests HOLE NO. TB-2

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE 0.0 MLLW	Hole No. TB-2
PROJECT BLAST EFFECT MITIGATION TESTS	INSTALLATION WILMINGTON DISTRICT	SHEET 3 of 3 SHEETS

ELEVATION MLLW	DEPTH (feet)	LEGEND	CLASSIFICATION OF MATERIALS (Description)	% CORE RECOVERY	BOX OR SAMPLE NO.	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant)
-44.0	44		Rocky Point Member (cont.)	91		Corrected Depth 44.3'
			44.3' to 44.7' No recovery			44.3' to 44.7' cleaned hole
	45				Box	PULL 2: 44.7' to 50.0' RUN 5.3' UL 3.75' REC 1.45' GAIN 0.0' LOSS 3.85'
			45.4' to 45.8' Irregular sub-vertical break		1	Hyd. press: 550 psi
			45.7' Irregular subhorizontal break			Drilling time: 6 min.
	46		45.9' to 46.15' Broken rock		of	RQD - 0%
			46.15' to 49.9' Unaccountable Loss core		1	
				28		
	47	Core Loss				
	48					
	49					
				49.9'		Correct Depth 49.9'
-50.0	50		BOTTOM OF HOLE @ 50.0'			

ENG FORM 1836-A PREVIOUS EDITIONS ARE OBSOLETE. MAR 71 | PROJECT Blast Effect Mitigation Tests | HOLE NO. TB-2

Hole No. TB-8

DRILLING LOG	DIVISION SOUTH ATLANTIC	INSTALLATION WILMINGTON DISTRICT	SHEET 1 OF 2 SHEETS

1. PROJECT: BLAST EFFECT MITIGATION TESTS	10. SIZE AND TYPE OF BIT: 2-7/8" Side Discharge Drag
2. LOCATION (Coordinates or Station): (Upper Big Island) NC Lombert (NAD83): E. 2319547 N. 142030	11. DATUM FOR ELEVATION SHOWN (TBM or MSL): Mean Lower Low Water; NQ2 diamond coring
3. DRILLING AGENCY: S. & M.E., Inc. (Raleigh Office)	12. MANUFACTURER'S DESIGNATION OF DRILL: CME 55 (Barge Mounted)
4. HOLE NO. (As shown on drawing title and file number): TB-8	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED 6; UNDISTURBED 0
5. NAME OF DRILLER: Mike Moseley	14. TOTAL NUMBER CORE BOXES: 1
6. DIRECTION OF HOLE: [X] VERTICAL [ ] INCLINED ___ DEG. FROM VERT.	15. ELEVATION GROUND WATER: N/A
	16. DATE HOLE: STARTED 01 Jul 98; COMPLETED 01 Jul 98
7. THICKNESS OF OVERBURDEN: 39.1' (32.4' of Wat	17. ELEVATION TOP OF HOLE: 0.0 MLLW
8. DEPTH DRILLED INTO ROCK: 8.8'	18. TOTAL CORE RECOVERY FOR BORING: 6.6'/7.5' = 88 %
9. TOTAL DEPTH OF HOLE: 47.9'	19. SIGNATURE OF INSPECTOR: Greg Hippert, ZAPATA ENGINEERING

ELEVATION MLLW	DEPTH (feet)	LEGEND	CLASSIFICATION OF MATERIALS (Description)	% CORE RECOVERY	BOX OR SAMPLE NO.	REMARKS (Drilling time, water loss, depth of weathering, etc. if significant)
0.0	0	Water	0.0' to 32.4' Water RIVER BOTTOM @ 32.4'			Field log transcribed and/or annotated by Tong C. How, geologist, 13 Aug 98. NOTE: CHANGED SCALE @ 32.0', 38.0' & 40.0' Weight of Rods (WR) indicates the overburden material was penetrated without blows from the hammer but from the weight of the rods. BLOWS/FOOT
-32.4	32.4		SW, Brown-gray, fine to coarse sand with layers of black silt, ML, and organics 33.6'		Jar 1	Drive 1: 32.4' to 33.4' Blows: Weight of Rods 0 33.4' to 33.6' Cleaned hole
	34		GW, Light gray, highly silty, fine to coarse, sandy gravel (weathered limestone)		Jar 2	Drive 2: 33.6' to 35.1' Blows: 15-17-13 Rec 1.2' 30
	36				Jar 3	Drive 3: 35.1' to 36.6' Blows: 13-9-13 Rec 1.5' 22
	38				Jar 4	Drive 4: 36.6' to 38.1' Blows: 14-15-16 Rec 1.3' 31 38.1' to 38.2' Cleaned hole
	39		TOP OF ROCK @ 39.1'		Jar 5	Drive 5: 38.2' to 39.1' Blows: 23-100/0.4' Rec 0.7' 100 Splitspoon Refusal @ 39.1'
-39.1	39.1 39.5 40		CASTLE HAYNE LIMESTONE, UNIT B Limestone: Moderately hard to hard, unweathered, aphanitic to fine grained, pale-orange, fossiliferous, pitted to vuggy, glauconitic 39.1' to 39.3' Irregular subvertical break 39.7', 40.1', 40.3', 40.5' & 40.9' Irregular subhorizontal mechanical break 40.6' to 41.1' Phosphate pebble conglomerate	100	Box 1 of 1	At 39.1' changed to NQ2 diamond core bit & barrel PULL 1: 39.1' to 43.4' RUN 4.3' UL 0.0' REC 4.3' GAIN 0.0' LOSS 0.0' Hyd. press: 550 psi Drill water return: 90% Drilling time: 21 min. RQD = 3.8'/4.3' = 88.4%
-41.0	41		CONTINUED ON SHEET 2 NOTE: Soils field classified in accordance with the Unified Soil Classification System.			BLOWS/FOOT: NUMBER REQUIRED TO DRIVE 1⅜" ID SPLITSPOON WITH 140 LB. HAMMER FALLING 30 INCHES

ENG FORM 1836 PREVIOUS EDITIONS ARE OBSOLETE. PROJECT Blast Effect HOLE NO. TB-8

Hole No. TB-9

DRILLING LOG | DIVISION: SOUTH ATLANTIC | INSTALLATION: WILMINGTON DISTRICT | SHEET 1 OF 2 SHEETS

1. PROJECT: BLAST EFFECT MITIGATION TESTS
2. LOCATION (Coordinates or Station) (Upper Big Island) NC Lambert (NAD83): E. 2319487 N. 142340
3. DRILLING AGENCY: S. & M.E., Inc. (Raleigh Office)
4. HOLE NO. (As shown on drawing title and file number): TB-9
5. NAME OF DRILLER: Mike Moseley
6. DIRECTION OF HOLE: [X] VERTICAL [ ] INCLINED ______ DEG. FROM VERT.
7. THICKNESS OF OVERBURDEN: 39.0' (31.9' of Water)
8. DEPTH DRILLED INTO ROCK: 10.2'
9. TOTAL DEPTH OF HOLE: 49.2'
10. SIZE AND TYPE OF BIT: 2-7/8"-Side Discharge Drag
11. DATUM FOR ELEVATION SHOWN (TBM or MSL): Mean Lower Low Water; NQ2 diamond coring
12. MANUFACTURER'S DESIGNATION OF DRILL: CME 55 (Barge Mounted)
13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED 4; UNDISTURBED 0
14. TOTAL NUMBER CORE BOXES: 1
15. ELEVATION GROUND WATER: N/A
16. DATE HOLE: STARTED 02 Jul 98; COMPLETED 02 Jul 98
17. ELEVATION TOP OF HOLE: 0.0 MLLW
18. TOTAL CORE RECOVERY FOR BORING: 5.4'/10.2' = 52.9 %
19. SIGNATURE OF INSPECTOR: Greg Hippert, ZAPATA ENGINEERING

ELEVATION MLLW	DEPTH (feet)	LEGEND	CLASSIFICATION OF MATERIALS (Description)	% CORE RECOVERY	BOX OR SAMPLE NO.	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant)
0.0	0	Water	0.0' to 31.9' Water			Field log transcribed and/or annotated by Tong C. How, geologist, 13 Aug 98. NOTE: CHANGED SCALE @ 31.0' & 39.0'. Weight of Rods (WR) or Weight of Hammer (WH) indicates the overburden material was penetrated without blows from the hammer but from the weight of the tools alone
	31		RIVER BOTTOM @ 31.9'			BLOWS/FT
-31.9	31.9		ML, Black silt with fibrous organics		Jar 1	Drive 1: 31.9' to 33.4' Blows: WR/1.0'-WH/0.5' Rec 0.8' — 0
	33					33.4' to 34.6' Cleaned hole
			34.6'			
	35		GW, Light gray, slightly silty, fine to coarse, sandy gravel (weathered limestone)		Jar 2	Drive 2: 34.6' to 36.1' Blows: 4-4-5 Rec 0.8' — 9
						36.1' to 36.8' Cleaned hole
	37				Jar 3	Drive 3: 36.8' to 38.3' Blows: 10-13-14 Rec 1.4' — 27; 38.3' to 38.4' Cleaned hole
			TOP OF ROCK @ 39.0'		Jar 4	Drive 4: 38.4' to 39.0' Blows: 80-20/0.1' — 100
-39.0	39		CASTLE HAYNE LIMESTONE, UNIT B. Limestone: Moderately hard, unweathered, aphanitic to fine grained, pale-orange, fossiliferous, pitted to vuggy, glauconitic, few fossil molds. 39.3', 39.7', 40.2', 40.4' & 40.6' Irregular subhorizontal, mechanical break. 39.0' Irregular subhorizontal break	100	Box 1 of 1	At 39.0' changed to NQ2 diamond core bit & barrel. PULL 1: 39.0' to 44.1' RUN 5.1' UL 0.0' REC 4.8' GAIN 0.0' LOSS 0.3'. Hyd. press: 550 psi. Drill water return: 50%. Drilling time: 20 min. RQD = 3.35'/4.8' = 69.8%
	39.5					
	40					
-40.2	40.2		ROCKY POINT MEMBER OF PEEDEE FORMATION			
-40.5	40.5		CONTINUED ON SHEET 2 NOTE: Soils field classified in accordance with the Unified Soil Classification System.			BLOWS/FOOT: NUMBER REQUIRED TO DRIVE 1⅜" ID SPLITSPOON WITH 140 LB. HAMMER FALLING 30 INCHES

ENG FORM 1836 PREVIOUS EDITIONS ARE OBSOLETE. | PROJECT: Blast Effect | HOLE NO. TB-9

Hole No. TB-10

DRILLING LOG	DIVISION SOUTH ATLANTIC	INSTALLATION WILMINGTON DISTRICT	SHEET 1 OF 3 SHEETS
1. PROJECT BLAST EFFECT MITIGATION TESTS		10. SIZE AND TYPE OF BIT 2-7/8" Side Discharge Drag	
2. LOCATION (Coordinates or Station) (Upper Big Island) NC Lambert (NAD83): E. 2319405 N. 142372		11. DATUM FOR ELEVATION SHOWN (TBM or MSL) Mean Lower Low Water	NQ2 diamond coring
3. DRILLING AGENCY S. & M.E., Inc. (Raleigh Office)		12. MANUFACTURER'S DESIGNATION OF DRILL CME 55 (Barge Mounted)	
4. HOLE NO. (As shown on drawing title and file number) TB-10		13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN	DISTURBED 13 / UNDISTURBED 0
5. NAME OF DRILLER Mike Moseley		14. TOTAL NUMBER CORE BOXES 1	
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED ______ DEG FROM VERT.		15. ELEVATION GROUND WATER N/A	
7. THICKNESS OF OVERBURDEN 38.2' (13.7' of Water)		16. DATE HOLE	STARTED 02 Jul 98 / COMPLETED 02 Jul 98
8. DEPTH DRILLED INTO ROCK 10.6'		17. ELEVATION TOP OF HOLE 0.0 MLLW	
9. TOTAL DEPTH OF HOLE 48.8'		18. TOTAL CORE RECOVERY FOR BORING 5.8'/10.3' = 56.3%	
		19. SIGNATURE OF INSPECTOR Greg Hippert, ZAPATA ENGINEERING	

ELEVATION MLLW	DEPTH (feet)	LEGEND	CLASSIFICATION OF MATERIALS (Description)	% CORE RECOVERY	BOX OR SAMPLE NO.	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant)
0.0	0	Water	0.0' to 13.7' Water			Field log transcribed and/or annotated by Tong C. How, geologist, 13 Aug 98. NOTE: CHANGED SCALE @ 13.0' Weight of Rods (WR) indicates the overburden material was penetrated without blows from the hammer but from the weight of the rods.
	13		RIVER BOTTOM @ 13.7'			BLOWS/FOOT
-13.7	13.7		13.7' to 19.0' Wood		Jar 1	Drive 1: 13.7' to 15.2' Blows: WR-1-1 — 2
	15					15.2' to 15.3' Cleaned hole
					Jar 2	Drive 2: 15.3' to 16.8' Blows: 2-4-7 — 11
	17				Jar 3	Drive 3: 16.8' to 18.3' Blows: 1-1-2 NO RECOVERY — 3
			19.0'			Cleaned hole to 19.0'
-19.0	19		SP, Tan, fine to medium sand and wood		Jar 4	Drive 4: 19.0' to 20.5' Blows: WR-1-3 Rec 0.1' — 4
			20.5'			
	21		No wood, trace of shell fragments		Jar 5	Drive 5: 20.5' to 22.0' Blows: 3-2-2 Rec 0.9' — 4
	23				Jar 6	Drive 6: 22.0' to 23.5' Blows: 1-2-2 Rec 0.5' — 4
					Jar 7	Drive 7: 23.5' to 25.0' Blows: 1-4-6 Rec 0.8' — 10
	25				Jar 8	Drive 8: 25.0' to 26.5' Blows: 1-2-3 Rec 0.6' — 5
			26.8' Brown-tan, fine sand			Cleaned hole to 26.8'
-27.0	27					Drive 9 (cont. below)
			CONTINUED ON SHEET 2			BLOWS/FOOT: NUMBER REQUIRED TO DRIVE 1⅜" ID SPLITSPOON WITH 140 LB. HAMMER FALLING 30 INCHES
			NOTE: Soils field classified in accordance with the Unified Soil Classification System.			

ENG FORM 1836 MAR 71 PREVIOUS EDITIONS ARE OBSOLETE. | PROJECT Blast Effect Mitigation Tests | HOLE NO. TB-10

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE 0.0 MLLW	Hole No. TB-10
PROJECT BLAST EFFECT MITIGATION TESTS	INSTALLATION WILMINGTON DISTRICT	SHEET 3 of 3 SHEETS

ELEVATION MLLW	DEPTH (feet)	LEGEND	CLASSIFICATION OF MATERIALS (Description)	% CORE RECOVERY	BOX OR SAMPLE NO.	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant)
-41.5	41.5		Rocky Point Member cont. from above			Pull 1 cont. from above
			41.4' Irregular subhorizontal mechanical break			
	42		42.2, 42.7', & 43.1' Irregular subhorizontal break			
			41.5' to 41.6', 41.7' to 41.9', 42.2' to 42.4', 42.6' to 42.9' & 43.6' to 44.1' Infilling of Castle Hayne lithology	63		
	42.5		42.6' to 43.1' Moderately weathered			
			42.9' to 43.1' & 43.3' to 44.0' Irregular subhvertical break			
	43		43.3' to 44.0' Moderately hard, moderately weathered		Box	43.4' to 45.9' Soft drilling
			43.6' to 43.9' Broken rock	43.3'		Corrected Depth 43.3'
			43.9' & 44.4' Irregular subhorizontal break		1	PULL 2: 43.4' to 48.8' RUN 5.4' UL 3.8' REC 1.1' GAIN 0.0' LOSS 4.3'
	44				of	
			44.4' to 48.2' Unaccountable Loss		1	Hyd. press: 550 psi Drill water return: 50% Drilling time: 5 min.
	45					RQD = 0.45'/4.9' = 9.2%
				22		
	46	Core Loss				
	47					46.9' to 48.4' Soft drilling
	48			48.2'		Corrected Depth 48.2'
			48.2' to 48.8' Core Left in Hole			
-48.8	48.8		BOTTOM OF HOLE @ 48.8'			

ENG FORM 1836-A PREVIOUS EDITIONS ARE OBSOLETE.
MAR 71

PROJECT Blast Effect Mitigation Tests

HOLE NO. TB-10

Hole No. WH 98-64

DRILLING LOG	DIVISION South Atlantic	INSTALLATION Wilmington District	SHEET 1 OF 4 SHEETS

1. PROJECT Wilmington Harbor Comprehensive	10. SIZE AND TYPE OF BIT 2 7/8" Side Discharge Drag
2. LOCATION (Coordinates or Station) N 142451 E 2319512 (NAD 83)	11. DATUM FOR ELEVATION SHOWN MLLW
3. DRILLING AGENCY S&ME, Inc., Raleigh, NC	12. MANUFACTURER'S DESIGNATION OF DRILL CME 55 (Barge Mounted)
4. HOLE NO. (As shown on drawing title and file number) WH 98-64	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED 9; UNDISTURBED 0
5. NAME OF DRILLER Ray Norwood	14. TOTAL NUMBER CORE BOXES 1
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED ___ DEG. FROM VERT.	15. ELEVATION GROUND WATER N/A
	16. DATE HOLE: STARTED 20 MAY 98; COMPLETED 20 MAY 98
7. THICKNESS OF OVERBURDEN 40.3 ft (Water 40.1 ft)	17. ELEVATION TOP OF HOLE 0.0 MLLW
8. DEPTH DRILLED INTO ROCK 43.5 ft	18. TOTAL CORE RECOVERY FOR BORING 77.5 %
9. TOTAL DEPTH OF HOLE 83.8 ft	19. SIGNATURE OF INSPECTOR Gina Long (Zapata Engineering)

ELEVATION	DEPTH	LEGEND	CLASSIFICATION OF MATERIALS (Description)	% CORE RECOVERY	BOX OR SAMPLE NO.	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant)
			0.0 to 40.1 ft, Water			Note: changed Scale @ 40 ft, 45 ft and 83 ft
	40					
-40.1	40.1		RIVER BOTTOM @ 40.1 ft			
			GW, Dark gray limestone rock fragments		1	100/2½"
-40.3	40.3		TOP OF ROCK @ 40.3 ft			
			CONTINUED ON SHEET 2			

ENG FORM 1836 PREVIOUS EDITIONS ARE OBSOLETE. PROJECT Wilm Hbr Comp HOLE NO. WH 98-64

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE 0.0 MLLW		Hole No. WH98-64
PROJECT WILM HAR COMP		INSTALLATION Wilmington District	SHEET 3 OF 4 SHEETS

ELEVATION	DEPTH	LEGEND	CLASSIFICATION OF MATERIALS (Description)	% CORE RECOVERY	BOX OR SAMPLE NO.	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant)
-46.0			No Recovery - continued			
			SM, Gray silty fine sand, calcareous, trace limestone and shell fragments (Peedee Formation)		3	46.2 - 47.7 Rec 1.0 4-5-6
	48				4	48.6 - 50.1 Rec 1.5 2-4-3
	50					Sample on 5-ft centers
	52					
	54		ML, Gray fine sandy silt, calcareous		5	53.7 - 55.2 Rec 1.5 10-14-16
	56					
	58				6	58.6 - 60.1 Rec 1.5 12-11-15
	60					
	62					
	64				7	63.5 - 65.0 Rec 1.5 7-8-18
	66					
	68					
-68.7	68.7					

ENG FORM 1836-A PREVIOUS EDITIONS ARE OBSOLETE. MAR 71 | PROJECT WILM HAR COMP | HOLE NO. WH98-64

Hole No. WH98-65

DRILLING LOG	DIVISION SOUTH ATLANTIC	INSTALLATION WILMINGTON DISTRICT	SHEET 1 OF 2 SHEETS

1. PROJECT WILMINGTON HARBOR COMPREHENSIVE STUDY	10. SIZE AND TYPE OF BIT 3 7/8" Side-Discharge Drag Bit
2. LOCATION (Coordinates or Station) N142194, E2319562 (NAD 83)	11. DATUM FOR ELEVATION SHOWN MLLW
3. DRILLING AGENCY S&ME, Inc. (Raleigh, NC)	12. MANUFACTURER'S DESIGNATION OF DRILL ARDCO C-1000 (Barge Mounted)
4. HOLE NO. (As shown on drawing title and file number) WH98-65	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED 18; UNDISTURBED 0
5. NAME OF DRILLER BILLY RACKLEY	14. TOTAL NUMBER CORE BOXES N/A
6. DIRECTION OF HOLE ☒ VERTICAL ☐ INCLINED ____ DEG. FROM VERT.	15. ELEVATION GROUND WATER N/A
	16. DATE HOLE STARTED 06 MAY 98; COMPLETED 06 MAY 98
7. THICKNESS OF OVERBURDEN 39.1ft (Water 15.1ft)	17. ELEVATION TOP OF HOLE 0.0 MLLW
8. DEPTH DRILLED INTO ROCK N/A	18. TOTAL CORE RECOVERY FOR BORING N/A %
9. TOTAL DEPTH OF HOLE 39.1ft	19. SIGNATURE OF INSPECTOR DAVID COSANS (ZAPATA ENGINEERING)

ELEVATION (MLLW)	DEPTH (feet)	CLASSIFICATION OF MATERIALS (Description)	% CORE RECOVERY	BOX OR SAMPLE NO.	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant)
0.0	0	0.0 to 15.1 ft, Water			WOR - Weight of Rods; WOH - Weight of Hammer; NOTE: CHANGED SCALE @ 15 FT
-15.1	15	RIVER BOTTOM @ 15.1 ft			20 40 60 80 100
		ML-OL, Dark brown clayey silt with organics		1	BLOWS/FOOT: NUMBER REQUIRED TO DRIVE 1 3/8" I.D. SPLIT SPOON WITH 140 LB. HAMMER FALLING 30 INCHES; WOR
	17			2A	
				2B	WOR/12"-3
		SP-SM, Dark brown gray silty fine to medium sand, trace fibrous organics			
	19	SP, Brown fine to medium sand		3	WOR-WOH-1
		trace organics			
	21			4	1-2-2
		gray brown			
	23			5	1-1-3
				6	2-4-7
	25			7	4-6-7
	27	brown gray fine sand		8	2-3-4
		light brown gray fine to medium sand			
	29			9	2-3-5
		light gray, trace coarse sand		10	
-31.2	31				3-6-6
		CONTINUED ON SHEET 2			
		NOTE: Soils field classified in accordance with the Unified Soil Classification System.			

DRILLING LOG	DIVISION South Atlantic	INSTALLATION Wilmington District	SHEET 1 OF 3 SHEETS

1. PROJECT: WILMINGTON HARBOR COMPREHENSIVE	10. SIZE AND TYPE OF BIT: 2 7/8" Side Discharge Drag
2. LOCATION (Coordinates or Station): N 142196 E 2319568 (NAD 83)	11. DATUM FOR ELEVATION SHOWN: MLLW
3. DRILLING AGENCY: S&ME, Inc. Raleigh, NC	12. MANUFACTURER'S DESIGNATION OF DRILL: CME 55 (Barge Mounted)
4. HOLE NO. (As shown on drawing title and file number): WH98-65H	13. TOTAL NO. OF OVER-BURDEN SAMPLES TAKEN: DISTURBED 3; UNDISTURBED 0
5. NAME OF DRILLER: Ray Norwood	14. TOTAL NUMBER CORE BOXES: 1
6. DIRECTION OF HOLE: [X] VERTICAL [ ] INCLINED ___ DEG. FROM VERT.	15. ELEVATION GROUND WATER: N/A
	16. DATE HOLE: STARTED 8 MAY 98; COMPLETED 9 MAY 98
7. THICKNESS OF OVERBURDEN: 39.5 ft (Water 23.2 ft)	17. ELEVATION TOP OF HOLE: 0.0 MLLW
8. DEPTH DRILLED INTO ROCK: 10.2 ft	18. TOTAL CORE RECOVERY FOR BORING: 84.9 %
9. TOTAL DEPTH OF HOLE: 49.7 ft	19. SIGNATURE OF INSPECTOR: Greg Hippert (Zapata Engin.)

ELEVATION a	DEPTH b	LEGEND c	CLASSIFICATION OF MATERIALS (Description) d	% CORE RECOVERY e	BOX OR SAMPLE NO. f	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant) g
			0.0 to 23.2 ft, water			Note: Changed Scale @ 35 ft
	10					
	20					
-23.2	23.2		RIVER BOTTOM @ 23.2 ft.			
	30		Wash drilled w/o sampling. See WH98-65 for classification.			
	35					
	36					
	38					
	39.1		GW, Gray fine to coarse sandy gravel, trace silt, glauconite, shell fragments		1	39.1 - 39.5', Rec. 0.4 Split Spoon refusal @ 39.5 ft 100/4½"
-39.5	39.5		Top of Rock @ 39.5 ft			
			CONTINUED ON SHEET 2			

ENG FORM 1836 PREVIOUS EDITIONS ARE OBSOLETE. MAR 71 | PROJECT: Wilm Har Comp | HOLE NO. WH98-65H

DRILLING LOG (Cont Sheet)	ELEVATION TOP OF HOLE 0.0 MLLW	Hole No. WH98-65A
PROJECT WILM HAR COMP	INSTALLATION Wilmington District	SHEET 3 OF 3 SHEETS

ELEVATION	DEPTH	LEGEND	CLASSIFICATION OF MATERIALS (Description)	% CORE RECOVERY	BOX OR SAMPLE NO.	REMARKS (Drilling time, water loss, depth of weathering, etc., if significant)
-46.8	46.8		CONTINUED			
			SM, Gray silty fine to coarse sand with gravel-size limestone fragments		2	46.8-47.6 Rec 0.8
						96-100/3"
	48					
						48.4-49.7 Rec 1.1
	49				3	
-49.7	49.7					27-72-29/3"
			BoH @ 49.7 ft			Split spoon refusal @ 49.7 ft

ENG FORM 1836-A PREVIOUS EDITIONS ARE OBSOLETE. PROJECT WILM HAR COMP HOLE NO. WH98-65A

Appendix B
Peak Measured Water Shock Parameters, BEM Tests 2-9

Test 2

Meas. No.	Location		Peak pressure	Peak impulse	Peak energy flux density
	Range, ft	Depth	psi	psi-msec	ft-lb/in^2
North 1a	35	surface	125	181.5	136.9
North 1b	35	mid-depth	Bad measurement		
North 1c	35	bottom	196.3	1033.5	1184.4
North 2a	70	surface	Bad measurement		
North 2b	70	mid-depth	35.6	209.1	50.2
North 2c	70	bottom	34.4	1222.7	228.1
North 3a	140	surface	6.92	11.8	0.731
North 3b	140	mid-depth	9.37	26.3	2.00
North 3c	140	bottom	Bad measurement		
North 4a	280	surface	1.99	1.11	0.0106
North 4b	280	mid-depth	Bad measurement		
North 4c	280	bottom	2.84	5.57	0.0385
North 5a	560	surface	Bad measurement		
North 5b	560	mid-depth	Bad measurement		
North 5c	560	bottom	Bad measurement		
South 1a	35	surface	145.4	164.3	178.7
South 1b	35	mid-depth	Bad measurement		
South 1c	35	bottom	225.2	503.0	712.7
South 2a	70	surface	45.1	Questionable	
South 2b	70	mid-depth	Bad measurement		
South 2c	70	bottom	48.0	393.8	120.6
South 3a	140	surface	Bad measurement		
South 3b	140	mid-depth	2.81	6.92	0.370

South 3c	140	bottom	2.97	11.1	0.581
South 4a	280	surface	Bad measurement		
South 4b	280	mid-depth	Bad measurement		
South 4c	280	bottom	Bad measurement		
South 5a	560	surface	Bad measurement		
South 5b	560	mid-depth	Bad measurement		
South 5c	560	bottom	Bad measurement		

Test 3

Meas. No.	Location		Peak pressure	Peak impulse	Peak energy flux density
	Range, ft	Depth	psi	psi-msec	ft-lb/in^2
North 1a	35	surface	860.8	146.8	746.0
North 1b	35	mid-depth	Bad measurement		
North 1c	35	bottom	Bad measurement		
North 2a	70	surface	187.6	79.4	129.9
North 2b	70	mid-depth	282.6	82.2	207.8
North 2c	70	bottom	Bad measurement		
North 3a	140	surface	131.1	28.0	25.8
North 3b	140	mid-depth	90.1	38.4	27.70
North 3c	140	bottom	Bad measurement		
North 4a	280	surface	57.7	8.47	3.07
North 4b	280	mid-depth	Bad measurement		
North 4c	280	bottom	51.1	8.20	3.09
North 5a	560	surface	4.71	2.64	0.640
North 5b	560	mid-depth	Bad measurement		
North 5c	560	bottom	Bad measurement		
South 1a	35	surface	Bad measurement		
South 1b	35	mid-depth	Bad measurement		
South 1c	35	bottom	452.8	234.8	348.9
South 2a	70	surface	Bad measurement		
South 2b	70	mid-depth	Bad measurement		
South 2c	70	bottom	410.2	170.9	222.1
South 3a	140	surface	Bad measurement		
South 3b	140	mid-	Bad		

		depth	measurement		
South 3c	140	bottom	64.7	48.7	14.7
South 4a	280	surface	20.8	2.00	0.182
South 4b	280	mid-depth	45.7	1.06	0.275
South 4c	280	bottom	40.1	15.8	2.01
South 5a	560	surface	8.05	Questionable	
South 5b	560	mid-depth	15.0	4.10	1.16
South 5c	560	bottom	Bad measurement		

Test 4

Meas. No.	Location		Peak pressure	Peak impulse	Peak energy flux density
	Range, ft	Depth	psi	psi-msec	ft-lb/in^2
North 1a	35	surface	377.2	58.1	118.1
North 1b	35	mid-depth	Bad measurement		
North 1c	35	bottom	Bad measurement		
North 2a	70	surface	75.9	65.7	26.1
North 2b	70	mid-depth	Bad measurement		
North 2c	70	bottom	Bad measurement		
North 3a	140	surface	2.69	7.6	0.177
North 3b	140	mid-depth	3.89	7.48	0.24
North 3c	140	bottom	Bad measurement		
North 4a	280	surface	1.89	7.04	0.104
North 4b	280	mid-depth	2.95	9.02	0.203
North 4c	280	bottom	2.70	8.32	0.211
North 5a	560	surface	0.770	1.36	<0.1
North 5b	560	mid-depth	0.70	1.63	<0.1
North 5c	560	bottom	Bad measurement		
South 1a	35	surface	Bad measurement		
South 1b	35	mid-depth	Bad measurement		
South 1c	35	bottom	Bad measurement		
South 2a	70	surface	Bad measurement		
South 2b	70	mid-depth	Bad measurement		
South 2c	70	bottom	Bad measurement		
South 3a	140	surface	3.72	8.57	0.256

South 3b	140	mid-depth	9.55	19.3	1.330
South 3c	140	bottom	12.6	28.2	2.73
South 4a	280	surface	1.00	0.940	<0.1
South 4b	280	mid-depth	2.45	12.4	0.781
South 4c	280	bottom	Bad measurement		
South 5a	560	surface	1.60	3.54	<0.1
South 5b	560	mid-depth	Bad measurement		
South 5c	560	bottom	Bad measurement		

Test 5

Meas. No.	Location		Peak pressure	Peak impulse	Peak energy flux density
	Range, ft	Depth	psi	psi-msec	ft-lb/in^2
North 1a	35	surface	1190.4	200.7	1020.7
North 1b	35	mid-depth	Bad measurement		
North 1c	35	bottom	Bad measurement		
North 2a	70	surface	278.9	91.4	274.6
North 2b	70	mid-depth	Bad measurement		
North 2c	70	bottom	Bad measurement		
North 3a	140	surface	51.7	16.8	8.46
North 3b	140	mid-depth	53.4	19.3	6.05
North 3c	140	bottom	20.3	18.2	1.34
North 4a	280	surface	Bad measurement		
North 4b	280	mid-depth	8.65	3.48	0.397
North 4c	280	bottom	6.09	2.87	0.733
North 5a	560	surface	4.80	0.838	0.199
North 5b	560	mid-depth	3.70	0.139	0.212
North 5c	560	bottom	2.94	0.748	0.103
South 1a	35	surface	Bad measurement		
South 1b	35	mid-depth	Bad measurement		
South 1c	35	bottom	Bad measurement		
South 2a	70	surface	80.3	35.6	28.5
South 2b	70	mid-depth	Bad measurement		
South 2c	70	bottom	42.5	76.1	15.5
South 3a	140	surface	Bad measurement		
South 3b	140	mid-depth	22.2	26.6	3.06

South 3c	140	bottom	20.8	26.8	3.06
South 4a	280	surface	8.54	3.450	0.214
South 4b	280	mid-depth	1.69	0.317	<0.1
South 4c	280	bottom	10.1	1.64	0.600
South 5a	560	surface	4.90	1.05	0.369
South 5b	560	mid-depth	6.9	1.53	0.526
South 5c	560	bottom	Bad measurement		

Test 5a

Meas. No.	Location		Peak pressure	Peak impulse	Peak energy flux density
	Range, ft	Depth	psi	psi-msec	ft-lb/in^2
North 1a	35	surface	1145.6	177.5*	1488.1
North 1b	35	mid-depth	Bad measurement		
North 1c	35	bottom	Questionable		
North 2a	70	surface	Bad measurement		
North 2b	70	mid-depth	416.0	199.6	313.9
North 2c	70	bottom	257.6	28.7	57.3
North 3a	140	surface	51.6	13.7	7.71
North 3b	140	mid-depth	68.6	20.9	9.41
North 3c	140	bottom	31.2	10.7	1.98
North 4a	280	surface	Bad measurement		
North 4b	280	mid-depth	28.3	4.05	1.99
North 4c	280	bottom	6.72	4.13	1.60
North 5a	560	surface	3.90	1.04	0.156
North 5b	560	mid-depth	Bad measurement		
North 5c	560	bottom	3.07	0.518	0.165
South 1a	35	surface	Bad measurement		
South 1b	35	mid-depth	Bad measurement		
South 1c	35	bottom	Bad measurement		
South 2a	70	surface	Bad measurement		
South 2b	70	mid-depth	Bad measurement		
South 2c	70	bottom	Bad measurement		
South 3a	140	surface	Bad measurement		
South 3b	140	mid-	26.2	12.4	3.47

		depth			
South 3c	140	bottom	13.8	20.7	3.19
South 4a	280	surface	4.35	2.89	0.785
South 4b	280	mid-depth	Bad measurement		
South 4c	280	bottom	7.92	4.00	0.948
South 5a	560	surface	2.75	0.823	0.116
South 5b	560	mid-depth	6.6	1.83	0.401
South 5c	560	bottom	6.00	0.383	0.170
* Measurement failed prior to development of absolute peak value					

Test 6

Meas. No.	Location		Peak pressure	Peak impulse	Peak energy flux density
	Range, ft	Depth	psi	psi-msec	ft-lb/in^2
North 1a	35	surface	No data		
North 1b	35	mid-depth	No data		
North 1c	35	bottom	No data		
North 2a	70	surface	No data		
North 2b	70	mid-depth	No data		
North 2c	70	bottom	No data		
North 3a	140	surface	No data		
North 3b	140	mid-depth	No data		
North 3c	140	bottom	No data		
North 4a	280	surface	No data		
North 4b	280	mid-depth	No data		
North 4c	280	bottom	No data		
North 5a	560	surface	No data		
North 5b	560	mid-depth	No data		
North 5c	560	bottom	No data		
South 1a	35	surface	Bad measurement		
South 1b	35	mid-depth	Bad measurement		
South 1c	35	bottom	240.0	490.2	553.9
South 2a	70	surface	Bad measurement		
South 2b	70	mid-depth	Bad measurement		
South 2c	70	bottom	Bad measurement		
South 3a	140	surface	Bad measurement		
South 3b	140	mid-depth	Bad measurement		

South 3c	140	bottom	3.64	35.0	2.31
South 4a	280	surface	Bad measurement		
South 4b	280	mid-depth	Bad measurement		
South 4c	280	bottom	1.96	Questionable	0.75
South 5a	560	surface	0.320	0.454	<0.1
South 5b	560	mid-depth	0.422	Questionable	<0.1
South 5c	560	bottom	0.370	Questionable	<0.1

Test 7

Meas. No.	Location		Peak pressure	Peak impulse	Peak energy flux density
	Range, ft	Depth	psi	psi-msec	ft-lb/in^2
North 1a	35	surface	Bad measurement		
North 1b	35	mid-depth	422.4	133.3	338.7
North 1c	35	bottom	Questionable		
North 2a	70	surface	130.6	48.4	61.6
North 2b	70	mid-depth	94.0	45.8	24.9
North 2c	70	bottom	Questionable		
North 3a	140	surface	85.6	13.9	5.52
North 3b	140	mid-depth	78.8	12.2	7.17
North 3c	140	bottom	21	10.7	2.78
North 4a	280	surface	Bad measurement		
North 4b	280	mid-depth	40.7	Questionable	
North 4c	280	bottom	20.80	4.04	1.90
North 5a	560	surface	7.70	0.905	0.172
North 5b	560	mid-depth	6.27	1.06	0.161
North 5c	560	bottom	Questionable		
South 1a	35	surface	Bad measurement		
South 1b	35	mid-depth	Bad measurement		
South 1c	35	bottom	258.7	698.1	1127.7
South 2a	70	surface	111.2	87.6	100.1
South 2b	70	mid-depth	114.7	232.0	193.6
South 2c	70	bottom	134.0	460.2	413.8
South 3a	140	surface	Bad measurement		
South 3b	140	mid-depth	47.8	12.2	18.80

South 3c	140	bottom	Bad measurement		
South 4a	280	surface	22.60	3.64	2.46
South 4b	280	mid-depth	Bad measurement		
South 4c	280	bottom	23.2	6.50	3.98
South 5a	560	surface	7.85	4.76	2.34
South 5b	560	mid-depth	11.2	5.86	1.97
South 5c	560	bottom	10.80	2.52	0.701

Test 8

Meas. No.	Location		Peak pressure	Peak impulse	Peak energy flux density
	Range, ft	Depth	psi	psi-msec	ft-lb/in^2
North 1a	35	surface	Bad measurement		
North 1b	35	mid-depth	Bad measurement		
North 1c	35	bottom	Bad measurement		
North 2a	70	surface	Bad measurement		
North 2b	70	mid-depth	Bad measurement		
North 2c	70	bottom	Bad measurement		
North 3a	140	surface	Bad measurement		
North 3b	140	mid-depth	Bad measurement		
North 3c	140	bottom	Bad measurement		
North 4a	280	surface	Bad measurement		
North 4b	280	mid-depth	Bad measurement		
North 4c	280	bottom	Bad measurement		
North 5a	560	surface	0.666	Questionable	<0.1
North 5b	560	mid-depth	0.740	Questionable	<0.1
North 5c	560	bottom	Bad measurement		
South 1a	35	surface	Bad measurement		
South 1b	35	mid-depth	Bad measurement		
South 1c	35	bottom	626.0	1168.3	734.1
South 2a	70	surface	12.6	104.1	53.8
South 2b	70	mid-depth	17.3	52.9	38.2
South 2c	70	bottom	5.21	125.5	8.41

South 3a	140	surface	3.21	28.7	9.87
South 3b	140	mid-depth	3.10	18.7	8.38
South 3c	140	bottom	Bad measurement		
South 4a	280	surface	Bad measurement		
South 4b	280	mid-depth	Bad measurement		
South 4c	280	bottom	3.28	Questionable	Questionable
South 5a	560	surface	0.423	1.50	<0.1
South 5b	560	mid-depth	0.927	Questionable	Questionable
South 5c	560	bottom	0.600	1.36	<0.1

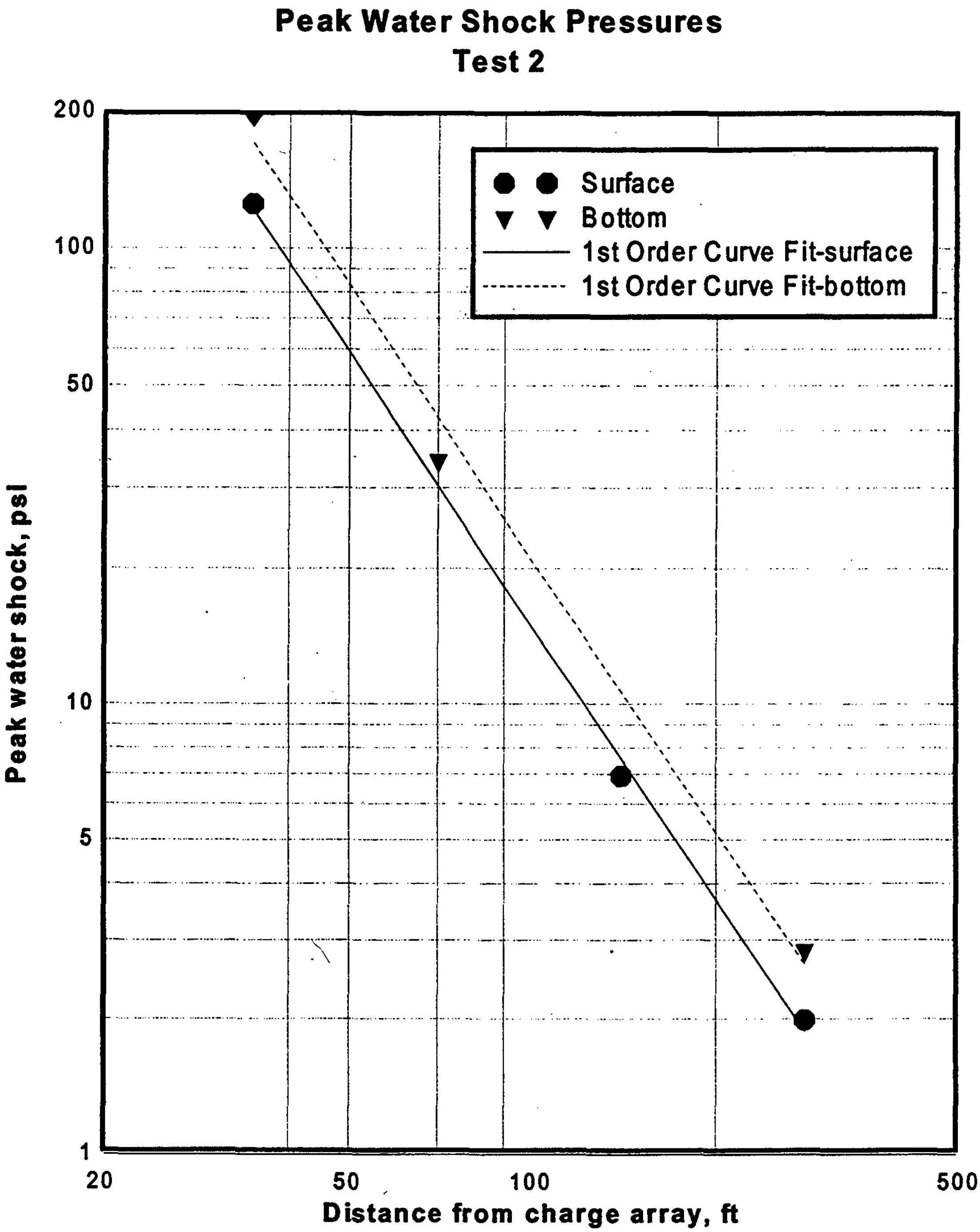
Test 9

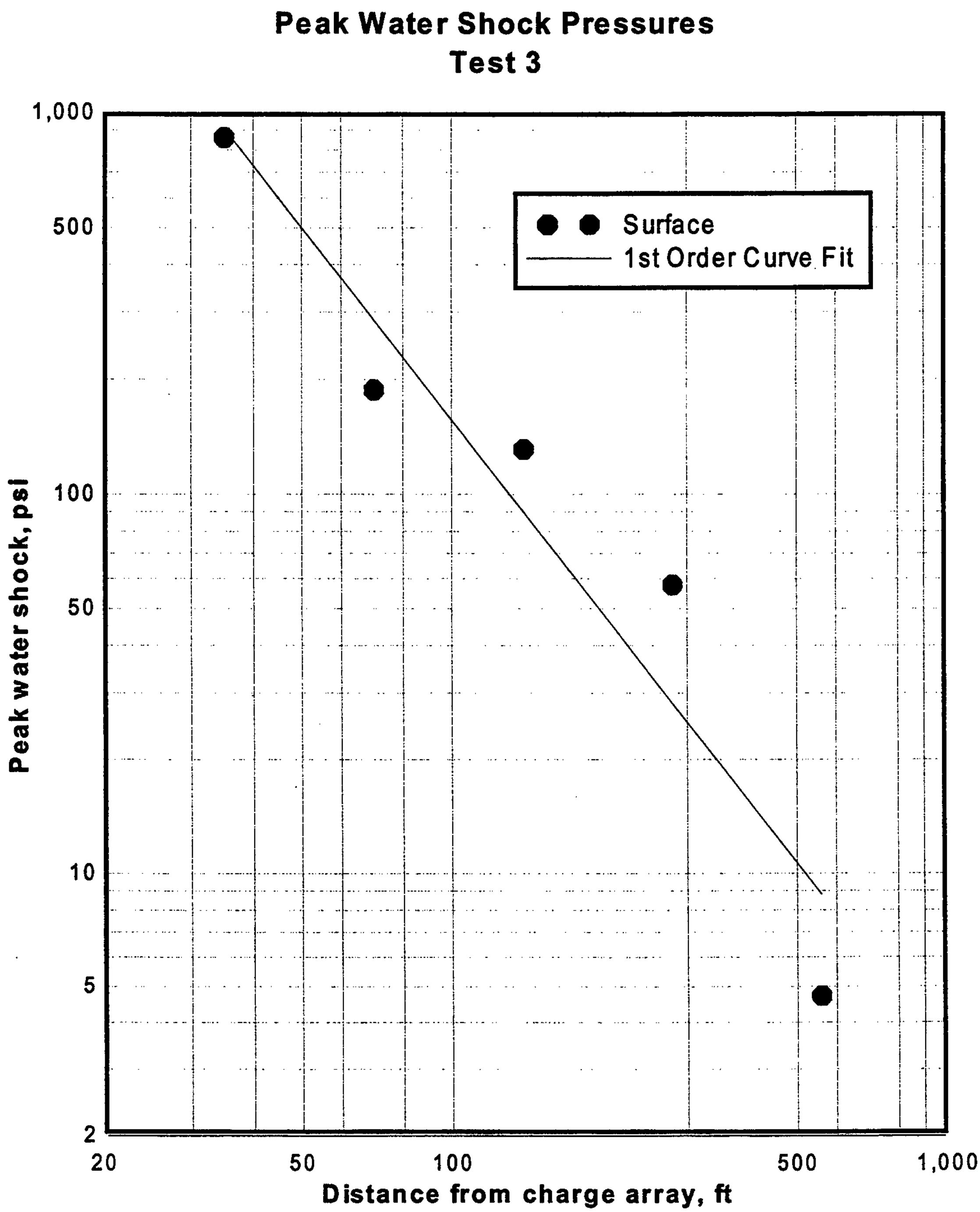
Meas. No.	Location		Peak pressure	Peak impulse	Peak energy flux density
	Range, ft	Depth	psi	psi-msec	ft-lb/in^2
North 1a	35	surface	401.5	187.2	670.1
North 1b	35	mid-depth	745.4	208.3	1718.8
North 1c	35	bottom	130.2	244.6	114.7
North 2a	70	surface	217.6	77.8	234.5
North 2b	70	mid-depth	416.6	172.7	266.4
North 2c	70	bottom	405.7	47.8	196.9
North 3a	140	surface	70.3	17.9	19.8
North 3b	140	mid-depth	62.0	14.9	23.9
North 3c	140	bottom	43.5	Questionable	Questionable
North 4a	280	surface	Bad measurement		
North 4b	280	mid-depth	12.8	6.01	2.38
North 4c	280	bottom	15.1	8.21	2.72
North 5a	560	surface	5.88	1.10	0.377
North 5b	560	mid-depth	3.43	Questionable	<0.1
North 5c	560	bottom	3.09	Questionable	<0.1
South 1a	35	surface	Bad measurement		
South 1b	35	mid-depth	197.2	377.4	650.5
South 1c	35	bottom	224.1	693.7	1209.3
South 2a	70	surface	Questionable		
South 2b	70	mid-depth	121.6	164.1	186.2
South 2c	70	bottom	101.0	215.1	352.1
South 3a	140	surface	63.4	20.0	13.1
South 3b	140	mid-depth	57.3	38.6	26.80
South 3c	140	bottom	76.5	27.9	31.8

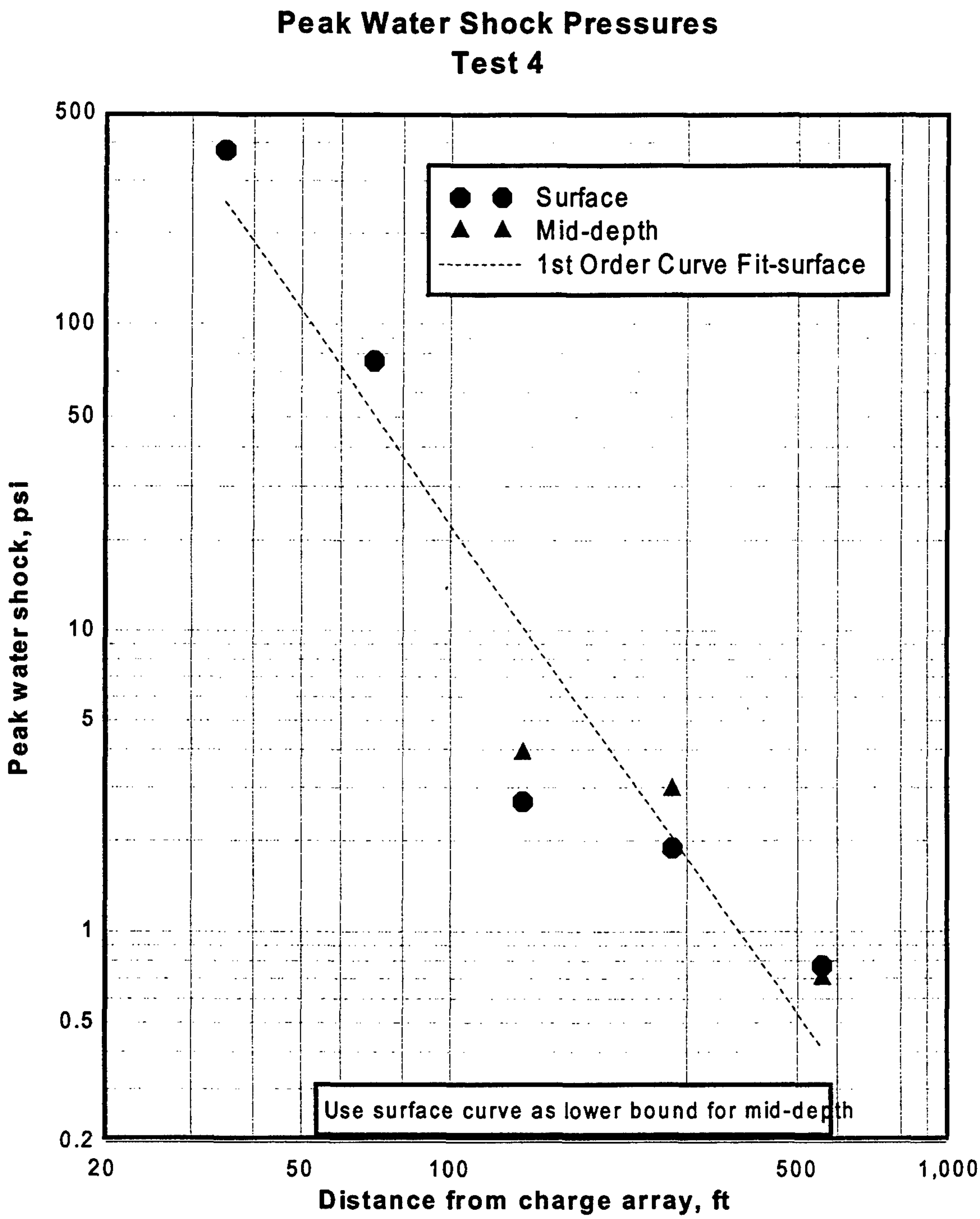
South 4a	280	surface	5.10	1.45	0.213
South 4b	280	mid-depth	8.61	0.518	0.398
South 4c	280	bottom	18.1	Questionable	Questionable
South 5a	560	surface	6.64	Questionable	0.508
South 5b	560	mid-depth	6.3	0.78	0.906
South 5c	560	bottom	Bad measurement		

Appendix C

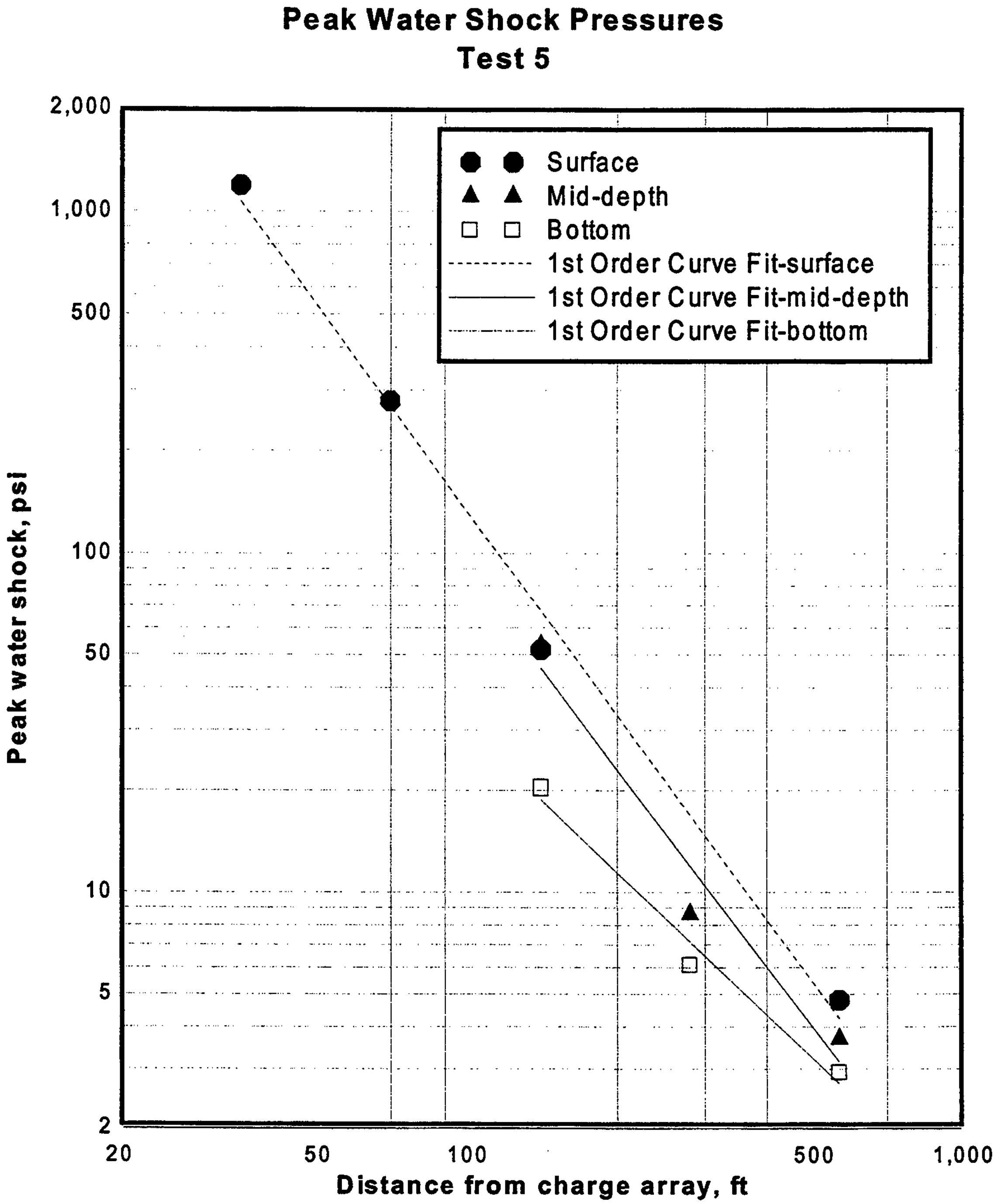
Peak Water Shock Pressures, BEM Tests 2-9

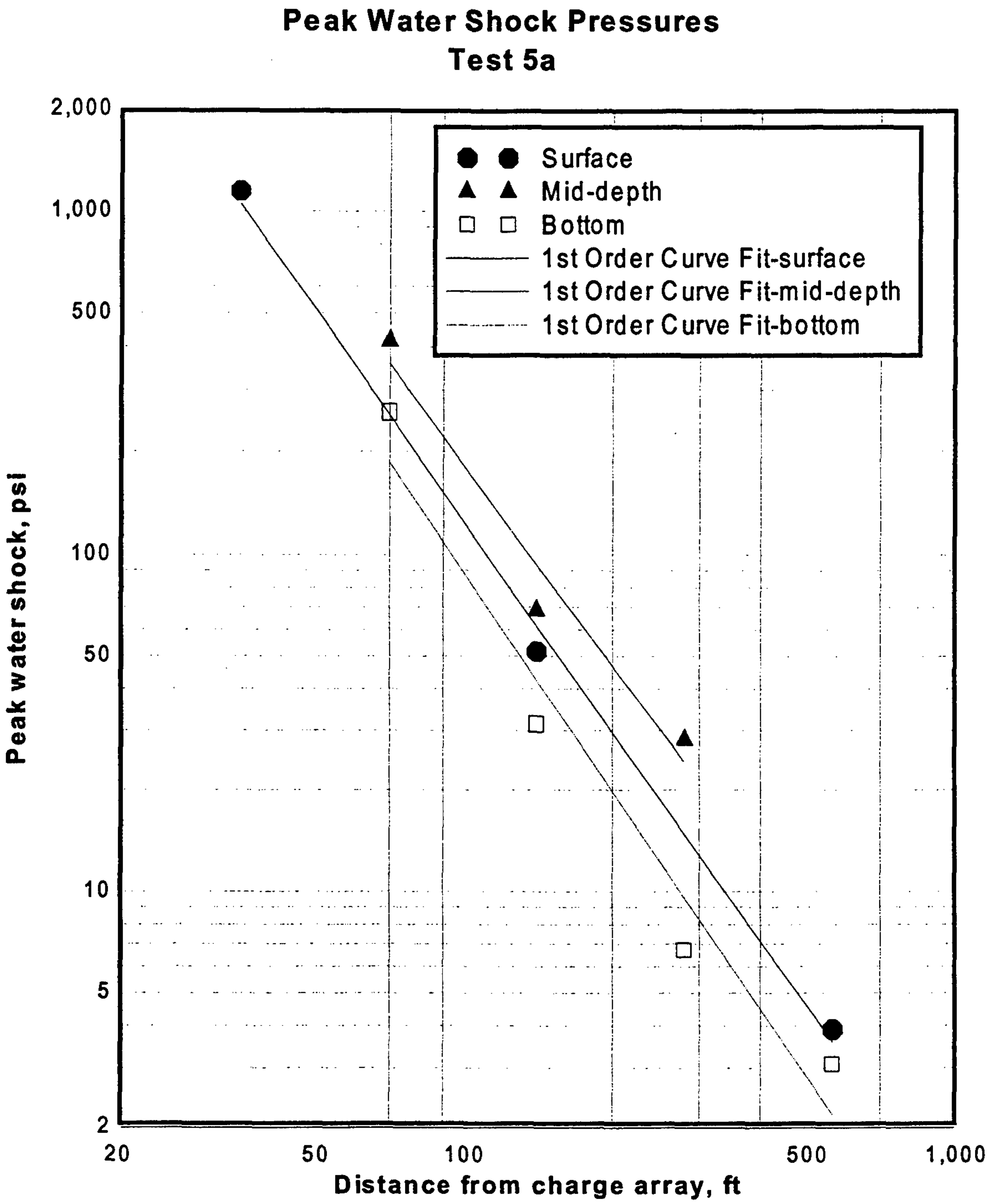

Peak Water Shock Pressures
Test 2
Surface
Bottom
1st Order Curve Fit-surface
1st Order Curve Fit-bottom
Peak water shock, psi
200
100
50
10
5
1
20
50
100
500
Distance from charge array, ft


Peak Water Shock Pressures
Test 3
Surface
1st Order Curve Fit
Peak water shock, psi
1,000
500
100
50
10
5
2
20
50
100
500
1,000
Distance from charge array, ft

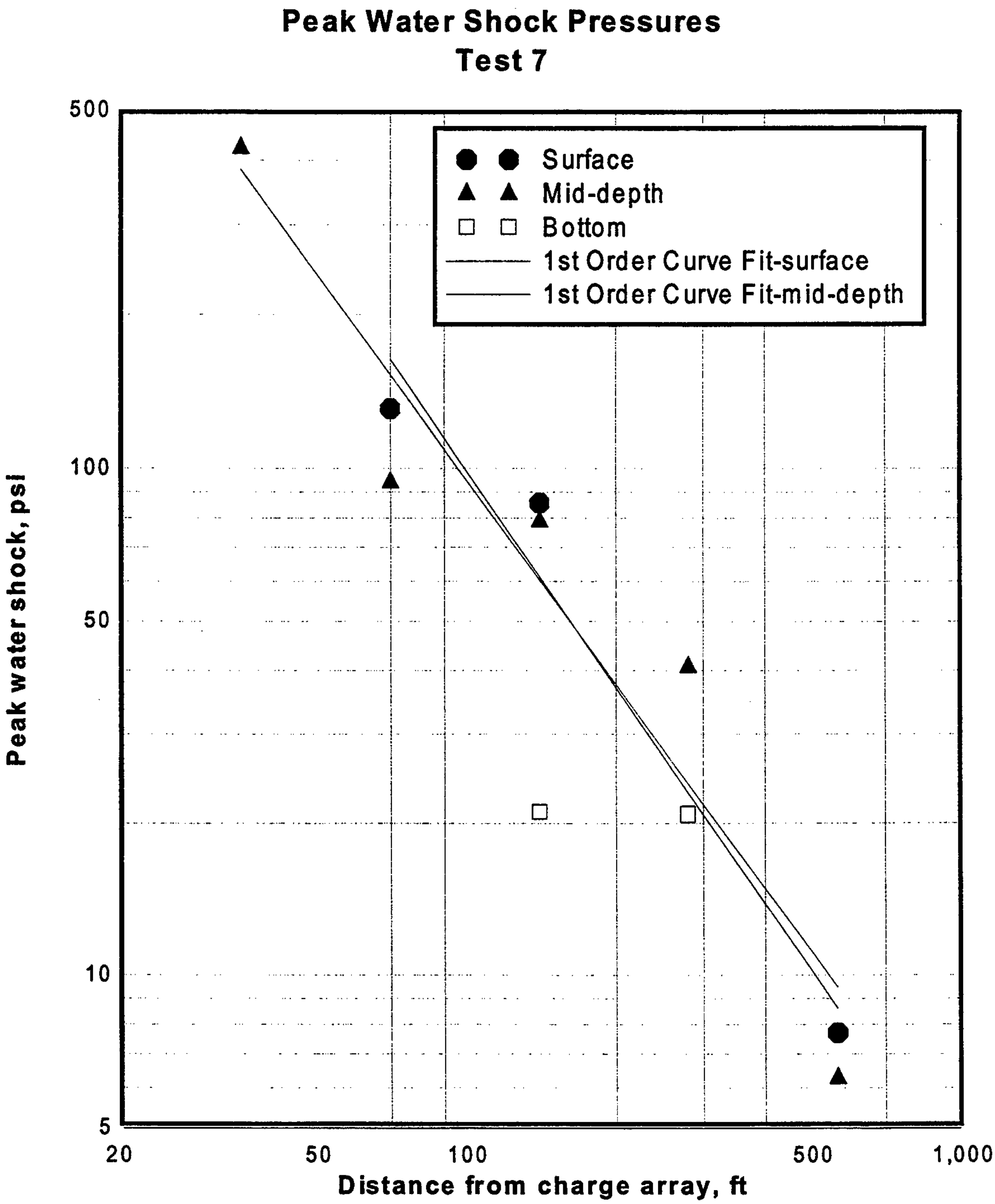


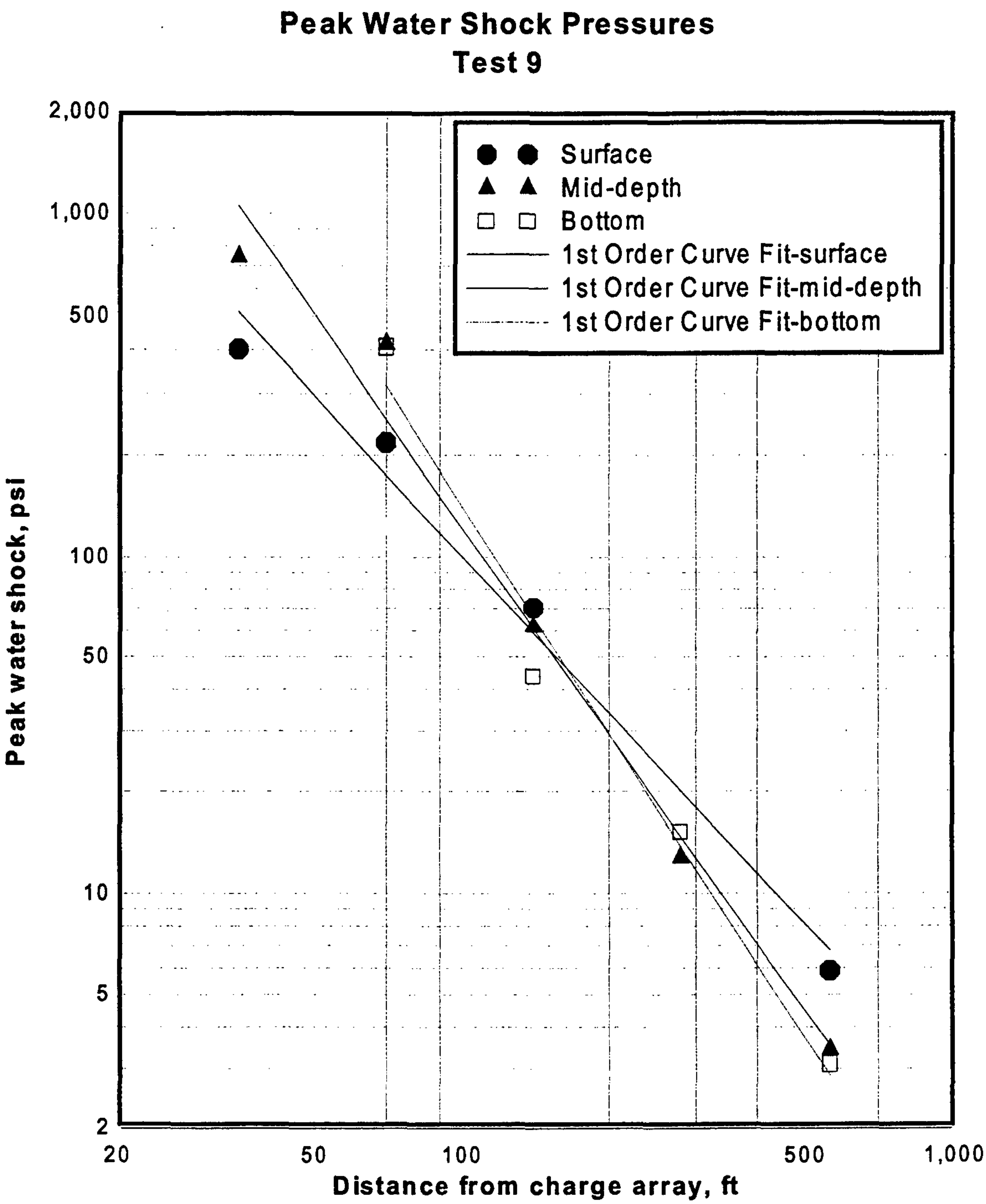
Peak Water Shock Pressures
Test 4
Surface
Mid-depth
1st Order Curve Fit-surface
Use surface curve as lower bound for mid-depth
500
100
50
10
5
1
0.5
0.2
20
50
100
500
1,000
Peak water shock, psi
Distance from charge array, ft


Peak Water Shock Pressures
Test 5
Surface
Mid-depth
Bottom
1st Order Curve Fit-surface
1st Order Curve Fit-mid-depth
1st Order Curve Fit-bottom
Peak water shock, psi
2,000
1,000
500
100
50
10
5
2
20
50
100
500
1,000
Distance from charge array, ft

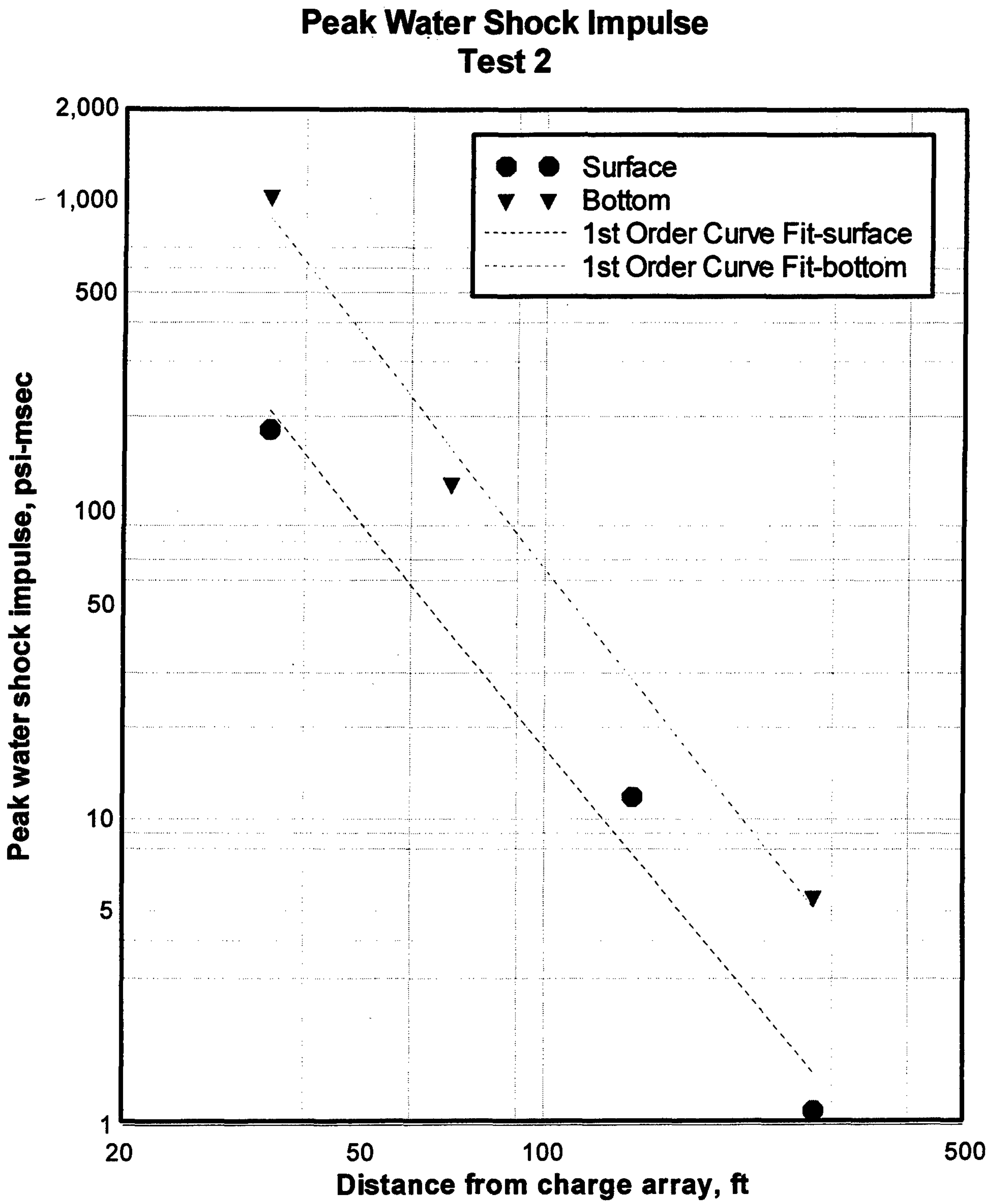


Peak Water Shock Pressures
Test 5a
Surface
Mid-depth
Bottom
1st Order Curve Fit-surface
1st Order Curve Fit-mid-depth
1st Order Curve Fit-bottom
2,000
1,000
500
100
50
10
5
2
20
50
100
500
1,000
Peak water shock, psi
Distance from charge array, ft

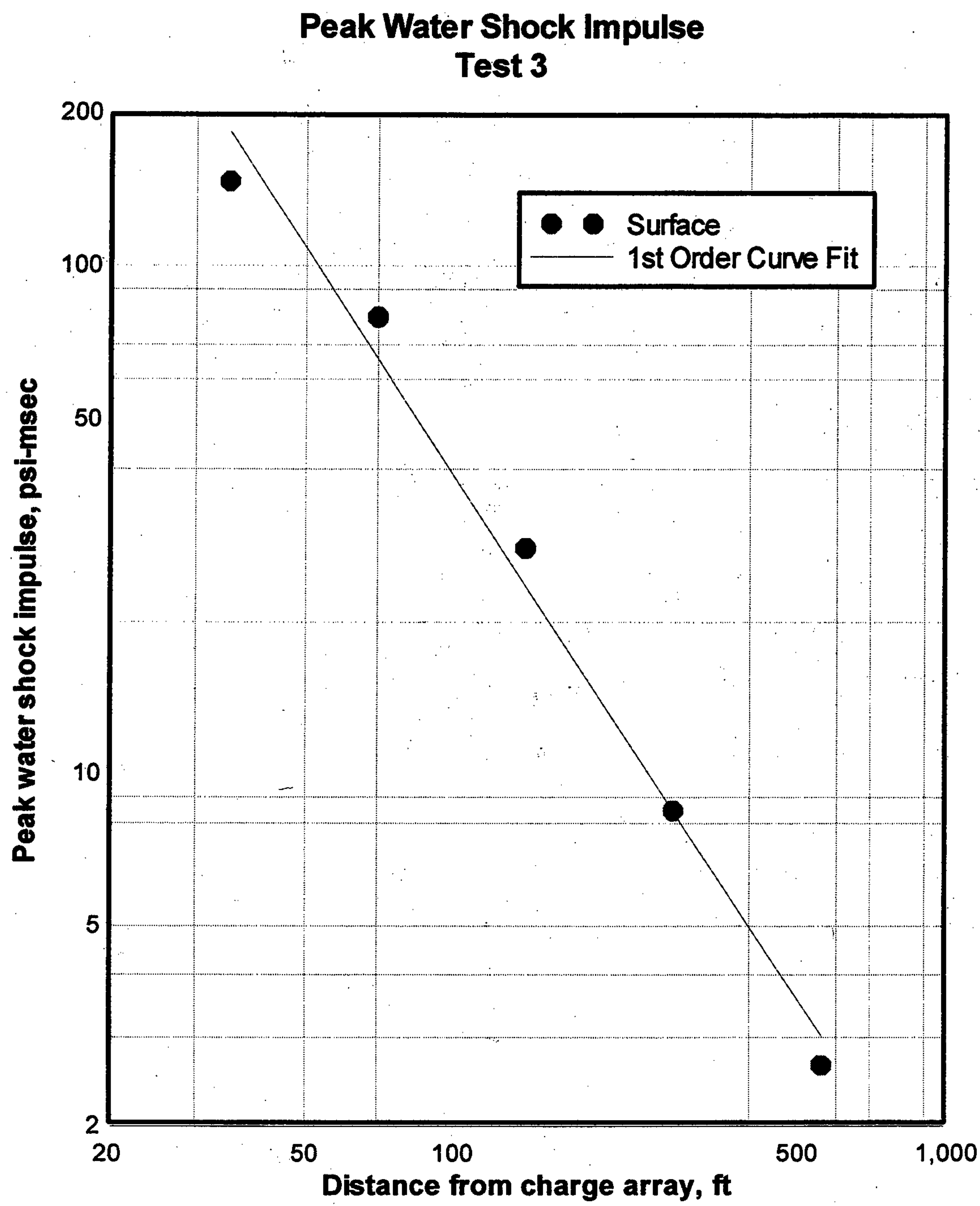

Peak Water Shock Pressures
Test 7
Surface
Mid-depth
Bottom
1st Order Curve Fit-surface
1st Order Curve Fit-mid-depth
Peak water shock, psi
500
100
50
10
5
20
50
100
500
1,000
Distance from charge array, ft

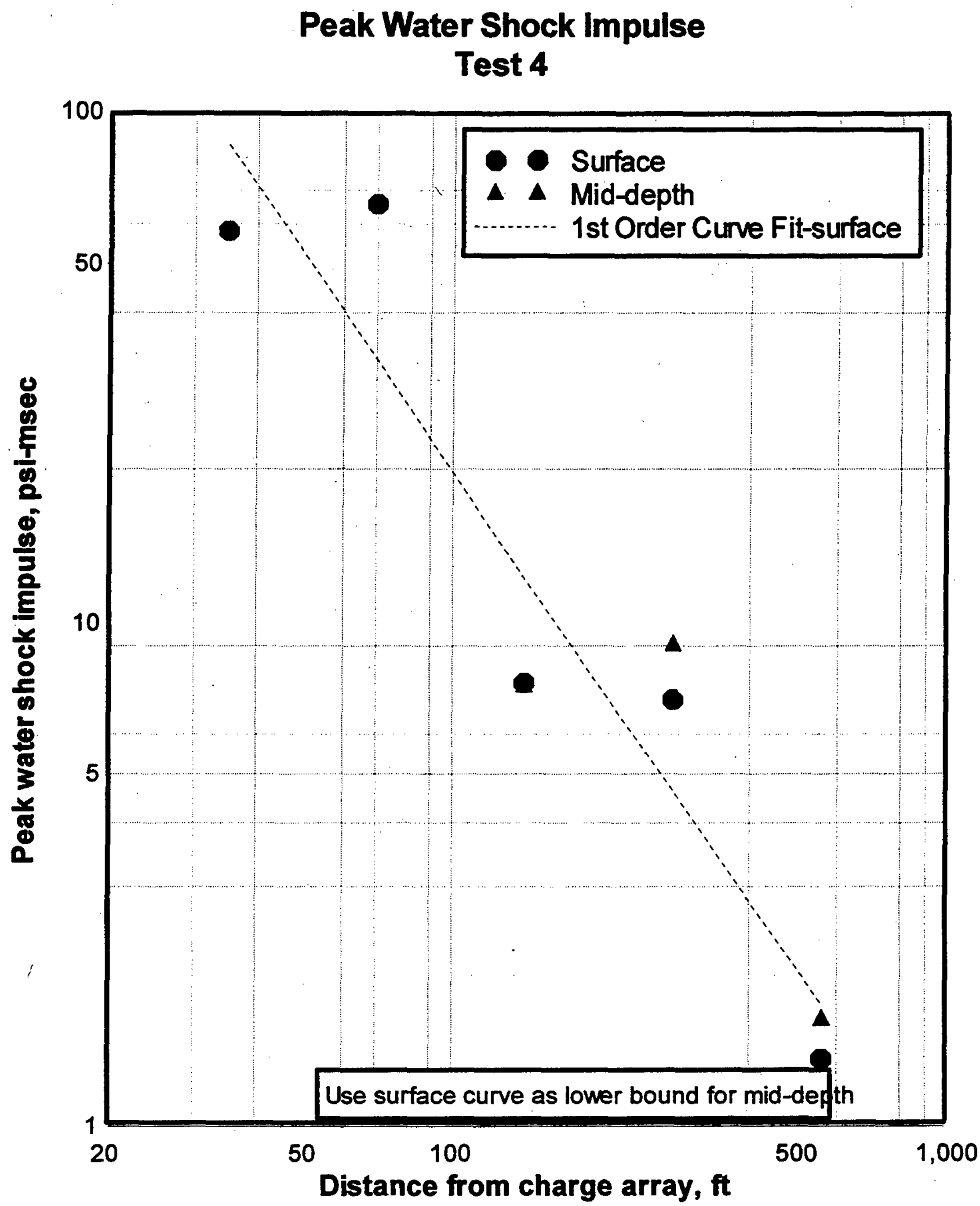

Peak Water Shock Pressures
Test 9
Surface
Mid-depth
Bottom
1st Order Curve Fit-surface
1st Order Curve Fit-mid-depth
1st Order Curve Fit-bottom
2,000
1,000
500
100
50
10
5
2
20
50
100
500
1,000
Peak water shock, psi
Distance from charge array, ft

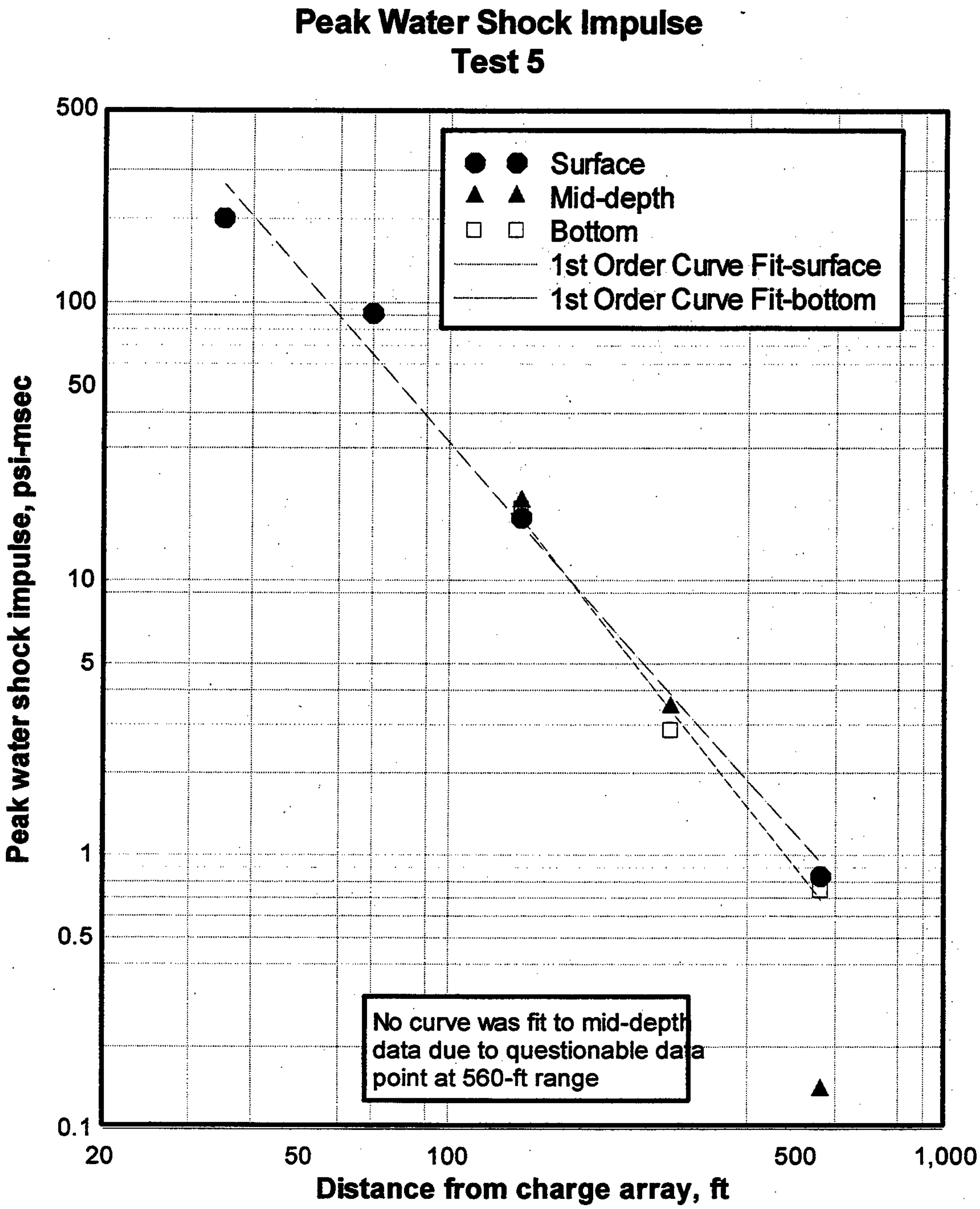
Appendix D
Peak Water Shock Impulse, BEM Tests 2-9

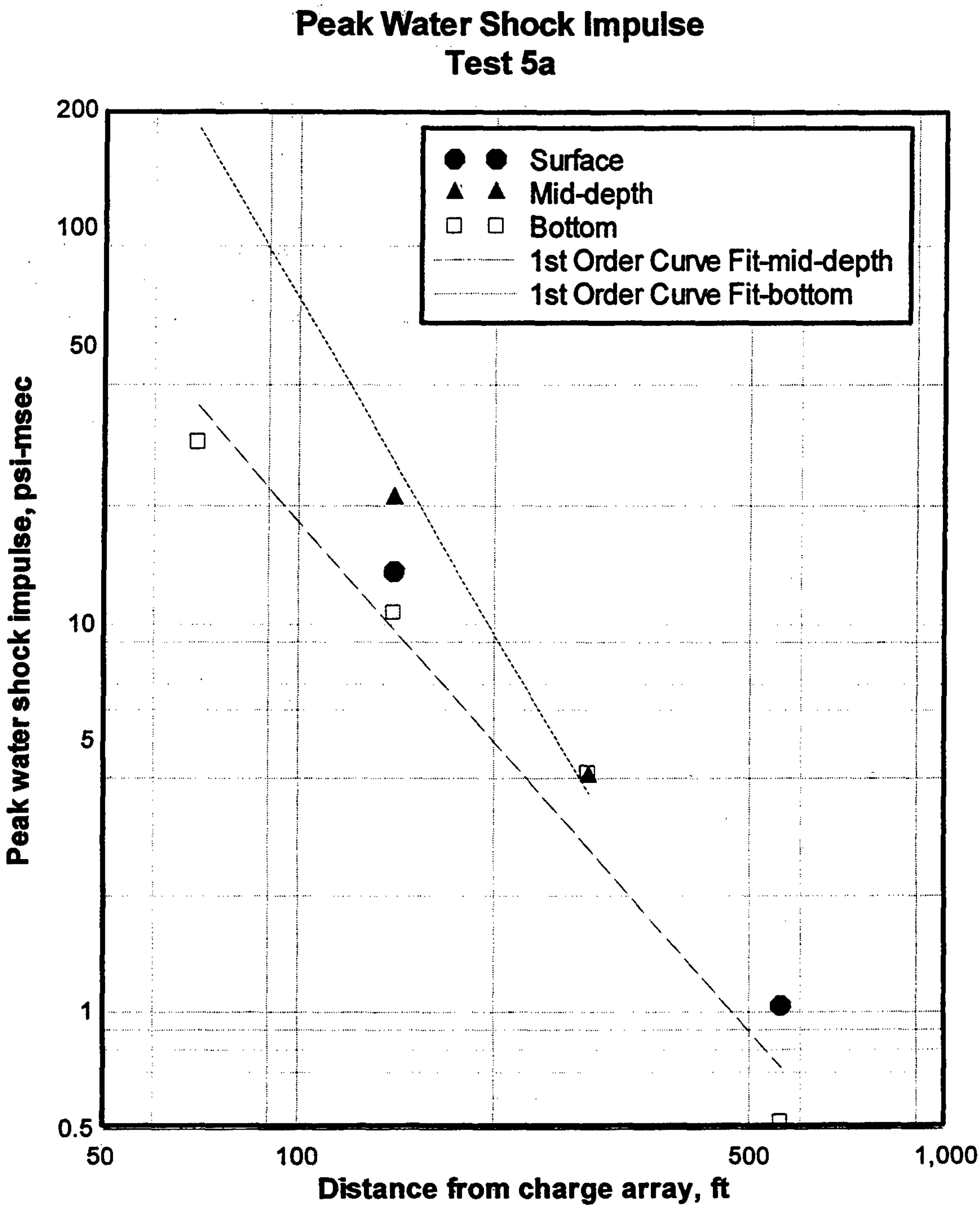


Peak Water Shock Impulse
Test 2
2,000
1,000
500
100
50
10
5
1
20
50
100
500
Surface
Bottom
1st Order Curve Fit-surface
1st Order Curve Fit-bottom
Peak water shock impulse, psi-msec
Distance from charge array, ft

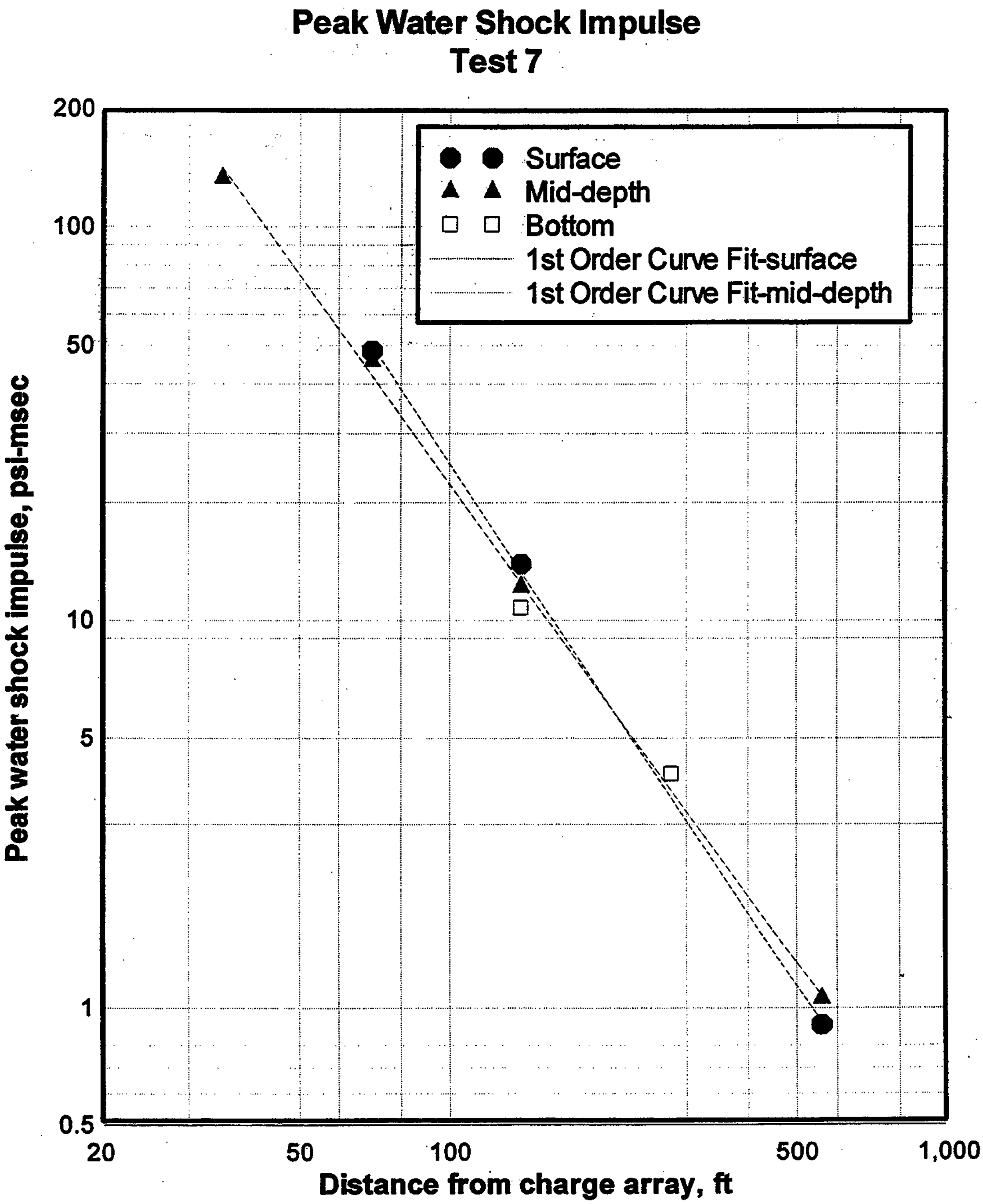

Peak Water Shock Impulse
Test 3
Surface
1st Order Curve Fit
200
100
50
10
5
2
20
50
100
500
1,000
Peak water shock impulse, psi-msec
Distance from charge array, ft


Peak Water Shock Impulse
Test 4
Surface
Mid-depth
1st Order Curve Fit-surface
Use surface curve as lower bound for mid-depth
Peak water shock impulse, psi-msec
100
50
10
5
1
20
50
100
500
1,000
Distance from charge array, ft

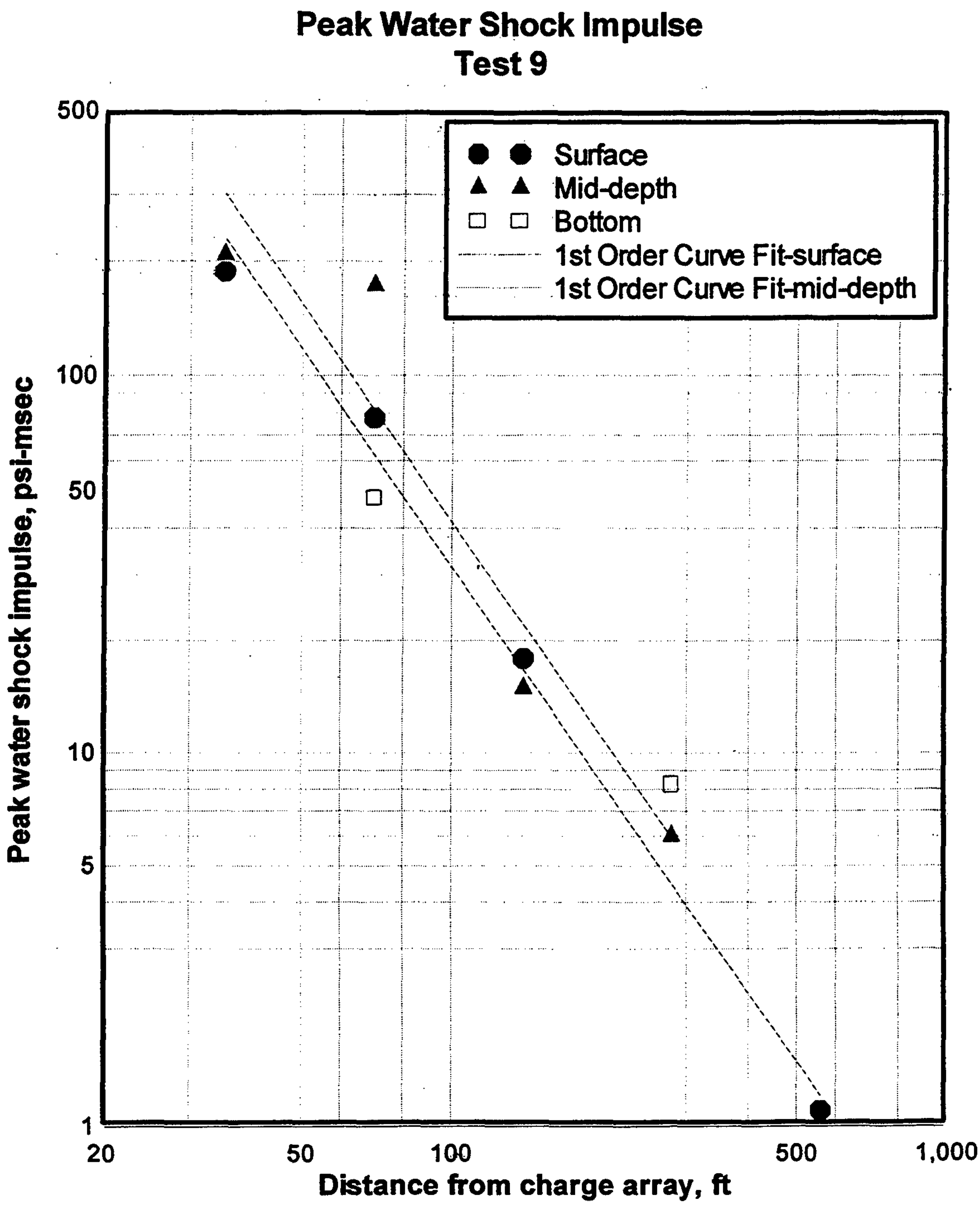

Peak Water Shock Impulse
Test 5
500
100
50
10
5
1
0.5
0.1
20
50
100
500
1,000
Surface
Mid-depth
Bottom
1st Order Curve Fit-surface
1st Order Curve Fit-bottom
No curve was fit to mid-depth data due to questionable data point at 560-ft range
Peak water shock impulse, psi-msec
Distance from charge array, ft



Peak Water Shock Impulse
Test 5a
200
100
50
10
5
1
0.5
50
100
500
1,000
Surface
Mid-depth
Bottom
1st Order Curve Fit-mid-depth
1st Order Curve Fit-bottom
Peak water shock impulse, psi-msec
Distance from charge array, ft



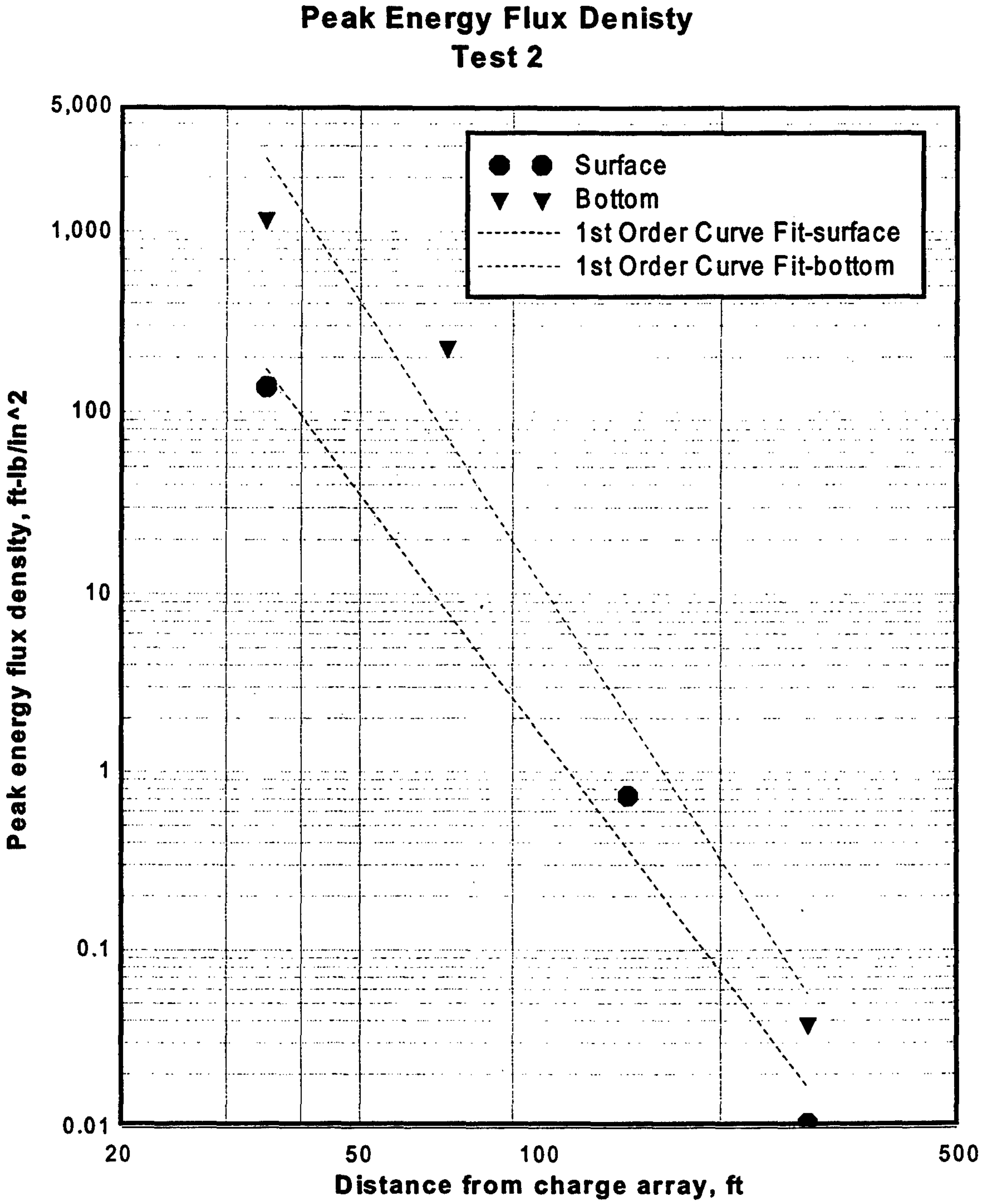
Peak Water Shock Impulse
Test 7
Surface
Mid-depth
Bottom
1st Order Curve Fit-surface
1st Order Curve Fit-mid-depth
Peak water shock impulse, psi-msec
200
100
50
10
5
1
0.5
20
50
100
500
1,000
Distance from charge array, ft



Peak Water Shock Impulse
Test 9
Surface
Mid-depth
Bottom
1st Order Curve Fit-surface
1st Order Curve Fit-mid-depth
500
100
50
10
5
1
Peak water shock impulse, psi-msec
20
50
100
500
1,000
Distance from charge array, ft

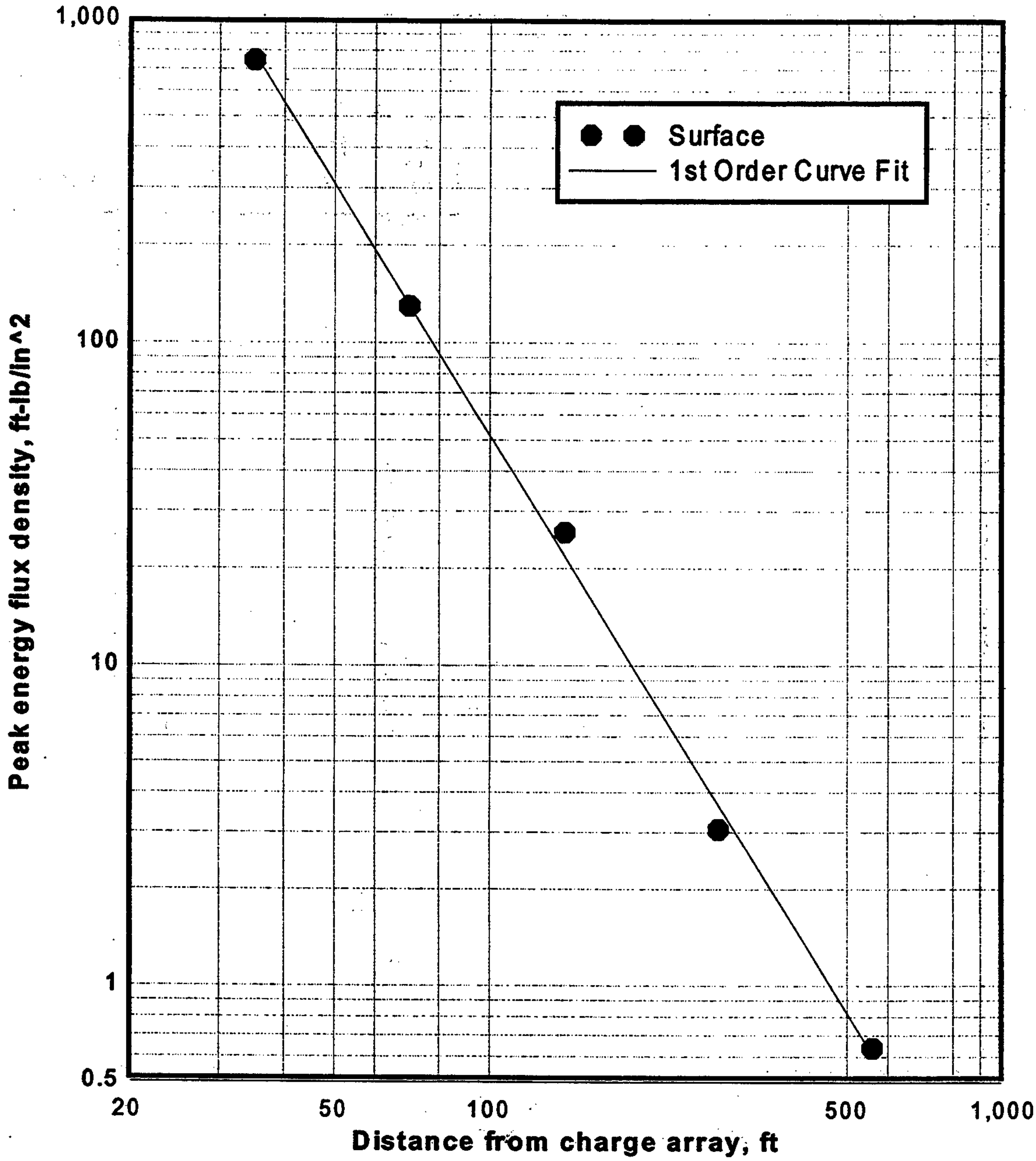
Appendix E

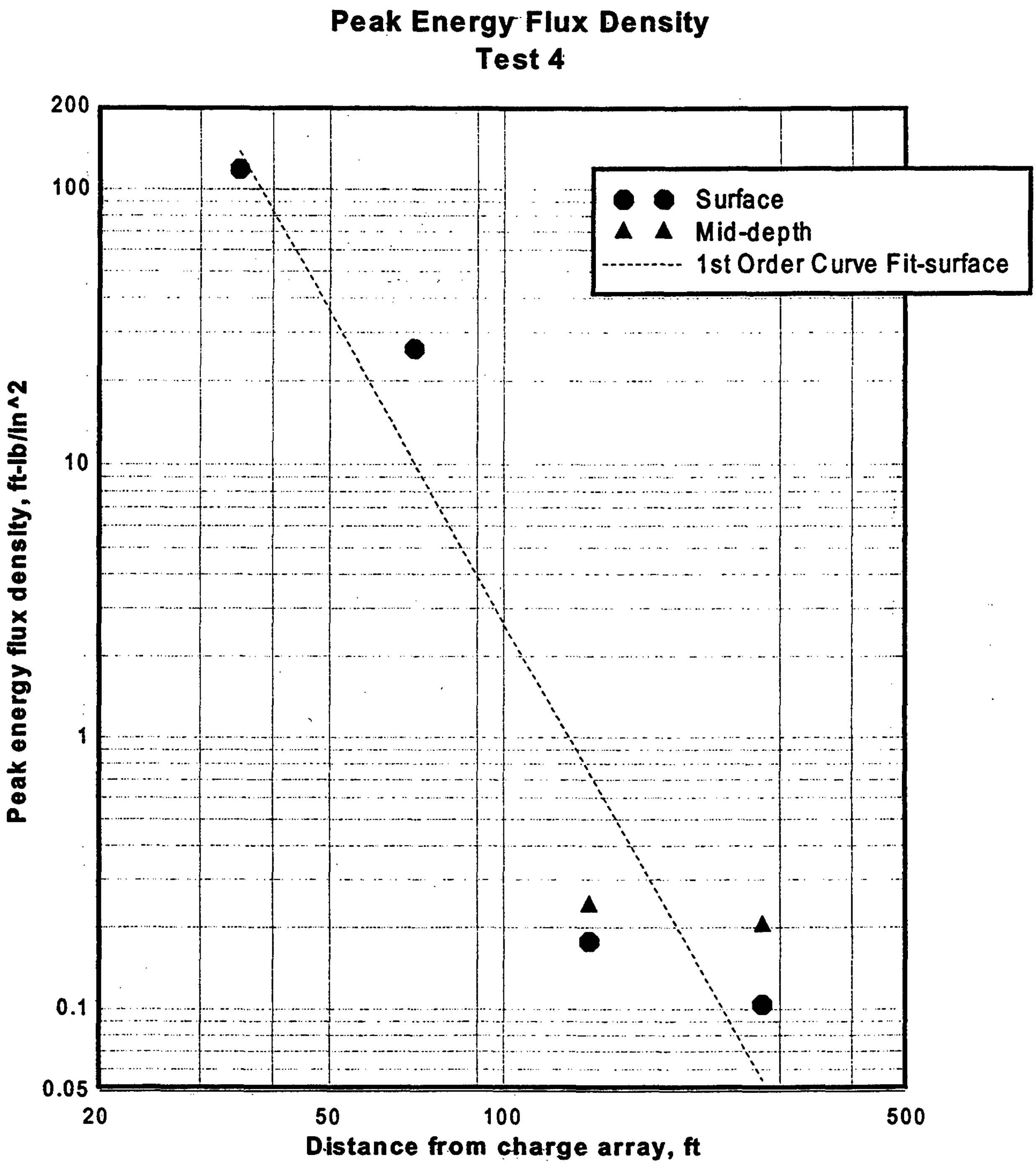
Peak Energy Flux Density, BEM Tests 2-9

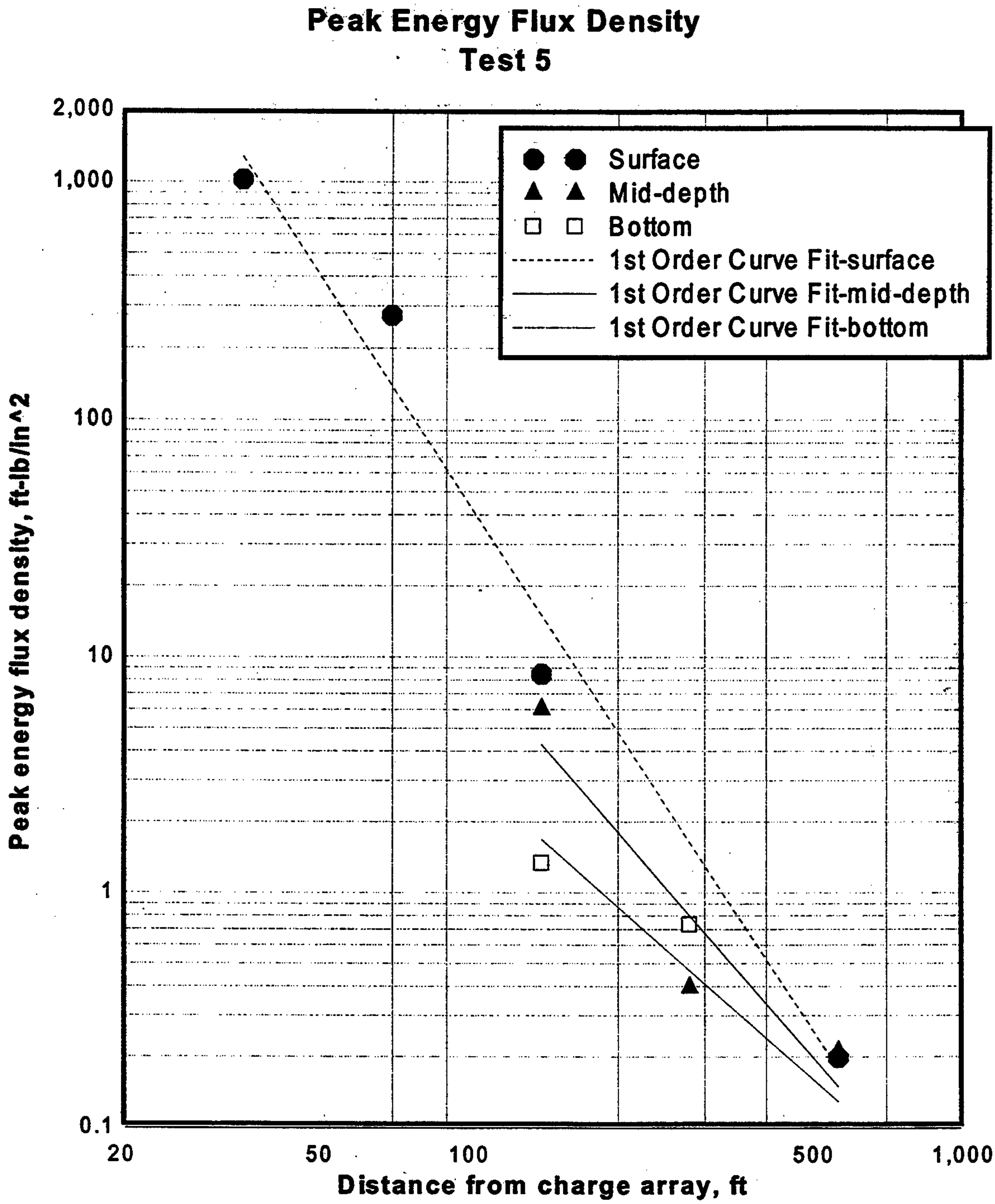


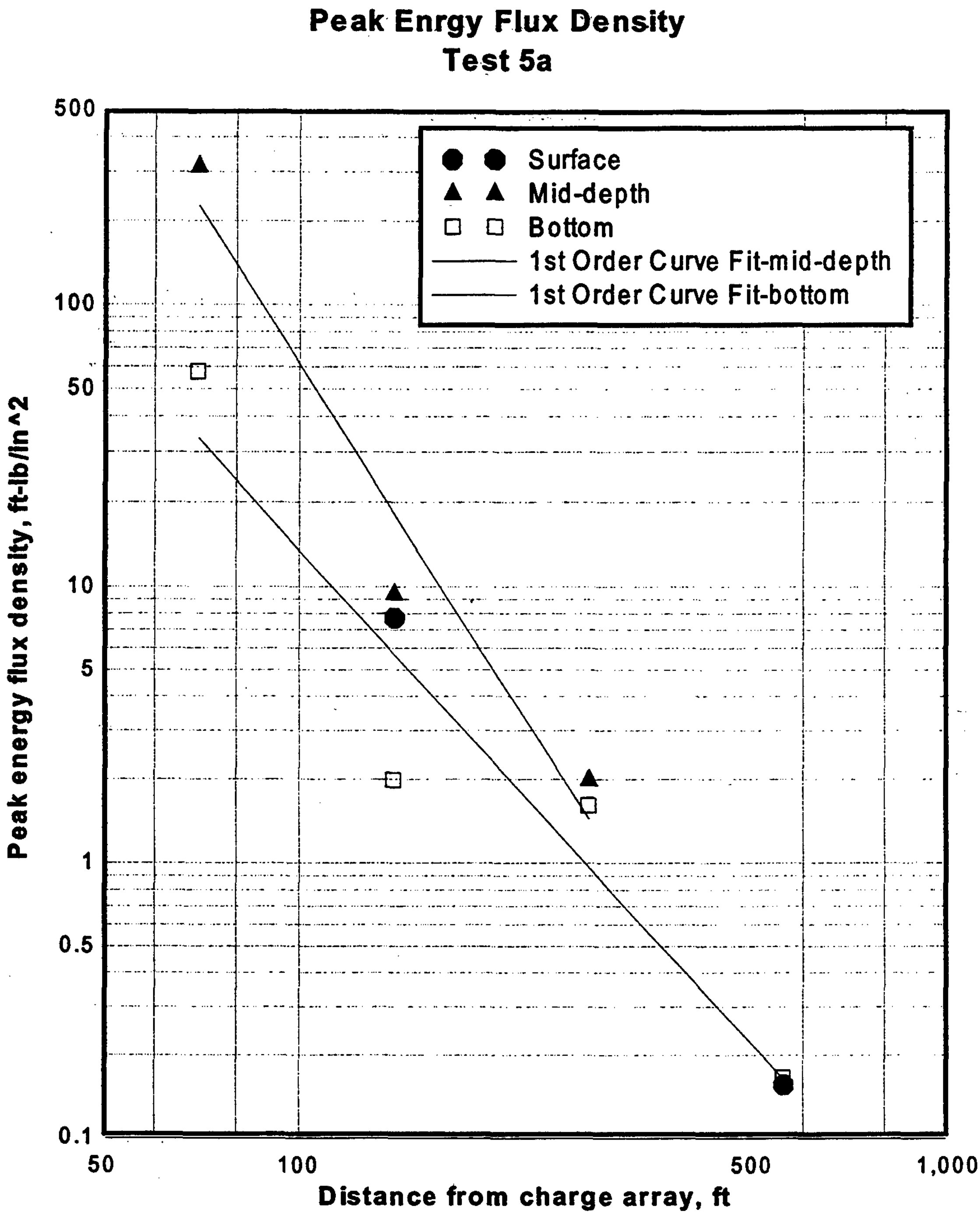
Peak Energy Flux Denisty
Test 2
Surface
Bottom
1st Order Curve Fit-surface
1st Order Curve Fit-bottom
5,000
1,000
100
10
1
0.1
0.01
20
50
100
500
Peak energy flux density, ft-lb/in^2
Distance from charge array, ft

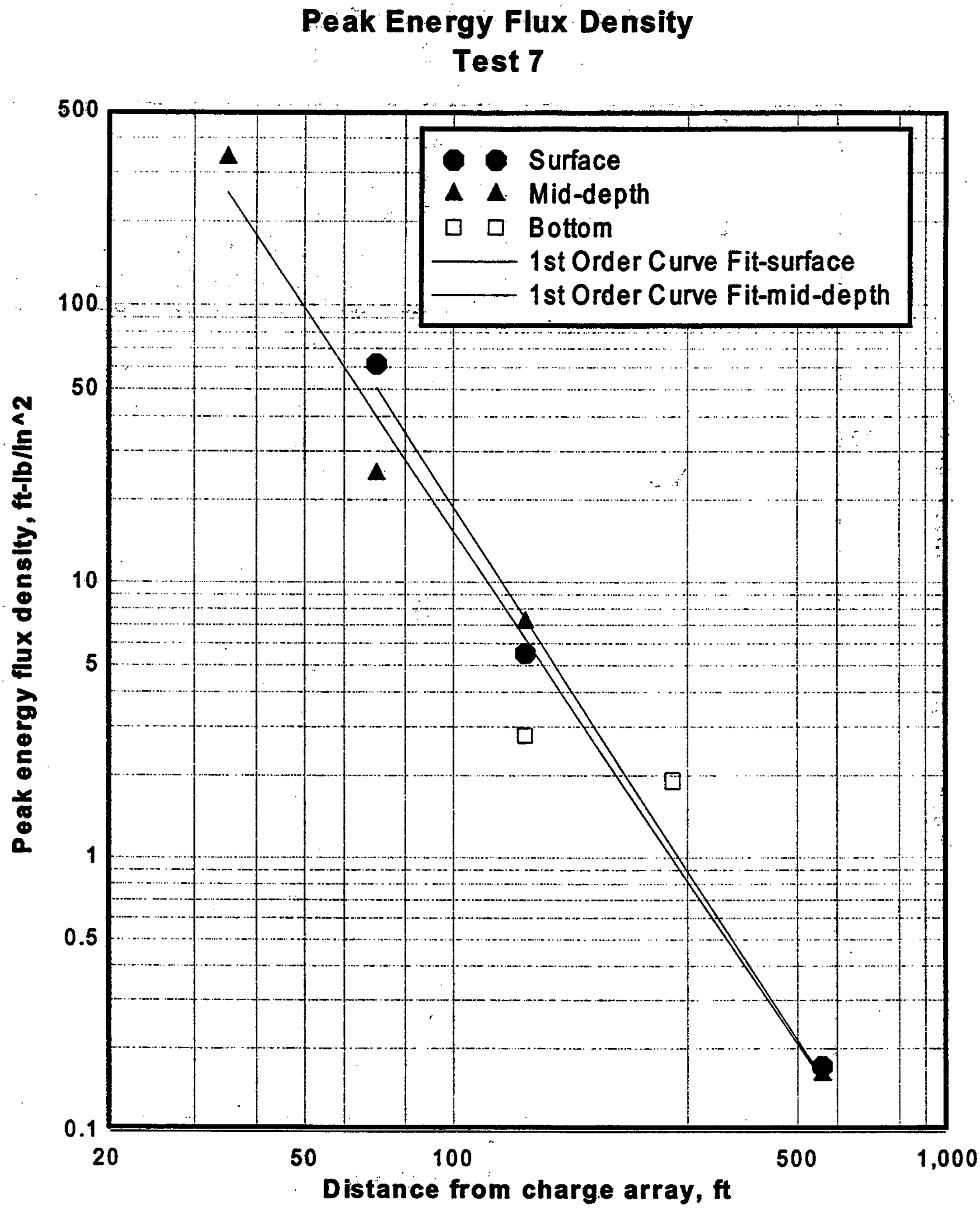
Peak Energy Flux Density
Test 3

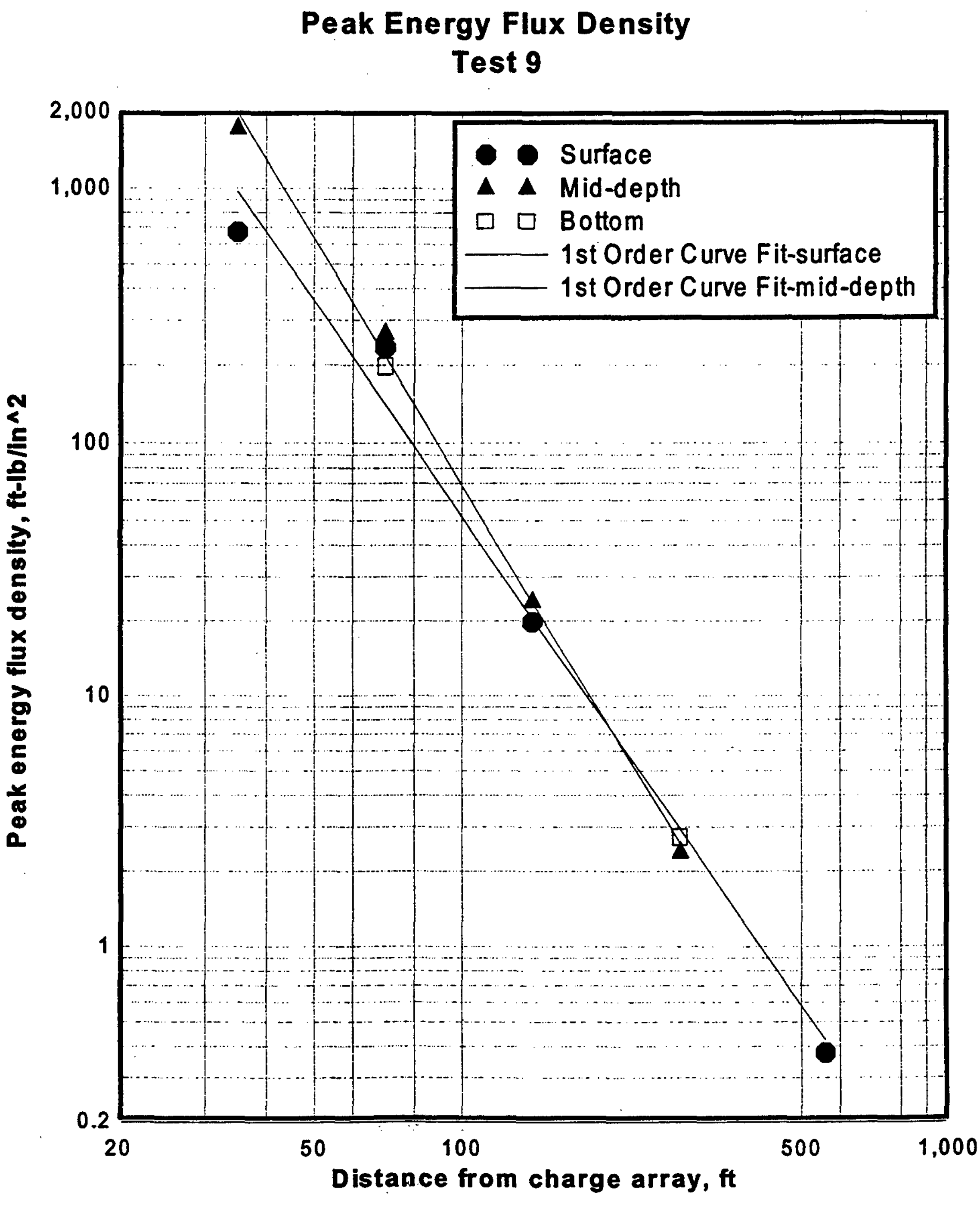



Peak Energy Flux Density
Test 4
Surface
Mid-depth
1st Order Curve Fit-surface
Peak energy flux density, ft-lb/in^2
200
100
10
1
0.1
0.05
20
50
100
500
Distance from charge array, ft


Peak Energy Flux Density
Test 5
Surface
Mid-depth
Bottom
1st Order Curve Fit-surface
1st Order Curve Fit-mid-depth
1st Order Curve Fit-bottom
2,000
1,000
100
10
1
0.1
20
50
100
500
1,000
Peak energy flux density, ft-lb/in^2
Distance from charge array, ft


Peak Enrgy Flux Density
Test 5a
Surface
Mid-depth
Bottom
1st Order Curve Fit-mid-depth
1st Order Curve Fit-bottom
500
100
50
10
5
1
0.5
0.1
50
100
500
1,000
Peak energy flux density, ft-lb/in^2
Distance from charge array, ft


Peak Energy Flux Density
Test 7
Surface
Mid-depth
Bottom
1st Order Curve Fit-surface
1st Order Curve Fit-mid-depth
Peak energy flux density, ft-lb/in^2
500
100
50
10
5
1
0.5
0.1
20
50
100
500
1,000
Distance from charge array, ft


Peak Energy Flux Density
Test 9
Surface
Mid-depth
Bottom
1st Order Curve Fit-surface
1st Order Curve Fit-mid-depth
2,000
1,000
100
10
1
0.2
20
50
100
500
1,000
Distance from charge array, ft
Peak energy flux density, ft-lb/in^2

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
August 2000

2. REPORT TYPE
Final Report

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Analysis of Water Shock Data and Bubble Screen Effectiveness on the Blast Effect Mitigation Test Series, Wilmington Harbor, North Carolina

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Denis D. Rickman

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Engineer Research and Development Center
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER

ERDC/SL TR-00-4

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This document summarizes the results of data analysis conducted by the U.S. Army Engineer Research and Development Center, Waterways Experiment Station (WES), in support of the Blast Effect Mitigation (BEM) Tests, Wilmington Harbor, North Carolina. Water shock data from the BEM Tests were analyzed in an attempt to evaluate the effectiveness of bubble screens in reducing the water shock produced during explosive excavation of the existing shipping channel in the Cape Fear River, North Carolina. The water shock data were also analyzed to determine the peak levels of water shock pressure, impulse, and energy-flux density produced by the blasting.

15. SUBJECT TERMS

Bubble screens	Underwater blasting
Rock blasting	Water Shock

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED		UNCLASSIFIED		100	

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WATERWAYS EXPERIMENT STATION, 3909 HALLS FERRY ROAD
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REPLY TO
ATTENTION OF:
CEERD-SD-R

26 September 2000

ERRATA SHEET

No. 1

ANALYSIS OF WATER SHOCK DATA AND BUBBLE SCREEN EFFECTIVENESS ON THE BLAST EFFECT MITIGATION TEST SERIES, WILMINGTON HARBOR, NORTH CAROLINA

ERDC/SL TR-00-4

August 2000

Insert attached References (omitted from printed copy).